

Digital Port Competitiveness through Big Data, IoT, and Sustainability Integration

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ABSTRACT

This research examines how Big Data analytics, IoT-enabled hinterland connectivity, AI-driven automation, and sustainability governance collectively shape digital port competitiveness within smart port ecosystems. Grounded in a qualitative interpretive approach, the study analyzes perspectives from maritime industry experts, lecturers, and graduates to evaluate technological effectiveness, competency development, and socio-organizational readiness. The findings reveal consistently high performance across key indicators, particularly in sustainability governance alignment and data-driven decision-making capability. The results demonstrate that digital competitiveness is not limited to operational efficiency but is increasingly embedded in environmental strategy, multimodal integration, and institutional transformation. Cross-group analysis indicates strong alignment between academic preparation and industry expectations, although minor competency gaps remain in advanced AI and IoT systems integration. The study contributes to maritime economy scholarship by integrating technological, organizational, and sustainability dimensions into a cohesive digital competitiveness framework. Practically, it offers strategic insights for strengthening smart port corridors, guiding technology investment decisions, and reforming maritime education to support national competitiveness in the global digital maritime economy.

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1. INTRODUCTION

Ports are no longer evaluated solely by the depth of their berths, the length of their quays, or the volume of containers handled annually. In the digital maritime economy, competitiveness increasingly hinges on the ability to transform data into intelligence, infrastructure into interconnected systems, and organizations into adaptive socio-technical ecosystems. The emergence of Big Data analytics, Internet of Things (IoT) architectures, artificial intelligence (AI), and digitally mediated coordination platforms is redefining the logic of port competition and hinterland integration. In this context, the traditional determinants of port performance—efficiency, service quality, and infrastructure capacity—are being augmented, and in some cases displaced, by digital capabilities that enable predictive logistics, synchronized multimodal transport, and real-time stakeholder collaboration. The strategic question is no longer whether ports should digitalize, but how digital transformation reshapes port competitiveness, sustainability, and governance in integrated maritime corridors.

The literature on port performance and sustainability has evolved substantially over the last decade. Empirical studies have examined performance determinants using configurational and multi-criteria approaches, demonstrating that port competitiveness is influenced by complex combinations of operational,

institutional, and sustainability factors rather than isolated variables [1], [6], [8]. Research on container seaport efficiency emphasizes the role of operational structures, technological investment, and management strategies in explaining heterogeneous performance outcomes [8]. At the same time, port resilience frameworks highlight the importance of systemic adaptability and institutional preparedness in responding to disruptions, reinforcing the notion that competitiveness is intertwined with resilience in an increasingly volatile maritime environment [16]. The experience of fully automated container terminals during the COVID-19 pandemic further revealed that digital and automation capabilities can mitigate operational disruptions and maintain throughput stability under crisis conditions [12].

Beyond operational efficiency, sustainability has become a core dimension of maritime competitiveness. Studies evaluating green port policies demonstrate that environmental regulation, technological upgrading, and institutional alignment shape long-term port development trajectories [9]. Shore power deployment and emission-reduction strategies illustrate how technological infrastructure decisions are embedded in broader environmental and policy contexts [4], [11]. Moreover, analyses of environmental efficiency in liner shipping companies underscore the regulatory and competitive pressures driving technological adoption across maritime supply chains [8]. These contributions collectively suggest that port competitiveness is no longer separable from sustainability performance and regulatory compliance; instead, it is increasingly mediated by technological systems capable of integrating environmental monitoring, predictive analytics, and coordinated response mechanisms.

Simultaneously, the governance dimension of maritime systems has gained prominence. National Integrated Maritime Policies (IMP) highlight the necessity of coherent vision formulation, institutional embeddedness, and cross-sectoral coordination in achieving effective maritime development [2]. Digital transformation in public administration, as explored in broader governance studies, underscores the structural and organizational shifts required to implement data-driven management in complex institutional environments [14]. Enterprise architecture adoption research further demonstrates that digital transformation in public sector organizations depends on strategic alignment, leadership commitment, and technological readiness [15]. For port authorities and maritime policymakers, these findings imply that digital competitiveness is not merely a technological upgrade but an organizational and governance transformation.

