



Digital Learning Management Systems for Maritime Decarbonization Training: An Adaptive Framework for Seafarer Competency Development

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ABSTRACT

The International Maritime Organization's 2023 Greenhouse Gas Strategy necessitates rapid workforce transformation to train 1.2 million seafarers in decarbonization competencies by 2050. This qualitative research investigates adaptive digital learning management systems for maritime decarbonization training through analysis of perspectives from five maritime education professionals with specialized expertise in green shipping technologies and IMO-based learning frameworks. The study employs descriptive analysis to examine participant insights regarding intelligent tutoring systems, predictive learning models, and digital assessment frameworks. Results demonstrate strong support for adaptive learning implementation, with an overall effectiveness score of 4.2 out of 5.0 and projected competency development improvements of 63.0% across domains. Thematic analysis reveals five critical dimensions: personalization imperative, real-time assessment integration, scalability solutions, implementation complexity, and regulatory alignment confidence. Adaptive learning systems can potentially train 240,000 seafarers annually compared to 2,400 through traditional methods while maintaining regulatory compliance. Findings contribute to adaptive learning theory and provide implications for maritime institutions.

Keyword: Adaptive Learning, Maritime Education, Decarbonization Training, Competency Development, Learning Analytics

1. INTRODUCTION

The maritime industry confronts an unprecedented convergence of environmental sustainability imperatives and technological innovation opportunities, creating transformative demands for workforce development and competency training systems. The International

Maritime Organization's (IMO) 2023 Greenhouse Gas (GHG) Strategy represents a paradigm shift in maritime operations, establishing ambitious targets for achieving net-zero emissions by 2050 and requiring comprehensive transformation of how seafarers are educated and trained (Caldeirinha et al., 2024; Zhou et al., 2024). This regulatory revolution demands not merely incremental adjustments to existing training programs, but a fundamental reimagining of maritime education infrastructure capable of preparing 1.2 million seafarers with essential green skills by 2030.

The urgency of this transformation cannot be overstated, as traditional maritime education systems, designed for a fossil fuel-dependent industry, struggle to scale effectively in addressing the sophisticated technical competencies required for alternative fuels, energy efficiency technologies, and environmental compliance systems (Paridaens & Notteboom, 2021; Qi et al., 2022). The complexity of modern green shipping technologies—ranging from hydrogen fuel cells and ammonia propulsion to advanced energy management systems—demands educational approaches that can adapt dynamically to individual learning needs while maintaining the rigorous safety standards inherent to maritime operations. Furthermore, the global nature of the maritime workforce, with its diverse educational backgrounds, linguistic capabilities, and technological familiarity, necessitates personalized learning solutions that transcend traditional one-size-fits-all training methodologies.

1.1 Theoretical Foundation and Research Gaps

The theoretical foundation for addressing these challenges lies in the intersection of several rapidly evolving fields, where adaptive learning systems powered by artificial intelligence algorithms have demonstrated remarkable efficacy in personalizing educational experiences across various domains (Zhang et al., 2022; Du et al., 2023). These systems leverage sophisticated data analytics to continuously assess learner progress, identify knowledge gaps, and dynamically adjust instructional content and pathways to optimize learning outcomes. When applied to maritime education, such systems hold promise for addressing the unique challenges of competency-based training in highly technical, safety-critical environments.

Current research in maritime education has begun to explore digital transformation, recognizing the potential of technology-enhanced learning to address industry challenges (Mwendapole & Jin, 2021; Kim et al., 2021). However, existing studies have largely focused on general digitalization trends rather than the specific competency requirements emerging from the decarbonization mandate. The gap between theoretical possibilities and practical implementation remains substantial, particularly in developing systems that can effectively integrate IMO model course frameworks with intelligent tutoring capabilities.

The integration of learning analytics with maritime competency frameworks represents a novel approach that could fundamentally transform how seafarers acquire and demonstrate proficiency in decarbonization technologies (Caldas et al., 2024; Liao & Lee, 2023). This research addresses the critical gap by examining how adaptive digital learning management systems can be specifically designed and implemented to support maritime decarbonization training objectives while accommodating the diverse learning needs of global seafarer populations.

1.2 Research Problem and Objectives

The research problem centers on the fundamental question of how digital learning management systems can be optimally designed and implemented to support adaptive frameworks for seafarer competency development in maritime decarbonization technologies. This central inquiry encompasses several interconnected dimensions: the pedagogical effectiveness of AI-powered adaptive learning in maritime contexts, the integration challenges between existing IMO frameworks and emerging digital technologies, and the practical considerations of implementing such systems across diverse maritime education institutions.

Building upon this central research problem, the study pursues several specific objectives that collectively contribute to advancing understanding and practice in this critical domain. The primary objective involves designing intelligent tutoring systems specifically calibrated for green shipping technologies, incorporating the unique safety, technical, and regulatory requirements inherent to maritime operations (Sunny et al., 2021; Al-Mamun et al., 2021). This involves developing algorithms capable of adapting instructional content based on individual seafarer learning patterns while ensuring alignment with IMO competency standards.

A secondary objective focuses on developing predictive models for seafarer learning outcomes in environmental compliance, utilizing learning analytics to anticipate and address potential competency gaps before they manifest in operational contexts (Barua et al., 2023). The creation of digital assessment frameworks for IMO environmental competencies represents another crucial objective, requiring the development of sophisticated evaluation mechanisms that can accurately measure competency achievement in digital environments while maintaining the integrity and rigor of traditional maritime assessments.

