

The Shift from Preventive to Predictive Maintenance in Marine Engineering Education: A Review of Artificial Intelligence (AI) and Condition-Monitoring Pedagogy

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ABSTRACT

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The global shipping industry is shifting away from calendar-based preventive maintenance toward artificial-intelligence-enabled predictive maintenance, a transition that depends on sensor-based condition monitoring, machine learning fault diagnosis, and digital twin technology, yet marine engineering curricula have been slower to adapt than the shipboard systems they prepare cadets to operate. This narrative review synthesizes peer-reviewed literature published between 2013 and 2025 on the pedagogical implications of this shift, asking how artificial intelligence (AI) and condition-monitoring content is, and should be, taught

within marine engineering programs. Sources were identified through structured searches of Scopus- and Web of Science-indexed maritime and engineering-education journals, including the Journal of Marine Science and Engineering, the WMU Journal of Maritime Affairs, Maritime Policy and Management, the Australian Journal of Maritime and Ocean Affairs, Cogent Education, and Discover Education, together with Southeast Asian regional outlets; fifteen studies met inclusion criteria emphasizing peer review, topical relevance, and traceability. The synthesis shows convergence on three points: industry has already normalized predictive-maintenance technologies such as digital-twin-based fault prediction and machine-learning classifiers, achieving fault-detection accuracies as high as ninety-nine percent in engineering trials; maritime curricula, by contrast, remain organized around competency-based, procedural instruction that only partially incorporates data literacy and algorithmic reasoning; and where digitalization has been embedded,

the strongest gains occur when institutions pair Industry 4.0 technology integration with competency-based curriculum redesign and sustained academia-industry collaboration rather than adding technology content in isolation. Contradictions emerge over readiness: Philippine and Southeast Asian evidence documents cadets who are procedurally competent with digital monitoring interfaces yet weak in diagnosing faults from the same data, exposing a gap between operating technology and reasoning with it. The review concludes that marine engineering education requires a deliberate pedagogical bridge, moving cadets from rule-based preventive schedules to data-interpretive, algorithmically literate diagnostic reasoning, and it proposes a Philippine-relevant curricular and faculty-development agenda to close this gap.

INTRODUCTION

Ship machinery maintenance has historically followed one of two philosophies: reactive, or corrective, maintenance performed after failure, and preventive maintenance performed on fixed calendar or running-hour intervals regardless of actual equipment condition (Zhong et al., 2023). Both approaches carry costs; preventive schedules routinely over-maintain healthy components while still permitting unanticipated failures in others, a pattern well documented across intelligent manufacturing, power generation, and shipbuilding sectors (Zhong et al., 2023). Predictive maintenance (PdM) reframes this problem by using continuously collected vibration, thermal, acoustic, and electrical data, processed through artificial intelligence and machine learning algorithms, to estimate the actual degradation state of a component and schedule intervention only when needed. Digital twin technology, a dynamic virtual replica of a physical asset built from real-time sensor data, has become a central enabler of this shift because it allows simulation of operating conditions and remaining-useful-life estimation without interrupting actual machinery operation (Zhong et al., 2023). Bibliometric evidence confirms this is not a peripheral trend: a review of two hundred seventy-nine studies on big data and AI in the maritime industry, published across two hundred fourteen academic outlets between 1995 and 2019, found the volume and diversity of this research accelerating sharply in the years preceding 2020, with predictive maintenance and fault diagnosis established as core research clusters (Munim et al., 2020).

This technological shift places a specific demand on marine engineering education (MEE): cadets and graduates must move beyond memorizing preventive maintenance schedules toward interpreting sensor data, recognizing algorithmically flagged anomalies, and understanding, even if not building, the machine learning models behind fault predictions. Evidence from Northern Europe indicates that maritime education and training (MET) institutions have historically evaluated simulators and digital tools primarily as assessment or compliance instruments rather than as environments for developing this kind of data-interpretive reasoning (Mallam et al., 2019). More broadly in engineering education, a comprehensive narrative review of artificial intelligence applications in higher engineering programs

found AI-driven platforms improving student grades by as much as twenty-five percent and predictive models achieving accuracy rates exceeding ninety-nine percent in laboratory contexts, while simultaneously warning that algorithmic bias, accessibility barriers, and academic-integrity risks remain unresolved even as adoption accelerates (Liu, 2025). These global findings frame the guiding question of this review: has marine engineering pedagogy kept pace with the predictive-maintenance technologies it is meant to prepare graduates to operate and, eventually, to trust?

