Journal of Marine Engineering Research
Volume 2 Nomor 1 January 2026
e-ISSN: 3089-8471; p-ISSN: 3089-848X, Page 17-32
Available online at: https://jurnal.poltekpelsulut.ac.id/index.php/marine

Integrated Fleet Management Systems and Operational Efficiency of Marine Propulsion Maintenance: Evidence from Indonesian Shipping Companies

Nafi Almuzani
Maritime Institute, Sekolah Tinggi Ilmu Pelayaran Jakarta, North Jakarta, Indonesia
Email: nafistip72@gmail.com

Abstract. *Aging fleet infrastructure and fragmented maintenance management continue to undermine the operational performance and regulatory compliance of Indonesian domestic shipping operators. Despite growing adoption of digital fleet management systems across the global maritime sector, empirical evidence linking integrated system adoption to propulsion maintenance efficiency outcomes remains sparse — particularly within developing maritime economies navigating simultaneous pressures of infrastructure modernization, environmental regulation, and service expansion. This study investigates how integrated fleet management systems influence propulsion system uptime, maintenance cost reduction, and compliance with Class survey schedules among Indonesian shipping companies. Employing a mixed-methods design combining structured questionnaire surveys with semi-structured expert interviews, the study recruited 60 fleet managers and chief engineers from 20 shipping companies operating within the Indonesian domestic shipping network. Findings reveal that companies with high-level integrated fleet management adoption report significantly superior propulsion uptime rates, reduced unplanned maintenance expenditure, and stronger Class survey compliance compared to companies relying on fragmented or non-integrated management approaches. The study offers a cross-disciplinary framework bridging operations management theory and marine engineering maintenance practice, and provides evidence-based recommendations for maritime policy and institutional fleet management reform in Indonesia.*

Keywords: *fleet management systems; propulsion maintenance; operational efficiency; Indonesian shipping; digital integration*

1. Introduction

Marine propulsion systems constitute the operational heart of any commercial vessel, and their reliable performance is foundational to the economic viability, regulatory compliance, and safety record of shipping companies worldwide. Yet in Indonesia — the world's largest archipelagic nation, whose domestic shipping network underpins the economic integration of over 17,000 islands — propulsion system maintenance remains a persistent and underaddressed challenge. Aging fleet infrastructure, limited dry-dock capacity, fragmented maintenance record systems, and a shortage of certified marine engineers compound one another to produce a maintenance environment in which unplanned machinery breakdowns, extended off-hire periods, and Class survey non-compliance represent not exceptional events but recurring operational realities. Against this backdrop, the question of how integrated fleet management systems might enhance propulsion maintenance efficiency in the Indonesian context emerges as both practically urgent and empirically underexplored.

Fleet management systems — digital platforms designed to integrate vessel performance monitoring, maintenance scheduling, spare parts inventory, crew management, and regulatory compliance documentation — have been adopted with

Received: March 01, 2025; Revised: October 15, 2025;
Accepted: January 29, 2026; Published: January 31, 2026

increasing momentum across global commercial shipping over the past decade. The logic underpinning their adoption is straightforward: by centralizing and systematizing information flows across the maintenance lifecycle, integrated systems reduce the information asymmetries, coordination failures, and documentation gaps that characterize fragmented maintenance environments. The evolution of these systems has accelerated alongside broader digital transformation trends in the maritime sector, driven by the convergence of Internet of Things (IoT) sensor technology, cloud-based data management, and AI-supported predictive maintenance analytics (Ciancarini et al., 2024). As Elbouzidi et al. (2023) demonstrate in their review of AI applications in asset management through digital twin technology, the integration of real-time operational data with predictive modeling capabilities fundamentally alters the economics and effectiveness of maintenance management in capital-intensive operational environments.

Within the Indonesian maritime context, the urgency of enhanced fleet management is compounded by the regulatory landscape. National integrated maritime policies establish the institutional frameworks within which shipping companies operate and must meet compliance obligations, yet policy integration across the ministries of transportation, energy, and environment — each of which exercises jurisdiction over aspects of fleet operation — has historically been uneven (Paridaens & Notteboom, 2021). The introduction of the Tol Laut (Maritime Highway) program as a national connectivity initiative has further intensified pressure on domestic shipping operators to maintain reliable vessel availability schedules, as route cancellations attributable to propulsion failures carry consequences not only for individual companies but for the supply chain continuity of remote island communities dependent on maritime freight. In this policy and operational context, fleet management system integration has ceased to be merely a matter of corporate efficiency optimization and has acquired the character of a national infrastructure concern.

