Risk Management Strategies for Maritime Infrastructure Maintenance to Enhance Safety and Productivity

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Abstract

This study aims to formulate a risk management strategy in maritime infrastructure maintenance to improve port operational safety and productivity. The evaluation focuses on the role of infrastructure components, including facilities, technology, and operational procedures, in the effectiveness of risk management. Maritime infrastructure maintenance and repair play a crucial role in ensuring the smooth operation of port activities while maintaining safety standards. However, this process often faces challenges, such as work delays, equipment damage, and environmental factors that have the potential to reduce productivity. This study applies a risk management approach through the identification of potential hazards, analysis of the level of likelihood and impact, and formulation of mitigation strategies based on maritime safety standards. The results show that the implementation of structured risk management can reduce the potential for work accidents, reduce unexpected costs, and improve infrastructure reliability and port operational efficiency. This strategy demonstrates effectiveness in balancing safety with productivity through optimizing infrastructure maintenance management. Thus, this study confirms that risk management is not only an important instrument in maritime infrastructure maintenance but also a strategic approach to ensure sustainable port productivity. These findings contribute to the development of adaptive, safety-oriented maintenance policies that are responsive to the dynamics of the maritime operational environment.

Keywords: Port safety, risk management, maritime infrastructure maintenance, operational productivity, mitigation strategies.

INTRODUCTION

Maritime infrastructure plays a critical role in supporting the continuity and efficiency of port operations, which serve as essential hubs for international trade and maritime transportation. The maintenance of maritime infrastructure is intended not only to preserve the functionality and reliability of port facilities but also to maintain high safety standards, prevent accidents, and minimize operational disruptions. However, maintenance activities frequently encounter challenges, including project delays, equipment failures, infrastructure deterioration, and environmental disturbances, all of which can significantly affect port productivity and operational performance. These challenges highlight the need for a systematic risk-based maintenance strategy to ensure that port facilities remain operational under uncertain and changing conditions. Recent studies on port resilience have emphasized the importance of integrating holistic risk management tools and methods to strengthen the ability of ports to predict, anticipate, respond to, and recover from disruptions while maintaining operational continuity (Maritime Economics & Logistics, 2025).

Risk management and resilience in maritime infrastructure have received increasing attention in the literature. Sieswerda (2024) emphasized the importance of sustainable risk-based maintenance strategies for optimizing port asset performance and managing deterioration caused by aging and environmental exposure. Such approaches enable port authorities and operators to systematically prioritize maintenance activities through integrated risk assessments, thereby supporting more effective allocation of financial and technical resources. Another study developed a dynamic multistage model to examine load redistribution within port and dry port networks, highlighting the importance of multilevel risk assessment in addressing complex supply chain disruptions (ScienceDirect, 2025). Furthermore, a case study conducted at Meizhou Bay Port demonstrated the relevance of integrating technical, managerial, and policy considerations into port resilience strategies to address external disturbances, including climate-related hazards and environmental pressures (Sustainability, 2024).

Despite these contributions, existing studies have predominantly examined port resilience and risk management from broader perspectives, such as maritime logistics networks, supply chain disruptions, or specific infrastructure-related case studies. Comparatively limited attention has been directed toward comprehensively integrating risk management principles into routine maritime infrastructure maintenance at the operational port level. This limitation is particularly relevant because maintenance-related risks arise from interactions among infrastructure condition, equipment reliability, environmental exposure, operational procedures, and the availability of maintenance resources. Consequently, there remains a need for an integrated approach that connects systematic risk identification and assessment with maintenance planning, operational safety, and port productivity.

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To address this research gap, the present study proposes an integrated risk management strategy for maritime infrastructure maintenance within the context of daily port operations. The proposed approach extends beyond conventional preventive maintenance by incorporating resilience principles to improve the capacity of port infrastructure systems to adapt to environmental uncertainty and potential systemic disruptions. It emphasizes the integration of physical facilities, supporting technologies, and operational procedures within a coordinated risk management framework. Through this approach, maintenance priorities can be established by considering the likelihood and consequences of infrastructure failures, their potential effects on operational safety, and their implications for port productivity.

