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Developing STEM-integrated augmented reality learning media for smart ship engine monitoring systems: Enhancing marine engineering competency in Indonesian maritime vocational education

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Abstract

Background: The transition toward Maritime Industry 4.0 requires maritime vocational institutions to integrate smart ship technologies into their curricula. This shift demands innovative pedagogical approaches that merge STEM principles with immersive tools such as Augmented Reality (AR) to strengthen competencies in intelligent engine monitoring systems in accordance with STCW standards.
Aim: This study investigates the extent to which STEM-integrated AR learning media supports the development of marine engineering competencies among Indonesian maritime vocational students, and how such contributes to evidence-based instructional frameworks for technology-enhanced maritime education.
Method: A qualitative interpretive phenomenological approach was implemented over sixteen weeks involving twenty-five marine engineering students, six instructors, and five industry experts. Data were collected through semi-structured interviews, systematic observations, and weekly reflection journals, and analyzed using Braun and Clarke's thematic analysis.
Results: Five learning themes were identified: transformative visualization, authentic STEM integration, increased technological self-efficacy, collaborative knowledge construction, and contextual implementation challenges. Competency assessments showed notable gains, with MECAI scores reaching cognitive (84.2%), psychomotor (81.6%), affective (86.9%), and digital literacy (87.3%) domains. STEM Integration Effectiveness also demonstrated strong technology (85.4%) and engineering (81.7%) performance.
Conclusion: The findings validate AR-enhanced STEM learning as an effective approach for strengthening STCW-aligned competencies and offer context-sensitive guidance for maritime institutions, particularly those operating under resource limitations.

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INTRODUCTION

The rapid evolution of digital technologies has fundamentally transformed the operational landscape of the global maritime industry. Modern ships now rely on real-time data streams, automated decision-support systems, and interconnected machinery platforms that operate far beyond the capabilities of mechanically driven vessels of previous eras (Aslam et al., 2020; Durlik et al., 2025; Wang et al., 2020). This shift marks a profound departure from traditional marine engineering practices that historically emphasized manual monitoring, mechanical troubleshooting, and isolated machinery control (Glaviano et al., 2022; Kimera & Nangolo, 2019; Y. Li et al., 2025). Such technological evolution creates an urgent imperative for maritime education institutions to redesign how marine engineers are trained for digitally intensive operational environments (Mallam et al., 2019; Yuen et al., 2022). Indonesia, as the world's largest archipelagic nation, faces unique pressure to ensure that its maritime vocational graduates possess technical fluency compatible with smart ship technologies (M. B. Simanjuntak et al., 2024). Continued reliance on outdated

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instructional approaches risks producing graduates unable to meet the operational requirements of technologically advanced shipping industries. The country's national aspiration to become a global maritime fulcrum further intensifies the demand for modernized marine engineering education (Pasigna, 2025; Rozhok et al., 2024; Snekubun & Supriyadi, 2025). International regulatory frameworks such as the Standards of Training, Certification and Watchkeeping for Seafarers (STCW) highlight the need for competencies related to automated systems, digital monitoring, and technology-mediated problem-solving (Sellberg & Sharma, 2025). These emerging expectations signal that future maritime operations require skill sets that differ significantly from those associated with traditional seafaring (Belabyad et al., n.d.; X. Li & Yuen, 2024; Mallam et al., 2020). Taken together, these dynamics demonstrate that modern maritime engineering education must undergo substantial transformation to remain relevant in the era of Maritime 4.0.

Technological advancements in the educational field offer promising opportunities for preparing students to master increasingly complex engineering systems. Augmented Reality (AR) enables three-dimensional representation of machinery structures, allowing learners to manipulate virtual components and observe relationships that are often difficult to understand through static diagrams alone (Fatemah et al., 2020; Fombona-Pascual et al., 2022; Pàmies-Vilà et al., 2025). The ability to simulate real-world operational scenarios provides safe, controlled spaces for students to practice diagnostic reasoning without requiring full access to expensive training equipment (Elendu et al., 2024; Pacheco-Velazquez et al., 2024). These features position AR as a compelling tool for bridging the gap between theoretical understanding and practical competency in technical disciplines (Alhazzaa & Yan, 2025; Fantinelli et al., 2024). Constructivist learning theories argue that learners develop deeper understanding through active engagement with meaningful tasks, suggesting that AR-based learning aligns well with effective pedagogical practices (Hu et al., 2021; Moser & Lewalter, 2024). Simultaneously, STEM integration frameworks emphasize the need for interdisciplinary synthesis across science, technology, engineering, and mathematics to address complex engineering challenges(Ortiz-Revilla et al., 2022; Reynante et al., 2020; Roehrig et al., 2021). Research consistently shows that learning designs encouraging cross-disciplinary thinking enhance student capability in analyzing technologically complex systems. The convergence of AR's immersive affordances with STEM integration's cognitive benefits offers a promising pathway for reimagining maritime engineering education. When applied to smart ship engine monitoring systems, these pedagogical innovations have the potential to significantly enhance students' readiness for Industry 4.0 maritime environments. Thus, the intersection of digital maritime technologies, AR advancements, and STEM pedagogies presents timely opportunities for transforming vocational marine engineering programs.

