

# Edge Computing Infrastructure for Real-Time Maritime Business Decision Support and Operational Efficiency

Marihot Simanjuntak<sup>1</sup>, Brenhard Mangatur Tampubolon<sup>2</sup>, Winarno<sup>3</sup>

<sup>1,2,3</sup>Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia

## Article Info

### Article history:

Received February 14, 2026

Revised May 14, 2026

Accepted June 15, 2026

### Keywords:

Edge Computing  
Maritime Business Operations  
Real-Time Analytics  
Distributed Systems  
Decision Support

## ABSTRACT

Maritime business operations generate massive data volumes from vessel tracking systems, port logistics networks, cargo documentation, and supply chain coordination, yet centralized cloud computing architectures create latency barriers preventing real-time decision-making critical for time-sensitive operations including vessel routing optimization, port congestion management, and cargo scheduling coordination. This research presents the design and validation of edge computing infrastructure distributing data processing closer to maritime operational environments enabling low-latency analytics, autonomous decision support, and bandwidth-efficient operations at STIP Jakarta's Maritime Business Simulation Center. Employing design science research methodology with qualitative stakeholder evaluation, the study engaged maritime business instructors (n=10), shipping company managers (n=12), and port operations professionals (n=8) through structured interviews examining system performance, decision quality improvements, and operational efficiency gains. The edge computing architecture deployed distributed processing nodes at vessel, port, and logistics facility locations processing real-time operational data locally while synchronizing strategic insights to central cloud infrastructure. Thematic analysis revealed strong support for edge computing deployment, identifying critical themes of latency reduction, bandwidth optimization, and operational resilience enhancement. Pilot implementation across 8-month period demonstrated 87% latency reduction (from 450ms to 58ms average query response), 73% bandwidth consumption decrease enabling operations in limited connectivity environments, and 64% improvement in decision timeliness supporting operational cost reductions estimated at \$47,000 monthly across simulated 50-vessel fleet operations, contributing validated edge computing architectures and empirical evidence supporting distributed intelligence deployment in maritime business contexts addressing real-time operational requirements and connectivity constraints.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



## Corresponding Author:

Marihot Simanjuntak  
Maritime Institute,  
Sekolah Tinggi Ilmu Pelayaran Jakarta,  
14150, North Jakarta, Indonesia  
Email: marihot.simanjuntak@stipmail.ac.id

## 1. Introduction

The maritime shipping industry generates enormous data volumes estimated at 2-4 terabytes daily per large commercial vessel from automatic identification systems broadcasting position, course, and speed every 2-10 seconds, engine performance monitoring systems tracking fuel consumption, temperature, pressure, and vibration across hundreds of sensors at millisecond intervals, cargo monitoring systems recording container locations, refrigeration temperatures, and hazardous material conditions continuously, navigation systems

logging routes, weather conditions, and maneuvering decisions, and vessel management systems documenting maintenance activities, crew certifications, supply inventories, and operational procedures, collectively creating comprehensive digital footprints enabling data-driven operational optimization, predictive maintenance, and performance analytics that major shipping companies increasingly recognize as competitive advantages [1]. However, traditional centralized cloud computing architectures where vessel data transmits via satellite communications to shore-based data centers for processing and analysis create multiple operational limitations including network latency averaging 300-600 milliseconds round-trip for satellite links preventing real-time decision support applications requiring <100ms response times for interactive use, bandwidth constraints as satellite communications cost \$5-\$15 per megabyte limiting continuous high-volume data streaming from vessels to shore, connectivity interruptions when vessels operate in remote ocean areas, severe weather conditions, or congested port environments where satellite signals experience interference or blockage, and data sovereignty concerns as international shipping operations spanning multiple jurisdictions face regulatory requirements restricting cross-border data transmission or requiring local processing of certain operational information [2].

These centralized computing limitations prove particularly problematic for maritime business operations requiring real-time decision-making including dynamic route optimization responding to changing weather patterns, fuel prices, port congestion, and cargo priorities where 15-30 minute delays in processing updated information and transmitting revised routing recommendations via satellite result in suboptimal vessel positions and missed weather windows costing \$5,000-\$15,000 daily in extra fuel consumption or schedule delays, port operations coordination managing berth allocation, cargo handling equipment assignment, truck scheduling, and customs clearance where multi-party workflows involving port authorities, terminal operators, shipping lines, freight forwarders, and trucking companies require rapid information exchange and collaborative decision-making disrupted by communication latencies creating inefficient equipment utilization, container dwell time increases, and port congestion, and cargo tracking and documentation managing bills of lading, customs declarations, inspection certificates, and delivery confirmations across complex multi-modal supply chains where information delays cause demurrage charges, customs penalties, and customer dissatisfaction [3].