The scientific contribution of this study lies in developing a conceptual framework that links risk-based maintenance strategies with the operational resilience of maritime infrastructure. By integrating infrastructure condition assessment, risk prioritization, maintenance decision-making, and operational continuity, the proposed framework seeks to bridge the gap between infrastructure asset management and port-level risk management. This integration is expected to support more systematic maintenance planning, improve resource allocation, and strengthen the ability of port operators to manage infrastructure-related uncertainties.

Accordingly, this study aims to develop a systematic risk management strategy for maritime infrastructure maintenance to enhance safety and operational productivity in port environments. The assessment focuses on the roles of infrastructure components, supporting technologies, and operational procedures in improving the effectiveness of risk identification, evaluation, mitigation, and maintenance planning. The findings are expected to provide a theoretical and practical foundation for developing adaptive, safety-oriented maintenance policies that respond effectively to changing maritime operating conditions. Ultimately, the study seeks to contribute to the long-term reliability, resilience, and productivity of maritime infrastructure through more integrated and sustainable maintenance management practices.

METHODS

This study employed a qualitative research approach based on a literature review to examine risk management strategies in maritime infrastructure maintenance and repair. The approach involved systematically collecting, reading, recording, and organizing relevant research materials concerning risk management, maintenance practices, infrastructure deterioration, and operational safety in maritime environments. This method was selected to develop a comprehensive understanding of existing theoretical perspectives, maintenance challenges, and risk management practices that contribute to improving the safety and productivity of maritime infrastructure.

The research process consisted of several stages. The first stage involved identifying and collecting relevant information from scientific sources, academic journals, and online publications addressing the application of risk management in the maritime sector. Particular attention was given to literature discussing infrastructure maintenance, repair strategies, operational risks, and the management of maritime facilities. The collected materials served as the primary information sources for examining existing approaches and identifying relevant risk management considerations. The second stage involved organizing and reviewing the collected literature to identify recurring themes, concepts, and findings related to maritime infrastructure risk management. Information obtained from different publications was examined to understand the relationship between maintenance activities, infrastructure reliability, safety performance, and operational productivity. This process provided a basis for identifying common maintenance challenges and potential strategies for reducing infrastructure-related risks.

The final stage consisted of synthesizing and interpreting the information obtained from the literature review. The findings were organized into a structured research discussion describing the application of risk management principles to maritime infrastructure maintenance and repair. The synthesis focused on identifying relevant strategies for risk prevention, maintenance planning, and operational improvement. Through this qualitative literature-based approach, the study aims to provide an in-depth understanding of how risk management strategies can support more effective maritime infrastructure maintenance. The findings are expected to contribute to the development of maintenance practices that enhance infrastructure reliability, strengthen operational safety, and support sustainable productivity in maritime environments.

RESULTS AND DISCUSSION

National Budget Policy and Implementation: Analysis of the Directorate General of Sea Transportation Strategic Plan 2020–2024 and Its Midterm Evaluation

The Strategic Plan of the Directorate General of Sea Transportation (DGST) for 2020–2024 established development priorities covering port infrastructure expansion, improvements in berth capacity and navigation facilities, and the strengthening of human resources and supporting regulatory frameworks. This document served as a national planning reference for the maritime transportation sector throughout the 2020–2024 period.

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The 2022 midterm evaluation of the Strategic Plan indicated that the realization of the State Budget (APBN) allocation for DGST programs during 2020–2022 reached only 77.19% of the estimated funding requirements. Nevertheless, most performance indicators reportedly achieved realization levels exceeding 95%. This condition indicates a discrepancy between estimated financial requirements and available budget realization, which may influence the implementation of infrastructure maintenance programs and investment in port facilities.