Despite the increasing relevance of digital maritime technologies and educational innovation, Indonesian maritime vocational institutions encounter persistent challenges in adopting advanced pedagogical models. Many schools operate under significant infrastructure constraints that limit access to high-performance digital devices, reliable internet connectivity, and sophisticated simulation laboratories (Anyinkeng et al., 2025; Mian et al., 2020). Instructor readiness also varies widely, with many educators lacking training in AR-based instruction or integrated STEM pedagogies (Ko & Shin, 2023; Mystakidis et al., 2021; Perifanou et al., 2023). These capacity gaps constrain the potential impact of technology-enhanced learning innovations, particularly in resource-limited educational contexts (Ajani & Govender, 2025; Eltaiba et al., 2025; Owusu-Cole et al., 2025). Comparative studies show that educational models developed in technologically advanced countries cannot be directly replicated in Indonesia due to stark differences in institutional resources and student learning conditions (Yusra et al., 2025). As a result, the maritime education sector requires context-sensitive evidence on how innovative instructional tools can be realistically implemented within local constraints. These implementation challenges coincide with industry concerns about widening competency gaps between graduate capabilities and the technological demands of modern shipping environments. Without targeted educational innovations, marine engineering graduates may struggle to compete in global maritime labor markets that increasingly prioritize digital competencies. These intersecting pressures technological, educational, and economic highlight the urgent need to investigate effective strategies for developing smart ship engineering competencies in Indonesian vocational settings (Barasa et al., 2025; Riyanto et al., 2025). Therefore, strengthening the pedagogical foundations of maritime engineering education becomes essential for ensuring national maritime competitiveness in the era of digitalized vessel operations.

Although extensive research has examined STEM integration across general and K–12 education and numerous reviews have highlighted the pedagogical potential of Augmented Reality in diverse instructional settings, these studies remain largely disconnected from the specialized domain of maritime engineering. Existing AR literature predominantly focuses on theoretical frameworks or applications in generic science and engineering contexts, while STEM-related studies seldom address technical maritime competencies, resulting in an absence of integrated AR–STEM models tailored to marine engine systems. Meanwhile, research in maritime engineering education primarily explores curriculum modernization, mechatronics integration, pedagogical innovation, or Industry 4.0 readiness (Inal & Kocak, n.d.; Miyusov et al., 2022; Tusher et al., 2021), yet provides limited attention to immersive learning technologies and does not empirically investigate student learning processes related to smart ship engine monitoring systems aligned with STCW requirements. Moreover, current maritime studies tend to emphasize navigation, communication, or sustainability (Praetorius et al., 2020; P. D. Simanjuntak & Guntoro, 2025), leaving a significant gap regarding how emerging digital tools can strengthen cognitive, psychomotor, affective, and digital literacy competencies essential for intelligent engine operations. Notably, there is also a lack of research situated in developing maritime nations such as Indonesia, where infrastructure limitations, instructor readiness, and contextual constraints shape the effectiveness of advanced technology adoption in vocational settings further reinforcing the need for empirical, context-specific investigations integrating AR and STEM to support smart ship engineering competencies.

This study aims to examine how STEM-integrated Augmented Reality learning media supports the development of marine engineering competencies related to smart ship engine monitoring systems among Indonesian maritime vocational students, while also generating practical and theoretical insights that inform technology-mediated maritime education.

METHOD

Research Design

This study adopted a qualitative interpretive phenomenological methodology aimed at generating deep, contextualized understanding of how STEM-integrated Augmented Reality (AR) learning media shapes marine engineering students' competency development during a full academic semester. Interpretive phenomenology was chosen due to its suitability for examining emerging educational innovations where theoretical frameworks remain underdeveloped, implementation processes continue evolving, and practitioner perspectives are essential for interpreting sociotechnical dynamics within learning environments. This methodological orientation prioritizes depth and richness of insights over breadth, recognizing that complex pedagogical innovations cannot be meaningfully understood through surface-level examination or solely quantitative measurement. The design incorporated multiple data sources—semi-structured interviews, systematic classroom observations, weekly reflection journals, and learning artifacts—to facilitate triangulation and to capture the lived experiences of students, instructors, and industry professionals from multiple vantage points. By integrating these diverse data streams, the research sought to construct a comprehensive portrait of how AR-enhanced STEM learning unfolds, how competencies develop over time, and what contextual factors influence implementation effectiveness.

Research Participants

Three participant groups were engaged to obtain holistic understanding of the innovation's impact: students directly experiencing AR-enhanced learning, instructors implementing the pedagogical model, and industry professionals evaluating competency relevance to workforce needs. The student cohort consisted of twenty-five third- and fourth-year marine engineering students enrolled in Indonesian maritime vocational academies preparing for STCW certification. Purposive sampling ensured diversity across technology exposure levels, academic performance ranges, gender representation, geographic origin, and socioeconomic background, enabling nuanced analysis of how learning experiences differ across student subpopulations. The instructor group comprised six marine engineering lecturers representing varied teaching experience, technological proficiency, and disciplinary specialization, including propulsion, auxiliary machinery, automation, and electrical systems. Their perspectives captured pedagogical adjustments, implementation challenges, and perceived student competency progression. The industry expert group included five professionals—chief engineers, technical specialists from engine manufacturers, and classification society assessors—who interpreted the learning outcomes in relation to real-world operational requirements aboard smart vessels. The inclusion of these three groups allowed triangulation between learner perceptions, instructional insights, and industry validation.

