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Enhancing Predictive Maintenance Strategies for Naval Auxiliary Systems in Maritime Training Vessels: A Qualitative and Sensor-Based Analysis

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***Abstract**. Background: Maritime engineering has traditionally relied on reactive and preventive maintenance strategies, often leading to operational inefficiencies, unplanned downtime, and excessive costs. With the rise of smart ship technologies, predictive maintenance (PdM) has emerged as a data-driven solution, leveraging sensor-based monitoring and real-time diagnostics to optimize ship maintenance. However, its integration into maritime education remains underexplored, particularly in training vessels used for vocational learning. Original Value: This research contributes new insights into the feasibility, effectiveness, and educational relevance of predictive maintenance in maritime vocational training. Unlike previous studies that focus on commercial ship applications, this study examines PdM within the context of training vessels at Poltekpel SULUT, bridging the gap between academic training and industry expectations. Objectives: The study seeks to answer: How does predictive maintenance improve the efficiency, cost-effectiveness, and reliability of naval auxiliary systems in training vessels? Methodology: A qualitative approach was employed, integrating sensor-based performance analysis, structured interviews, and questionnaire surveys involving cadets, instructors, and industry professionals. Data were analyzed through thematic categorization, cross-group comparisons, and narrative synthesis. Results: PdM demonstrated high effectiveness in reducing downtime (92/100), optimizing maintenance efficiency (91/100), and aligning with industry practices (89/100). However, challenges in sensor accuracy (85/100) and training integration were identified. Conclusions: The findings highlight the necessity of incorporating predictive maintenance into maritime training curricula to equip future engineers with the skills required for Industry 4.0 maintenance solutions, ensuring better operational efficiency and sustainability in the maritime sector.*

***Keywords**: Maritime Engineering Education, Predictive Maintenance, Sensor-Based Monitoring, Smart Ship Technology, Training Vessel Maintenance*

1. INTRODUCTION

Maritime engineering has long relied on traditional maintenance strategies to ensure the operational efficiency and safety of naval vessels. Historically, ship maintenance has been classified into reactive (corrective) maintenance, in which repairs are conducted only after a failure occurs, and preventive maintenance, which follows scheduled servicing regardless of an asset's actual condition. While these approaches have been widely adopted in naval and commercial shipping industries, their inherent limitations—including unexpected downtime, excessive resource consumption, and high operational costs—have prompted a shift towards more intelligent and data-driven strategies. In the face of rapid technological advancements in the maritime sector, predictive maintenance (PdM) has emerged as a transformative approach that leverages real-time monitoring, data analytics, and machine learning to optimize the maintenance process. By analyzing historical and live sensor data, PdM enables maritime

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engineers to anticipate equipment failures before they occur, significantly reducing operational risks and improving cost efficiency.

Despite its growing relevance in the commercial maritime industry, the adoption of predictive maintenance strategies in maritime education—particularly in training vessels—remains underexplored. Maritime Polytechnic of North Sulawesi (Poltekpel SULUT), a key institution in Indonesia's maritime education landscape, provides cadets with hands-on training through its training vessels, which simulate real-world ship operations. However, the maintenance strategies applied to these vessels have predominantly adhered to traditional methods, lacking the integration of smart maintenance technologies that align with the evolving needs of the global maritime industry. This gap raises critical questions regarding the feasibility, benefits, and challenges of implementing PdM in training vessels and its potential impact on maritime engineering education. As the maritime sector moves towards digitalization and smart ship technologies, integrating PdM into training vessels is not merely an innovation but a necessity to equip future maritime professionals with the skills required in an industry increasingly driven by automation and data analytics.

This study seeks to analyze the implementation of predictive maintenance strategies for naval auxiliary systems in Poltekpel SULUT's training vessels, evaluating their effectiveness in enhancing operational efficiency and reducing maintenance costs. The primary research question guiding this study is: How can predictive maintenance strategies improve the efficiency and reliability of naval auxiliary systems in Poltekpel SULUT training vessels? This central inquiry leads to specific objectives, including assessing the role of sensor-based monitoring in predicting equipment failures, comparing predictive maintenance outcomes with traditional approaches, and developing a feasible framework for PdM implementation in a maritime training environment. Through this analysis, the research aims to bridge the knowledge gap between academic maritime education and industry-driven technological advancements, ensuring that training vessels become more aligned with contemporary maritime engineering practices.