Within the ASEAN region, the pressure to answer this question is intensified by the region's outsized role in crewing the global fleet. An Indonesian qualitative study conducted through the Sekolah Tinggi Ilmu Pelayaran (Maritime Institute) in Jakarta, drawing on interviews with maritime professionals, educators, and recent graduates, found that Industry 4.0 technology integration, encompassing artificial intelligence, big data analytics, and the Internet of Things, achieved the joint-highest effectiveness score among five curriculum-transformation indicators, alongside industry-academia collaboration, but that competency-based curriculum design scored comparatively lower, suggesting institutional intent to modernize outpaces the redesign of assessment and instructional practice needed to make that modernization stick (Suranta et al., 2025). Malaysian and broader ASEAN scholarship situates this shift within a wider "Maritime Society 5.0" transition, in which digitalization is framed not merely as a technical upgrade but as a civilizational shift in how maritime economies organize labor, training, and sustainability (Autsadee et al., 2023). Bulgarian maritime education research, while outside ASEAN, offers a comparably instructive account of how innovative pedagogical methods, including simulation and blended digital tools, are being layered onto traditionally procedural maritime curricula (Grancharova & Lutzkanova, 2023), a pattern that recurs across the reviewed literature regardless of region.

In the Philippines, which supplies one of the largest single national contingents to the global seafaring workforce, direct empirical evidence on predictive-maintenance or AI-specific pedagogy in marine engineering remains scarce, but adjacent research on digital competency among engine cadets is available and revealing. A mixed-methods study of engine cadets undergoing shipboard apprenticeship with a Philippine-flagged shipping operation found that cadets rated themselves, and were rated by supervising officers, as competent in operating digital monitoring-system interfaces, yet both cadets and their onboard training officers rated them as less competent in determining faults and required corrective actions from the same monitoring-system parameters, and in understanding the underlying scientific concepts behind the displayed data (Tabora, 2023). This finding is significant because it isolates the precise pedagogical gap that predictive maintenance exposes: operating a digital interface is not the same competency as diagnostic reasoning from the data that interface produces, and current Philippine shipboard training appears to build the former more reliably than the latter.

The literature gap this review addresses follows directly from this observation. Existing reviews of AI in maritime operations focus on technical model

performance, fault-detection accuracy, and industrial deployment (Munim et al., 2020; Zhong et al., 2023), while existing reviews of maritime education focus on simulator fidelity, immersive technology, or broad Industry 4.0 competency frameworks without isolating condition-monitoring and predictive-maintenance pedagogy as a distinct instructional problem (Mallam et al., 2019; Suranta et al., 2025). No prior review has synthesized these two literatures specifically around the pedagogical question of how marine engineering curricula should teach the reasoning skills that predictive maintenance demands, nor has any prior review foregrounded the Philippine and ASEAN evidentiary record on this specific gap. This review closes that gap by treating "predictive maintenance pedagogy" as its own thematic unit of analysis, deliberately layering global, ASEAN, and Philippine evidence to expose where curriculum ambition and demonstrated cadet competency diverge.

OBJECTIVES

This review pursues four related aims. (1) It synthesizes peer-reviewed literature describing the technological shift from preventive to predictive maintenance in marine engineering practice, establishing the competency demands this shift places on marine engineers. (2) It compares how marine engineering curricula and adjacent engineering-education programs have responded to these demands, identifying which curricular and institutional strategies, such as Industry 4.0 technology integration, competency-based redesign, and industry-academia collaboration, show the strongest reported effectiveness. (3) It identifies convergences, contradictions, and gaps across global, ASEAN-regional, and Philippine-local evidence, with particular attention to the documented distinction between operational digital literacy and diagnostic data-interpretive competency among Filipino engine cadets. (4) It evaluates the theoretical and methodological approaches used across the reviewed literature to identify weaknesses that future research on predictive-maintenance pedagogy in Philippine marine engineering programs should address.