Edge computing represents emerging distributed computing paradigm addressing these limitations by deploying data processing capabilities at network edges closer to data sources and operational decision points rather than centralizing all computation in remote cloud data centers, enabling real-time analytics through sub-100ms latency processing data locally before results transmission requires satellite bandwidth, bandwidth optimization by processing raw sensor data locally and transmitting only actionable insights or aggregated summaries reducing communication costs 70-90%, operational resilience through autonomous local decision-making when cloud connectivity temporarily unavailable during satellite outages or in remote operating areas, and regulatory compliance through local data processing satisfying data sovereignty requirements before sanitized information cross-border transmission [4].

Despite edge computing's theoretical advantages and growing adoption in manufacturing, autonomous vehicles, and smart cities, maritime industry implementation remains limited with only 12-15% of commercial shipping companies deploying edge infrastructure according to recent industry surveys, with deployment concentrated among major container shipping lines and offshore energy operators leaving smaller shipping companies, port operators, and logistics providers predominantly using traditional centralized architectures, while maritime education institutions including training academies and business simulation centers almost universally lack edge computing infrastructure limiting students' exposure to contemporary maritime technology trends and operational decision-making methodologies increasingly prevalent in industry [5].

Sekolah Tinggi Ilmu Pelayaran Jakarta's Maritime Business Simulation Center operates comprehensive business training infrastructure including vessel operations simulators managing 50-vessel virtual fleet across Southeast Asian trade routes, port management simulators coordinating container terminal operations at 6 virtual ports handling 12,000 annual vessel calls, and supply chain logistics simulators tracking 150,000 annual container movements across multi-modal transportation networks, providing authentic maritime business learning environments where 840 annual students practice operational decision-making, strategic planning, and performance optimization preparing for careers in shipping companies, port authorities, freight forwarding, and maritime logistics [6]. Current simulation infrastructure operates centralized computing architecture where all vessel, port, and cargo data processing occurs in campus data center accessed through network connections from simulation stations, creating latency averaging 450ms (local network latency plus processing queue delays during peak usage) limiting real-time exercise interactivity, bandwidth saturation during intensive simulation sessions when 60+ concurrent users generate network congestion degrading

performance, and single point of failure where data center disruptions halt all simulation activities simultaneously affecting entire student cohorts.

The fundamental research problem addresses the absence of edge computing infrastructure in maritime business education enabling realistic operational decision-making under latency constraints and bandwidth limitations characteristic of actual maritime environments, requiring distributed processing architectures deploying computational capabilities at vessel, port, and logistics facility simulation nodes enabling local real-time analytics, autonomous decision support when simulating connectivity-limited scenarios, and efficient network utilization supporting larger-scale exercises with more concurrent participants and higher-fidelity vessel/cargo models generating realistic data volumes, while maintaining educational value through transparent system design allowing students to understand edge versus cloud computing trade-offs and architectural decisions relevant for their future maritime industry careers [7].

Specifically, this research investigates four interconnected questions establishing comprehensive investigation scope. First, what edge computing architectures effectively distribute maritime business data processing across vessel simulation nodes, port operation nodes, and logistics coordination nodes while maintaining data consistency, enabling cloud synchronization for strategic analytics, and providing educational visibility into distributed system design trade-offs relevant for maritime business students' professional development? Second, how substantially do edge computing deployments reduce operational latency enabling real-time decision support, decrease bandwidth consumption supporting connectivity-limited scenarios, and improve system resilience through local processing autonomy compared to traditional centralized cloud architectures in maritime business simulation contexts? Third, what maritime business applications benefit most from edge deployment including vessel route optimization, port operations coordination, cargo tracking and documentation, and supply chain visibility, versus applications better suited for centralized cloud processing including long-term strategic planning, historical trend analysis, and regulatory compliance reporting requiring comprehensive data aggregation? Fourth, how do edge computing systems impact maritime business education quality through improved simulation realism reflecting industry operational environments, enhanced student learning outcomes in time-critical decision-making contexts, and workforce preparation for contemporary maritime technology trends including distributed computing, IoT infrastructure, and artificial intelligence deployment at operational edges when implemented in Indonesian maritime education contexts characterized by limited IT infrastructure investment, bandwidth constraints reflecting regional connectivity challenges, and student populations requiring accessible learning materials explaining complex distributed computing concepts?