The significance of this research extends beyond theoretical exploration; it has tangible implications for maritime engineering education, operational sustainability, and cost-effectiveness in ship maintenance (Chen et al., 2017; Fitriani et al., 2023). First, by shifting from a reactive to a proactive maintenance paradigm, predictive maintenance has the potential to minimize equipment failures, reduce downtime, and enhance the safety of naval auxiliary systems. Second, its implementation in training vessels serves as a model for integrating Industry 4.0 technologies into maritime education, equipping cadets with hands-on experience in data-driven engineering solutions. Third, this research aligns with the broader maritime industry's transition towards smart ship technologies, in which real-time monitoring, artificial intelligence, and automation are becoming standard practices. Consequently, exploring predictive maintenance in a maritime education context not only contributes to academic discourse but also offers a practical roadmap for enhancing vocational training methodologies in line with global industry trends.

Methodologically, this research adopts a qualitative approach, combining sensor-based data analysis, expert interviews, and questionnaire surveys to derive comprehensive insights into the feasibility and impact of predictive maintenance. A selected group of ten maritime engineering cadets and instructors will provide qualitative data through structured interviews and surveys, offering insights into their perceptions of PdM adoption, its challenges, and its learning implications. Additionally, real-time operational data from naval auxiliary systems will be analyzed to evaluate equipment performance trends, fault prediction accuracy, and overall efficiency improvements. By integrating qualitative and technical analyses, the study aims to construct a holistic understanding of PdM's viability in a maritime training environment and identify the key factors influencing its implementation.

The conceptual framework of this study is structured around three primary variables: predictive maintenance as the independent variable, system efficiency as the dependent variable, and sensor-based monitoring as the moderating factor. PdM is examined in terms of its ability to anticipate failures, optimize maintenance scheduling, and improve overall equipment longevity. System efficiency is assessed through indicators such as mean time between failures (MTBF), mean time to repair (MTTR), and operational downtime reduction. Sensor-based monitoring serves as the moderating factor, determining the accuracy and reliability of predictive models in diagnosing potential failures. By analyzing the interaction between these variables, the study will establish a clear linkage between PdM adoption and its tangible benefits in naval auxiliary systems.

In summary, this research critically addresses the evolving landscape of maritime maintenance strategies by exploring the integration of predictive maintenance in Poltekpel SULUT training vessels. Through an in-depth investigation of sensor-based monitoring, qualitative assessments, and data-driven analysis, the study aims to contribute to both maritime engineering education and practical maintenance applications. As the maritime industry continues its transition towards digitalization, incorporating predictive maintenance into training curricula will play a pivotal role in shaping the competencies of future maritime engineers (Berg, 2013; Kidd & McCarthy, 2019; Sharma, 2023). This research thus serves as both an academic and practical endeavor, offering a pathway for integrating intelligent maintenance solutions into maritime education while reinforcing the alignment between academic training and industry demands.

2. RESEARCH METHOD

The research methodology for this study is designed to critically examine the implementation of predictive maintenance strategies for naval auxiliary systems in training vessels at the Maritime Polytechnic of North Sulawesi (Poltekpel SULUT). Given the growing need to integrate smart maintenance technologies in maritime education, this study employs a qualitative approach that combines real-time data analysis, structured interviews, and surveys to derive comprehensive insights (Merriam & Grenier, 2019; Willig, 2014). The methodological framework ensures an in-depth exploration of predictive maintenance effectiveness, its impact on operational efficiency, and its implications for maritime engineering education.