Despite the evident practical significance of this issue, the empirical literature on fleet management systems and propulsion maintenance efficiency in Indonesian shipping companies remains remarkably sparse. The majority of existing studies on maritime operational efficiency have concentrated on port-level productivity metrics (Caldas et al., 2024; Mwendapole & Jin, 2021), liner shipping environmental performance (Liao & Lee, 2023), or the risk management dimensions of intelligent ship operations (Zhang et al., 2022). While these contributions advance understanding of maritime operational efficiency at the network and environmental level, they offer limited insight into the vessel-

level maintenance management processes that determine whether propulsion systems are available to serve those networks in the first instance. The operational efficiency of shipping companies thus represents a layer of analysis systematically underserved by the existing literature — a gap that the present study directly addresses.

Furthermore, the institutional and organizational diversity of Indonesian shipping companies — spanning large state-owned operators such as PT PELNI, medium-sized privately owned inter-island carriers, and smaller coastal operators — creates a research context of considerable heterogeneity in system adoption, financial capacity, and maintenance culture. Understanding how fleet management system integration translates into maintenance efficiency outcomes across this spectrum of company types generates insights that are both nationally specific and internationally relevant, given the parallel challenges facing shipping industries in other developing maritime economies.

This study pursues three interrelated objectives: first, to assess the level and nature of fleet management system integration among Indonesian domestic shipping companies across a representative sample; second, to examine the empirical relationship between integration level and key propulsion maintenance efficiency indicators, including system uptime rates, unplanned maintenance costs, and Class survey compliance; and third, to identify the institutional, organizational, and technological factors that mediate the relationship between system integration and maintenance outcomes. The guiding research question is: To what extent does the level of fleet management system integration predict propulsion maintenance operational efficiency among Indonesian domestic shipping companies, and what organizational factors mediate this relationship?

The significance of this study extends across multiple dimensions. Theoretically, it contributes a cross-disciplinary analytical framework that bridges operations management, digital transformation theory, and marine engineering practice — a synthesis underrepresented in the current maritime management literature (Shi et al., 2023). Empirically, it generates primary evidence from Indonesian shipping companies, addressing a critical void in the regional maritime management knowledge base. Practically, its findings carry direct implications for corporate maintenance strategy, maritime regulatory policy, and the institutional promotion of digital fleet management adoption as a lever for improving domestic shipping reliability and safety performance.

2. Literature Review

2.1 Conceptual Framework: Fleet Management Systems and Propulsion Maintenance

Fleet management systems in the maritime context refer to integrated digital

platforms that consolidate vessel performance data, planned maintenance schedules, spare parts logistics, certification tracking, and regulatory compliance documentation within a unified information environment. The transition from paper-based or siloed digital maintenance records to genuinely integrated fleet management platforms represents a qualitative shift in the management of propulsion and auxiliary machinery maintenance, enabling condition-based and predictive maintenance strategies to supplement or replace purely time-based maintenance schedules. This shift aligns with broader digital transformation trends in industrial asset management, where the integration of AI-assisted analytics with real-time operational data has been identified as a primary driver of maintenance cost reduction and asset availability improvement (Elbouzidi et al., 2023). The application of digital twin technologies — virtual replicas of physical assets that enable real-time performance monitoring and failure prediction — represents the leading edge of this transformation and is increasingly being explored within maritime propulsion system management.

Operational efficiency in marine propulsion maintenance encompasses several interrelated dimensions: system uptime (the proportion of scheduled operating time during which the propulsion system is fully functional), mean time between failures, unplanned maintenance cost as a proportion of total maintenance expenditure, and compliance with Class society survey schedules that condition vessels' legal authorization to operate. These dimensions are not independent; improvements in condition-monitoring and predictive maintenance capability — the primary contribution of integrated fleet management systems — reduce unplanned failures, thereby simultaneously improving uptime, reducing emergency maintenance costs, and enabling more systematic Class survey preparation. The technology management literature confirms that organizations with higher levels of digital system integration consistently achieve superior asset management outcomes across capital-intensive industrial sectors (Shi et al., 2023), though direct empirical evidence within the maritime propulsion maintenance domain remains limited.