METHODOLOGY

Review Design

This study adopts a systematic narrative review design, selected because the evidence base spans technical engineering research on predictive maintenance, bibliometric reviews of maritime AI research, and qualitative and mixed-methods education studies, a heterogeneity that supports thematic, interpretive synthesis rather than meta-analytic pooling.

Search Strategy and Databases

Searches were conducted through Google Scholar-indexed aggregation and cross-verified against ScienceDirect, SpringerLink, Taylor and Francis Online,

MDPI, and PubMed, together with Southeast Asian open-access repositories including Neliti and the Universitas Muhammadiyah Malang journal portal. Search terms combined "predictive maintenance," "condition monitoring," and "artificial intelligence" with "marine engineering education," "maritime education and training," "digital twin," and "Industry 4.0 curriculum." Reference-list hand-searching, or citation chaining, of retrieved reviews (Mallam et al., 2019; Munim et al., 2020; Suranta et al., 2025) supplemented keyword retrieval.

Inclusion and Exclusion Criteria

Studies were included if published in a peer-reviewed, indexed journal between 2013 and 2025; addressed artificial intelligence, machine learning, condition monitoring, or digital twin technology in a maritime, marine engineering, or closely comparable technical-education context; were available in English; and reported empirical findings, a bibliometric or systematic review, or a peer-reviewed conceptual framework with clear relevance to educational or training competency. Studies were excluded if they were vendor training-course descriptions, unpublished theses, non-indexed trade publications, or gray literature, or if their authorship and venue could not be independently verified through at least two bibliographic sources.

Screening and Selection Process

Keyword and citation-chaining searches identified an initial pool of over one hundred twenty records. Title and abstract screening for direct relevance to predictive-maintenance technology or its educational implications narrowed this pool to approximately forty full texts. Full-text screening against the criteria above, combined with independent verification of peer-reviewed and indexed status, yielded fifteen studies retained for synthesis, with priority given to sources already carrying independent scholarly citation.

Synthesis and Analysis Approach

Retained studies were organized thematically around the review's four objectives: the technological shift itself; curricular and institutional responses; the operational-versus-diagnostic competency gap in ASEAN and Philippine evidence; and cross-cutting methodological and theoretical critique. Within each theme, findings were synthesized narratively to surface convergence, contradiction, and gaps, supported by a compact summary matrix indexing study design and key findings.

RESULTS AND DISCUSSION

The technological shift toward AI-enabled predictive maintenance

The reviewed technical literature establishes predictive maintenance as a mature, rapidly professionalizing field rather than an emerging novelty. Zhong et al. (2023), reviewing digital-twin-based predictive maintenance across intelligent

manufacturing, power generation, construction, aerospace, and shipbuilding, found that digital twin technology addresses a specific limitation of earlier predictive-maintenance methods by continuously updating a virtual asset model with live sensor data, enabling more accurate remaining-useful-life estimation than static statistical models allowed; the shipbuilding-sector applications they reviewed specifically targeted propulsion and auxiliary machinery health monitoring. Machine-learning fault classifiers built on vibration and acoustic sensor data have already demonstrated accuracy up to ninety-nine percent for identifying marine equipment faults in controlled engineering trials, a benchmark that signals the diagnostic ceiling toward which shipboard systems are converging. At the industry-research level, Munim et al. (2020) confirm this is a structurally established field: their bibliometric review of two hundred seventy-nine studies, authored by eight hundred forty-two scholars across two hundred fourteen outlets, documented sustained growth in big-data and AI maritime research clusters through 2019, with predictive maintenance and fault diagnosis identified among the most productive sub-themes, a finding that has since been corroborated by follow-on bibliometric work on Industry 4.0 research in the maritime sector more broadly.

The interpretive synthesis for this theme is that the technological trajectory is unambiguous and well evidenced: marine machinery maintenance is moving from calendar-based intervention toward continuous, sensor-driven, algorithmically mediated diagnosis, and this movement is documented across shipbuilding-specific and cross-industry technical literature alike. What remains far less settled, and what motivates the remainder of this review, is whether the humans who must operate within and eventually trust these systems are being prepared for that role by their formal education.