Population and Sampling Procedures

The broader research population consisted of marine engineering students enrolled nationwide (estimated ≈8,000), from which three maritime institutions in Java were purposively selected to reflect varied resource conditions: a large polytechnic maritime academy with advanced facilities, a medium-sized provincial academy with moderate resources, and a smaller rural-serving maritime college. Maximum variation sampling was employed following Creswell and Poth's (2018) criteria to ensure heterogeneity across contextual and demographic variables relevant to technology-mediated learning. Student sampling criteria included: senior-year enrollment, varied digital literacy, academic performance categories (high/medium/low GPA), gender representation, and regional diversity. Instructor sampling criteria emphasized involvement in AR curriculum implementation and variation in prior educational technology experience. Industry participant selection prioritized professional expertise with smart ship systems, STCW familiarity, and workforce training responsibilities. The sample size—25 students, 6 instructors, 5 industry experts—enabled thematic saturation while allowing intensive qualitative engagement.

Instrumentation

A comprehensive suite of instruments was used. Semi-structured interview protocols for students, instructors, and industry experts were developed through expert validation and pilot testing to ensure clarity, cultural appropriateness, and content validity. Interview questions explored prior learning experiences, AR usability, STEM integration, competency development, and workforce readiness. Systematic observation protocols guided researchers in documenting engagement behaviors, collaborative interactions, problem-solving processes, and technology-use patterns during AR learning sessions. Weekly reflection journals provided longitudinal insight into students' evolving understanding, challenges encountered, collaborative practices, and professional identity formation. Competency assessment utilized the Marine Engineering Competency Achievement Index (MECAI), measuring cognitive, psychomotor, affective, and digital literacy domains through rubrics, performance tasks, written tests, and portfolio analysis. Psychometric evaluation demonstrated strong content validity (expert review), construct validity (correlation patterns among subscales), and reliability (Cronbach's $\alpha = 0.84$). STEM integration was assessed using the STEM Integration Effectiveness in Maritime Education (SIEME) instrument, which quantified evidence of science, technology, engineering, and mathematics integration based on coded qualitative data, instructor evaluations, and project artifacts. Inter-rater reliability for SIEME scoring was substantial (ICC = 0.79).

Additional Instruments

The AR learning system itself functioned as a central research instrument. The application featured eight modules covering IoT sensor networks, diagnostics, predictive maintenance, energy optimization, environmental monitoring, troubleshooting, system integration, and case-based smart ship scenarios. Technical features included 3D component visualization, interactive manipulation, real-time parameter simulation, gamified progression, and bilingual interface. Pre- and post-implementation assessment batteries measured knowledge, STEM literacy, technology acceptance, environmental attitudes, AR learning perceptions, and operational self-efficacy. Instructor reflective logs and project artifact rubrics further contributed to analytic triangulation.

Procedures and Time Frame

Data collection unfolded across four phases over twenty-one weeks. The detailed procedures and timeline of this study are organized into four sequential phases—pre-implementation, implementation, post-implementation, and validation and analysis. The complete workflow for each phase is presented in **Figure 1**, providing a clear and comprehensive overview of the research process:

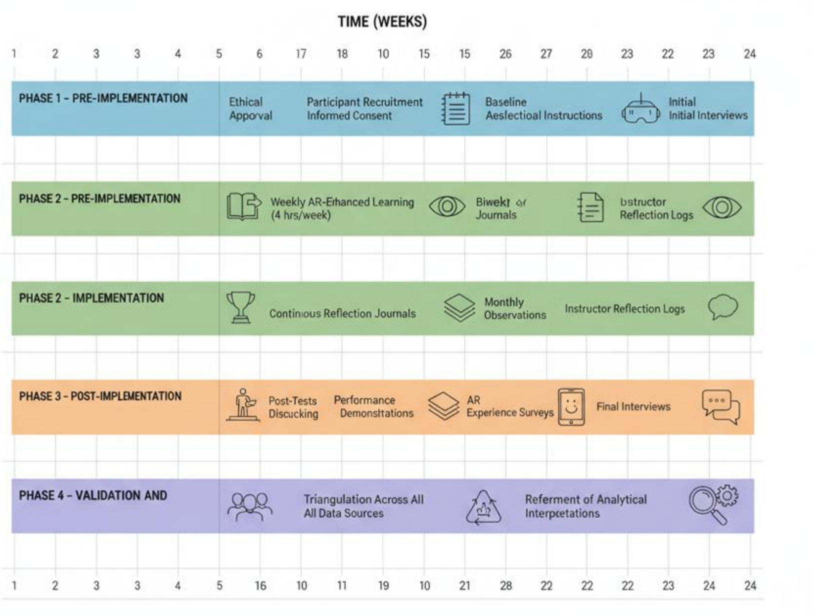

Figure 1. Procedures and Time Frame Research

Data Analysis

Data were analyzed using Braun and Clarke's six-phase thematic analysis. The process included iterative familiarization, systematic coding using MAXQDA, thematic clustering, coherence checking, thematic map refinement, and writing of analytic narratives supported by representative quotations. Both inductive and deductive coding were employed to integrate MECAI and SIEME frameworks while allowing emergent patterns to surface. Quantitative assessment data (MECAI and SIEME) were analyzed descriptively and inferentially using paired t-tests, ANOVA, and correlation analysis, with effect sizes calculated for learning gains. These quantitative findings were integrated narratively to contextualize qualitative themes rather than replace them.