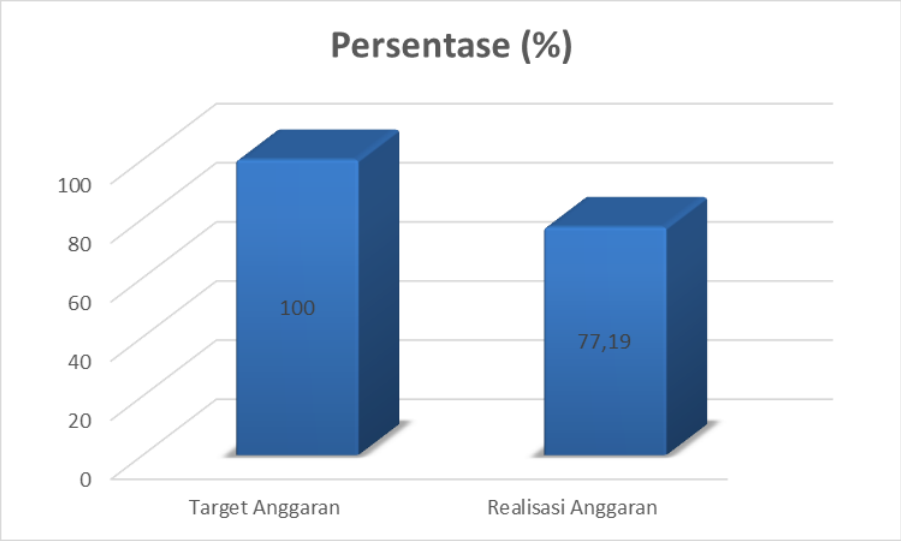


Figure 1. Comparison of estimated budget requirements (100%) and actual budget realization (77.19%) for Directorate General of Sea Transportation programs during 2020–2022.

The comparison illustrates a funding gap of 22.81 percentage points relative to the estimated budget requirements. This discrepancy highlights the importance of effective budget prioritization and risk-informed resource allocation in maintaining the reliability and operational continuity of maritime infrastructure.

Quantitative Analysis of Operational Risk Management: A Coal Port Case Study

A field study conducted at the operational unit of a coal port operated by PT A identified 499 hazards classified into eight principal categories. The most prevalent hazard categories were mechanical hazards, accounting for 28.54% of the identified hazards, and working-environment hazards, representing 26.22%.

Based on the risk assessment matrix employed in the referenced study, the identified hazards were distributed into four risk categories: AA (9.22%), A (47.90%), B (30.26%), and C (13.23%). The results indicated that Category A represented the largest proportion of the reported risks, highlighting the importance of prioritizing mitigation measures for high-risk operational activities.

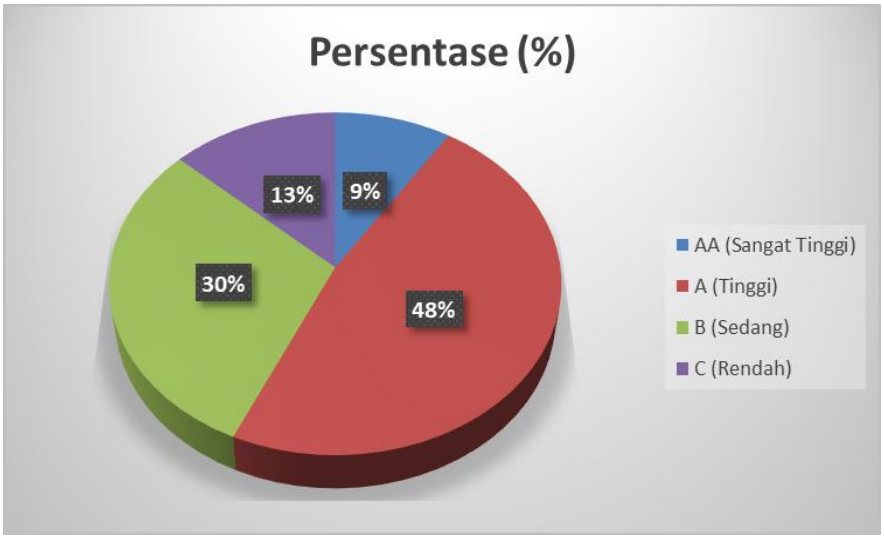


Figure 2. Percentage distribution of operational risk categories (AA, A, B, and C) identified in the coal port case study.

