International Journal of Computer Science and Information Technology (IJISIT)
Volume 2, No. 2 (2025) pp. 153-162
e-ISSN 3063-4156 | p-ISSN 3063-4172
DOI: 10.55123/ijisit.v2i2.54

Internet of Things-Enabled Smart Classroom Infrastructure for Maritime Education: Real-Time Learning Analytics and Student Engagement Optimization at Maritime Institute

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Article Info

Article history:

Received October 11, 2025
Revised November 18, 2025
Accepted December 30, 2025

Keywords:

Internet of Things
Learning Analytics
Maritime Education
Smart Classrooms
Student Engagement

ABSTRACT

The integration of Internet of Things (IoT) technologies into educational infrastructure represents a transformative opportunity for enhancing student engagement, optimizing learning outcomes, and enabling data-driven pedagogical decision-making in maritime education contexts where technical complexity and high-stakes professional competency requirements create strong imperatives for instructional effectiveness. This sequential mixed-methods study investigates the impact of IoT-enabled smart classroom infrastructure on student engagement and learning outcomes at Sekolah Tinggi Ilmu Pelayaran (STIP) Jakarta through convergent analysis of structured questionnaire data from maritime academy students (n=180) and instructors (n=35) experiencing both IoT-equipped and traditional classrooms, complemented by Focus Group Discussions exploring pedagogical mechanisms and implementation experiences. Quantitative findings demonstrate that IoT smart classrooms significantly improve student engagement by 36.5 percent ($p < .001$, Cohen's $d = 1.23$) and learning outcomes by 28.1 percent ($p < .001$, $d = 0.94$) relative to traditional classroom baselines, with real-time feedback effectiveness showing largest improvement at 54.6 percent. Correlation analysis reveals engagement-learning outcome relationships are substantially stronger in smart classrooms ($r = 0.81$) than traditional settings ($r = 0.59$), indicating IoT technologies enhance both engagement levels and pedagogical conversion of engagement into learning gains. Qualitative FGD analysis identifies visibility-accountability effects and instructor responsiveness enabled by real-time learning analytics as primary improvement mechanisms. The study proposes an IoT Smart Classroom Integration Framework incorporating response systems, analytics dashboards, environmental optimization, and faculty development for data-driven pedagogy.

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1. INTRODUCTION

The physical classroom has served as the foundational spatial container of formal education for centuries, its architecture and organization fundamentally shaping the pedagogical possibilities, social dynamics, and learning experiences of generations of students across all educational levels, disciplines, and cultural contexts. Yet throughout most of this extensive history, the classroom has remained what might be termed a "dumb" space in the information technology sense—a passive physical container that provides essential environmental functions including shelter from weather, seating arrangements facilitating group instruction, ambient lighting enabling visual information processing, and display surfaces such as blackboards or whiteboards for instructor content presentation, but that generates no systematic data about the complex learning processes occurring within its walls, provides no real-time feedback mechanisms enabling instructors to monitor student comprehension or cognitive engagement as instruction unfolds, and offers no automated capabilities for adapting environmental conditions or instructional delivery modalities to the actual attentional states, comprehension levels, or learning preferences of the diverse students it hosts [1].

The emergence and progressive miniaturization of Internet of Things (IoT) technologies—distributed networks of interconnected sensors, actuators, wireless communication devices, and edge computing systems that can collect environmental and behavioral data, transmit information across digital networks, process data streams through cloud or local analytics platforms, and actuate physical responses to detected conditions in real time—is fundamentally transforming this centuries-old paradigm of the classroom as passive container, enabling the creation of what educational technologists increasingly designate as "smart classrooms" that function as active, responsive, data-generating learning environments capable of continuously sensing indicators of student engagement and environmental quality, automatically monitoring and optimizing physical conditions affecting cognitive performance, capturing granular learning analytics documenting comprehension patterns and participation dynamics, and providing instructors with real-time visibility into classroom processes that were previously entirely invisible or knowable only through delayed, indirect measures such as examination performance assessed weeks after initial instruction [2].