2.2 Digital Transformation and Maritime Operational Management

The maritime sector has historically been a laggard in digital transformation compared to comparable capital-intensive industries, a pattern attributable to the geographic distribution of vessel operations, the regulatory conservatism of classification society frameworks, and the organizational fragmentation of shipping company management structures. However, accelerating regulatory pressure from IMO decarbonization and efficiency mandates, combined with the demonstrated cost savings

achievable through predictive maintenance and route optimization, has driven a significant acceleration in maritime digital adoption over the past decade (Zhang et al., 2022). Ciancarini et al. (2024) document the structural challenges that organizations face in transitioning from legacy information architectures to integrated digital management platforms, noting that successful digital transformation requires not only technological investment but organizational capability development, process redesign, and leadership commitment — factors that differentially favor larger, better-resourced organizations.

In the context of port and shipping network operations, studies examining automation and digitalization effects on operational efficiency provide relevant analogies for the vessel-level fleet management question. Kim et al. (2022) demonstrate that fully automated container terminals achieved superior operational performance continuity compared to partially automated counterparts during the COVID-19 disruption period, attributable to the reduced dependency of integrated automated systems on the real-time coordination of human operational decisions — a parallel to the maintenance management advantages of integrated fleet monitoring platforms. Similarly, the seaport efficiency literature (Caldas et al., 2024; Mwendapole & Jin, 2021) consistently identifies information integration and coordination quality as primary determinants of throughput performance, suggesting a systemic logic — information integration as an efficiency driver — that operates across the vessel-to-port continuum of maritime operations.

2.3 Indonesian Shipping: Institutional Context and Maintenance Challenges

Indonesia's domestic shipping sector operates within a complex institutional environment shaped by the Cabotage Principle (requiring goods transported between Indonesian ports to be carried on Indonesian-flagged vessels), the Tol Laut connectivity program, and the regulatory oversight of the Ministry of Transportation and class societies including BKI (Biro Klasifikasi Indonesia). These policy frameworks create both demand for reliable vessel availability and compliance obligations that require systematic maintenance management (Paridaens & Notteboom, 2021). The empirical literature on Indonesian maritime service quality identifies reliability, schedule adherence, and vessel condition as primary dimensions of service performance in the domestic shipping context (cf. Mwendapole & Jin, 2021), all of which are directly shaped by the effectiveness of propulsion maintenance management.

The transition toward LNG bunkering and alternative fuel propulsion systems, driven by IMO emissions reduction mandates, introduces additional complexity into the propulsion maintenance management environment of Indonesian shipping companies

(Chae et al., 2021; Liao & Lee, 2023). As propulsion systems incorporate increasingly sophisticated emissions control and fuel management technologies, the maintenance knowledge, documentation, and monitoring capabilities required for their effective management intensify — underscoring the urgency of integrated fleet management system adoption as a prerequisite for managing technically complex next-generation propulsion systems. Port resilience frameworks (Kim et al., 2021) further highlight the systemic implications of vessel maintenance reliability, demonstrating that unplanned vessel unavailability creates cascading disruptions across port scheduling, freight logistics, and inter-island supply chains that extend far beyond the immediate commercial losses of the individual shipping company.

2.4 Research Gap and Conceptual Position

The reviewed literature confirms that while the efficiency benefits of digital integration are well established across port-level and network-level maritime operations, and while the digital transformation literature provides robust theoretical frameworks for understanding organizational adoption dynamics, the specific empirical relationship between fleet management system integration and propulsion maintenance efficiency outcomes in Indonesian shipping companies has not been systematically investigated. This gap is both conceptual — in the absence of a cross-disciplinary operations management framework applied to vessel-level maritime maintenance — and empirical, in the absence of primary data from Indonesian domestic shipping operators that would enable policy-relevant conclusions. The present study addresses both dimensions, positioning itself at the intersection of maritime management, digital transformation theory, and operational maintenance engineering to generate evidence directly applicable to policy and practice.