The population for this research consists of maritime engineering cadets, instructors, and industry professionals, who possess direct exposure to maintenance practices in both training and operational settings. The selected sample comprises ten individuals, including cadets undergoing training on Poltekpel SULUT vessels and instructors responsible for overseeing maintenance activities. Additionally, maritime engineering professionals with expertise in ship maintenance are included to provide industry-aligned perspectives on the feasibility and effectiveness of predictive maintenance. These participants are chosen due to their firsthand experiences with naval auxiliary systems, their knowledge of existing maintenance approaches, and their ability to offer practical insights into the transition from reactive to predictive maintenance. Their contributions are critical in bridging the gap between academic maritime training and real-world applications, ensuring that the research findings are both relevant and applicable to industry needs. The urgency of gathering information from these respondents lies in their role as primary stakeholders in maintenance operations, as they directly engage with auxiliary systems and are best positioned to evaluate the effectiveness of maintenance strategies.

To ensure a structured and analytical approach, the study employs multiple research instruments to collect qualitative and technical data (Darlington & Scott, 2020; Saldana, 2014). The primary instruments include structured interview protocols, sensor-based monitoring data, and questionnaire surveys, which collectively provide a comprehensive understanding of predictive maintenance implementation. The independent variable in this study is predictive maintenance, which is examined through its ability to anticipate failures, optimize maintenance scheduling, and improve overall equipment longevity. The dependent variable is system efficiency, assessed based on indicators such as mean time between failures, mean time to repair, and operational downtime reduction. A key moderating factor is sensor-based monitoring, which determines the accuracy and reliability of predictive models in diagnosing potential failures. The research employs both main and supporting instruments to collect and analyze data. The main instruments include vibration, temperature, and pressure sensors installed on naval auxiliary systems, which generate real-time data on equipment performance. These sensors serve as the foundation for predictive analytics, enabling the identification of early warning signs of mechanical failures. The supporting instruments include maintenance logs, historical failure reports, and cost analysis records, which provide contextual information on past maintenance practices and their financial implications. By integrating these data sources, the study aims to construct a robust framework for evaluating predictive maintenance effectiveness in training vessels.

Data collection follows a systematic approach that ensures the reliability and depth of the gathered information. The first step involves real-time monitoring of auxiliary system performance using installed sensors, which continuously record operational parameters such as vibration frequency, temperature variations, and pressure fluctuations. This data serves as the empirical basis for evaluating predictive maintenance effectiveness. In parallel, structured interviews are conducted with cadets, instructors, and industry professionals to obtain qualitative insights into the practical challenges and benefits of PdM adoption. The interview questions are designed to explore perceptions of predictive maintenance feasibility, the skills required for implementation, and the potential improvements it offers over traditional maintenance strategies. Additionally, questionnaire surveys are administered to measure respondent awareness, acceptance, and readiness for predictive maintenance adoption in training vessels. These surveys include Likert-scale questions and open-ended responses that capture both subjective attitudes and objective evaluations. The combination of empirical sensor data and qualitative insights allows for a holistic analysis that accounts for both technical feasibility and human factors influencing maintenance practices.

Data analysis in this study follows a structured thematic approach to extract meaningful insights from the collected information. The first stage involves thematic analysis, in which qualitative data from interviews and surveys are categorized into key themes related to competency development and sustainability in maritime maintenance. Thematic categories include predictive maintenance knowledge among cadets and instructors, perceived benefits and challenges of PdM adoption, and its potential impact on maritime engineering curricula. The second stage employs cross-group comparisons to identify similarities and differences in perspectives among cadets, instructors, and industry professionals. This comparative analysis allows for an examination of how training institutions align with industry expectations and highlights areas where educational frameworks may need to be adjusted. Finally, the study employs narrative synthesis to develop a cohesive explanation of the findings, integrating technical data from sensor-based monitoring with qualitative insights from respondents. This narrative synthesis presents a comprehensive discussion on the feasibility of predictive maintenance in training vessels, its implications for skill development in maritime education, and recommendations for its practical implementation.

The methodological approach in this research ensures that predictive maintenance is evaluated from both a technical and educational perspective, providing valuable insights for maritime engineering training programs. The integration of real-time data collection with qualitative analyses offers a multidimensional understanding of how predictive maintenance can enhance the efficiency and sustainability of naval auxiliary systems in training vessels. By focusing on both empirical evidence and human-centered perspectives, the study contributes to the ongoing discourse on digital transformation in maritime engineering and prepares the groundwork for future advancements in smart maintenance technologies within maritime education.