IoT-enabled smart classroom infrastructure encompasses a diverse and expanding ecosystem of interconnected technologies deployed across multiple functional domains serving distinct but complementary educational objectives. Environmental sensing and control systems employ temperature sensors, humidity monitors, CO2 concentration detectors, and photometric light sensors to continuously measure ambient conditions, with data transmitted to building automation controllers that automatically adjust HVAC systems, window blinds, and lighting fixtures to maintain temperature ranges, air quality levels, and illumination conditions empirically associated with sustained cognitive performance, attention maintenance, and reduced mental fatigue during extended learning sessions [3]. Attendance and participation tracking systems utilize RFID badge readers deployed at classroom entrances, biometric sensors including facial recognition cameras or fingerprint scanners, or computer vision algorithms analyzing video streams to automatically record student attendance with precision impossible through manual roster-calling, monitor physical presence duration detecting early departures or extended absences from seats, and in more sophisticated implementations detect behavioral indicators of engagement including head orientation toward instructor or presentation screens, postural attention versus slouching or distraction, and participation gestures such as hand-raising for questions [4].

Interactive display technologies integrate large-format touchscreen panels, wireless presentation systems enabling students to share content from personal devices, and IoT-connected projectors with automatic input switching and environmental adaptation features that collectively transform static instructor-to-student content delivery into dynamic multi-directional information sharing supporting collaborative learning interactions, peer-to-peer knowledge exchange, and student content creation as active learning pedagogies rather than passive reception [5]. Classroom response systems—handheld clickers, smartphone-based polling applications, or gesture recognition interfaces—enable real-time formative assessment where instructors pose comprehension check questions and immediately view aggregate student response distributions, identifying concepts requiring additional explanation when significant proportions select incorrect answers or express confusion, transforming assessment from exclusively summative end-of-unit evaluation into continuous diagnostic feedback informing instructional adjustment [6].

Learning analytics platforms represent perhaps the most pedagogically transformative component of smart classroom ecosystems, aggregating data streams from learning management systems tracking digital resource access and assignment completion, classroom response systems capturing comprehension check responses and participation frequency, attendance tracking systems documenting physical presence patterns, and environmental sensors monitoring ambient conditions, then processing these heterogeneous data through machine learning algorithms to generate real-time dashboards visualizing student engagement levels, comprehension patterns, attention dynamics, and individual or subgroup learning trajectories that enable instructors to identify students requiring additional support, adjust teaching pace when aggregate comprehension falls below thresholds, clarify concepts showing widespread misunderstanding, and personalize interventions targeting specific learning needs revealed through analytics rather than relying on intuition or delayed exam feedback [7]. These multifaceted technologies, when integrated into unified smart classroom

e- ISSN 3063-4156 | p-ISSN 3063-4172

ecosystems rather than deployed as isolated point solutions, fundamentally transform the instructor's informational environment from one characterized by uncertainty and severely delayed feedback—where student comprehension must be inferred from indirect behavioral cues and is definitively assessed only through periodic examinations administered weeks after initial material presentation when remediation opportunities are constrained—to one of continuous, granular, real-time awareness enabling immediate pedagogical response, dynamic instructional optimization, and proactive intervention before comprehension gaps accumulate into learning failures.

The potential educational value of IoT smart classroom infrastructure is particularly pronounced in specialized professional education contexts such as maritime academies, where multiple contextual factors create especially strong incentives for pedagogical innovation and learning optimization that justify the substantial investments required for comprehensive smart classroom implementation. First, the technical complexity and cognitive demands of maritime curricula—encompassing advanced mathematics for stability calculations and celestial navigation, physics principles underlying ship hydrostatics and propulsion systems, intricate regulatory frameworks including MARPOL environmental compliance and SOLAS safety requirements, and operational procedures for navigation equipment, machinery systems, and emergency response—generate significant learning challenges even for well-prepared students, creating pedagogical premium on any technologies or practices that enhance comprehension and retention [8]. Second, the diversity of student backgrounds and prior academic preparation levels typical in maritime academy cohorts—ranging from students with strong secondary science and mathematics foundations to those entering from vocational technical schools with limited theoretical preparation—creates substantial within-classroom heterogeneity in learning readiness, comprehension speed, and support needs that traditional uniform-pace instruction struggles to accommodate effectively but that real-time learning analytics might enable instructors to address through differentiated intervention [9].

Third, the high-stakes nature of maritime professional competency outcomes, where knowledge deficits and procedural errors can generate catastrophic consequences including vessel casualties, environmental disasters, or loss of life, establishes particularly stringent standards for training effectiveness that justify educational technology investments potentially unjustifiable in lower-stakes educational contexts [10]. Fourth, the specific pedagogical challenges of maritime education including the need to develop both theoretical understanding and practical operational competencies, to integrate knowledge across traditionally siloed disciplines (navigation drawing on mathematics, physics, meteorology, and regulatory frameworks simultaneously), and to maintain student engagement during technically dense material presentations create opportunities for smart classroom technologies to address distinctive maritime education challenges rather than merely incremen

tally improving generic teaching practices applicable across all disciplines.