3. Method

This study employed a mixed-methods research design integrating a structured questionnaire survey with semi-structured expert interviews to investigate the relationship between fleet management system integration and propulsion maintenance operational efficiency among Indonesian domestic shipping companies. The mixed-methods approach was selected to enable both quantitative measurement of maintenance efficiency indicators across a representative sample of companies and qualitative depth of understanding regarding the organizational and institutional factors mediating system integration outcomes — factors that resist adequate capture through survey instruments alone (Shi et al., 2023).

The study population comprised Indonesian domestic shipping companies

registered with the Directorate General of Sea Transportation and operating vessels of 500 gross tonnes or above on inter-island routes under the Tol Laut program or comparable domestic service classifications. From this population, 20 companies were selected through stratified purposive sampling, stratified by company size (large: more than 20 vessels; medium: 6–20 vessels; small: 1–5 vessels) and by ownership type (state-owned and privately owned), to ensure representativeness of the institutional and organizational diversity characterizing the Indonesian domestic shipping sector. Within each company, three respondents were recruited: the Fleet Manager or Technical Superintendent, the Chief Engineer of a designated representative vessel, and a Shore-based Maintenance Coordinator — yielding a total survey sample of 60 respondents.

The primary research instrument was a structured questionnaire comprising three modules. The first module assessed Fleet Management System Integration Level using a validated 20-item scale measuring the extent to which maintenance scheduling, condition monitoring, spare parts management, Class compliance tracking, and inter-departmental information sharing were integrated within a unified digital platform, scored on a five-point Likert scale and converted to a composite integration index ranging from 0 to 100. The second module collected Propulsion Maintenance Efficiency data through three operationalized indicators: system uptime rate (percentage of scheduled operating days on which the main propulsion system was fully available, averaged over the preceding 12 months); unplanned maintenance cost ratio (unplanned propulsion maintenance expenditure as a percentage of total propulsion maintenance budget); and Class survey compliance rate (percentage of required Class survey milestones completed within the mandated timeframe over the preceding survey cycle). The third module captured organizational and institutional contextual variables including company age, fleet age profile, crewing model, and IT infrastructure capacity. Semi-structured interviews were conducted with Fleet Managers from a subsample of eight companies — selected to maximize variation across integration level and company size — to elicit qualitative accounts of implementation challenges, organizational change processes, and perceived maintenance outcome changes attributable to system integration (Husain et al., 2021).

Data analysis proceeded through the three specified procedures. Thematic Analysis was applied to interview transcripts, generating themes around system adoption barriers, organizational capability requirements, and perceived maintenance outcome improvements. Cross-group Comparison was applied to quantitative survey data, comparing maintenance efficiency indicators across high, medium, and low integration

level groups defined by tercile division of the composite integration index. Narrative Synthesis integrated the quantitative comparative findings and qualitative themes into a coherent interpretive account addressing the study's research question. Descriptive statistics and one-way ANOVA were applied to test the significance of cross-group efficiency differences. All data were collected following institutional ethical review approval and participant informed consent.

4. Results and Analysis

4.1 Overview of Findings

Analysis of questionnaire survey data and interview transcripts generated a coherent and analytically significant picture of the relationship between fleet management system integration and propulsion maintenance operational efficiency among Indonesian domestic shipping companies. Findings are organized across four sub-sections: fleet management system integration profiles, propulsion uptime and unplanned maintenance costs, Class survey compliance performance, and qualitative accounts of organizational and institutional mediating factors.

4.2 Fleet Management System Integration Profiles

The composite Fleet Management System Integration Index revealed a markedly polarized distribution across the 20 sampled companies. Table 1 presents the integration profiles of sampled companies, organized by integration level group and company size category.