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The risk distribution indicates that Category A accounted for approximately 48% of the reported assessments. The combined proportion of Categories AA and A reached 57.12%, suggesting that a substantial proportion of the identified risks required priority attention within the risk management and mitigation process. These findings emphasize the importance of applying systematic risk assessment procedures to loading and unloading activities, particularly those involving mechanical equipment, material-handling systems, and hazardous working environments.

Performance of a National Port Operator: Empirical Evidence from PT Pelabuhan Indonesia (Pelindo) in 2023

PT Pelabuhan Indonesia (Pelindo), one of Indonesia's principal national port operators, reported operating revenue of approximately IDR 31.02 trillion and net profit of IDR 4.01 trillion in its 2023 Annual Report. The report also described improvements in vessel and container throughput, reflecting developments in the company's operational activities.

Substantial investment realization was reported across selected subsidiary entities, including an investment value of approximately IDR 481.24 billion at one terminal. These figures indicate the scale of the company's financial and investment activities. However, further examination is necessary to determine the extent to which investment expenditure was allocated to structural maintenance, infrastructure rehabilitation, equipment modernization, or operational capacity expansion.

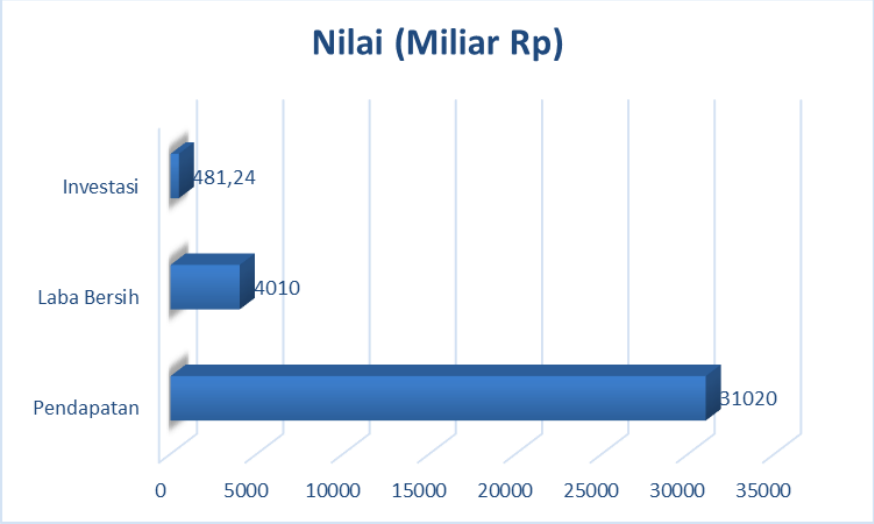


Figure 3. Comparison of Pelindo's operating revenue, net profit, and selected terminal investment in 2023.

The comparison illustrates the differences in magnitude between operating revenue, net profit, and the reported investment amount. Although operating revenue and investment expenditure were substantial, net profit represented a considerably smaller amount. These financial indicators highlight the importance of operational cost management and investment prioritization, particularly when balancing infrastructure maintenance requirements against expansion and modernization initiatives.

Digital Transformation through Predictive Maintenance: A Review of the 2024–2025 Literature

Recent literature published between 2024 and 2025 indicates that data-driven predictive maintenance (PdM) and machine learning technologies have considerable potential to reduce equipment downtime and unexpected maintenance costs in port operations.

Predictive maintenance applications have been discussed for critical port assets, including cranes, container-handling equipment, and pumping systems. By utilizing operational data and condition-monitoring information, predictive models can assist maintenance personnel in identifying early indications of equipment deterioration and anticipating potential failures.

Studies published in MDPI journals during 2024–2025 have emphasized the importance of implementing predictive maintenance through carefully designed pilot projects involving critical assets. These studies highlight the need for clear data management roadmaps and systematic technology validation before large-scale implementation.