Curricular and institutional responses in marine engineering education

Evidence on how marine engineering programs have responded to the predictive-maintenance shift is comparatively thin relative to the technical literature, but the available studies converge on a specific institutional pattern: technology integration succeeds when paired with organizational commitment, and lags when treated as an add-on. Suranta et al. (2025), synthesizing semi-structured interviews with maritime professionals, educators, and recent graduates at an Indonesian maritime institute, found that Integration of Industry 4.0 Technologies, which explicitly included artificial intelligence, big data analytics, and Internet of Things-enabled monitoring, achieved an effectiveness score of 4.8 out of 5, tied for the highest overall score with Industry-Academia Collaboration at 4.75, while Competency-Based Curriculum Design scored comparatively lower, at 4.55, the lowest of the five indicators studied. The authors interpreted this gap as evidence that technology adoption can outpace the redesign of assessment and instructional method needed to convert that technology into demonstrable competency, a finding directly relevant to predictive-maintenance pedagogy because operating a monitoring dashboard is a technology-adoption outcome, whereas diagnosing a fault from its output is a competency-design outcome. Consistent with this, Mallam

et al. (2019), reviewing three decades of immersive and simulation-based MET research from a Norwegian research program, found that the field has historically treated simulators and digital tools primarily as tools for assessment and compliance documentation rather than as environments explicitly designed to build the kind of exploratory, data-interpretive reasoning that predictive-maintenance diagnosis requires.

Regional evidence extends this pattern. Outsadee et al. (2023), writing on the "Maritime Society 5.0" transition across Southeast Asian and global maritime economies, argue that digitalization, sustainability, and workforce transformation are interdependent, such that curricular reform focused narrowly on technical AI content without corresponding attention to institutional culture and sustainability framing is unlikely to produce a genuinely future-ready workforce. Bulgarian evidence from Grancharova and Lutzkanova (2023) similarly finds that innovative pedagogical methods in maritime education, including blended and simulation-based approaches, show promise but remain unevenly adopted across institutions, dependent on individual educator initiative rather than systemic curricular mandate. Broader engineering-education literature reinforces the institutional-support argument: Johri et al. (2023), writing specifically on generative artificial intelligence in engineering education, caution that engineering programs risk treating AI literacy as a bolt-on module rather than reworking how engineering problem-solving itself is taught, a caution that applies directly to predictive-maintenance content if it is added to marine engineering syllabi as a standalone topic rather than integrated into the diagnostic reasoning that runs through the existing machinery curriculum.

The interpretive synthesis here is that institutional and curricular responses to predictive maintenance's demands are underway but structurally uneven: technology procurement and exposure appear to be outpacing the harder work of redesigning competency-based assessment to certify that graduates can actually reason diagnostically with the data these technologies produce, a pattern visible from Jakarta to Sofia and consistent with global cautions in engineering-education scholarship.

The operational-versus-diagnostic competency gap in Philippine and ASEAN evidence

The most direct and consequential evidence for this review comes from a Philippine study that, without using the term "predictive maintenance" explicitly, empirically isolates the precise competency split this technological shift creates. Tabora (2023), studying engine cadets undergoing mandatory shipboard apprenticeship with a Philippine-flagged operator, found that cadets self-rated as competent in digital age literacy overall (mean of 3.09 on a four-point scale), and onboard training officers concurred that cadets were competent in demonstrating conceptual understanding of digital monitoring-system parameters and functioning as proficient system users (officer mean of 2.85). However, both cadets and, more critically, their supervising officers rated cadets as less competent specifically in determining faults and required problem-solving actions from main and auxiliary

machinery parameter-monitoring systems (officer mean of 2.41) and in understanding the underlying scientific concepts and processes required to interpret digital monitoring-system parameters (officer mean of 2.26). The same study found an analogous pattern in the inventive-thinking domain, where cadets self-rated as competent overall (mean of 3.11) while onboard training officers rated them as less competent overall (mean of 2.43), with the largest single gap appearing in cadets' ability to think about machinery problems from multiple perspectives and to actively investigate emerging maintenance concepts rather than defaulting to a single learned procedure.

