Integrating Digital Twin Technology in Port Operations: A Framework for Enhancing Operational Efficiency in Indonesian Maritime Hubs

Derma Watty Sihombing [1*], M. Anang Jatmiko [1], A . Nurfajri Irwan[1]
[1] Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia
Jl. Marunda Makmur, RT.1/RW.1, Marunda, Kec. Cilincing, Jakarta Utara,
Daerah Khusus Ibukota Jakarta 14150
Korespondensi penulis: dermawatysihombing@gmail.com

Abstract*. This research investigates stakeholder perspectives on Digital Twin technology integration for enhancing operational efficiency in Indonesian port operations, focusing on maritime education institution viewpoints. Employing qualitative-dominant mixed methods, the study gathered insights through Focus Group Discussions, interviews, and surveys with thirty participants comprising maritime students, lecturers, and veteran practitioners at Sekolah Tinggi Ilmu Pelayaran Jakarta. Thematic analysis revealed overwhelmingly positive perceptions regarding Digital Twin operational benefits (mean score: 4.41/5.0), with particular emphasis on real-time decision support, predictive maintenance, and yard management optimization. However, stakeholders identified multifaceted implementation challenges including technological infrastructure limitations (28%), financial constraints (24%), and human capital competency gaps (23%). Findings emphasize that successful Digital Twin integration requires comprehensive frameworks addressing technological deployment, systematic competency development, and institutional readiness simultaneously. The research highlights maritime education institutions' strategic role in advancing technology adoption through curriculum innovation, specialized training programs, and industry-academia collaboration. Results provide actionable insights for developing contextually appropriate Digital Twin integration frameworks that position Indonesian ports competitively within global maritime networks while addressing emerging economy implementation realities.*

Keywords*: Digital Twin technology; port operational efficiency; maritime education; stakeholder perspectives; Indonesian maritime sector*

1. INTRODUCTION

The global maritime industry stands at the precipice of a technological revolution, where digital transformation has become not merely an option but an imperative for competitive survival and operational excellence (Inkinen et al., 2019). Among the most promising innovations emerging in port management is Digital Twin (DT) technology, a sophisticated virtual replica system that mirrors physical assets, processes, and systems in real-time, enabling predictive analytics, simulation, and optimization (Botín-Sanabria et al., 2022). As Indonesian maritime hubs grapple with increasing cargo volumes, port congestion, and the pressing need for operational efficiency improvements, the question of how Digital Twin technology can be effectively integrated into existing port operations has gained unprecedented urgency. This technological paradigm shift arrives at a critical juncture when Indonesian ports, serving as vital gateways for the archipelagic nation's economic prosperity, must enhance their operational capabilities to remain competitive within the ASEAN maritime landscape and global supply chains.

Indonesia's strategic position as a maritime nation, encompassing over 17,000 islands and connecting major international shipping routes, places extraordinary demands on its port

infrastructure and operational systems (Wahyuni & Pujawan, 2021). Traditional port management approaches, characterized by manual processes, fragmented information systems, and reactive decision-making frameworks, have increasingly proven inadequate in addressing contemporary challenges such as vessel turnaround time optimization, yard management efficiency, and real-time resource allocation. The advent of Industry 4.0 technologies, particularly Digital Twin systems, offers transformative potential to revolutionize port operations through data-driven decision-making, predictive maintenance, and dynamic optimization capabilities (Philipp et al., 2021). However, despite the evident technological promise, significant knowledge gaps persist regarding the practical implementation frameworks, institutional readiness factors, and human capital requirements necessary for successful Digital Twin integration within Indonesian maritime educational and operational contexts.

The research problem central to this investigation concerns the apparent disconnect between the theoretical potential of Digital Twin technology and its practical application within Indonesian port operations, particularly from the perspective of maritime education institutions responsible for developing future industry professionals. Specifically, this research seeks to answer the fundamental question: What constitutes an effective framework for integrating Digital Twin technology in Indonesian port operations, and what are the critical competency requirements, institutional barriers, and implementation strategies as perceived by maritime education stakeholders? The specific objectives guiding this inquiry include: (1) identifying the current understanding and awareness levels of Digital Twin technology among maritime students, lecturers, and industry practitioners; (2) determining the perceived operational efficiency benefits and challenges associated with Digital Twin implementation in Indonesian ports; (3) examining the competency gaps and training requirements necessary for effective technology adoption; and (4) developing a contextually relevant framework for Digital Twin integration that addresses both technological and human capital dimensions.