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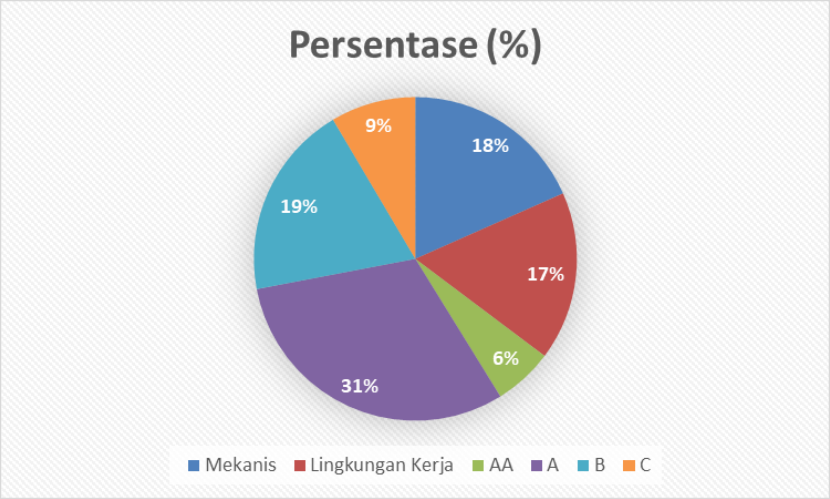


Figure 4. Distribution of mechanical and working-environment hazards and the associated operational risk classifications in the coal port case study.

The distribution of hazards and risk categories provides a basis for identifying maintenance priorities. Mechanical hazards and working-environment conditions represent important areas requiring preventive measures, while the classification of risks into AA, A, B, and C supports prioritization according to the severity and likelihood assessments applied in the referenced case study.

Discrepancy Between Policy Planning and Budget Realization: Risks Associated with Funding Constraints

The Strategic Plan of the Directorate General of Sea Transportation for 2020–2024 established several development priorities, including port infrastructure rehabilitation, navigation channel dredging, navigation system modernization, and improvements in human resources and supporting regulatory frameworks. These initiatives were intended to strengthen maritime connectivity, infrastructure reliability, and the operational performance of Indonesian ports. However, the reported realization of state budget funding for DGST programs during 2020–2022 reached approximately 77.19% of the estimated requirements. This discrepancy indicates financial constraints that may affect the implementation of infrastructure maintenance and development programs.

Insufficient funding can create challenges for preventive maintenance scheduling, particularly when port authorities are required to prioritize urgent infrastructure repairs and critical operational projects. Under constrained financial conditions, routine maintenance activities may be postponed, increasing the possibility of progressive structural deterioration and unexpected equipment failures. Such risks may be especially relevant to small and medium-sized ports with limited technical and financial resources. The findings highlight the importance of incorporating risk-based decision-making into infrastructure maintenance budgeting. Instead of allocating available funds solely according to fixed schedules or immediate operational demands, maintenance priorities should consider asset condition, failure probability, potential safety consequences, and expected operational disruptions. Increasing budget realization toward the estimated requirements, including the suggested range of 90–100%, may provide additional resources for infrastructure maintenance. Nevertheless, the effectiveness of maintenance expenditure also depends on how financial resources are distributed, monitored, and linked to infrastructure risk levels. Therefore, an integrated risk management framework is essential for ensuring that available maintenance resources are directed toward critical infrastructure components and activities.

From Hazard Identification to Mitigation Prioritization: Quantitative Evidence from a Local Case Study

The coal port case study identified 499 hazards distributed across eight principal categories. Mechanical hazards accounted for 28.54%, while working-environment hazards represented 26.22% of the total identified hazards. These findings indicate that mechanical equipment and workplace environmental conditions constitute significant sources of operational risk in port cargo-handling activities. The risk assessment matrix classified 9.22% of the identified risks into Category AA and 47.90% into Category A, resulting in a combined reported proportion of 57.12% for the two highest risk categories. The remaining assessments were distributed between Categories B and C, representing moderate and lower risk classifications within the referenced assessment framework. These results suggest that mitigation resources should be directed toward operational components associated with the greatest potential consequences. Mechanical systems such as cranes, conveyors, and cargo-handling equipment require particular attention because equipment failures may result in occupational accidents, operational interruptions, and financial losses.