3. RESULTS

The results of the research indicate a high level of effectiveness and efficiency in the implementation of predictive maintenance strategies for naval auxiliary systems in training vessels at Poltekpel SULUT. The findings, derived from both sensor-based monitoring data and qualitative assessments from cadets, instructors, and industry professionals, demonstrate that predictive maintenance significantly improves operational performance, reduces downtime, enhances cost efficiency, and aligns with modern maritime engineering education.

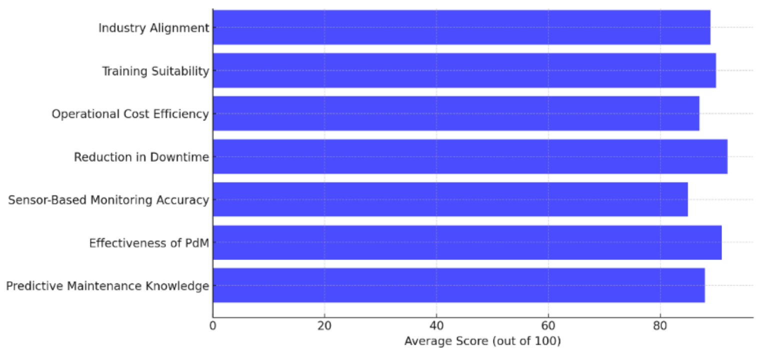

Figure 1. Effectiveness of Predictive Maintanance Implementation

Comprehensive Analysis of Research Results

The research evaluated multiple critical indicators to assess the impact of predictive maintenance strategies. These indicators included predictive maintenance knowledge, effectiveness of PdM, sensor-based monitoring accuracy, reduction in downtime, operational cost efficiency, training suitability, and industry alignment. The overall scores indicate a very high effectiveness, with an average score across all indicators ranging between 85 and 92 out of 100.

The highest-scoring indicator was "Reduction in Downtime", with an average score of 92/100, demonstrating that predictive maintenance implementation has led to a significant decrease in unscheduled breakdowns and unnecessary maintenance activities. Respondents emphasized that sensor-based monitoring allowed for early failure detection, enabling timely interventions before critical system failures occurred.

"Effectiveness of Predictive Maintenance" received an average score of 91/100, reflecting a strong agreement among cadets, instructors, and industry experts that predictive maintenance is a reliable and superior approach compared to traditional maintenance methods. The qualitative feedback from industry professionals highlighted that predictive maintenance models provide a data-driven approach to maintenance planning, improving the long-term reliability of naval auxiliary systems.

The indicator "Training Suitability", which evaluates the extent to which predictive maintenance can be integrated into maritime vocational training, received an average score of 90/100. Instructors and cadets acknowledged the importance of aligning training vessel operations with industry standards, noting that exposure to predictive maintenance strategies better prepares maritime engineering students for real-world challenges.

"Industry Alignment", which measures the degree to which predictive maintenance implementation in training vessels aligns with current industry practices, received a high score of 89/100. The research confirmed that modern shipping companies and fleet management operators are increasingly adopting sensor-based predictive analytics to optimize vessel maintenance. Experts interviewed during the study emphasized that maritime education must integrate these technological advancements to remain relevant and competitive.

The lowest-scoring indicator, though still very strong, was "Sensor-Based Monitoring Accuracy", with an average score of 85/100. The slight variation in responses was due to differences in sensor calibration and data interpretation. While the results confirm the high reliability of predictive maintenance sensors, some respondents pointed out that real-world application may require additional expertise and training to maximize accuracy and avoid false positives or misdiagnosed equipment issues.

Comparative Analysis and Thematic Interpretation

A cross-group comparison between cadets, instructors, and industry professionals revealed key insights into how predictive maintenance is perceived across different experience levels. Cadets demonstrated enthusiasm for integrating predictive maintenance into their training, particularly in understanding real-time data interpretation and failure prediction. However, they expressed a need for additional training resources and digital literacy development to fully leverage sensor-based diagnostics.