Table 1. Fleet Management System Integration Profiles by Company Size and Ownership Type

Integration Level Group	N (Companies)	Integration Index Mean (0–100)	Large Company (%)	Medium Company (%)	Small Company (%)	State-Owned (%)
High Integration (≥70)	7	81.4	71%	29%	0%	57%
Medium Integration (40–69)	8	54.2	25%	63%	12%	25%
Low Integration (<40)	5	24.7	0%	20%	80%	0%
Total / Overall Mean	20	55.3	—	—	—	—

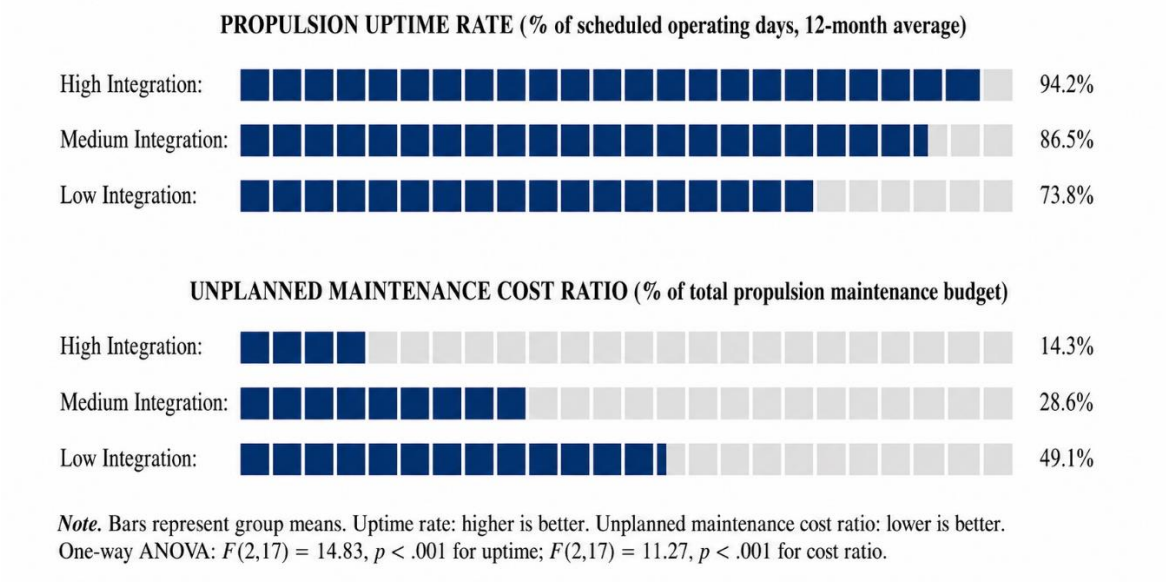
Note. Integration index based on 20-item Fleet Management System Integration Scale (0–100). Company size: Large = >20 vessels; Medium = 6–20 vessels; Small = 1–5 vessels.

The data in Table 1 reveal a strong association between company size, ownership type, and system integration level. All seven high-integration companies were either large-scale or medium-scale operators, with state-owned enterprises comprising 57% of the high-integration group — reflecting the greater financial capacity and regulatory accountability of larger and government-affiliated operators to invest in and maintain integrated digital management platforms. Conversely, the five low-integration companies were overwhelmingly small, privately owned operators (80% small-scale) whose integration indices averaged only 24.7 out of 100, reflecting reliance on paper-based maintenance logs, non-integrated spreadsheet systems, or standalone single-function software modules that lack cross-departmental data sharing capability. This distributional pattern has direct implications for equity in policy interventions aimed at promoting fleet management digitalization: blanket adoption mandates would fall disproportionately on precisely those smaller operators least equipped — financially and organizationally — to comply.

Interview data from Fleet Managers in low-integration companies consistently identified two primary barriers to system integration: initial implementation cost (cited by all five low-integration company Fleet Managers as the primary constraint) and a shortage of shore-based IT personnel capable of configuring and maintaining integrated platforms (cited by four of five). These findings resonate with Ciancarini et al.'s (2024) analysis of digital transformation barriers in resource-constrained organizational contexts, where financial and human capital limitations interact to sustain legacy information architectures even where the operational case for integration is recognized.

4.3 Propulsion Uptime and Unplanned Maintenance Costs

The relationship between fleet management system integration level and propulsion maintenance efficiency indicators — uptime rate and unplanned maintenance cost ratio — represents the empirical core of the study's findings. Figure 1 presents comparative propulsion uptime rates and unplanned maintenance cost ratios across the three integration level groups.