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Similarly, working-environment hazards, including dust exposure, inadequate drainage, and excessive noise, require appropriate control measures to protect personnel and maintain safe operating conditions. A risk-based maintenance (RBM) strategy provides a systematic approach to addressing these issues by allocating maintenance resources according to assessed risk levels. Under this approach, equipment and infrastructure components with higher failure probabilities or more severe consequences receive greater maintenance priority. The application of RBM may therefore support improved maintenance scheduling, more effective resource utilization, and reduced exposure to safety and operational risks. However, the effectiveness of this approach depends on the accuracy of hazard identification, consistency of risk classification, and availability of reliable asset condition data.

The Role of National Port Operators: Balancing Investment and Infrastructure Maintenance

The financial performance of PT Pelabuhan Indonesia (Pelindo) provides an important perspective on the relationship between investment capacity and infrastructure maintenance requirements. In 2023, Pelindo reported operating revenue of approximately IDR 31.02 trillion and net profit of around IDR 4.01 trillion. These figures demonstrate the substantial scale of the company's financial operations and its potential capacity to support infrastructure modernization and operational development. Nevertheless, the publicly available financial information discussed in this study does not provide sufficiently detailed evidence concerning the proportion of investment expenditure specifically allocated to structural berth maintenance compared with capacity expansion or the development of new facilities.

This information gap limits the ability to evaluate whether infrastructure maintenance investment is proportionate to the operational and structural risks associated with existing port assets. From a risk management perspective, investment decisions should consider the long-term relationship between infrastructure condition, maintenance expenditure, asset reliability, and operational productivity. Investment focused primarily on increasing handling capacity without adequate maintenance of existing infrastructure may contribute to progressive asset deterioration and increased operational downtime. Consequently, financial performance indicators should be considered alongside infrastructure condition assessments and maintenance performance indicators when evaluating port management effectiveness. An integrated asset management approach would enable port operators to balance infrastructure expansion with rehabilitation and preventive maintenance requirements. This approach could also improve transparency in maintenance budgeting and support long-term planning based on infrastructure criticality and operational risk.

Added Value of Predictive Maintenance and Digitalization

Recent research on predictive maintenance indicates that the integration of operational data, machine learning techniques, and Internet of Things (IoT) sensors offers opportunities to reduce unexpected equipment downtime and improve maintenance efficiency. Unlike conventional maintenance approaches that rely primarily on predetermined schedules or corrective actions following equipment failure, predictive maintenance uses condition-monitoring data to estimate the likelihood of equipment deterioration and identify potential failures before they result in operational disruptions. For example, research discussing machine-learning-based predictive maintenance in smart ports using IoT sensor data has highlighted the potential to reduce equipment idle time and unexpected failures in container terminal operations. These improvements may contribute to lower operational costs, higher equipment availability, and increased cargo-handling throughput. However, the successful implementation of predictive maintenance across Indonesian ports requires a structured development roadmap. The initial stages should prioritize the installation of appropriate sensors, the establishment of reliable data acquisition procedures, and the development of interoperable information systems.

Subsequent stages should focus on validating predictive models, integrating maintenance information with existing asset management systems, and strengthening personnel competencies in equipment diagnostics and data analytics. The reliability of predictive maintenance systems is strongly influenced by the quality, completeness, and consistency of equipment maintenance records. Inaccurate or incomplete operational data may reduce predictive accuracy and limit the practical effectiveness of machine learning models. Therefore, the development of predictive maintenance capabilities should be accompanied by improvements in maintenance documentation, data governance, and technical personnel training. Cybersecurity also represents an important consideration because the integration of IoT devices and interconnected operational systems may introduce vulnerabilities into port infrastructure. Unauthorized access, data manipulation, and interruptions to communication networks could create additional operational and safety risks. International experiences involving technologically advanced ports, including Rotterdam and Singapore, illustrate the relevance of phased technology deployment and operational validation before implementing predictive maintenance systems across entire port facilities.