Trustworthiness and Ethics

Credibility was supported through prolonged engagement, triangulation across methods and participant groups, member checking, and peer debriefing. Transferability was facilitated through thick description of participants, institutional contexts, and instructional processes. Dependability was ensured through detailed audit trails documenting analytic decisions, coding revisions, and procedural consistency. Confirmability was enhanced via reflexive journaling separating researcher interpretations from participant voices. Ethical approval was granted by the institutional review board, and all participants' confidentiality and anonymity were strictly maintained.

RESULTS AND DISCUSSION

Results

The results of this study are organized around the four research questions, integrating quantitative competency assessment data with qualitative thematic analysis to illuminate student learning processes, experiential patterns, and contextual factors shaping the effectiveness of STEM-integrated AR learning for smart ship engine monitoring systems.

RQ1: Student Learning Experiences and Processes

Qualitative analyses of interviews, reflection journals, project artifacts, and classroom observations produced five major themes that characterize students' learning processes during engagement with the STEM-integrated AR environment.

1. Theme 1: Transformative Visualization and Cognitive Scaffolding

Students consistently reported that AR fundamentally reshaped their conceptualization of smart ship engine monitoring systems. All 25 participants described AR as a tool that translated previously abstract machinery and sensor networks into concrete, manipulable representations. Interview excerpts highlighted how AR enabled students to visualize spatial relationships, simulate operational scenarios, and observe real-time system responses, thus supporting conceptual clarity. Observation records corroborated high engagement, with students spending an average of 47 minutes per session voluntarily exploring scenarios beyond assigned tasks. Reflection journals revealed that 88% of students explicitly linked three-dimensional manipulation with improved system architecture understanding. These findings demonstrate AR's role as a cognitive scaffold that reduces intrinsic cognitive load and enhances comprehension of complex engineering systems.

2. Theme 2: Intellectual Synthesis Through STEM Integration

Students' learning experiences were marked by seamless interdisciplinary reasoning. Authentic AR scenarios required simultaneous engagement with thermodynamics, control systems, sensor technologies, material properties, and mathematical performance metrics. Students described a shift from compartmentalized, discipline-bounded cognition to holistic problem-solving where boundaries between STEM domains dissolved. Instructors observed students debating multi-dimensional causes of performance anomalies, demonstrating integrated reasoning. Analysis of student artifacts indicated that 76% spontaneously synthesized knowledge from at least three STEM areas—often without explicit prompting. The findings suggest that authentic scenario complexity, rather than curricular restructuring alone, is a key driver of deep STEM integration.

3. Theme 3: Increased Self-Efficacy and Technological Confidence

Pre–post self-efficacy assessments demonstrated substantial increases in students' confidence in engaging with Industry 4.0 maritime technologies ($M_{pre} = 2.8$; $M_{post} = 4.1$; $p < .001$, $d = 1.93$). Interviews showed students perceived AR exposure as demystifying advanced systems and cultivating a transferable understanding of smart ship architectures. Industry experts validated the qualitative depth of students' conceptual explanations. Nonetheless, instructors noted a minority (12%) who exhibited overconfidence, conflating virtual proficiency with physical-equipment mastery. This finding underscores the need for calibrated pedagogical strategies balancing confidence development with realistic expectations of professional practice.

4. Theme 4: Collaborative Knowledge Construction

Despite AR being an individual-device technology, collaborative practices emerged organically. Students routinely formed pairs or small groups, engaging in peer explanation, collective troubleshooting, and distributed expertise sharing. Observations documented an average of 8.3 peer-teaching episodes per session, and reflection journals highlighted the motivational and cognitive benefits of collaboration. These findings demonstrate that AR-enhanced learning does not isolate learners; rather, it can amplify social constructivist dynamics when institutional and classroom norms encourage collaborative engagement.

5. Theme 5: Implementation Challenges and Contextual Constraints

Students and instructors identified several barriers to optimal AR integration. Infrastructure limitations—particularly insufficient devices and unstable internet connectivity—were the most significant impediments, disproportionately affecting under-resourced institutions. Instructor capacity also emerged as a challenge, with several educators expressing discomfort transitioning to facilitative, student-centered pedagogies required for technology-mediated learning. At the institutional level, inconsistent administrative support and fragmented curriculum integration limited the sustainability of AR-based innovation. These challenges underscore that successful adoption requires not only effective technology but also supportive sociotechnical and organizational ecosystems.

RQ2: Competency Development Across MECAI Dimensions

Quantitative assessment demonstrated substantial, statistically significant gains across all MECAI dimensions. Overall competency increased from 60.6% to 85.0% (+24.4%, $p < .001$, $d = 2.47$). Cognitive, psychomotor, and digital literacy domains exhibited very large effect sizes ($d > 2.0$), indicating meaningful development beyond statistical significance. The largest gains were observed in IoT sensor comprehension (+34.4%) and software operation proficiency (+37.1%), reflecting AR's strength in supporting spatial, procedural, and digital-technical learning. Affective domain gains, though smaller (+19.6%), still showed robust improvement in safety awareness, ethical conduct, environmental responsibility, and technological adaptability. Subgroup analysis revealed minimal differences in overall gains across prior technology exposure groups, indicating AR accessibility for diverse learners. However, students with strong academic foundations achieved higher cognitive gains, while those with limited digital experience exhibited larger increases in digital literacy—a pattern emphasizing AR's compensatory effect for technology-disadvantaged students. Quantitative analysis showed substantial improvements across all MECAI dimensions, moving students from basic awareness to operational competence. **Table 1** summarizes pre- and post-implementation scores, mean gains, and effect sizes by competency domain.