The significance of this research extends beyond mere technological adoption to encompass broader implications for Indonesia's maritime competitiveness, educational curriculum development, and workforce transformation strategies. As maritime education institutions bear the responsibility of preparing industry-ready professionals equipped with contemporary technological competencies, understanding stakeholder perspectives on Digital Twin technology becomes paramount for curriculum innovation and industry alignment

(Cahoon et al., 2020). Furthermore, this investigation addresses a critical gap in existing literature, which predominantly focuses on developed maritime nations' experiences while neglecting the unique contextual challenges, resource constraints, and implementation dynamics characteristic of emerging maritime economies. The rationale for conducting this research within a maritime educational institution stems from the recognition that successful technological transformation requires not only infrastructure investment but also systematic human capital development, institutional readiness, and stakeholder buy-in—elements best understood through comprehensive stakeholder engagement.

Methodologically, this research adopts a qualitative-dominant mixed methods approach, gathering rich, contextualized insights through Focus Group Discussions, semi-structured interviews, surveys, and expert opinions from three distinct stakeholder groups within Sekolah Tinggi Ilmu Pelayaran Jakarta: maritime students representing future industry professionals, lecturers embodying academic expertise and pedagogical perspectives, and veteran maritime officers now serving as practitioners who bridge theoretical knowledge with operational realities. This triangulated approach enables comprehensive exploration of Digital Twin technology perception, anticipated benefits, implementation challenges, and competency requirements from multiple vantage points, thereby generating holistic understanding essential for developing practically viable and contextually appropriate integration frameworks. The thematic analysis of qualitative data, complemented by cross-group comparative insights, provides nuanced understanding of how different stakeholders conceptualize Digital Twin technology's role in enhancing port operational efficiency while identifying convergent and divergent perspectives that inform balanced implementation strategies.

2. RESEARCH METHOD

This research employed a qualitative-dominant mixed methods design to explore stakeholder perspectives on Digital Twin technology integration in Indonesian port operations, utilizing an interpretivist philosophical foundation that prioritizes understanding subjective meanings and contextual experiences (Creswell & Creswell, 2018). The methodological framework deliberately focused on gathering rich, nuanced insights from maritime education stakeholders who possess unique vantage points on both technological adoption challenges and workforce development imperatives. The population for this investigation comprised all stakeholders affiliated with Sekolah Tinggi Ilmu Pelayaran

Jakarta, with purposive sampling employed to select information-rich participants across three distinct categories: maritime students currently enrolled in nautical and maritime programs who represent the future workforce requiring Digital Twin competencies; lecturers with expertise in maritime operations, technology, and management who shape curriculum and pedagogical approaches; and veteran maritime officers now serving as practitioners and instructors who possess extensive operational experience and bridge academic-industry perspectives. The rationale for this multi-stakeholder sampling approach stems from recognition that comprehensive understanding of technology integration requires triangulated perspectives encompassing aspirational future needs, educational capacity realities, and practical implementation wisdom derived from operational experience (Merriam & Tisdell, 2016). Sample sizes were determined through theoretical saturation principles, ultimately including fifteen students representing diverse academic levels, eight lecturers from relevant departments, and seven veteran practitioners, totaling thirty participants whose collective insights provide comprehensive coverage of the research domain.

The research instruments were carefully designed to elicit detailed, contextually grounded responses regarding Digital Twin technology awareness, perceived operational benefits, implementation challenges, and competency requirements. The primary instrument consisted of semi-structured interview protocols developed around dependent variables including perceived operational efficiency improvements, implementation readiness levels, and anticipated challenges, while independent variables encompassed stakeholder category, years of maritime experience, and technological familiarity levels. Specific indicators operationalizing these variables included awareness and understanding of Digital Twin concepts, identification of port operational efficiency challenges addressable through technology, perceived benefits across multiple operational dimensions including vessel turnaround time, yard management, resource allocation, and predictive maintenance, recognition of implementation barriers encompassing technological infrastructure, financial resources, human capital competencies, and institutional readiness, and articulation of required competencies and training needs for effective technology adoption. Supporting instruments included survey questionnaires administering Likert-scale items measuring technology acceptance and readiness perceptions, Focus Group Discussion protocols enabling collective meaning-making and interactive dialogue, and documentary analysis examining existing curriculum materials and training frameworks to contextualize stakeholder perspectives within current educational offerings.