STIP Jakarta, as Indonesia's premier maritime education institution preparing future deck officers, marine engineers, and maritime administrators for safety-critical professional roles in domestic and international shipping industries, faces these pedagogical challenges acutely while simultaneously operating under institutional resource constraints that make instructional efficiency and learning outcome optimization particularly important. Traditional classroom instruction in STIP Jakarta's technically demanding curricula—covering subjects including ship stability and strength, marine propulsion systems, celestial and electronic navigation, maritime law and regulations, cargo handling and stowage, and emergency response procedures—often operates under conditions of significant instructor uncertainty about real-time student comprehension dynamics. Instructors lecturing on the mathematical principles underlying metacentric height calculations, presenting the complex regulatory frameworks of MARPOL Annex VI emission standards, or explaining the operational procedures for ECDIS navigation systems typically possess limited visibility into whether students are following the presentations with comprehension, which specific concepts are generating confusion requiring additional explanation, when aggregate attention and engagement are declining below productive thresholds, or which individual students are experiencing particular comprehension difficulties requiring targeted support [11].

This informational uncertainty generates multiple forms of pedagogical inefficiency that constrain learning effectiveness and waste limited instructional contact time. Instructors may proceed too quickly past material that significant student subsets have not adequately grasped, building subsequent instruction on shaky conceptual foundations that generate cumulative comprehension deficits only becoming apparent during summative assessments when remediation is difficult. Alternatively, instructors may pace too slowly through material that students have already mastered through pre-class reading or prior coursework, failing to optimize limited contact hours for higher-value learning activities. Without real-time feedback on student engagement levels, instructors may persist with instructional approaches that have lost student attention—extended lectures becoming monotonous, examples that fail to clarify underlying principles, or interactive activities that students find confusing rather than enlightening—missing opportunities to adjust delivery modalities when engagement declines below productive thresholds [12].

IoT smart classroom infrastructure addresses these pedagogical uncertainties directly by making the previously invisible dynamics of student engagement, comprehension, and attention continuously visible to instructors through real-time learning analytics dashboards presented on instructor workstation displays or personal tablets. When instructors can observe through classroom response system data that 60 percent of students have marked a ship stability concept as "not understood" after initial explanation, or when attention tracking analytics indicate that aggregate engagement levels have declined 40 percent below baseline suggesting widespread disengagement, instructors can immediately adjust their teaching approach—pausing to provide additional explanation with alternative examples, working through a practice problem demonstrating concept application, shifting from lecture to interactive discussion to re-engage student participation, or calling a brief break to restore attention capacity—rather than discovering comprehension failures only retrospectively through poor examination performance weeks later when learning opportunities have passed and remediation requires additional contact time outside already constrained schedules [7].

This real-time feedback loop fundamentally transforms teaching from a predominantly feed-forward process—where instructors deliver content according to pre-planned sequences with limited mid-delivery adjustment based on actual student learning states—into a dynamically responsive, cybernetic process that continuously adapts instructional delivery to real-time evidence of student comprehension levels, engagement intensity, and learning needs as they emerge during instruction rather than being inferred retrospectively. However, the realization of this pedagogical potential is not automatic upon smart classroom infrastructure installation but depends critically on instructor capacity to interpret learning analytics data accurately, integrate real-time feedback into pedagogical decision-making processes effectively, and redesign instructional approaches to leverage the technological affordances that IoT systems provide—competencies that require explicit faculty development investment and sustained institutional support to develop rather than emerging spontaneously when technologies are deployed [13].

Despite growing international research literature documenting smart classroom effectiveness in general higher education contexts, empirical investigation specifically examining IoT smart classroom impact within maritime education environments remains notably limited, and no systematic assessment of smart classroom infrastructure effects on student engagement and learning outcomes at STIP Jakarta has previously been conducted despite the institution's substantial investment in IoT classroom technologies over recent years. This research gap is consequential because educational technology effectiveness is demonstrably context-dependent, varying significantly across disciplinary cultures, student population characteristics, institutional environments, and pedagogical traditions in ways that make direct transferability of findings from general university contexts to specialized professional academies uncertain and potentially misleading [14]. Understanding whether and how IoT smart classrooms improve student engagement and learning outcomes specifically within STIP Jakarta's maritime education context—identifying which technological components generate greatest pedagogical value, which instructor practices most effectively leverage IoT affordances, what student experiences and perceptions shape technology-mediated engagement, and what implementation barriers constrain realization of potential benefits—requires empirical investigation grounded in actual STIP Jakarta student and instructor experiences rather than extrapolation from research conducted in dissimilar institutional and disciplinary contexts.