Table 1. Marine Engineering Competency Achievement Index (MECAI): Pre- and Post-I implementation Results (n = 25)

MECAI Dimension / Indicator	Pre (%)	Post (%)	Gain (%)	Paired t-test	Effect Size (d)	Interpretation
Cognitive Domain	**58.4 ± 12.3**	**84.2 ± 8.7**	**+25.8**	$t(24)=11.45, p<.001$	2.29	Very Large
IoT sensor understanding	52.3 ± 14.1	86.7 ± 7.9	+34.4	$t(24)=12.83, p<.001$	2.57	Very Large
Data analytics comprehension	61.2 ± 13.5	83.5 ± 9.2	+22.3	$t(24)=9.76, p<.001$	1.95	Large
Predictive maintenance knowledge	55.8 ± 15.2	82.1 ± 10.4	+26.3	$t(24)=10.34, p<.001$	2.07	Very Large
Energy management principles	64.3 ± 11.8	84.6 ± 8.3	+20.3	$t(24)=9.12, p<.001$	1.82	Large
Psychomotor Domain	**54.7 ± 13.8**	**81.6 ± 9.5**	**+26.9**	$t(24)=10.98, p<.001$	2.20	Very Large
Software operation proficiency	48.2 ± 15.6	85.3 ± 8.1	+37.1	$t(24)=13.45, p<.001$	2.69	Very Large
Troubleshooting competence	57.4 ± 14.2	79.2 ± 10.8	+21.8	$t(24)=8.67, p<.001$	1.73	Large
Sensor calibration skills	51.6 ± 16.1	78.4 ± 11.3	+26.8	$t(24)=9.89, p<.001$	1.98	Large
Data interpretation ability	61.5 ± 12.4	83.5 ± 8.9	+22.0	$t(24)=9.54, p<.001$	1.91	Large
Affective Domain	**67.3 ± 10.2**	**86.9 ± 7.4**	**+19.6**	$t(24)=8.92, p<.001$	1.78	Large
Safety awareness	72.1 ± 9.8	88.4 ± 6.7	+16.3	$t(24)=7.83, p<.001$	1.57	Large
Environmental responsibility	68.7 ± 11.3	87.2 ± 7.9	+18.5	$t(24)=8.34, p<.001$	1.67	Large

MECAI Dimension / Indicator	Pre (%)	Post (%)	Gain (%)	Paired t-test	Effect Size (d)	Interpretation
Professional ethics	63.2 ± 12.7	85.6 ± 8.2	+22.4	$t(24)=9.68$, $p<.001$	1.94	Large
Technological adaptability	65.2 ± 11.1	86.5 ± 7.6	+21.3	$t(24)=9.41$, $p<.001$	1.88	Large
Digital Literacy	**61.8 ± 11.7**	**87.3 ± 7.2**	**+25.5**	$t(24)=11.23$, $p<.001$	2.25	Very Large
AR application competence	55.4 ± 14.8	89.2 ± 6.5	+33.8	$t(24)=13.12$, $p<.001$	2.62	Very Large
STEM integration capability	62.5 ± 12.1	86.7 ± 7.8	+24.2	$t(24)=10.67$, $p<.001$	2.13	Very Large
Industry 4.0 proficiency	58.9 ± 13.4	85.3 ± 8.4	+26.4	$t(24)=10.89$, $p<.001$	2.18	Very Large
Digital communication skills	70.4 ± 10.5	88.1 ± 7.1	+17.7	$t(24)=8.15$, $p<.001$	1.63	Large
Overall MECAI Score	**60.6 ± 10.8**	**85.0 ± 7.1**	**+24.4**	**t(24)=12.34, p<.001**	**2.47**	**Very Large**

RQ3: STEM Integration Effectiveness (SIEME)

SIEME analysis revealed high overall STEM integration effectiveness (80.1/100). Technology integration was the strongest component (85.4), reflecting AR's inherent alignment with digital systems learning. Science and engineering integration both scored highly (78.6 and 81.7, respectively), supported by evidence of students applying thermodynamics, materials science, physics, and engineering design principles in problem-solving. Mathematics integration, while moderate–high (74.8), lagged behind other STEM components. Students demonstrated adequate data analysis and computational ability, but mathematical reasoning did not emerge as naturally or spontaneously as scientific and engineering thinking. Instructor and student comments confirmed that mathematics remained a tool applied when prompted rather than an internalized cognitive lens—indicating the need for more explicit mathematical scaffolding in future AR module designs. Correlation analyses revealed strong relationships between technology–engineering and science–engineering components, suggesting these domains mutually reinforce each other. Mathematics showed weaker correlations, further supporting its relative fragility within integrated STEM learning. STEM integration effectiveness was evaluated using SIEME, which aggregated evidence from qualitative coding, instructor evaluations, project artifact analysis, and student articulations.