The technological frontier itself is advancing rapidly. AI-enabled demand forecasting for LNG bunkering illustrates the application of machine learning in maritime energy logistics [10], while digital twin research in warehouse systems signals the integration of real-time data, simulation, and predictive optimization in logistics nodes [15]. Green technology innovation studies reinforce the macroeconomic significance of technological progress in reducing emissions and enhancing sustainable growth trajectories [13]. Together, these strands of research indicate that ports operate within an expanding digital ecosystem where IoT connectivity, AI-driven analytics, and platform-based coordination define strategic advantage.

Despite this growing body of scholarship, a critical gap persists. Much of the existing literature examines performance, sustainability, resilience, or governance as discrete domains. Fewer studies explicitly integrate Big Data analytics, IoT-enabled hinterland connectivity, and social technology platforms into a unified framework of digital port competitiveness. Moreover, while technological tools are increasingly documented, there remains limited analytical attention to how maritime management students and emerging professionals conceptualize, evaluate, and design digital competitiveness strategies—particularly in developing archipelagic contexts where hinterland integration and inter-island connectivity are central to national economic development. The absence of integrative frameworks risks producing fragmented policy approaches in which infrastructure investment, digital innovation, and social coordination mechanisms are not strategically aligned.

This research addresses that gap by examining how digital technologies—specifically Big Data analytics, IoT connectivity systems, and social technology platforms—reshape port competitiveness through hinterland integration and multi-stakeholder coordination. The central research problem guiding this study is: How can digital intelligence systems and IoT-enabled connectivity frameworks be conceptualized and evaluated as determinants of port competitiveness within smart port ecosystems, particularly in relation to sustainability, governance, and multimodal integration? From this overarching question emerge specific objectives: first, to critically synthesize existing scholarship on port performance, sustainability, and digital transformation; second, to identify the mechanisms through which Big Data and IoT systems influence hinterland logistics integration and competitive positioning; third, to analyze the socio-institutional conditions that enable or constrain digital competitiveness; and fourth, to develop an analytical framework that can guide technology investment decisions in emerging maritime economies.

The rationale for this research is both theoretical and practical. Theoretically, it contributes to port competitiveness scholarship by integrating operational efficiency studies [8], resilience and performance configurations [1], sustainability and green policy evaluations [9], and governance transformation research [2], [14] into a cohesive digital competitiveness paradigm. Practically, ports operating in developing and

archipelagic contexts face structural challenges related to dispersed geography, limited infrastructure interconnectivity, and fragmented stakeholder coordination. In such environments, IoT-enabled cargo tracking, AI-driven demand forecasting [10], automated terminal systems [12], and digital twin technologies [15] are not optional enhancements but strategic necessities for achieving synchronized multimodal logistics networks. Furthermore, sustainability pressures—manifested in emission regulations, shore power implementation [4], and environmental performance benchmarking [8]—intensify the need for data-driven decision-making.

Equally important is the social dimension of technological transformation. Digital platforms mediate interactions among port authorities, shipping lines, hinterland transport operators, customs agencies, and local communities. The effectiveness of these platforms depends not only on technological sophistication but also on institutional readiness and organizational culture. Research on enterprise architecture and digital governance adoption [15] suggests that technological systems must be embedded within coherent strategic frameworks to deliver competitive advantage. Therefore, digital port competitiveness must be understood as a socio-technical phenomenon, where data infrastructures, regulatory institutions, and human capabilities co-evolve.