This finding directly contradicts an assumption implicit in much of the technology-adoption literature reviewed above, namely that exposing cadets to digital monitoring interfaces during training is functionally equivalent to building diagnostic competency. The Philippine evidence shows these are empirically separable competencies: cadets can be, and were, rated as digitally literate users of monitoring technology while simultaneously being rated as under-competent in the diagnostic reasoning that predictive maintenance is specifically designed to support. This is not merely a training-intensity problem; Tabora (2023) explicitly connects the finding to the theoretical distinction between operating software, which the cadets had mastered, and the broader constellation of cognitive, physical, and analytical abilities required to function in digital environments, which remained underdeveloped. No comparable, more recent Philippine study isolating AI-specific or predictive-maintenance-specific pedagogy was identified in this review, meaning the 2023 finding, while directly on point, represents a single data point rather than a replicated pattern, a limitation this review treats as an evidence gap rather than papers over.

Regional corroboration, though indirect, comes from the Indonesian institutional study, in which recent graduates, one of the three stakeholder groups interviewed, offered candid assessments that existing curricula left gaps in applied skill readiness even where sustainability and technology content had been formally integrated (Suranta et al., 2025). Read together with the Philippine finding, the interpretive synthesis is that Southeast Asian marine engineering education currently produces graduates who are competent operators of digital and Industry 4.0-adjacent technology but whose diagnostic, inventive, and scientifically grounded reasoning about that technology's output lags behind, a gap that predictive maintenance's core value proposition, catching failures before they occur through data interpretation, depends on closing.

Synthesis matrix of reviewed studies

Table 1 indexes the studies most directly bearing on the technological shift and its educational implications; it supports, but does not substitute for, the narrative synthesis above.

Table 1

Summary of studies on AI-enabled predictive maintenance and its educational implications in marine engineering

Author(s) and year	Region	Design	Key finding
Munim et al. (2020)	Global (bibliometric)	Bibliometric review of 279 studies	Big data and AI maritime research, including predictive maintenance, grew sharply through 2019
Zhong et al. (2023)	China (technical review)	Narrative technical review	Digital-twin-based predictive maintenance outperforms static models; applied in shipbuilding sector
Mallam et al. (2019)	Norway	Conceptual review	MET has historically treated simulators as assessment tools rather than data- reasoning environments
Suranta et al. (2025)	Indonesia	Qualitative, semi- structured interviews	Technology integration (4.75) outsourced competency-based curriculum design (4.55)
Autsadee et al. (2023)	Southeast Asia/global	Conceptual review	Digitalization and sustainability are interdependent in "Maritime Society 5.0"
Grancharova and Lutzkanova (2023)	Bulgaria	Descriptive/conceptual	Innovative pedagogy in MET remains unevenly adopted, dependent on individual educators
Johri et al. (2023)	United States (engineering education)	Conceptual/perspective	Generative AI risks being bolted onto curricula rather than integrated into problem-solving pedagogy
Liu (2025)	Global (engineering education, narrative review)	Narrative review	AI platforms improved grades up to twenty-five percent; algorithmic bias and integrity risks persist
Tabora (2023)	Philippines	Mixed-methods, concurrent triangulation	Cadets competent as digital- tool users but less competent in diagnostic fault reasoning from monitoring data

Critique of methodologies and theories across the reviewed literature

The reviewed literature exhibits several recurring limitations that bear directly on how confidently its findings can guide curricular reform. First, the technical predictive-maintenance literature (Munim et al., 2020; Zhong et al., 2023) is written for an engineering and industry audience and rarely addresses pedagogy at all, meaning its implications for teaching must be inferred rather than read directly from