Note. Bars represent group means. Uptime rate: higher is better. Unplanned maintenance cost ratio: lower is better. One-way ANOVA: $F(2,17) = 14.83$, $p < .001$ for uptime; $F(2,17) = 11.27$, $p < .001$ for cost ratio.

Figure 1. Propulsion System Uptime Rate and Unplanned Maintenance Cost Ratio by Integration Level Group

The contrasts illustrated in Figure 1 are striking in both magnitude and consistency. High-integration companies achieved a mean propulsion uptime rate of 94.2% — a figure approaching the international benchmark of 95% for well-managed commercial fleets — compared to 86.5% for medium-integration companies and 73.8% for low-integration operators. The difference between high and low integration groups represents an average of 20.4 additional operational days per vessel per year, a figure with direct and substantial implications for revenue generation and route reliability. One-way ANOVA confirmed that integration level group differences in uptime were statistically significant ($F(2,17) = 14.83$, $p < .001$).

The unplanned maintenance cost differential is equally analytically significant. Low-integration companies directed an average of 49.1% of their total propulsion maintenance budgets to unplanned (reactive) maintenance expenditure — nearly three and a half times the rate of high-integration companies (14.3%). This ratio reflects the fundamental economic inefficiency of reactive maintenance regimes: emergency repairs, expedited spare parts procurement, and unscheduled dry-docking each carry substantial cost premiums relative to planned maintenance procedures. The finding is consistent with the digital twin and predictive maintenance literature reviewed by Elbouzidi et al. (2023), who document cost reduction ratios of similar magnitude in manufacturing and logistics asset management contexts where integrated condition monitoring replaces reactive maintenance scheduling.

4.4 Class Survey Compliance Performance

Table 2 presents Class survey compliance rates across the three integration level groups, disaggregated by survey type to reveal how integration effects vary across the different compliance obligation dimensions.

Table 2. Class Survey Compliance Rates by Integration Level Group and Survey Type (%)

Survey Type	High Integration (%)	Medium Integration (%)	Low Integration (%)	ANOVA Significance
Annual survey compliance	97.1	89.3	74.2	$p < .01$
Intermediate survey compliance	95.4	84.7	69.6	$p < .01$
Special (5-year) survey compliance	92.8	80.2	61.4	$p < .001$
Propulsion-specific inspection completion	96.3	83.1	65.8	$p < .001$
Overall Compliance Mean	95.4	84.3	67.8	$p < .001$

Note. Compliance rate = percentage of required survey milestones completed within mandated timeframe over the preceding Class survey cycle. N = 7 (high), 8 (medium), 5 (low).

Table 2 reveals that high-integration companies achieved near-complete Class survey compliance across all survey types (overall mean: 95.4%), while low-integration companies fell substantially below acceptable compliance thresholds across all categories (overall mean: 67.8%). The compliance deficit is most acute for special five-year surveys (61.4% in low-integration companies), which require comprehensive propulsion system dismantling and inspection — a process that demands precisely the type of systematic, long-range maintenance documentation and planning capability that integrated fleet management systems are specifically designed to provide. The operational and regulatory consequences of survey non-compliance are severe: vessels that fail to meet Class requirements risk trading certificate suspension, forcing them out of commercial operation and — in the Indonesian context — potentially triggering obligations under the Tol Laut program that cannot be fulfilled, with cascading effects for inter-island supply chain reliability (Kim et al., 2021; Paridaens & Notteboom, 2021).

Interview data from Fleet Managers in high-integration companies consistently attributed their compliance performance to automated survey milestone reminder systems, digitized maintenance history archives enabling rapid documentation preparation, and condition monitoring data that allowed engineers to anticipate and address emerging

defects before Class inspections. As one Technical Superintendent articulated: *"Before the integrated system, we were always reactive — finding out what was wrong during the survey. Now the system tells us three months in advance what needs attention."* This account illustrates the mechanism through which integration enhances compliance: by converting what had been a reactive documentation exercise into a prospective management process, integrated systems structurally reduce the likelihood of compliance failures attributable to maintenance neglect or documentation gaps.