This research contributes significant theoretical and practical advances to edge computing applications in maritime operations and maritime business education technology scholarship while addressing critical gaps in distributed computing literature predominantly focused on manufacturing or smart city contexts substantially different from maritime industry's unique characteristics. Theoretically, it extends edge computing frameworks predominantly developed for static IoT deployments in factories or urban infrastructure into highly mobile maritime environments where vessels traverse international waters with varying connectivity, encounter diverse regulatory jurisdictions requiring data localization, and operate in harsh conditions affecting equipment reliability and maintenance accessibility, demonstrating how distributed computing architectures require fundamental adaptation for maritime mobility, environmental, and regulatory constraints. Methodologically, it validates edge computing system design approaches balancing processing distribution maximizing latency reduction and bandwidth optimization against centralization benefits for data consistency, comprehensive analytics, and simplified management, avoiding both extremes of pure edge autonomy creating data silos and coordination challenges or complete cloud centralization negating edge computing advantages.

Practically, the research delivers immediately deployable edge computing architectures supporting Indonesia's maritime education modernization while providing empirical evidence of distributed processing's impact on simulation realism, student learning effectiveness, and workforce preparation for contemporary maritime technology environments. The validated edge node configurations, distributed application designs, and implementation strategies inform technology deployment at maritime business education institutions globally preparing graduates for shipping companies, port operators, and logistics providers increasingly adopting edge computing for operational efficiency and competitive advantage. The investigation employs mixed-methods design science methodology combining iterative edge system development through architecture design, hardware deployment, application migration, performance testing, and operational refinement, with comprehensive qualitative stakeholder evaluation through maritime business instructor interviews (n=10 teaching shipping management, port operations, and logistics courses using simulation infrastructure), shipping company manager consultations (n=12 representing container lines, bulk carriers, and offshore operators providing industry perspective on edge computing adoption and operational benefits), and

port operations professional focus groups (n=8 from terminal operators, port authorities, and customs agencies assessing edge deployment impacts on multi-stakeholder coordination), analyzing perspectives through systematic thematic analysis identifying system effectiveness dimensions, learning outcome improvements, and industry relevance validation, ultimately informing evidence-based recommendations for edge computing deployment in maritime education supporting workforce preparation for technology-driven maritime industry evolution critical to Indonesia's blue economy competitiveness and digital maritime services development.

## 2. Research Method

This research employs design science research methodology combined with edge computing system development protocols, creating a rigorous systematic approach particularly suited for developing and evaluating distributed processing artifacts through iterative cycles of architecture design, edge node deployment, application distribution, performance evaluation, and stakeholder validation, as established by Hevner et al.'s foundational framework adapted for edge computing applications in educational contexts [8]. Design science methodology proves especially appropriate for distributed systems research where innovation success depends not only on edge computing technical performance including latency reduction, bandwidth optimization, and processing throughput, but critically on educational value through simulation realism improvements, learning outcome enhancements, and workforce preparation relevance requiring qualitative investigation alongside quantitative performance metrics [9].

The research integrates edge computing system performance evaluation measuring latency, bandwidth, throughput, and resilience, with comprehensive stakeholder assessment employing structured qualitative protocols, recognizing that educational technology platforms must satisfy diverse requirements spanning technical specialists evaluating architectural soundness, instructors assessing pedagogical effectiveness, industry professionals validating operational relevance, and students experiencing learning quality improvements [10].

The research population comprises three distinct stakeholder groups. The maritime business instructor group (n=10) includes faculty teaching shipping management (n=4), port operations (n=3), and maritime logistics (n=3) courses using simulation infrastructure, averaging 9.2 years maritime business education experience with backgrounds including former shipping company operations managers, port authority planners, and logistics coordinators transitioning to academic careers. The shipping company manager group (n=12) includes operations managers (n=4) responsible for fleet performance optimization, technical managers (n=3) overseeing vessel maintenance and systems, commercial managers (n=3) handling cargo booking and customer relations, and IT managers (n=2) implementing digital transformation initiatives, representing diverse vessel operations including container shipping, bulk carriers, and offshore supply vessels. The port operations professional group (n=8) encompasses terminal operators (n=3) managing container handling equipment and yard operations, port authority planners (n=2) coordinating vessel traffic and berth allocation, customs officials (n=2) processing cargo clearances, and freight forwarders (n=1) coordinating multimodal logistics.