Furthermore, the substantial capital and operational expenses associated with comprehensive smart classroom infrastructure deployment—including hardware procurement for sensors, displays, and networking equipment; software licensing for analytics platforms and classroom management systems; facilities modification for equipment installation and network infrastructure; faculty development for pedagogical integration; and ongoing technical support for system maintenance and troubleshooting—make evidence-based assessment of actual educational value particularly important for institutional decision-making about technology investment priorities [15]. Without empirical demonstration that IoT smart classrooms measurably improve engagement and learning outcomes sufficient to justify costs, institutions risk allocating limited resources to technology investments generating minimal educational return while neglecting alternative investments (faculty hiring, curriculum development, student support services) potentially offering superior learning impact per expenditure unit.

This study investigates IoT-enabled smart classroom infrastructure impact on student engagement and learning outcomes at STIP Jakarta through sequential mixed-methods research integrating quantitative survey assessment with qualitative Focus Group Discussion exploration. The research examines whether smart classrooms significantly improve engagement and outcomes relative to traditional classrooms, identifies specific technological components and pedagogical practices generating greatest impact, explores student and instructor experiences shaping technology-mediated learning, and proposes evidence-grounded recommendations for optimizing smart classroom effectiveness and guiding continued infrastructure investment at STIP Jakarta and comparable maritime education institutions.

The study is guided by the central research question: To what extent does IoT-enabled smart classroom infrastructure improve student engagement and learning outcomes in maritime education at STIP Jakarta, and what technological components, pedagogical practices, and implementation strategies most effectively leverage IoT affordances for engagement and learning optimization? This question encompasses both outcome assessment (quantifying engagement and learning improvements) and mechanism investigation (identifying how and why improvements occur and what factors enable or constrain effectiveness), recognizing that technology impact depends not merely on hardware deployment but on pedagogical integration, instructor capability, and student acceptance.

2. METHODS

This study employed a sequential mixed-methods research design integrating quantitative survey data collection measuring student engagement and learning outcomes with qualitative Focus Group Discussions exploring pedagogical mechanisms, user experiences, and implementation challenges [16]. The sequential structure prioritized quantitative assessment to establish empirical magnitude of smart classroom impacts, followed by qualitative investigation explaining mechanisms underlying quantitative patterns and identifying optimization strategies.

The study population comprised two complementary stakeholder groups. Maritime academy students enrolled in STIP Jakarta's nautical science, marine engineering, and maritime administration programs who had experienced instruction in both IoT-enabled smart classrooms and traditional classrooms during their academic programs (n=180) enabled within-subject comparison of engagement and learning across classroom technology conditions. Students were stratified across programs (60 per program) and year levels (first through fourth year, 45 per level) ensuring representation across the full STIP Jakarta population with varying technology exposure durations and curricular contexts.

Maritime education instructors teaching core curriculum courses at STIP Jakarta who had delivered instruction in both smart classroom and traditional classroom environments (n=35) provided complementary instructor perspectives on teaching effectiveness, student-instructor interaction quality, and pedagogical decision-making impacts. The two-group design was essential because smart classroom effectiveness emerges from interaction between student learning experiences and instructor pedagogical practices, requiring both perspectives for comprehensive assessment [1].

The primary survey instrument comprised 42 structured questionnaire items organized across six indicator dimensions aligned with smart classroom technology domains and pedagogical objectives. Student engagement metrics (8 items) measured self-reported attention sustainability, active participation frequency, cognitive involvement intensity, and motivation levels comparing IoT smart classroom versus traditional classroom experiences. Learning outcome performance (7 items) assessed perceived comprehension depth, knowledge retention duration, examination score improvement, and practical competency development across classroom conditions. Real-time feedback effectiveness (8 items) evaluated utility of classroom response systems for comprehension monitoring, learning analytics dashboard clarity, and instructor responsiveness to feedback data. Environmental quality (6 items) measured satisfaction with automated climate control, lighting optimization, acoustic management, and overall comfort in smart classrooms affecting sustained cognitive performance. Technology usability (7 items) assessed ease of use, system reliability, interface intuitiveness, and technical support adequacy for IoT classroom systems. Overall satisfaction and preference (6 items) captured general smart classroom evaluation and recommendation likelihood.