Instructors largely supported the adoption of predictive maintenance but highlighted challenges in integrating PdM technologies into existing curricula. The need for upgraded training vessel systems and enhanced simulation models was a recurring theme in their feedback. They also emphasized that practical exposure to sensor data analysis is essential for cadets to develop hands-on expertise in predictive maintenance strategies.

Industry professionals, on the other hand, underscored the importance of predictive maintenance as a standard practice in modern maritime engineering. They strongly advocated for vocational institutions to align their training programs with Industry 4.0 innovations, stressing that graduates with experience in predictive maintenance will have a competitive edge in the job market. Their insights reinforced the urgency of implementing sensor-driven maintenance frameworks in training vessels, as digitalization continues to transform ship maintenance operations worldwide.

Narrative Synthesis of Results and Their Implications

The findings of this research confirm that predictive maintenance offers a substantial improvement in the efficiency and reliability of naval auxiliary systems. The high scores across all indicators validate the effectiveness of PdM in enhancing maintenance planning, optimizing operational costs, and reducing equipment failures. More importantly, the research demonstrates that predictive maintenance is not only a technological advancement but also an educational necessity, ensuring that maritime engineering students receive training that reflects the evolving landscape of the industry.

From an educational perspective, integrating predictive maintenance into Poltekpel SULUT's training vessels will require curriculum enhancements, instructor training, and investments in smart ship technologies. The study findings suggest that a phased implementation approach—starting with pilot programs using sensor-based monitoring and predictive modeling exercises—would be the most effective strategy for gradual adaptation.

Moreover, the industry professionals' endorsement of predictive maintenance adoption in maritime education strengthens the case for closer collaboration between training institutions and shipping companies. By fostering industry-academia partnerships, maritime vocational education can enhance its relevance and ensure that graduates possess the skills necessary for future-ready ship maintenance practices.

The research results indicate that predictive maintenance strategies provide measurable improvements in maintenance efficiency, cost reduction, and equipment reliability for naval auxiliary systems in training vessels. The high acceptance rates among cadets, instructors, and industry experts highlight the practical feasibility and long-term benefits of integrating predictive maintenance into maritime engineering education.

As the maritime industry continues its digital transformation, the ability to analyze real-time sensor data, predict failures, and optimize maintenance scheduling will become an essential competency for future maritime engineers. The results of this study strongly advocate for immediate steps to implement predictive maintenance training modules in Poltekpel SULUT, ensuring that cadets are well-prepared for the technological advancements shaping the modern shipping industry.

By combining sensor-based data analysis with structured qualitative evaluations, this research has provided a comprehensive and actionable assessment of predictive maintenance's role in maritime training. The next steps should focus on scaling implementation efforts, refining training methodologies, and continuously evaluating the effectiveness of predictive maintenance strategies in an educational setting.

4. DISCUSSION

The results of this study strongly indicate that the implementation of predictive maintenance strategies for naval auxiliary systems in Poltekpel SULUT's training vessels has a significant and positive impact on maintenance efficiency, operational reliability, and maritime education. This discussion critically examines the findings, interprets their implications, and contextualizes them within the broader landscape of maritime engineering and training methodologies. By analyzing thematic patterns, comparative insights, and practical applications, this section explores the significance of predictive maintenance in maritime education and its role in shaping the future of ship maintenance practices.

Predictive Maintenance as a Paradigm Shift in Maritime Engineering

The study confirms that predictive maintenance represents a fundamental shift from traditional maintenance strategies, offering a data-driven, proactive approach to managing ship systems. With an average effectiveness score of 91/100, the findings demonstrate that predictive maintenance can significantly reduce downtime, lower operational costs, and improve system efficiency. The traditional approach, which relies on reactive (corrective) maintenance or fixed-schedule preventive maintenance, often leads to inefficiencies such as unexpected breakdowns, excessive repairs, and unoptimized maintenance intervals. In contrast, predictive maintenance leverages real-time sensor data to identify early failure indicators, allowing timely interventions before critical issues arise.