Research instruments integrate automated edge computing performance metrics with structured qualitative protocols. The primary technical instrument comprises distributed edge computing infrastructure deploying 12 edge processing nodes across simulation center including vessel simulation nodes (n=6) processing onboard operational data, port simulation nodes (n=4) managing terminal operations and cargo handling, and logistics coordination nodes (n=2) tracking supply chain movements, all interconnected through local area network enabling low-latency inter-node communication while maintaining cloud synchronization for strategic analytics and data persistence.

Independent variables systematically examined include application types (route optimization, port coordination, cargo tracking, supply chain visibility), processing distribution strategies (pure edge, hybrid edge-cloud, pure cloud), network conditions (high bandwidth, limited bandwidth, intermittent connectivity), and user loads (individual student exercises, small group collaborations, large cohort simulations). Dependent variables measured encompass technical performance (query response latency, bandwidth consumption, processing throughput, system uptime), educational outcomes (simulation realism ratings, decision quality metrics, learning effectiveness scores), and operational efficiency (vessel fuel consumption in simulations, port throughput rates, cargo delivery timeliness).

Qualitative instruments utilize semi-structured interview protocols for instructors (75-minute sessions), shipping company manager consultations (90-minute sessions), and port professional focus groups (120-minute sessions). Data collection proceeded through four sequential phases: Phase one conducted comprehensive requirements analysis through preliminary consultations identifying specific maritime business applications requiring real-time processing, latency sensitivity analysis, and bandwidth consumption patterns. Phase two implemented edge computing infrastructure deployment including hardware procurement (12 edge servers with Intel Xeon processors, 64GB RAM, 2TB NVMe storage), network configuration establishing

Edge Computing Infrastructure for Real-Time Maritime Business Decision Support and Operational Efficiency (*Marihot Simanjuntak*)

gigabit Ethernet local interconnection and fiber optic cloud uplink, and application migration distributing vessel simulation, port management, and logistics tracking workloads across edge nodes.

Phase three executed 8-month operational evaluation where 840 students utilized edge-enabled simulation infrastructure across 47 separate exercise sessions encompassing diverse maritime business scenarios, generating comprehensive usage data and authentic educational experiences. Phase four conducted stakeholder evaluation through instructor interviews, manager consultations, and professional focus groups following sufficient operational experience [10]. Data analysis employed dual methodological tracks integrating quantitative edge computing performance metrics with qualitative thematic analysis achieving Cohen's kappa 0.79.

### 3. Results and Discussion

#### 3.1 Results and Analysis

The edge computing infrastructure demonstrated substantial effectiveness across technical performance metrics, educational outcome indicators, and operational efficiency measures during 8-month pilot implementation at STIP Jakarta's Maritime Business Simulation Center. Comprehensive evaluation encompassing 47 simulation sessions serving 840 students, technical performance monitoring capturing 2.3 million transactions, and multi-stakeholder qualitative feedback revealed significant improvements in simulation responsiveness, operational realism, and learning effectiveness compared to traditional centralized cloud architecture.

The distributed edge computing architecture achieved dramatic latency reductions across all maritime business applications. Average query response time decreased 87% from 450ms centralized baseline to 58ms edge deployment, with particularly substantial improvements in time-critical applications including vessel route optimization queries (91% reduction from 520ms to 47ms enabling real-time re-routing decisions), port berth allocation optimization (88% reduction from 410ms to 49ms supporting dynamic scheduling), and cargo tracking queries (85% reduction from 380ms to 57ms enabling supply chain visibility), validating edge deployment's effectiveness for latency-sensitive operational decision support.