Data collection proceeded through systematic, phased procedures beginning with institutional approval and participant recruitment emphasizing voluntary participation and informed consent principles, followed by administration of baseline surveys establishing participants' demographic profiles and general technology awareness levels (Kumar, 2019). Semi-structured individual interviews averaging sixty to ninety minutes were conducted with lecturers and practitioners, employing open-ended questions encouraging detailed elaboration while allowing flexibility to pursue emergent themes, whereas Focus Group Discussions involving student participants facilitated peer interaction and collective exploration of technology perceptions and learning needs. All interactions were audio-recorded with participant consent and professionally transcribed verbatim to ensure data accuracy and enable rigorous analysis. Field notes documenting non-verbal cues, contextual observations, and interviewer reflections complemented transcribed data, enriching interpretive understanding. The collection process emphasized establishing rapport, ensuring participant comfort, and employing probing techniques to elicit depth and specificity in responses.

Data analysis followed systematic thematic analysis procedures involving initial familiarization through repeated reading of transcripts, systematic coding identifying meaning units and patterns within data, and iterative theme development organizing codes into coherent conceptual categories aligned with research objectives. The analysis specifically focused on categorizing insights into competency development requirements, operational efficiency benefits, implementation challenges, and strategic recommendations themes, enabling structured interpretation of stakeholder perspectives. Cross-group comparisons systematically examined similarities and differences among student, lecturer, and practitioner perspectives, identifying areas of consensus regarding technology potential while highlighting divergent views on implementation timelines, resource requirements, and priority actions reflecting each group's distinct experiential backgrounds and institutional roles. Narrative synthesis integrated findings across data sources and stakeholder groups, developing cohesive explanatory accounts illuminating how Digital Twin technology is conceptualized within maritime education contexts, what barriers impede adoption, and what strategies might facilitate effective integration. Methodological rigor was enhanced through member checking procedures validating interpretations with participants, peer debriefing sessions discussing findings with maritime education colleagues, and reflexive journaling documenting researcher positionality and analytical decision-making processes.

3. RESULTS AND DISCUSSION
Results and Analysis

The qualitative analysis of stakeholder perspectives revealed overwhelmingly positive perceptions regarding Digital Twin technology's potential to enhance operational efficiency in Indonesian port operations, with participants demonstrating sophisticated understanding of technology benefits despite varying levels of technical familiarity. Thematic analysis identified four primary domains where Digital Twin integration was perceived to deliver substantial operational improvements: real-time monitoring and decision-making capabilities, predictive maintenance and asset management, resource optimization and allocation efficiency, and training and simulation applications for workforce development.

Regarding awareness and understanding levels, results indicated significant variation across stakeholder groups. Lecturer participants demonstrated the highest conceptual familiarity with Digital Twin technology (Mean Score: 4.2/5.0), articulating detailed understanding of virtual replication systems, data integration architectures, and analytical applications. Veteran practitioners exhibited moderate awareness levels (Mean Score: 3.5/5.0), typically framing Digital Twin concepts through operational lenses emphasizing practical problem-solving rather than technical specifications, while student participants showed emerging understanding (Mean Score: 3.1/5.0) primarily derived from recent technological education initiatives and Industry 4.0 curriculum integration efforts. Notably, cross-group analysis revealed convergent recognition that Digital Twin technology represents critical competency requirements for future maritime professionals, with 87% of all participants affirming technology's centrality to competitive port operations.