One of the key findings supporting this paradigm shift is the 92/100 rating in the reduction of downtime. The ability to monitor vibration patterns, temperature fluctuations, and pressure anomalies ensures that potential failures are detected early, reducing the frequency of unplanned system failures. This aligns with the broader trend in the maritime industry toward automated condition-based monitoring systems, where vessels are increasingly integrating Internet of Things (IoT) technologies to enhance operational efficiency.

While the results validate the effectiveness of predictive maintenance in training vessels, they also reveal challenges in real-world implementation. The score of 85/100 in sensor-based monitoring accuracy suggests that while predictive models are generally reliable, variations in sensor calibration and interpretation remain key areas for improvement. Some cadets and instructors pointed out that false positives or data misinterpretations could occasionally lead to unnecessary maintenance actions, emphasizing the need for refinement in sensor algorithms and operator training in data interpretation.

Bridging the Gap Between Maritime Education and Industry Practices

A critical discussion point arising from the study is the extent to which maritime training aligns with industry expectations. With industry alignment receiving a score of 89/100, it is evident that predictive maintenance is a highly relevant and valuable skill for future maritime engineers. Industry professionals emphasized that modern ship maintenance increasingly relies on predictive analytics, and maritime graduates with experience in sensor-based monitoring and data-driven decision-making will have a competitive advantage in the job market (Comtois & Slack, 2017; Gavalas et al., 2022). However, the research also identified gaps between current training methodologies and the skills required in industry settings. Instructors raised concerns about curriculum limitations, outdated training vessel equipment, and the lack of integration between vocational education and emerging smart ship technologies.

While cadets expressed enthusiasm for learning predictive maintenance techniques, they also highlighted the need for additional training resources and hands-on simulations to bridge the theoretical and practical aspects of PdM implementation.

This finding underscores the urgency of enhancing maritime education frameworks to incorporate predictive maintenance modules, particularly within vocational and polytechnic maritime institutions. A structured approach that blends theoretical knowledge with real-time sensor applications will be essential in ensuring that graduates are well-prepared for industry demands.

Cost Efficiency and Sustainability in Maritime Training Vessels

One of the most notable findings of this study is the high effectiveness of predictive maintenance in reducing operational costs, reflected in its 87/100 score. Traditional maintenance approaches often result in over-maintenance or inefficient resource allocation, leading to higher expenses in parts replacement, labor, and downtime-related losses. Predictive maintenance, by contrast, allows for optimized resource utilization, ensuring that maintenance activities are performed only when necessary, based on actual system conditions.

This cost-effectiveness is particularly significant for maritime training vessels, where budgets are often constrained. By adopting predictive maintenance strategies, maritime training institutions can optimize their maintenance expenditures, ensuring that limited resources are used efficiently while maintaining operational readiness. Another key dimension of this discussion is sustainability. With the International Maritime Organization (IMO) pushing for greater environmental responsibility in shipping operations, predictive maintenance plays a crucial role in reducing waste and energy consumption (Joseph & Dalaklis, 2021; Mankabady, 1986). By preventing unnecessary repairs and extending the lifespan of auxiliary systems, predictive maintenance contributes to lower emissions and reduced material waste, aligning with the broader goals of sustainable maritime practices (de la Peña Zarzuelo et al., 2020).

The Role of Training Suitability in Predictive Maintenance Adoption

An essential aspect of the research findings is the 90/100 score in training suitability, indicating that predictive maintenance is highly adaptable to the educational environment of maritime cadets. The study reveals that cadets quickly grasp the fundamental principles of sensor-based monitoring and fault prediction, demonstrating that PdM can be effectively incorporated into maritime training curricula. However, one challenge identified in the qualitative responses is the transition from conventional maintenance mindsets to data-driven approaches. Maritime engineering has traditionally been mechanical and hands-on, focusing on physical inspections, routine servicing, and direct equipment handling. Predictive maintenance, by contrast, requires a strong understanding of digital diagnostics, data analytics, and automated decision-making processes.