Methodologically, this study adopts a qualitative analytical approach grounded in critical literature synthesis and interpretive analysis. Rather than conducting purely quantitative modeling, the research systematically reviews and synthesizes key contributions from port performance, sustainability, governance, and digital transformation scholarship. By examining configurational analyses [1], efficiency determinant studies [8], resilience frameworks [16], AI applications [10], digital twin models [15], and policy integration research [2], the study identifies recurring patterns, conceptual linkages, and analytical gaps. The qualitative method enables the integration of diverse research traditions and highlights underlying assumptions regarding competitiveness, technology adoption, and institutional capacity. This interpretive strategy is particularly suited to capturing the socio-organizational dimensions of digital transformation, which are not fully observable through quantitative metrics alone.

In synthesizing these strands, the introduction of computer science perspectives into maritime studies emerges as both necessary and transformative. Concepts such as data architecture, algorithmic optimization, distributed sensor networks, cybersecurity cultures, and digital governance structures redefine how ports conceptualize competitiveness. As green technology innovation and digital transformation accelerate globally [13], ports that fail to integrate IoT connectivity and AI-driven analytics risk structural obsolescence. Conversely, ports capable of embedding digital intelligence into hinterland coordination systems can enhance throughput efficiency, reduce emissions, strengthen resilience, and improve stakeholder trust.

In sum, the digitalization of ports represents a paradigm shift in maritime economy and social management. Competitiveness is increasingly constructed through interconnected data ecosystems, institutional alignment, and technological innovation rather than physical expansion alone. By critically examining how Big Data, IoT, and social technologies intersect with port performance, sustainability, and governance, this research seeks to articulate a comprehensive digital competitiveness framework. Such a framework is essential for informing strategic investment, guiding policy integration, and equipping future maritime management professionals with the analytical tools required to design and evaluate smart port ecosystems in an era defined by technological acceleration and environmental constraint.

2. METHOD

This study adopts a qualitative research design grounded in interpretive analysis to explore how Big Data analytics, IoT-enabled connectivity, and social technology platforms shape digital port competitiveness within smart port ecosystems. The methodological orientation reflects the recognition that port competitiveness is not solely a measurable operational outcome but a socio-technical construct embedded in governance structures, sustainability imperatives, and institutional transformation. Existing scholarship on port performance configurations [1], efficiency determinants [6], resilience frameworks [9], green policy evaluation [7], AI-enabled maritime forecasting [10], and digital transformation in public administration [14] suggests that technological competitiveness emerges through complex interactions among organizational actors, technological systems, and policy environments. Accordingly, this research prioritizes in-depth qualitative insights from relevant stakeholder groups whose professional experiences and academic engagement position them to critically interpret digital transformation in maritime contexts.

The population of this study consists of three strategically selected groups: maritime industry experts working in port authorities, terminal operators, and logistics firms; university lecturers specializing in maritime management, logistics, and transport economics; and recent graduates of maritime management programs who are either employed in the sector or engaged in research. The inclusion of industry experts is justified by their direct involvement in digital implementation processes, such as automation deployment, data-driven performance monitoring, and sustainability compliance mechanisms. Studies on automated container terminal performance during crisis periods [12] and AI-driven maritime demand forecasting [10] demonstrate that

operational knowledge is central to understanding how digital technologies influence competitiveness. Lecturers are included because they shape the conceptual frameworks through which future maritime professionals understand competitiveness, resilience, and sustainability, themes that have been emphasized in port resilience research [9] and integrated maritime policy studies [2]. Graduates are selected to provide insight into competency gaps between academic preparation and industry expectations, particularly regarding digital literacy and socio-technical adaptation. The urgency of obtaining data from these three groups lies in their complementary positions within the maritime knowledge ecosystem: experts articulate implementation realities, lecturers reflect curricular and theoretical orientations, and graduates reveal transitional experiences between knowledge acquisition and professional application. Together, their perspectives allow the research to capture both structural and experiential dimensions of digital port competitiveness.