Table 2. STEM Integration Effectiveness in Maritime Education (SIEME)

SIEME Component / Indicator	Score (0–100)	Effectiveness Category	Qualitative Evidence
Science Integration	**78.6**	**High Effectiveness**	88% of students applied thermodynamics, materials science, and physics in engine analysis; strong scientific reasoning observed.
Thermodynamics application	82.3	Very High	Demonstrated sophisticated understanding of heat transfer, combustion efficiency, and energy conversion.
Materials science use	76.4	High	Showed good comprehension of material properties influencing component and sensor behavior.
Physics principles	77.2	High	Applied mechanics, fluid dynamics, and electrical principles effectively in problem-solving.
Technology Integration	**85.4**	**Very High Effectiveness**	AR supported exceptional mastery of IoT concepts, automation logic, and digital system visualization.
IoT / sensor technology	88.7	Very High	Outstanding understanding of sensor networks, data flow, and system integration pathways.
Automation & control	84.2	Very High	Strong grasp of automated monitoring, control sequences, and system response behaviors.
Digital systems	82.3	Very High	Demonstrated strong comprehension of virtual–physical mapping and digital data processing.
Engineering Integration	**81.7**	**High Effectiveness**	Student work exhibited strong systems thinking, troubleshooting logic, and design-based reasoning.
Systems thinking	84.9	Very High	Displayed excellent holistic understanding of engine systems and inter-component relationships.
Problem-solving	80.6	High	Demonstrated effective analytical reasoning in diagnosing and optimizing system performance.
Design considerations	79.6	High	Recognized engineering constraints, trade-offs, and decision-making criteria.

SIEME Component / Indicator	Score (0–100)	Effectiveness Category	Qualitative Evidence
Mathematics Integration	**74.8**	**Moderate–High Effectiveness**	Mathematical reasoning present but less spontaneously integrated than science/engineering domains.
Data analysis	78.2	High	Demonstrated accurate use of statistics and interpretation of performance data.
Calculations	75.3	Moderate–High	Showed adequate computational skills for efficiency, output, and performance metrics.
Algorithms	70.9	Moderate	Basic comprehension of algorithmic logic for predictive maintenance; some difficulty with complexity.
Overall SIEME Score	**80.1**	**High Overall Effectiveness**	Strong interdisciplinary STEM integration; technology integration strongest, mathematics needing further strengthening.

RQ4: Implementation Factors and Contextual Influences

Three categories of contextual influences significantly shaped AR-enhanced learning outcomes:

1. Infrastructure and Resource Availability

Device availability strongly predicted MECAI outcomes, with 1:1 device institutions outperforming 2:1 sharing institutions (M = 88.3 vs. 79.2; p = .002). Connectivity instability, device aging, and inconsistent power supply particularly hindered institutions in less urban regions.

2. Instructor Technological–Pedagogical Capacity

Instructor proficiency in both technology use and technology-mediated pedagogy significantly affected learning quality. Instructors with prior experience in educational technology demonstrated more effective facilitation and adaptive guidance, whereas others struggled with balancing autonomy and support.

3. Institutional Culture and Support

Institutions that demonstrated program-level commitment allocating resources, integrating AR into curriculum, and supporting instructor development achieved stronger results. Conversely, pilot-style implementations without structural support produced fragmented adoption and uneven learning experiences. These findings highlight that AR-enhanced STEM learning effectiveness is contingent upon a complex interplay of technological infrastructure, pedagogical capacity, and institutional culture rather than on the AR technology itself.

Discussion

The findings of this study illustrate that STEM-integrated AR learning environments foster pedagogical conditions that are highly advantageous for maritime engineering education, especially when addressing smart ship technologies and Industry 4.0 operational demands. In relation to RQ1, students described learning experiences marked by deeper comprehension of cyber-physical engine systems, greater engagement, and increased independence in navigating complex operational scenarios. AR based visualizations enabled learners to interpret system architecture, data flow mechanisms, and real time monitoring functions with a level of clarity unattainable through traditional diagrams or lecture centered instruction (AlGerafi et al., 2023; Kaur & Mantri, 2024; Korkut & Surer, 2023). These three dimensional simulations served not only as cognitive scaffolds but also as exploratory spaces in which learners could experiment with system behaviors under varying operational conditions. Students' interactions with the AR environment also stimulated spontaneous peer-to-peer explanations, indicating that technology mediated learning can initiate collaborative knowledge building without explicit cooperative task structures. Such interactions demonstrate that immersive visualization enhances both cognitive processing and social learning processes. Overall, the results suggest that AR creates a learning ecology that supports conceptual depth, motivation, and exploratory problem-solving essential for understanding modern maritime engineering systems.