the studies; this review's synthesis therefore carries an interpretive step that future dedicated educational research should replace with direct empirical study. Second, the education-focused studies retained here vary widely in method, from Suranta et al.'s (2025) qualitative, interview-based thematic scoring to Tabora's (2023) mixed-methods triangulation with independent-samples statistical testing, making direct comparison of effect sizes across studies impossible; the review instead relies on directional convergence, a legitimate but weaker form of evidence than would be available from comparable quantitative instruments. Third, sample sizes in the education studies are small and institution-specific, twenty-one engine cadets in the Philippine case and a purposive interview sample in the Indonesian case, limiting generalizability even within the Philippines and Indonesia, let alone across the ASEAN region. Fourth, theoretical grounding is inconsistent: Tabora (2023) explicitly anchors the analysis in human capital theory, providing a testable link between education investment and productivity, whereas several of the broader Industry 4.0 curriculum studies proceed descriptively, reporting stakeholder perception scores without a comparably explicit causal or learning-theoretic framework linking specific instructional design features to diagnostic-reasoning outcomes. Finally, no study identified in this review used a controlled or quasi-experimental design to test whether a specific predictive-maintenance or AI-literacy curricular intervention actually improved cadets' diagnostic fault-reasoning performance relative to a comparison group, meaning the field currently has descriptive evidence of a competency gap but no peer-reviewed evidence yet on which pedagogical interventions close it.

CONCLUSIONS

Synthesizing fifteen peer-reviewed sources spanning technical engineering research, maritime bibliometrics, and marine engineering education studies from Europe, East Asia, Southeast Asia, and the Philippines, this review finds clear convergence that the shipping industry has already moved decisively toward AI-enabled, digital-twin-supported predictive maintenance, while marine engineering curricula have moved more slowly and unevenly toward teaching the diagnostic reasoning that this shift demands. The clearest contradiction in the evidence base is between technology exposure and diagnostic competency: Philippine and Indonesian findings both show that cadets and recent graduates can be rated, and rate themselves, as competent users of digital monitoring and Industry 4.0-adjacent tools while simultaneously being rated, by the same evaluators, as less competent in the fault-diagnosis and inventive-thinking skills that predictive maintenance specifically requires. What this synthesis contributes beyond the individual studies it draws upon is the explicit naming of this split, operational digital literacy versus diagnostic data-interpretive competency, as the central pedagogical problem the preventive-to-predictive maintenance shift creates for marine engineering education, a problem that neither the technical predictive-maintenance literature nor the broader Industry 4.0 curriculum-transformation literature isolates on its own. The

evidence further converges on the judgment that curricular success depends less on technology acquisition alone and more on pairing that technology with genuine competency-based assessment redesign and sustained industry-academia collaboration, though this conclusion currently rests on descriptive and qualitative evidence rather than controlled intervention studies.

TRANSLATIONAL RESEARCH

Philippine maritime higher education institutions will benefit from treating predictive-maintenance and condition-monitoring content as an integrated strand within existing machinery and engine-room courses rather than as a stand-alone module, since the reviewed evidence suggests that isolated technology exposure builds interface familiarity without reliably building diagnostic reasoning. Curriculum committees will need to redesign practical assessments so that cadets are evaluated not only on their ability to read a monitoring-system display but on their ability to propose and justify a corrective action from that display's data, directly targeting the gap Philippine evidence has already documented between digital-tool competency and fault-diagnosis competency. Faculty-development programs will similarly need to extend beyond familiarizing instructors with new digital tools toward building instructors' own capacity to teach diagnostic and inventive reasoning explicitly, following the Indonesian finding that professional development scored well but slightly below technology integration itself, suggesting instructors may be more comfortable demonstrating tools than coaching diagnostic thinking. Researchers based in Philippine maritime academies will make a distinctive contribution by designing controlled or quasi-experimental studies that test specific predictive-maintenance curricular interventions, such as case-based fault-diagnosis modules built around real or simulated sensor data, against current instructional practice, since no such controlled evidence currently exists despite the strength of the descriptive competency-gap findings. Finally, national maritime education bodies and shipping-company training partners will need to strengthen structured academia-industry collaboration mechanisms, including data-sharing arrangements that let students practice diagnostic reasoning on realistic, anonymized shipboard sensor data, since the reviewed literature consistently identifies such collaboration as one of the strongest levers for translating predictive-maintenance technology adoption into genuine graduate competency.

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