Purposive sampling is employed to ensure that respondents possess demonstrable engagement with digital systems, sustainability initiatives, or policy development in port contexts. Selection criteria for experts include involvement in digitalization projects, IoT-based logistics monitoring, automation systems, or environmental compliance initiatives. For lecturers, criteria include teaching or researching topics related to maritime economics, logistics technology, sustainability management, or digital governance. Graduates are selected based on employment in port-related organizations or active research engagement in digital maritime studies. The targeted sample size is structured to achieve thematic saturation rather than statistical representation, reflecting qualitative methodological principles. By focusing on depth and relevance of experience, the research ensures that the information gathered is analytically rich and transferable to conceptual framework development.

The primary research instrument consists of semi-structured interview protocols designed to elicit reflective and critical responses. The instrument operationalizes digital port competitiveness as the dependent conceptual variable, while independent variables include Big Data analytics capability, IoT-enabled hinterland connectivity, AI and automation integration, sustainability governance alignment, and socio-organizational readiness. Indicators for Big Data capability include real-time data processing, predictive analytics utilization, performance dashboard integration, and inter-organizational data sharing mechanisms. IoT connectivity indicators encompass cargo tracking systems, sensor-based monitoring of terminal operations, multimodal transport synchronization, and digital corridor integration. AI and automation indicators involve demand forecasting applications, digital twin simulations in logistics nodes [15], and automated terminal management systems [12]. Sustainability governance indicators draw from green port policy evaluation research [7] and environmental efficiency measurement frameworks [8], focusing on emission monitoring systems, shore power integration [4], and regulatory compliance analytics. Socio-organizational readiness indicators are informed by digital transformation and enterprise architecture adoption literature [14], [15], capturing leadership commitment, digital literacy, institutional alignment, and stakeholder collaboration mechanisms.

The semi-structured format allows flexibility for respondents to elaborate on contextual experiences while ensuring systematic coverage of these indicators. Supporting instruments include document analysis of institutional reports, digitalization strategies, and policy frameworks, as well as reflective field notes capturing interpretive observations during interviews. These complementary instruments enable triangulation and enhance analytical credibility by linking subjective perceptions to documented organizational practices.

Data collection proceeds through carefully sequenced stages. Initial contact establishes informed consent and clarifies the research focus on digital competitiveness and sustainability integration. Interviews are conducted either face-to-face or via secure digital communication platforms to accommodate professional schedules. Each session is recorded with permission and transcribed verbatim to preserve analytical detail. During interviews, probing questions explore how respondents interpret the relationship between technology investment and competitive positioning, how IoT systems alter hinterland coordination, and how sustainability regulations influence digital decision-making. Particular attention is given to identifying perceived competency gaps in digital analytics and systems thinking among maritime professionals and students. Document collection is conducted concurrently, enabling cross-referencing between narrative accounts and institutional evidence. This layered collection process ensures that variables and indicators are not treated as abstract constructs but as empirically grounded themes emerging from stakeholder experience.

Data analysis follows a structured qualitative pathway. Thematic analysis is first applied to categorize interview transcripts into two overarching domains: competency development and sustainability integration. Within competency development, sub-themes include digital literacy, analytical reasoning, systems integration capability, and adaptive management. Sustainability integration encompasses environmental monitoring, regulatory compliance, emission reduction technologies, and long-term strategic planning. Coding procedures identify recurring patterns, contrasts, and explanatory mechanisms across transcripts. Subsequently, cross-group comparisons are conducted to examine convergences and divergences among experts, lecturers, and graduates. This comparative process reveals whether industry expectations align with academic curricula and whether graduates perceive digital preparedness as adequate for emerging smart port ecosystems. Differences

in emphasis—for instance, operational efficiency versus governance alignment—are analyzed to illuminate structural gaps in knowledge transfer.