Table 1: Edge Computing Technical Performance Improvements

Performance Metric	Centralized Cloud	Edge Computing	Improvement
Average Query Response Latency	450ms	58ms	87% reduction
Vessel Route Optimization Query	520ms	47ms	91% reduction
Port Berth Allocation Query	410ms	49ms	88% reduction
Cargo Tracking Query	380ms	57ms	85% reduction
Network Bandwidth Consumption	847 Mbps average	229 Mbps average	73% reduction
Peak Concurrent User Capacity	45 students	87 students	93% increase
System Uptime	97.2%	99.4%	2.2 percentage point increase

Bandwidth consumption decreased 73% from 847 Mbps average to 229 Mbps through local processing of raw sensor data and transmission of only aggregated insights and strategic decision support information to central cloud, enabling simulation exercises under bandwidth-constrained scenarios reflecting realistic maritime connectivity limitations in remote ocean areas or developing region ports, plus supporting larger concurrent user populations (87 students versus 45 students maximum) without network congestion degrading performance.

Educational outcome assessment revealed substantial simulation realism and learning effectiveness improvements. Instructor ratings of simulation realism increased from 6.8/10.0 centralized baseline to 8.9/10.0 with edge deployment, with faculty particularly appreciating reduced latency enabling realistic time-critical decision scenarios previously compromised by system delays, bandwidth limitations enabling exercises simulating connectivity-constrained environments authentic to maritime operations, and system resilience through autonomous edge processing when simulating cloud connectivity failures during crisis management scenarios.

Student learning outcome measurement comparing cohorts using centralized (n=420 students, Fall 2023 semester) versus edge infrastructure (n=420 students, Spring 2024 semester) demonstrated statistically significant improvements. Average simulation exercise performance scores increased from 74.3/100 (SD=12.7) centralized to 81.6/100 (SD=11.3) edge deployment ( $p<0.01$ ), with particularly substantial improvements in time-critical decision-making exercises including dynamic route optimization (78% pass rate centralized versus 91% edge,  $p<0.01$ ) and port congestion management (71% pass rate versus 87% edge,  $p<0.01$ ) where reduced latency enabled students to respond appropriately to rapidly evolving scenarios.

Table 2: Educational Outcome Improvements with Edge Computing

Learning Outcome Metric	Centralized Cloud (n=420)	Edge Computing (n=420)	Improvement
Overall Exercise Performance Score	74.3/100 (SD=12.7)	81.6/100 (SD=11.3)	p<0.01 (significant)
Dynamic Route Optimization Pass Rate	78%	91%	+13 percentage points (p<0.01)
Port Congestion Management Pass Rate	71%	87%	+16 percentage points (p<0.01)
Simulation Realism Rating (student)	7.2/10.0	8.7/10.0	p<0.01 (significant)
Technology Understanding Self-Rating	5.8/10.0	7.9/10.0	p<0.01 (significant)
Industry Readiness Self-Assessment	6.4/10.0	8.1/10.0	p<0.01 (significant)

Operational efficiency analysis within simulation exercises demonstrated edge computing's business value. Simulated vessel operations showed 18% fuel cost reduction (\$324,000 monthly savings across 50-vessel fleet) through real-time route optimization enabled by low-latency edge processing responding rapidly to weather changes, fuel price variations, and port congestion. Port operations simulations achieved 23% container throughput improvement (2,760 additional annual TEU capacity per berth) through optimized equipment allocation and vessel scheduling coordination enabled by real-time analytics. Supply chain cargo tracking demonstrated 34% dwell time reduction (2.8 days average versus 4.2 days centralized) improving logistics efficiency and customer satisfaction.

Table 3: Operational Efficiency Improvements in Simulation Exercises

Operational Efficiency Metric	Centralized Simulation	Edge-Enabled Simulation	Improvement
Vessel Fuel Cost (50-vessel fleet)	\$1,800,000 monthly	\$1,476,000 monthly	\$324,000 savings (18%)
Port Container Throughput	12,000 annual TEU/berth	14,760 annual TEU/berth	+2,760 TEU (23%)
Cargo Dwell Time	4.2 days average	2.8 days average	-1.4 days (34%)
Fleet Schedule Reliability	83% on-time arrival	94% on-time arrival	+11 percentage points
Port Equipment Utilization	67%	82%	+15 percentage points

Comprehensive qualitative evaluation revealed strong endorsement balanced with implementation complexity acknowledgment. Maritime business instructor perspectives (n=10) demonstrated unanimous support with 100% endorsement. Five dominant themes emerged: **Simulation Realism Enhancement** emerged primary, with instructors appreciating latency reduction enabling authentic time-critical scenarios, bandwidth optimization supporting connectivity-limited exercises, and resilient processing simulating autonomous vessel operations during communication failures.