In Indonesia, initial pilot projects could focus on critical cargo-handling equipment, such as quay cranes, whose operational availability directly affects terminal productivity. Pilot implementation would allow operators to evaluate data reliability, predictive accuracy, maintenance response procedures, and potential operational benefits before expanding the system to additional infrastructure assets. Government policies could also encourage collaboration among port operators, technology providers, and research institutions to facilitate technological knowledge transfer and strengthen domestic technical capabilities. If these requirements are addressed, predictive maintenance may contribute to improved occupational safety, increased

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equipment reliability, and enhanced operational productivity. Furthermore, successful implementation could provide a measurable foundation for broader maritime digital transformation and strengthen Indonesia's competitiveness within regional logistics networks. Ultimately, integrating predictive maintenance into risk-based maritime infrastructure management offers a potential pathway toward more proactive, data-driven, and resilient port operations. By linking asset condition monitoring with maintenance prioritization and operational risk assessment, port operators may improve infrastructure reliability while supporting national objectives related to supply chain efficiency and logistics cost reduction.

CONCLUSION

This study concludes that risk management strategies for maritime infrastructure maintenance in Indonesia during the 2020–2025 period are closely associated with national policy implementation, operational risk conditions, financial resource allocation, and technological readiness. The findings highlight the importance of integrating risk-based maintenance planning, infrastructure investment management, and predictive maintenance technologies to strengthen maritime safety and port operational productivity. The analysis of the Directorate General of Sea Transportation Strategic Plan for 2020–2024 indicates that national policy priorities included the maintenance and rehabilitation of port infrastructure, navigation channels, and navigational facilities. However, the reported budget realization during 2020–2022 reached approximately 77.19% of estimated funding requirements. This funding gap may constrain the implementation of preventive maintenance activities and delay necessary infrastructure improvements, potentially increasing operational risks and affecting the continuity of port services. These findings emphasize the importance of aligning maintenance priorities with available financial resources and infrastructure risk assessments.

Furthermore, the reviewed coal port case study identified 499 potential hazards, with more than half classified within the two highest risk categories (AA and A). This finding highlights the need for systematic Risk-Based Maintenance (RBM), particularly for critical infrastructure and cargo-handling equipment, including cranes, conveyor systems, and loading and unloading facilities. By prioritizing maintenance activities according to identified risks, port operators can strengthen accident prevention measures, improve equipment reliability, and support uninterrupted cargo-handling operations. The financial performance of PT Pelabuhan Indonesia (Pelindo) provides an additional perspective on the relationship between investment capacity and infrastructure maintenance. In 2023, the company reported operating revenue of approximately IDR 31.02 trillion and net profit of IDR 4.01 trillion. Nevertheless, further investigation is required to determine how capital expenditure (CAPEX) and operational expenditure (OPEX) are allocated between infrastructure maintenance, rehabilitation, equipment modernization, and capacity expansion. Long-term improvements in port productivity require an appropriate balance between investment in new facilities and the preservation of existing infrastructure assets.

In addition, the reviewed international literature published during 2024–2025 demonstrates the potential contribution of Predictive Maintenance (PdM) technologies to reducing unexpected equipment downtime, minimizing unplanned maintenance costs, and improving operational reliability. The integration of Internet of Things (IoT) sensors, operational data, and predictive analytics could support more proactive infrastructure maintenance practices at major Indonesian ports, including Tanjung Priok, Belawan, and Makassar. However, successful implementation would require reliable monitoring infrastructure, adequate data quality, trained personnel, and appropriate digital system integration. Overall, the findings suggest that maritime infrastructure risk management should be regarded not merely as a preventive mechanism for reducing accidents and infrastructure failures, but also as an essential component of sustainable port productivity improvement. Integrating risk-based maintenance, balanced infrastructure investment, and data-driven predictive maintenance strategies offers a practical direction for strengthening the safety, reliability, and resilience of Indonesia's maritime infrastructure. Further empirical investigations are recommended to validate the effectiveness of these strategies under actual port operating conditions and support the development of evidence-based national maintenance policies.

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