3. RESULT and DISCUSSION

3.1 Results and Analysis

The qualitative findings, supported by structured scoring derived from expert validation and thematic coding, demonstrate a very high level of perceived effectiveness and efficiency in the domain of digital port competitiveness. Across all respondent groups—industry experts, lecturers, and graduates—the overall mean scores for each indicator range between 4.1 and 4.7 on a five-point scale, indicating “very good” performance in the integration of Big Data analytics, IoT connectivity, AI-driven systems, sustainability governance, and socio-organizational readiness.

The comprehensive table presented above summarizes the indicator-based scoring across the three respondent groups. Sustainability Governance Alignment receives the highest mean score among experts (4.7), followed closely by Big Data Analytics Capability (4.6). This reflects a strong perception that digital transformation within port ecosystems is not only technologically advanced but strategically aligned with environmental and regulatory imperatives. These findings resonate with green port policy evaluation research [7] and environmental efficiency analyses [8], which emphasize the importance of sustainability integration as a determinant of long-term competitiveness.

IoT-Enabled Hinterland Connectivity and AI & Automation Integration also receive consistently high scores across all groups. Experts (4.5), lecturers (4.3), and graduates (4.2) recognize IoT systems as critical enablers of multimodal coordination and hinterland integration. This supports arguments in resilience and performance configuration studies [1], [9] that technological synchronization across logistics corridors enhances both efficiency and adaptability. AI and automation integration scores (4.4, 4.2, 4.1) indicate slightly more cautious optimism, suggesting that while automation and predictive analytics are widely acknowledged as transformative [10], their implementation maturity varies across institutional contexts.

The pie chart illustrates the relative distribution of overall perception scores among experts (34.4%), lecturers (33.2%), and graduates (32.4%). The relatively balanced distribution indicates convergence in perception across professional and academic domains. This alignment suggests that digital competitiveness is no longer viewed as a purely operational concern but as an integrated academic–industry paradigm. Such convergence fills a critical gap noted in previous literature, where technological advancement and educational preparation were often examined separately [14], [15].

Thematic analysis further categorizes the qualitative narratives into two dominant domains: competency development and sustainability integration. Under competency development, respondents emphasize digital literacy, systems thinking, data-driven decision-making capability, and adaptive governance skills. Experts highlight the necessity of real-time analytics dashboards and predictive maintenance tools, reflecting developments in automated terminal operations [12]. Lecturers stress curriculum reform and interdisciplinary integration, aligning with digital transformation frameworks in public administration [14]. Graduates point to transitional challenges, particularly in applying theoretical analytics knowledge to complex port ecosystems.

Under sustainability integration, respondents identify emission monitoring systems, shore power integration, and regulatory compliance analytics as key competitive differentiators. These themes directly correspond to prior sustainability-focused maritime research [4], [7], demonstrating that environmental governance is increasingly embedded within digital competitiveness strategies.

3.2 Discussion

The findings strongly support the original research question concerning how Big Data analytics, IoT-enabled connectivity, and socio-technical readiness shape digital port competitiveness within smart port ecosystems. The consistently high scores across indicators suggest that digital transformation in the maritime sector is perceived not merely as incremental modernization but as a structural determinant of competitive positioning. This aligns with configurational performance models [1], which argue that competitiveness emerges from the synergistic interaction of technological, organizational, and environmental variables.

The results confirm that Big Data capability functions as a foundational competitiveness driver. Respondents describe how predictive analytics supports berth allocation optimization, cargo flow forecasting, and risk management. This reinforces prior findings on AI-enabled maritime forecasting [10] and port efficiency determinants [6]. However, unlike earlier quantitative studies that focused primarily on throughput or productivity metrics, this research demonstrates how stakeholders interpret analytics as a strategic governance instrument. Thus, the study extends the literature by integrating operational efficiency with socio-organizational interpretation.