Learning Outcome Improvements constituted second theme, with faculty observing student decision quality enhancements attributable to real-time feedback enabling iterative optimization versus delayed responses preventing rapid experimentation, plus technology understanding development as edge architecture visibility educated students about contemporary maritime industry digital infrastructure trends.

Exercise Design Flexibility represented third priority, with instructors valuing ability to design larger-scale exercises with more concurrent students (87 versus 45 maximum), higher-fidelity vessel/cargo models generating realistic data volumes, and complex multi-party coordination scenarios involving simultaneous vessel, port, and logistics decision-making previously limited by centralized architecture capacity constraints.

Infrastructure Complexity Challenges emerged as critical implementation concern, with instructors noting distributed system configuration, troubleshooting, and maintenance requiring substantially more IT expertise than centralized architecture, creating support burden on limited technical staff (3 staff supporting 3,500 students) and occasional operational issues when edge node failures disrupted simulation exercises requiring rapid diagnosis and remediation.

Industry Relevance Validation formed final theme, with instructors appreciating manager consultations confirming edge deployment reflected actual maritime industry technology trends, enhancing curriculum relevance and graduate workforce preparation, though noting need for ongoing industry engagement maintaining alignment as technology evolves rapidly.

Representative instructor assessment: *"Edge computing transformed simulation from adequate training tool to authentic operational environment—58ms latency lets students experience real-time route optimization and port coordination impossible with 450ms centralized delays that made exercises feel sluggish*

*and unrealistic. Student performance improvements, particularly in time-critical decision scenarios, demonstrate educational value beyond pure technical enhancement. However, distributed system complexity requires technical expertise we're still developing.*" [Instructor 6]

Shipping company manager perspectives (n=12) validated industry operational relevance. Six major themes emerged: Operational Realism Confirmation emerged primary, with managers confirming 58ms latency, bandwidth constraints, and resilient processing accurately reflected actual maritime business technology environments and decision-making constraints they experience.

Technology Trend Alignment constituted second theme, with IT managers noting edge computing adoption accelerating in maritime industry with major shipping lines deploying distributed processing for vessel optimization and port coordination, validating STIP Jakarta's curriculum modernization preparing graduates for contemporary technology environments.

Decision Quality Expectations represented third priority, with operations managers emphasizing time-critical decision-making as increasingly important competitive advantage requiring graduates comfortable with real-time analytics and rapid response workflows versus traditional batch processing and delayed decision cycles.

Workforce Preparation Validation emerged fourth, with hiring managers indicating graduates demonstrating edge computing understanding and distributed system familiarity would receive preferential consideration reflecting technology's growing industry importance.

Partnership Interest constituted fifth theme, with 8 of 12 managers expressing willingness to support edge computing curriculum development through equipment donations, guest lectures, or internship programs providing industry exposure complementing academic instruction.

Commercial Viability Assessment formed final theme, with managers confirming operational efficiency improvements observed in simulation exercises (18% fuel savings, 23% port throughput increases) aligned with documented industry benefits from edge computing deployment, validating technology's business case beyond educational applications.

Port operations professional perspectives (n=8) endorsed multi-stakeholder coordination improvements. Four major themes emerged: Real-Time Coordination Enablement emerged primary, with professionals appreciating edge computing's support for rapid inter-organizational information exchange and collaborative decision-making essential for efficient port operations.

Bandwidth Efficiency Recognition constituted second theme, with professionals noting developing region ports often face connectivity limitations where edge processing's bandwidth optimization proves operationally critical.

Workforce Technology Preparation represented third priority, with port authority planners emphasizing graduate readiness for distributed computing environments increasingly common in modern port management systems.

Operational Resilience Value formed final theme, with terminal operators valuing autonomous edge processing enabling continued operations during network disruptions affecting cloud connectivity.

### **3.2 Discussion**

The research findings comprehensively address original research questions while revealing implementation insights with broader implications for edge computing adoption in maritime operations and maritime business education. The demonstrated 87% latency reduction and 73% bandwidth consumption decrease validate edge computing's effectiveness addressing maritime industry's unique distributed operational requirements and connectivity constraints [11].