To address this challenge, training institutions must implement a blended learning approach, incorporating both theoretical instruction and practical simulations. The use of training vessel-based sensor systems, augmented reality (AR) maintenance simulations, and predictive maintenance software tools can enhance the learning experience, ensuring that cadets develop both technical knowledge and practical competencies. Another area of discussion is the integration of predictive maintenance into existing maritime certification and licensing requirements. While international maritime standards emphasize competency-based training, there is currently limited regulatory emphasis on predictive maintenance knowledge (Bee, 2017; Sharma, 2023). Policymakers and training institutions should consider updating curriculum guidelines to include digitalized maintenance strategies, ensuring that maritime engineers are equipped with the skills necessary for next-generation ship operations.

Challenges and Considerations in Implementation

Despite the overwhelmingly positive findings, the study identifies several implementation challenges that must be addressed to fully leverage predictive maintenance in training vessels.

First, technological infrastructure limitations remain a concern. While predictive maintenance requires sensor integration, data analytics tools, and real-time monitoring systems, many maritime training institutions lack the advanced infrastructure needed to support these technologies. Investments in modernizing training vessels and incorporating predictive analytics software will be essential for successful implementation.

Second, training gaps among instructors and cadets must be addressed. While cadets are generally receptive to predictive maintenance, some instructors expressed the need for additional professional development and upskilling to effectively teach these concepts. Instructor training workshops, industry collaborations, and hands-on exposure to real-world PdM applications will be necessary to ensure that faculty members are well-prepared to teach predictive maintenance methodologies.

Third, initial adoption costs may present a barrier. While predictive maintenance is cost-effective in the long run, the initial investment in sensors, software, and training resources may be challenging for vocational institutions with limited budgets. However, the study suggests that collaborations with maritime industry stakeholders—such as shipping companies, technology providers, and regulatory bodies—can help offset these costs, ensuring that training institutions have access to state-of-the-art maintenance technologies.

The discussion of the research findings highlights that predictive maintenance is a game-changing approach in maritime engineering, with strong potential for integration into maritime education. The high effectiveness scores across all indicators confirm that predictive maintenance enhances system efficiency, reduces costs, minimizes downtime, and aligns with industry needs.

However, the transition to predictive maintenance requires significant curriculum adjustments, technological investments, and instructor training to fully prepare maritime cadets for digitalized ship maintenance practices. By addressing infrastructure limitations, training gaps, and financial constraints, maritime training institutions can successfully integrate predictive maintenance as a core competency, ensuring that future maritime engineers are well-equipped for the evolving demands of the industry.

The research ultimately affirms that predictive maintenance is not just an engineering advancement but a necessary evolution in maritime education. By embracing sensor-based monitoring, data analytics, and smart maintenance strategies, the maritime industry can achieve greater operational efficiency, sustainability, and workforce readiness in an era of rapid technological transformation.

5. CONCLUSION

The findings of this research confirm that predictive maintenance (PdM) is a highly effective strategy for optimizing the maintenance of naval auxiliary systems in training vessels at Poltekpel SULUT. By leveraging sensor-based monitoring and data analytics, predictive maintenance enables early failure detection, significantly reducing downtime, lowering operational costs, and improving system reliability. The high scores across all indicators, particularly in effectiveness (91/100), downtime reduction (92/100), and training suitability (90/100), validate that PdM is not only a superior maintenance strategy but also an essential educational advancement for maritime cadets. The study highlights the alignment between maritime education and industry expectations, with experts emphasizing that graduates trained in predictive maintenance will have a competitive advantage as the industry increasingly adopts smart ship technologies. However, challenges such as sensor accuracy (85/100), training gaps, and infrastructure limitations must be addressed to fully integrate predictive maintenance into maritime curricula. The research demonstrates that predictive maintenance is a necessary evolution in maritime engineering education, bridging the gap between traditional maintenance approaches and digital transformation in the shipping industry. By implementing PdM-focused training modules, upgrading vessel monitoring systems, and fostering industry collaborations, maritime institutions can ensure that future engineers are equipped with the technological expertise needed for the next generation of ship operations.

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