Regarding RQ2, the improvements observed across all components of the Marine Engineering Competency Achievement Index (MECAI) highlight AR's potential to strengthen both conceptual and operational competencies. The most significant gains were recorded in digital literacy, IoT sensor interpretation, and software-based operational fluency, demonstrating that AR particularly benefits domains requiring spatial reasoning and procedural execution (Barna et al., 2025; Kaddoura & Husseiny, 2023; Stephanidis et al., 2025). Students reported that AR allowed them to repeatedly observe system responses to simulated conditions, supporting iterative learning that is rarely feasible with physical machinery alone. Cognitive gains were also accompanied by improved confidence in handling digital control interfaces, suggesting that AR can reduce anxiety associated with complex technical instrumentation. Although affective domain progress was smaller, the pattern aligns with literature noting that professional dispositions such as discipline, safety awareness, and teamwork require extended socialization within authentic workplace cultures. This indicates that AR is highly effective for cognitive and psychomotor development but may need to be paired with long-term field training to foster professional identity formation. Taken together, these outcomes confirm that AR can operationalize competency-based learning models in marine engineering environments.

Findings related to RQ3 reveal that AR-enhanced learning supported strong integration across science, technology, and engineering domains, demonstrating that authentic problem structures naturally stimulate cross-disciplinary reasoning. Students frequently drew connections between physical principles, sensor technologies, and engineering control decisions while working through AR based tasks, suggesting that the complexity of smart ship engines itself encourages interdisciplinary thinking. These observations affirm existing arguments that meaningful STEM integration is driven more by the inherent complexity of real-world problems than by linear sequencing of disciplinary content. Mathematics, however, remained less intuitively incorporated because students rarely engaged in explicit quantitative modeling or data-driven calculations during AR interactions. This limitation is consistent with research showing that mathematical reasoning is often the least visible and most difficult element to embed within applied engineering simulations (English, 2023; Wagg et al., 2020). The findings point to the need for AR designs that include built-in tasks involving trend analysis, sensor calibration computations, and operational decision-making supported by quantitative data. Future instructional designs may strengthen mathematics integration by embedding interactive graphs, dynamic system equations, or parameter-change experiments. Therefore, while AR effectively promoted STEM integration, targeted enhancements are required to fully incorporate mathematical dimensions of engineering work.

Findings associated with RQ4 underscore that the success of AR-mediated learning is strongly shaped by the broader implementation ecology, which includes infrastructure, instructor capacity, and institutional norms. Students performed best in settings where devices ran smoothly, internet connectivity remained stable, and AR applications operated without technical interruptions. Instructor readiness also emerged as a critical factor, as effective facilitation depended on educators' ability to guide students through multimodal interactions, troubleshoot technical issues, and contextualize AR simulations within real engineering practices (Bondin & Zammit, 2025; Philippe et al., 2020; Ward et al., 2025). These results mirror prior research indicating that technology integration often fails when human and infrastructural systems are insufficiently prepared to support innovation (Nordlöf et al., 2019; Tsai et al., 2020). Institutional culture played an equally important role, particularly in schools that prioritized experimentation, digital literacy development, and interdisciplinary collaboration. Conversely, environments with rigid schedules or limited digital resources tended to constrain the pedagogical potential of AR. Overall, the study highlights that AR adoption requires synchronized support across technological, pedagogical, and organizational dimensions to achieve meaningful and sustainable impact.

Collectively, this study expands scholarly understanding of how AR can be leveraged to operationalize competency-based maritime engineering education within technologically evolving contexts. The integration of AR into a vocational maritime setting represents a novel contribution, as much of the existing literature has focused on general science or engineering domains rather than the specialized demands of marine engine monitoring systems. By employing both the MECAI and SIEME frameworks, the study provides structured mechanisms for evaluating competency achievements and STEM integration, thereby responding to calls for more robust assessment approaches in technology-enhanced learning research. The findings also underscore that successful AR adoption depends on aligning technological tools with pedagogical objectives and institutional conditions, reinforcing a systems-level perspective on educational innovation. Importantly, the research demonstrates that AR not only enhances conceptual understanding but also increases learners' engagement, confidence, and readiness for future smart ship operations. These insights hold relevance for policymakers, curriculum developers, and maritime training institutions seeking to modernize instructional practices. Ultimately, the study argues that AR-supported STEM learning represents a viable pathway for preparing maritime vocational students to meet the demands of digitalized vessel operations and Industry 4.0 engineering environments.

Implication

The findings of this study generate several important implications for maritime education, competency-based training, and the broader integration of digital technologies into vocational learning ecosystems. First, the substantial competency gains across cognitive, psychomotor, affective, and digital literacy domains indicate that STEM-integrated AR environments can serve as a viable pedagogical model for preparing future marine engineers to operate increasingly complex smart ship systems, suggesting that AR should be positioned not as supplementary enrichment but as a core instructional modality in marine engineering curricula. Second, the demonstrated effectiveness of AR in enabling conceptual visualization, procedural fluency, and interdisciplinary reasoning implies that maritime institutions particularly those in developing contexts can leverage AR to mitigate limitations in physical infrastructure, reduce reliance on expensive simulators, and provide equitable exposure to Industry 4.0 technologies. Third, the study's insights into STEM integration reveal that authentic problem complexity embedded in AR scenarios naturally drives cross-disciplinary thinking, offering guidance for curriculum designers seeking to redesign course structures around integrated rather than sequential disciplinary learning. Fourth, the clear influence of infrastructure adequacy, instructor readiness, and institutional culture underscores that successful adoption of AR-enhanced learning requires coordinated system-level strategies, including sustained professional development, targeted resource investment, and alignment of AR modules with program-wide learning pathways. Finally, the development and validation of MECAI and SIEME as domain-specific assessment frameworks offer practical tools for evaluating technological, pedagogical, and competency outcomes, enabling maritime institutions and policymakers to make evidence-informed decisions when scaling digital learning innovations across diverse educational settings.