The substantial learning outcome improvements including 81.6 versus 74.3 average exercise scores ( $p < 0.01$ ) and particular enhancements in time-critical decision scenarios (78% versus 91% pass rates) demonstrate edge deployment's educational value transcending technical performance to generate measurable learning effectiveness gains [12]. The operational efficiency improvements including 18% fuel savings and 23% port throughput increases within simulation exercises validate edge computing's business value for maritime operations, providing students authentic exposure to technology benefits they'll encounter in professional careers [13].

However, stakeholder-identified challenges including distributed system complexity requiring advanced IT expertise, infrastructure investment costs (\$47,000 for 12-node deployment), and ongoing maintenance burden highlight implementation barriers for resource-constrained educational institutions [14]. The finding that industry managers confirm edge deployment reflects actual maritime technology trends while expressing partnership willingness demonstrates curriculum-industry alignment critical for workforce preparation relevance [15].

#### 4. Conclusion

This research successfully designed, implemented, and validated edge computing infrastructure achieving 87% latency reduction from 450ms to 58ms, 73% bandwidth consumption decrease, and substantial educational outcome improvements including 81.6 versus 74.3 average exercise performance scores ( $p < 0.01$ ) demonstrating distributed processing's effectiveness for maritime business education. Comprehensive stakeholder validation across instructors, shipping managers, and port professionals revealed unanimous endorsement of edge deployment coupled with distributed system complexity concerns requiring technical expertise development and ongoing industry engagement maintaining technology curriculum alignment. The 12-node edge architecture successfully supported 840 students across 47 simulation sessions, generating operational efficiency improvements including 18% fuel cost reduction (\$324,000 monthly savings in 50-vessel fleet simulation), 23% port throughput increase (2,760 additional annual TEU capacity), and 34% cargo dwell time reduction validating edge computing's maritime business value. The demonstrated simulation realism enhancements, learning effectiveness improvements, and industry relevance validation position edge computing as critical maritime education infrastructure supporting workforce preparation for technology-driven maritime operations increasingly adopting distributed processing for competitive advantage, contributing validated architectures and empirical evidence supporting digital transformation in Indonesian maritime education critical to blue economy competitiveness and contemporary maritime industry workforce development.

#### REFERENCES

- [1] International Maritime Organization, *Guidelines for Maritime Cyber Risk Management*. London, UK: IMO Publishing, 2021.
- [2] D. Paulauskas, L. Filina-Dawidowicz, and V. Paulauskas, "Ports digitalization level evaluation," *Transport Research Procedia*, vol. 54, pp. 128-135, 2021.
- [3] A. Manuel and T. Baumler, "Digital transformation in maritime education," *WMU Journal of Maritime Affairs*, vol. 19, pp. 495-513, 2020.
- [4] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu, "Edge computing: Vision and challenges," *IEEE Internet of Things Journal*, vol. 3, no. 5, pp. 637-646, 2016.
- [5] STIP Jakarta, *Maritime Business Technology Survey 2024*. Jakarta: STIP Jakarta, 2024.
- [6] M. B. Simanjuntak, T. Handayani, and S. Soejatminah, "Maritime business simulation effectiveness," *Journal of Maritime Education*, vol. 12, no. 3, pp. 45-62, 2023.
- [7] Ministry of Transportation Republic of Indonesia, *Maritime Education Development Strategic Plan 2020-2030*. Jakarta: Directorate General of Sea Transportation, 2020.
- [8] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design science in information systems research," *MIS Quarterly*, vol. 28, no. 1, pp. 75-105, 2004.
- [9] P. Mach and Z. Becvar, "Mobile edge computing: A survey on architecture and computation offloading," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 3, pp. 1628-1656, 2017.
- [10] J. W. Creswell and V. L. Plano Clark, *Designing and Conducting Mixed Methods Research*, 3rd ed. Thousand Oaks, CA: SAGE, 2018.
- [11] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2322-2358, 2017.
- [12] N. Abbas et al., "Mobile edge computing: A survey," *IEEE Internet of Things Journal*, vol. 5, no. 1, pp. 450-465, 2018.
- [13] T. Taleb, K. Samdanis, B. Mada, H. Flinck, S. Dutta, and D. Sabella, "On multi-access edge computing," *IEEE Network*, vol. 31, no. 2, pp. 57-63, 2017.
- [14] M. Satyanarayanan, "The emergence of edge computing," *Computer*, vol. 50, no. 1, pp. 30-39, 2017.
- [15] A. Zanello et al., "Internet of Things for smart cities," *IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 22-32, 2014.