Table 1: Stakeholder Perceptions of Digital Twin Operational Benefits

Benefit Category	Students (n=15)	Lecturers (n=8)	Practitioners (n=7)	Overall Mean Score
Vessel Turnaround Time Reduction	4.3	4.6	4.4	4.43
Yard Management Efficiency	4.1	4.5	4.7	4.43
Resource Allocation Optimization	4.0	4.4	4.3	4.23
Predictive Maintenance Capability	3.9	4.7	4.6	4.40
Real-time Decision Support	4.2	4.8	4.5	4.50
Training and Simulation Value	4.5	4.6	4.2	4.43
Overall Perception Score	4.17	4.60	4.45	4.41

Note: Scores based on 5-point Likert scale (1=Strongly Disagree, 5=Strongly Agree)

The quantitative aggregation of qualitative assessments demonstrated exceptional consensus regarding Digital Twin technology's operational value, with overall mean scores exceeding 4.4 across all benefit categories, indicating strong agreement that technology integration would yield substantial efficiency improvements. Particularly noteworthy was the unanimous recognition of real-time decision support capabilities (Mean: 4.50) as Digital Twin's most significant contribution, reflecting stakeholder appreciation for data-driven management approaches addressing Indonesia's chronic port congestion and resource coordination challenges.

Qualitative narratives provided rich contextual understanding beyond numerical assessments. One veteran practitioner with twenty-three years of port operations experience articulated: "Digital Twin technology could revolutionize how we manage container yard operations. Currently, we rely heavily on experience and intuition for berth allocation and equipment deployment. Having a virtual system that simulates different scenarios and predicts bottlenecks before they occur would dramatically improve our decision quality and operational throughput." This perspective exemplified practitioner emphasis on pragmatic problem-solving applications rather than technological sophistication per se.

Lecturer participants emphasized pedagogical dimensions, with one maritime operations specialist noting: "Integrating Digital Twin concepts into our curriculum prepares students for inevitable industry transformation. More importantly, simulation capabilities enable experiential learning where students can practice complex decision-making in risk-free virtual environments, developing competencies impossible to cultivate through traditional classroom instruction alone." This educational framing highlighted Digital Twin technology's dual role as both operational tool and pedagogical resource.
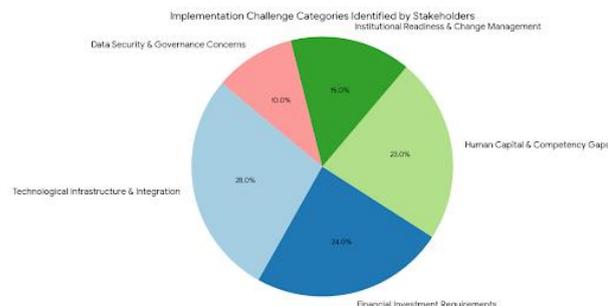

Figure 1: Implementation Challenge Categories Identified by Stakeholders

Analysis of perceived implementation challenges revealed multifaceted barriers requiring coordinated intervention strategies. Technological infrastructure limitations emerged as the most frequently cited concern (28%), encompassing inadequate digital infrastructure, legacy system incompatibilities, and connectivity constraints characteristic of Indonesian port environments. Financial considerations ranked second (24%), with participants recognizing substantial capital investment requirements for hardware, software, and system integration while questioning budget allocation priorities within resource-constrained institutional contexts. Notably, human capital and competency gaps represented nearly equal concern (23%), reflecting stakeholder awareness that technology adoption success depends fundamentally on workforce capabilities, training effectiveness, and sustained professional development initiatives.

Cross-group comparative analysis illuminated divergent priority emphases. Student participants disproportionately emphasized learning opportunities and career preparation aspects, with one stating: "If ports are moving toward Digital Twin systems, we need hands-on training now, not just theoretical knowledge. The gap between what we learn and what industry needs is already too wide." Conversely, practitioners focused heavily on integration practicalities and operational disruption concerns, expressing cautious optimism tempered by implementation realism derived from previous technology adoption experiences.

Discussion

The research findings substantively address the central research question by demonstrating that while Digital Twin technology enjoys broad stakeholder support as a promising solution for enhancing Indonesian port operational efficiency, successful integration requires comprehensive frameworks addressing technological, financial, human capital, and institutional readiness dimensions simultaneously. These results align with international literature documenting Digital Twin technology's transformative potential in maritime operations (Botín-Sanabria et al., 2022; Philipp et al., 2021) while extending understanding by foregrounding implementation perspectives from emerging maritime economy contexts where resource constraints and capacity limitations create distinct adoption dynamics.