All items employed five-point Likert scales (1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree) enabling statistical analysis. The instrument demonstrated strong internal consistency (Cronbach's $\alpha = 0.92$ across all items, ranging 0.87-0.94 across dimensional subscales) following pilot testing with 30 students not included in main study sample. Surveys were administered during regular class sessions to maximize participation, with completion time averaging 15-20 minutes.

Four Focus Group Discussion sessions explored qualitative experiences, pedagogical mechanisms, and implementation insights. Two student FGD sessions (n=12 each, total 24 students selected through stratified sampling ensuring program and year level representation) discussed learning experiences in smart versus traditional classrooms, perceived engagement and comprehension differences, technology usability challenges, and improvement recommendations. Two instructor FGD sessions (n=8 and 9 respectively, total 17 instructors representing diverse subject areas including navigation, engineering, maritime law, and general sciences) examined teaching effectiveness impacts, pedagogical practice modifications enabled by IoT technologies, learning analytics interpretation and utilization, and faculty development needs for optimal technology integration.

Sessions lasted 90-110 minutes each, conducted in STIP Jakarta seminar rooms using semi-structured discussion guides organized around the six survey dimensions to enable direct quantitative-qualitative integration while allowing emergent theme exploration. Guides included open-ended questions ("How do real-time classroom response systems affect your teaching decision-making?"), scenario-based prompts ("Describe a situation where learning analytics helped you identify and address student comprehension difficulties"), and comparative probes ("Compare your engagement levels in smart versus traditional classroom environments"). Sessions were audio-recorded with participant consent, transcribed verbatim generating 127 pages of transcript data, and analyzed using Braun and Clarke's thematic analysis approach [17] involving data familiarization through repeated reading, systematic coding identifying meaning units, theme development grouping related codes, theme review validating coherence, and interpretation connecting themes to research questions. Two researchers independently coded transcripts with inter-coder reliability of 0.89, resolving discrepancies through discussion.

Quantitative survey data were analyzed using SPSS version 27.0. Paired-samples t-tests compared mean scores for smart classroom versus traditional classroom conditions on each survey dimension, assessing whether engagement and learning outcome differences reached statistical significance. Independent samples t-tests examined whether student and instructor perceptions differed significantly. Pearson correlation analysis investigated relationships between engagement metrics and learning outcomes, testing whether engagement-outcome correlations differed between smart and traditional classroom conditions. Effect sizes were calculated using Cohen's d with standard interpretations: d=0.20 small, d=0.50 medium, d=0.80 large effects [18]. Statistical significance threshold was $p < .05$ with Bonferroni correction for multiple comparisons.

3. RESULTS

Integrated analysis of quantitative survey and qualitative FGD data produced convergent evidence that IoT-enabled smart classroom infrastructure significantly improves student engagement and learning outcomes at STIP Jakarta, with quantitative results documenting statistically significant improvements across all measured dimensions and qualitative data illuminating specific mechanisms generating these improvements.

Table 1. Smart Classroom vs. Traditional Classroom: Comparative Performance Across Six Indicator Dimensions (N=215)

Performance Indicator	Students: Smart Classroom (n=180)	Students: Traditional (n=180)	Instructors: Smart (n=35)	Instructors: Traditional (n=35)	Overall Smart Mean	Overall Traditional Mean	Improvement	Effect Size (Cohen's d)
Student Engagement	4.21	3.14	4.38	3.08	4.26	3.12	+36.5%	1.23 (large)
Learning Outcomes	4.07	3.23	4.18	3.14	4.10	3.20	+28.1%	0.94 (large)
Real-Time Feedback Effectiveness	4.34	2.87	4.51	2.76	4.39	2.84	+54.6%	1.42 (large)
Environmental Quality	4.29	3.41	4.37	3.38	4.31	3.40	+26.8%	0.78 (medium-large)
Technology Usability	3.94	N/A	3.87	N/A	3.92	N/A	N/A	N/A
Overall Satisfaction	4.18	3.21	4.33	3.11	4.22	3.18	+32.7%	1.08 (large)

Note: Scale interpretation: 1.00-1.79=Very Low; 1.80-2.59=Low; 2.60-3.39=Moderate; 3.40-4.19=Good; 4.20-5.00=Excellent. All smart vs. traditional comparisons significant at p < .001 (paired-samples t-tests). Technology usability assessed only for smart classrooms (no traditional comparison).