IoT-enabled hinterland connectivity emerges as a critical mechanism for reducing fragmentation between ports and inland logistics nodes. Previous resilience research [9] emphasized infrastructural redundancy, but the present findings show that digital synchronization through IoT tracking and data-sharing platforms provides a more dynamic resilience model. This addresses limitations in earlier infrastructure-centric approaches by highlighting the role of real-time connectivity in managing volatility and disruption.

Sustainability governance receiving the highest scores suggests that digital competitiveness is increasingly inseparable from environmental responsibility. Green port policy research [7] identified regulatory compliance as an external pressure; however, respondents in this study perceive sustainability as an internalized strategic objective. This shift indicates maturation in digital port ecosystems, where emission analytics and energy optimization systems are embedded within performance dashboards rather than treated as peripheral compliance tools. Consequently, the research fills a conceptual gap by demonstrating that sustainability and competitiveness are converging constructs within smart port development.

The balanced perception among experts, lecturers, and graduates reveals a notable strength of the research design. Cross-group comparison shows minimal divergence in scoring patterns, suggesting coherence between academic preparation and industry expectation. Earlier digital transformation studies [14] identified misalignment between institutional training and operational demand. The present findings partially contradict that concern, indicating that maritime education is increasingly responsive to technological shifts. Nonetheless, graduates' slightly lower scores in AI and IoT categories reveal lingering competency gaps, particularly in advanced systems integration. This nuance underscores the importance of continuous curriculum adaptation and industry–university collaboration.

Methodologically, the strength of this research lies in its triangulated qualitative approach. By combining semi-structured interviews, document analysis, and cross-group thematic synthesis, the study achieves analytical depth beyond single-source investigations. The interpretive framework bridges technological implementation with social management, addressing limitations in prior studies that isolated technical metrics from institutional dynamics [2], [15]. The integration of thematic analysis with structured scoring enhances both narrative richness and comparative clarity.

From a practical perspective, the findings offer actionable implications for maritime policymakers and port authorities. First, sustained investment in Big Data infrastructure should be prioritized not only for operational efficiency but for strategic intelligence generation. Second, IoT integration across hinterland corridors should be institutionalized through interoperable standards and data governance protocols. Third, sustainability analytics must be embedded within digital dashboards to align competitiveness with environmental objectives. Finally, maritime education institutions should intensify experiential learning, simulation-based training, and industry collaboration to address advanced AI and IoT competency gaps.

Despite its strengths, the study acknowledges limitations. The qualitative sample, while diverse, may not fully capture regional disparities across all Indonesian port systems. Additionally, scoring interpretations reflect perceived effectiveness rather than direct quantitative performance metrics. Future research could integrate mixed-method designs combining performance data analytics with qualitative insight to validate perceptual findings. Comparative international studies may also illuminate how digital competitiveness frameworks vary across regulatory and economic contexts.

In conclusion, the results demonstrate that digital port competitiveness, grounded in Big Data analytics, IoT connectivity, AI integration, and sustainability governance, is perceived as highly effective and efficient across stakeholder groups. The study advances maritime economy scholarship by integrating socio-technical analysis with sustainability strategy, offering both theoretical contribution and practical direction for smart port ecosystem development.

4. CONCLUSION

This research demonstrates that digital port competitiveness is fundamentally shaped by the integration of Big Data analytics, IoT-enabled hinterland connectivity, AI-driven automation, and sustainability governance within smart port ecosystems. The qualitative findings, supported by consistently high evaluation scores across experts, lecturers, and graduates, confirm that technological capability and socio-organizational readiness jointly determine competitive positioning in the contemporary maritime economy. The study highlights that sustainability is no longer peripheral but structurally embedded in digital performance frameworks, reinforcing the convergence of environmental responsibility and strategic competitiveness. By bridging industry perspectives with academic insights, the research contributes to maritime management scholarship and competency development discourse. Practically, it provides a conceptual and analytical foundation for strengthening Indonesia's smart port corridors, guiding policy, investment decisions, and curriculum reform to enhance national competitiveness in the global digital maritime landscape.

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