4.5 Organizational and Institutional Mediating Factors

Qualitative thematic analysis of interview data identified three organizational factors that significantly mediated the relationship between system integration level and maintenance efficiency outcomes: technical crew competency in digital system use, shore-based IT support capacity, and senior management commitment to data-driven maintenance decision-making. These factors align with the organizational transformation preconditions identified by Ciancarini et al. (2024) as necessary for successful digital platform integration in complex operational environments, and suggest that system acquisition alone — without accompanying investment in human capability development and organizational process redesign — is insufficient to realize the maintenance efficiency potential of integrated fleet management platforms. The shipping network optimization literature (Qi et al., 2022) further underscores that technological investments in maritime operations generate greatest returns when embedded within coherent operational management frameworks that translate system capabilities into consistent decision-making practices.

5. Discussion

The findings of this study generate several analytically significant insights into the relationship between fleet management system integration and propulsion maintenance operational efficiency, with important implications for maritime management practice, regulatory policy, and shipping industry digital transformation strategy in Indonesia.

The strong empirical association between integration level and propulsion uptime — with high-integration companies achieving 20.4 additional operational vessel-days per year compared to low-integration counterparts — provides compelling evidence for the operational efficiency value of integrated fleet management platforms in the Indonesian domestic shipping context. This finding extends and concretizes the theoretical argument advanced in the digital transformation literature (Ciancarini et al., 2024; Elbouzidi et al., 2023) by grounding it in primary data from a specific national maritime industry context

where the relationship between system integration and maintenance outcomes had not previously been empirically demonstrated. The magnitude of the uptime differential further suggests that the operational case for integration investment is robust even for medium-sized operators, where the revenue implications of 20 additional operational days per vessel per year are likely to generate returns substantially exceeding the cost of platform implementation.

The finding that unplanned maintenance costs account for nearly half of total propulsion maintenance budgets among low-integration companies is particularly significant from an organizational economics perspective. It confirms that reactive maintenance regimes carry not only operational costs — in terms of service disruption and vessel unavailability — but also direct financial inefficiencies that compound over time, progressively eroding the financial capacity of affected companies to invest in the system integration that would reduce those costs. This dynamic creates a maintenance efficiency trap that policy intervention may be necessary to disrupt: smaller operators whose limited financial resources prevent integration investment face escalating reactive maintenance costs that further reduce their investment capacity, entrenching rather than reversing the integration gap. The port resilience framework developed by Kim et al. (2021) provides conceptual support for understanding how these vessel-level maintenance deficiencies aggregate into systemic maritime network vulnerabilities — a systemic logic that strengthens the case for policy-level rather than purely market-led responses to fleet management digitalization.

The Class survey compliance differential is similarly instructive in its policy implications. A mean compliance rate of 67.8% among low-integration companies suggests that a substantial proportion of small-scale Indonesian domestic shipping operators may be operating in a condition of chronic regulatory non-compliance — a situation with direct consequences for vessel safety standards, seafarer safety, and the integrity of the classification system that underpins maritime insurance and liability frameworks (Liao & Lee, 2023). Regulatory enforcement without accompanying support for integration capability development risks compounding the operational difficulties of smaller operators without addressing the structural information management deficiencies that generate compliance gaps in the first instance.

The qualitative finding that human capability development and management commitment mediate the efficiency returns of system integration carries important practical implications for how fleet management digitalization programs are designed and

supported. Technical system acquisition without concurrent investment in crew digital literacy, shore-based IT capacity, and management process redesign produces under-realized returns — a pattern consistent with the organizational transformation literature (Ciancarini et al., 2024) and with the technology management findings of Shi et al. (2023). Maritime policy frameworks should therefore incorporate not only financial incentive mechanisms for system acquisition but capacity-building support for the human and organizational dimensions of effective digital integration.

Limitations of the study include the cross-sectional survey design, which precludes causal attribution of maintenance efficiency improvements to system integration in the absence of longitudinal data. The sample of 20 companies, while appropriate for the mixed-methods design, constrains generalizability to the full diversity of Indonesian domestic shipping operators. Future research should employ longitudinal panel designs tracking maintenance efficiency indicators before and after system integration events, and should extend the comparative framework to international shipping companies operating in the Indonesian market to enable benchmarking against global operational efficiency standards.