The overall student engagement improvement of 36.5 percent (from 3.12 to 4.26 on 5-point scale, $p < .001$, Cohen's $d = 1.23$) and learning outcome improvement of 28.1 percent (from 3.20 to 4.10, $p < .001$, $d = 0.94$) in IoT smart classrooms relative to traditional classrooms represent educationally significant effect sizes substantially exceeding conventional thresholds for large effects in educational intervention research ($d \geq 0.80$). These improvements directly confirm the study's central hypothesis that IoT infrastructure enhances maritime education effectiveness, establishing compelling quantitative evidence for smart classroom investment.

Real-time feedback effectiveness showed the largest improvement at 54.6 percent (from 2.84 to 4.39, $p < .001$, $d = 1.42$), reflecting the fundamental pedagogical transformation enabled by classroom response systems and learning analytics making student comprehension continuously visible rather than known only through delayed examination feedback. This dimension shifted from "Low" performance in traditional classrooms (mean 2.84) to "Excellent" in smart classrooms (mean 4.39), representing qualitative transformation rather than incremental improvement.

Environmental quality improvement of 26.8 percent (from 3.40 to 4.31, $p < .001$, $d = 0.78$) demonstrated IoT environmental sensing and automated control systems' effectiveness for optimizing ambient conditions supporting sustained cognitive performance. Students and instructors consistently rated smart classroom temperature stability, air quality, and lighting as superior to traditional classrooms where manual control generated suboptimal and variable conditions.

Technology usability achieved "Good" ratings (mean 3.92) indicating IoT classroom systems are generally user-friendly and reliable despite complexity, though not reaching "Excellent" levels suggesting improvement opportunities in interface design and technical support responsiveness.

Independent samples t-tests revealed no significant differences between student and instructor ratings across any dimension (all $p > .05$), indicating strong consensus that smart classrooms improve engagement and learning regardless of stakeholder role.

Table 2. Correlation Analysis: Engagement-Learning Outcome Relationships by Classroom Type (Student Respondents, n=180)

Engagement Metric	Learning Outcome Correlation: Smart Classroom	Learning Outcome Correlation: Traditional Classroom	Correlation Difference	Statistical Significance
Attention Sustainability	r = 0.73, p < .001	r = 0.48, p < .001	Δr = +0.25	Fisher's z = 3.42, p < .001
Participation Frequency	r = 0.68, p < .001	r = 0.52, p < .001	Δr = +0.16	Fisher's z = 2.18, p = .029
Response System Usage	r = 0.71, p < .001	N/A	N/A	N/A
Instructor Interaction Quality	r = 0.66, p < .001	r = 0.54, p < .001	Δr = +0.12	Fisher's z = 1.67, p = .095
Perceived Comprehension	r = 0.79, p < .001	r = 0.61, p < .001	Δr = +0.18	Fisher's z = 2.76, p = .006
Composite Engagement Index	r = 0.81, p < .001	r = 0.59, p < .001	Δr = +0.22	Fisher's z = 3.54, p < .001

Note: Learning outcomes measured via self-reported comprehension, retention, and examination performance. Fisher's z-tests assess whether correlation differences between classroom types are statistically significant.

The correlation analysis reveals that engagement-learning outcome relationships are substantially stronger in smart classrooms (composite $r = 0.81$, large effect) than traditional classrooms (composite $r = 0.59$, medium effect), with the difference statistically significant (Fisher's $z = 3.54$, $p < .001$). This finding indicates IoT technologies not only increase absolute engagement levels but enhance the pedagogical effectiveness of engagement by enabling more targeted, responsive teaching that converts student attention and participation into measurable learning gains.

Attention sustainability shows strongest correlation difference ($\Delta r = +0.25$), suggesting smart classroom technologies particularly enhance the learning value of sustained attention through real-time instructor responsiveness when analytics detect attention decline. Response system usage correlates strongly with learning outcomes ($r = 0.71$), validating active participation through digital feedback mechanisms as high-value learning activity.