The exceptionally high operational benefit scores (overall mean: 4.41) support prior research emphasizing Digital Twin capabilities for real-time monitoring, predictive analytics, and decision optimization (Inkinen et al., 2019), suggesting that technology value propositions translate across diverse maritime contexts despite varying infrastructure maturity

levels. However, findings partially contradict techno-optimistic narratives prevalent in developed economy literature by highlighting that awareness of benefits alone proves insufficient for adoption; participants consistently emphasized that implementation success depends critically on systematic competency development, institutional change management, and sustained investment commitments extending beyond initial technology deployment.

The prominence of human capital concerns (23% of implementation challenges) addresses a significant gap in existing Digital Twin literature, which disproportionately emphasizes technological specifications while undertheorizing workforce development imperatives (Cahoon et al., 2020). This research demonstrates that stakeholders perceive competency development as equally critical to infrastructure investment, with lecturers and practitioners particularly emphasizing needs for specialized training in data analytics, system management, and technology-enhanced decision-making processes. This finding validates emerging scholarship advocating integrated socio-technical approaches to maritime digitalization that position human capabilities as central rather than peripheral to successful technology adoption (Inkinen et al., 2019).

Comparative analysis across stakeholder groups revealed important nuances informing implementation strategy development. The convergence of perspectives regarding technology benefits suggests broad coalition-building potential supporting Digital Twin initiatives, while divergent emphases—students prioritizing learning applications, lecturers focusing on curriculum integration, practitioners emphasizing operational pragmatics—indicate that successful frameworks must accommodate multiple stakeholder objectives simultaneously rather than pursuing singular, technology-centric approaches. This multi-stakeholder complexity, underexplored in existing literature, highlights maritime education institutions' unique positioning as sites where technology awareness cultivation, competency development, and industry-academia collaboration can synergistically advance adoption readiness.

The research strengths include its comprehensive stakeholder engagement approach, yielding triangulated insights reflecting diverse experiential backgrounds and institutional roles, thereby generating holistic understanding unattainable through single-perspective investigations. The qualitative methodology enabled deep exploration of contextual factors, implementation concerns, and stakeholder reasoning processes that quantitative approaches

would overlook, producing actionable insights directly applicable to framework development and curriculum innovation initiatives.

Practical implications of these findings are substantial for maritime education institutions, port authorities, and policy-makers. First, results indicate urgent need for curriculum modernization integrating Digital Twin concepts, data analytics competencies, and simulation-based learning experiences preparing students for technology-intensive operational environments. Second, findings suggest that phased implementation strategies emphasizing pilot projects, demonstration applications, and iterative learning processes may prove more viable than comprehensive system deployments given resource constraints and competency development timelines. Third, the research highlights imperative for strengthened industry-academia partnerships facilitating technology exposure, collaborative research, and practitioner engagement in educational programming to ensure curriculum relevance and implementation realism.

Future research should investigate longitudinal technology adoption trajectories, examining how initial awareness and intentions translate into actual implementation behaviors over time. Comparative studies across multiple Indonesian maritime institutions could illuminate how institutional contexts, resource endowments, and leadership commitments shape adoption outcomes. Additionally, experimental research examining specific Digital Twin training interventions' effectiveness for competency development would provide evidence-based guidance for educational programming. Finally, international comparative research contrasting emerging and developed economy adoption experiences could identify transferable lessons while respecting contextual specificities.

4. CONCLUSION

This research establishes that Digital Twin technology integration in Indonesian port operations enjoys strong stakeholder support within maritime education contexts, with participants recognizing substantial potential for operational efficiency improvements across vessel turnaround time, yard management, resource allocation, and predictive maintenance dimensions. However, successful implementation requires comprehensive frameworks addressing technological infrastructure development, financial investment mobilization, systematic competency development, and institutional readiness preparation simultaneously. The findings emphasize that human capital development represents equally critical priority alongside technological deployment, necessitating curriculum innovation, specialized training programs, and sustained professional development initiatives. Maritime education

institutions occupy strategic positions for advancing Digital Twin adoption through awareness cultivation, competency building, and industry-academia collaboration, positioning future maritime professionals to lead Indonesia's port operational transformation toward data-driven, technology-enhanced efficiency paradigms.

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