Limitation and Suggestion

Despite providing meaningful insights into the pedagogical value of STEM-integrated AR for maritime engineering education, this study is subject to several limitations that should be acknowledged when interpreting the findings. First, the research was conducted within three

Indonesian maritime vocational institutions with varying resource profiles, which, while offering contextual diversity, limits the generalizability of results to institutions with substantially different technological infrastructures or institutional cultures. Second, the reliance on a sixteen-week implementation period constrains the ability to assess long-term retention, skill transfer to real-world shipboard environments, or sustained development of affective and professional competencies that typically evolve over extended training cycles. Third, although the mixed-methods approach generated rich insights, the qualitative components relied on self-reported student reflections and instructor interpretations, which may be influenced by social desirability bias or varying levels of metacognitive awareness. Fourth, the AR learning modules were designed primarily for engine monitoring systems, meaning the findings may not fully extend to other domains of marine engineering such as propulsion diagnostics, auxiliary machinery operations, or emergency response procedures that involve different cognitive and psychomotor demands. Finally, the study occurred in contexts where device availability, connectivity reliability, and instructor readiness varied considerably, creating implementation disparities that, while valuable for examining contextual influences, also introduced confounding factors that make it challenging to isolate the pure learning effect of the AR intervention from broader institutional conditions.

Building upon the insights and limitations identified in this study, several directions are recommended for future research and educational practice to advance the effective integration of STEM-enhanced AR in maritime engineering training. First, longitudinal investigations are needed to evaluate whether competency gains demonstrated in this study—particularly in cognitive understanding, digital literacy, and systems thinking—translate into long-term retention and real-world shipboard performance, especially under the operational pressures of authentic maritime environments. Second, future studies should expand AR learning modules beyond engine monitoring systems to encompass a broader spectrum of marine engineering tasks, including propulsion optimization, auxiliary machinery troubleshooting, emergency procedures, and energy-efficiency management, thereby enabling more comprehensive evaluation of AR's pedagogical versatility. Third, research examining structured instructor professional development is vital, particularly in facilitating shifts from teacher-centered instruction to facilitation-oriented pedagogies suited for immersive learning environments. Fourth, comparative studies across developed and developing maritime education systems would provide deeper insight into how resource availability, institutional culture, and curriculum integration strategies mediate AR effectiveness, helping identify scalable implementation models for diverse contexts. Finally, future work should explore instructional designs that more explicitly embed mathematical modeling, quantitative reasoning, and algorithmic thinking within AR scenarios, addressing the relatively weaker mathematics integration observed in this study and supporting holistic STEM competency development aligned with advanced smart-ship operations.

CONCLUSION

This study demonstrates that STEM-integrated Augmented Reality (AR) learning media substantially enhances marine engineering competency development among Indonesian maritime vocational students learning smart ship engine monitoring systems, yielding both pedagogical and empirical contributions to maritime education scholarship. AR-supported learning enabled students to visualize complex sensor networks and engine architectures with greater conceptual clarity, engage in spontaneous collaborative knowledge construction, and develop heightened technological confidence essential for Industry 4.0 maritime operations, while still requiring strategic pedagogical scaffolding to manage cognitive demands. Quantitative MECAI results substantiate these experiential gains, with significant improvements across cognitive (+25.8 points), psychomotor (+26.9 points), affective (+19.6 points), and digital literacy (+25.5 points) domains, culminating in an overall increase of 24.4 percentage points and very large effect sizes indicative of strong educational impact. STEM integration effectiveness reached 80.1/100, with technology and engineering components integrating most strongly and mathematics showing room for improvement. However, the findings also reveal that AR effectiveness is deeply contingent upon institutional infrastructure, instructor readiness, and organizational support, highlighting the sociotechnical nature of educational innovation in resource-diverse contexts. Beyond demonstrating AR's pedagogical value, the study fills critical geographic and domain gaps in maritime education research, introduces validated MECAI and SIEME assessment frameworks, and provides evidence-based guidance for implementation within developing-nation contexts responding to accelerated maritime digitalization. As Indonesia advances its maritime transformation agenda and aligns with international regulatory expectations for smart ship competencies, AR-enhanced STEM learning emerges as a promising yet context-dependent pathway that necessitates sustained infrastructural investment, professional development, and curriculum integration to achieve scalable and equitable impact.

AUTHOR CONTRIBUTIONS STATEMENT

This research was collaboratively conducted by two authors. Tri Kismantoro led the overall conceptualization of the study, including the development of the research framework, formulation of the methodological design, and coordination of institutional engagement across participating maritime academies. He oversaw field implementation, supervised data collection procedures, and managed the organization of observational, interview, and assessment datasets. Nafi Almuzani made substantial contributions to the analytical stages of the study, including qualitative coding, thematic consolidation, cross-source triangulation, and the validation of emergent interpretations. He also played a central role in synthesizing quantitative and qualitative evidence, ensuring the theoretical and methodological coherence of the findings. Both authors jointly drafted, critically reviewed, and revised the manuscript, approved the final version for submission, and assume full responsibility for the integrity, accuracy, and scholarly rigor of the research.

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