Table 3. Focus Group Discussion Thematic Analysis: Mechanisms and Implementation Insights (N=41 participants across 4 sessions)

Major Theme	Prevalence	Representative Quotes	Pedagogical Mechanism	Implementation Implications
Visibility and Accountability Effect (Students)	75% of student participants emphasized	"Knowing the instructor can see my response in real-time makes me pay closer attention and actually think through my answers rather than just passively listening"	Monitoring awareness creates psychological accountability sustaining engagement	Design analytics transparency: show students their data is visible but used pedagogically not punitively
Real-Time Responsiveness Transformation (Instructors)	82% of instructor participants emphasized	"When I see 60% marking 'not understood', I immediately stop and clarify rather than discovering the problem weeks later on the exam when it's too late to fix"	Learning analytics enable immediate pedagogical adjustment preventing comprehension gap accumulation	Provide instructor training on analytics interpretation and responsive teaching strategies

Environmental Optimization Impact	48% across both groups	"Consistent comfortable temperature and good lighting seem minor but really help me focus for full 2-hour sessions without fatigue"	Optimized ambient conditions sustain cognitive capacity and attention	Maintain automated environmental control systems; manual override reduces effectiveness
Technology Reliability Concerns	34% across both groups	"When response system crashes or analytics dashboard freezes, it disrupts the lesson flow and undermines confidence in the technology"	Technical failures create frustration and resistance to technology adoption	Invest in robust technical support, redundant systems, and instructor backup plans

Note: Prevalence indicates percentage of FGD participants emphasizing theme. Quotes selected as representative exemplars from multiple similar participant statements.

The dominant student theme was "visibility and accountability effect"—awareness that attention, participation, and comprehension are monitored through IoT sensors and response systems creates psychological accountability sustaining engagement even during challenging or intrinsically less interesting material. Students described how visible learning analytics dashboards showing aggregate class comprehension motivated them to actively signal understanding or confusion through response inputs, behaviors occurring less consistently in traditional classrooms where individual engagement invisibility permits disengagement without accountability.

Instructors identified "real-time responsiveness transformation" as most impactful smart classroom capability. The ability to observe through analytics that significant student proportions have not understood a concept enables immediate pedagogical adjustment—additional explanation, worked examples, clarifying questions—preventing comprehension gap accumulation that in traditional classrooms becomes apparent only during examinations weeks later when remediation is more difficult and costly in instructional time.

Environmental optimization and technology reliability emerged as important but secondary themes affecting smart classroom experience quality without directly generating engagement improvements. Reliable ambient condition optimization supports sustained cognitive performance, while technical failures undermine instructor and student confidence in IoT systems.

4. DISCUSSION

The findings provide robust mixed-methods evidence that IoT-enabled smart classroom infrastructure significantly improves student engagement (+36.5 percent) and learning outcomes (+28.1 percent) at STIP Jakarta, establishing compelling empirical support for smart classroom technology investment as high-impact maritime education quality enhancement strategy. These results align with and substantially extend existing smart classroom effectiveness literature, corroborating Zhu et al.'s [1] documentation of 25-35 percent engagement improvements in IoT-enabled university classrooms and Chen et al.'s [3] demonstration of 15-25 percent learning gains in technology-enhanced environments. The present study advances international findings by providing first systematic empirical assessment specifically within maritime education contexts, demonstrating benefits documented in general higher education settings transfer effectively to specialized technical curricula and professional competency development objectives characterizing maritime academy instruction.

The particularly large real-time feedback effectiveness improvement (+54.6 percent, $d = 1.42$)—the dimension showing greatest smart classroom advantage—carries important implications for understanding pedagogical mechanisms through which IoT technologies generate engagement and learning benefits. Alavi et al. [2] argued that smart classroom technologies' fundamental educational value lies not in content delivery efficiency—traditional lectures combined with textbooks already deliver content effectively—but in making learning processes visible thereby enabling instructional responsiveness optimizing limited classroom contact time. The substantially stronger engagement-learning outcome correlation in smart classrooms ($r = 0.81$) versus traditional classrooms ($r = 0.59$) provides direct empirical support for this visibility-responsiveness mechanism: when instructors observe engagement and comprehension in real time through IoT learning analytics, they can target pedagogical interventions more precisely to actual learning needs present at each moment, converting general instruction into personalized support more effectively addressing individual and subgroup comprehension gaps [7].

The correlation analysis finding that attention sustainability shows strongest correlation difference between classroom types ($\Delta r = +0.25$) suggests smart classroom technologies particularly enhance sustained attention's learning value through instructor capability to detect and respond to attention decline. In traditional classrooms, instructors may continue ineffective presentations unaware that student attention has declined, wasting contact time on content not cognitively processed. Smart classroom attention analytics enable instructors to detect decline and adjust delivery—shifting to interactive activity, introducing attention-grabbing example, or calling brief break—restoring attention before significant content is missed. This dynamic adjustment capability makes sustained attention more pedagogically productive in smart versus traditional environments.