6. Conclusion

This study has demonstrated that fleet management system integration is a statistically and practically significant determinant of propulsion maintenance operational efficiency among Indonesian domestic shipping companies, with high-integration operators achieving substantially superior propulsion uptime rates, lower unplanned maintenance cost ratios, and stronger Class survey compliance compared to medium and low integration counterparts. The findings reveal a maintenance efficiency trap among low-integration, small-scale operators whose reactive maintenance regimes generate escalating costs that constrain the very integration investments that could resolve them — a dynamic requiring policy-level intervention beyond purely market-driven adoption incentives. By bridging operations management theory, digital transformation scholarship, and maritime engineering practice within a primary-evidence Indonesian context, this study contributes a cross-disciplinary analytical framework that advances the understanding of fleet management digitalization as both an organizational efficiency strategy and a maritime safety governance imperative.

References

Caldas, P., Pedro, M. I., & Marques, R. C. (2024). An assessment of container seaport efficiency determinants. *Sustainability*, *16*(11), 4427.

https://doi.org/10.3390/su16114427

Chae, G.-Y., An, S.-H., & Lee, C.-Y. (2021). Demand forecasting for liquified natural gas bunkering by country and region using meta-analysis and artificial intelligence. *Sustainability*, *13*(16), 9058. https://doi.org/10.3390/su13169058

Ciancarini, P., Giancarlo, R., & Grimaudo, G. (2024). Digital transformation in the public administrations: A guided tour for computer scientists. *IEEE Access*, *12*, 20890–20915. https://doi.org/10.1109/access.2024.3363075

Elbouzidi, A. D., Artiba, A., Pellerin, R., Lamouri, S., Valencia, E. T., & Bélanger, M.-J. (2023). The role of AI in warehouse digital twins: Literature review. *Applied Sciences*, *13*(11), 6746. https://doi.org/10.3390/app13116746

Husain, O., Salim, N., Alias, R. A., Abdelsalam, S., Ramayah, T., Shehzad, H. M. F., & Hamzah, M. (2021). Modeling academic research collaborator selection using an integrated model. *IEEE Access*, *9*, 94216–94235. https://doi.org/10.1109/access.2021.3096250

Kim, B., Kim, G., & Kang, M.-H. (2022). Study on comparing the performance of fully automated container terminals during the COVID-19 pandemic. *Sustainability*, *14*(15), 9415. https://doi.org/10.3390/su14159415

Kim, S.-K., Choi, S., & Kim, C. (2021). The framework for measuring port resilience in Korean port case. *Sustainability*, *13*(21), 11883. https://doi.org/10.3390/su132111883

Liao, Y.-H., & Lee, H.-S. (2023). Using a directional distance function to measure the environmental efficiency of international liner shipping companies and assess regulatory impact. *Sustainability*, *15*(4), 3821. https://doi.org/10.3390/su15043821

Mwendapole, M. J., & Jin, Z. (2021). Evaluation of seaport service quality in Tanzania: From the Dar es Salaam seaport perspective. *Sustainability*, *13*(18), 10076. https://doi.org/10.3390/su131810076

Paridaens, H., & Notteboom, T. (2021). National integrated maritime policies (IMP): Vision formulation, regional embeddedness, and institutional attributes for effective policy integration. *Sustainability*, *13*(17), 9557. https://doi.org/10.3390/su13179557

Qi, J., Wang, S., & Zheng, J. (2022). Shore power deployment problem — A case study of a Chinese container shipping network. *Sustainability*, *14*(11), 6928. https://doi.org/10.3390/su14116928

Shi, Y., Ramayah, T., Hongmei, L., Zhang, Y., & Wang, W. (2023). Analysing the current status, hotspots, and future trends of technology management: Using the WoS and Scopus database. *Heliyon*, *9*(9), e19922.

https://doi.org/10.1016/j.heliyon.2023.e19922

Zhang, W., Zhang, Y., & Qiao, W. (2022). Risk scenario evaluation for intelligent ships by mapping hierarchical holographic modeling into risk filtering, ranking and management. *Sustainability*, *14*(4), 2103. https://doi.org/10.3390/su14042103