The FGD-identified "visibility and accountability effect" where students' awareness of monitoring creates psychological motivation to sustain engagement introduces important nuances regarding ethical dimensions of IoT surveillance in educational contexts. Hwang [4] cautioned that continuous student behavior monitoring through IoT sensors can be experienced as invasive surveillance generating anxiety and resistance rather than enhanced engagement, particularly when monitoring data are used punitively or students lack agency over data collection and use. The STIP Jakarta student FGD data suggest visibility effects are experienced positively rather than invasively when students perceive monitoring serving pedagogical rather than disciplinary purposes and when learning analytics are presented transparently with students having access to their own engagement and performance data enabling self-regulation [12].

This finding points to importance of ethical IoT implementation frameworks establishing clear data governance policies, providing students with data access and privacy protections, and positioning learning analytics as tools for student self-monitoring and instructor support rather than institutional surveillance or compliance enforcement. Zawacki-Richter et al. [11] emphasized that educational AI and analytics systems must be designed with explicit attention to fairness, transparency, accountability, and privacy rather than assuming technical capability justifies unlimited data collection and use.

The environmental quality improvement (+26.8 percent) demonstrates automated environmental control's contribution to learning optimization through maintaining conditions supporting sustained cognitive performance. Research on environmental psychology of learning demonstrates that temperature extremes, poor air quality, and inadequate lighting generate measurable cognitive performance decrements and accelerated mental fatigue [3]. Traditional classrooms relying on manual thermostat adjustment often experience suboptimal and variable conditions as instructors focus on teaching rather than environmental management. IoT automated systems continuously optimize conditions without instructor attention, creating stable environments supporting extended concentration.

The technology usability ratings (mean 3.92, "Good" but not "Excellent") suggest improvement opportunities in interface design and technical support responsiveness. Some FGD participants reported confusion about response system operation, analytics dashboard interpretation difficulties, or frustration with technical glitches interrupting instruction. Yang et al. [10] emphasized that educational technology effectiveness depends critically on usability and reliability—technically sophisticated systems generating learning benefits only when users can operate them easily and depend on consistent functionality. STIP Jakarta should invest in interface simplification, comprehensive user training, and robust technical support ensuring technology enhances rather than disrupts instruction.

The instructor FGD emphasis on real-time responsiveness transformation highlights that smart classroom benefits depend on instructor capability to interpret analytics and adjust pedagogy accordingly rather than merely having data available. Simply displaying analytics dashboards without faculty development on data interpretation and responsive teaching strategies may produce minimal impact. Xie et al. [9] documented that effective technology-enhanced personalized learning requires instructor professional development enabling analytics-informed instructional decision-making, differentiated intervention design, and adaptive teaching practices substantially different from traditional uniform-pace instruction.

This finding underscores importance of sustained faculty development investment accompanying smart classroom infrastructure deployment. STIP Jakarta should establish ongoing professional learning communities where instructors share analytics interpretation strategies, discuss responsive teaching practices, and collaboratively develop pedagogical approaches leveraging IoT affordances. One-time orientation training is insufficient for developing sophisticated analytics-informed teaching capability.

5. CONCLUSION

This sequential mixed-methods study demonstrates that IoT-enabled smart classroom infrastructure significantly improves student engagement (+36.5 percent) and learning outcomes (+28.1 percent) at STIP Jakarta, with real-time learning analytics emerging as most impactful technological component (+54.6 percent) enabling instructors to observe comprehension dynamics and adjust teaching responsiveness in ways traditional classrooms cannot replicate. Strong positive correlations between engagement metrics and learning outcomes in smart classrooms ($r = 0.81$) versus traditional settings ($r = 0.59$) confirm IoT technologies not only increase attention and participation but enhance pedagogical effectiveness of engagement through visibility-enabled instructional optimization. The IoT Smart Classroom Integration Framework proposed by this study—incorporating classroom response systems for continuous formative assessment, learning analytics dashboards providing real-time engagement and comprehension visibility, automated environmental control maintaining optimal cognitive performance conditions, transparent data governance ensuring ethical monitoring practices, and sustained faculty development enabling analytics-informed responsive pedagogy—provides STIP Jakarta and comparable maritime education institutions with evidence-grounded roadmap for expanding smart classroom infrastructure and ensuring technological investment translates into sustained engagement and learning improvements enhancing maritime education quality and graduate competency outcomes.

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