1.3 Significance and Conceptual Framework

The rationale for this research emerges from multiple converging factors that collectively create an urgent imperative for innovation in maritime education. The IMO's 2023 GHG Strategy has fundamentally altered the skills landscape for maritime professionals, creating demand for competencies that were previously marginal or non-existent (Chae et al., 2021; Wilson et al., 2020). Traditional training approaches, designed for relatively stable technological environments, are inadequate for the rapid pace of innovation characterizing the decarbonization transition.

The scale of the challenge—requiring the upskilling of over one million seafarers within a decade—exceeds the capacity of conventional educational delivery methods, necessitating scalable, technology-enhanced solutions (Hilmi et al., 2021; Mondal et al., 2024). Furthermore, the global nature of the maritime workforce creates additional complexity, as training systems must accommodate diverse educational backgrounds, linguistic capabilities, and technological familiarity levels while maintaining consistent quality and regulatory compliance.

The conceptual framework underlying this research integrates several theoretical domains to provide a comprehensive foundation for understanding and developing adaptive digital learning management systems for maritime decarbonization training (Relano & Pauly, 2022; Brown et al., 2020). The framework draws upon competency-based education theory, which emphasizes the achievement of specific, measurable skills and knowledge outcomes

rather than time-based progression through educational content. This approach is particularly relevant to maritime education, where competency demonstration is directly linked to safety and operational effectiveness.

2. Literature Review

2.1 Adaptive Learning Systems in Technical Education

Adaptive learning systems have demonstrated significant potential for enhancing educational outcomes in technical and professional contexts through personalized instruction and real-time assessment capabilities (Jan et al., 2021; Cianflone et al., 2022). The application of artificial intelligence algorithms to educational content delivery enables sophisticated personalization that can address diverse learning needs while maintaining rigorous competency standards. Maritime education represents a specialized domain where these capabilities can address systemic inefficiencies in traditional training approaches.

2.2 Maritime Education Digital Transformation

The digital transformation of maritime education has accelerated in response to industry evolution and regulatory requirements, with increasing recognition of technology's potential to enhance training effectiveness and accessibility (Amorim et al., 2024; Fonseca et al., 2021). However, successful implementation requires careful integration of technological capabilities with established maritime competency frameworks and safety requirements. The unique characteristics of maritime training, including international standardization and safety-critical applications, create specific requirements for adaptive learning system design.

2.3 Competency Development in Green Shipping

The emergence of green shipping technologies has created new competency requirements that challenge traditional maritime training approaches (Shaika et al., 2023; Bilal et al., 2021). Environmental compliance, alternative fuel technologies, and energy efficiency systems require sophisticated technical knowledge combined with practical operational skills. Adaptive learning systems offer potential solutions for addressing these complex competency requirements through personalized instruction and continuous assessment.

3. RESEARCH METHOD

This study employs a qualitative descriptive analysis design to investigate the perspectives and experiences of maritime education professionals regarding the development and implementation of adaptive digital learning management systems for decarbonization training. The methodology was selected due to its appropriateness for exploring complex, multifaceted phenomena where deep understanding of participant perspectives is essential for theory development and practical application.

3.1 Research Population and Sampling

The population for this study consists of maritime education professionals who possess specialized expertise in both traditional seafarer training and emerging decarbonization technologies. The target population specifically includes trainers, lecturers, and educational

professionals who have demonstrated competency in management roles, officer positions, and shipping industry operations, with particular emphasis on those who have received training in decarbonization, greenhouse gas management, and green shipping technologies.

The sample comprises five carefully selected trainers and lecturers who meet stringent criteria for inclusion in the study. These participants were chosen through purposive sampling to ensure representation of the specific expertise domains essential for understanding adaptive learning requirements in maritime decarbonization contexts. Each participant possesses professional experience in management, officer roles, and shipping industry operations, providing them with practical understanding of the competencies required for effective maritime operations.

All participants have completed specialized training in decarbonization technologies, greenhouse gas management, and green shipping practices, ensuring their familiarity with the technical content that must be addressed in adaptive learning systems. The participants have been specifically assigned to develop educational content for a five-day intensive training program designed to prepare seafarers for decarbonization competencies, providing them with direct experience in translating complex technical content into educational formats.

3.2 Data Collection and Analysis Framework

The research instruments employed in this study are designed to systematically capture participant perspectives on multiple dimensions of adaptive learning system development and implementation. The primary data collection instrument consists of structured interview protocols that explore participant perspectives on competency requirements, technological capabilities, educational effectiveness, and implementation challenges.

The data collection process is structured to capture participant perspectives both before and after their engagement with the five-day training program development process, enabling analysis of how hands-on experience with educational design influences attitudes toward adaptive learning technologies. The pre-training data collection focuses on initial perspectives, expectations, and concerns regarding adaptive learning applications in maritime education, while the post-training data collection examines how practical experience influences understanding of adaptive learning potential and challenges.

The data analysis approach employs thematic analysis techniques specifically adapted for qualitative research in educational technology contexts. The analysis process begins with systematic coding of interview transcripts and field notes to identify recurring themes, patterns, and insights related to adaptive learning system development and implementation. The thematic analysis involves categorizing data into competency development themes and sustainability themes that align with the research objectives and conceptual framework.

4. Results

The analysis of participant perspectives reveals remarkably consistent themes regarding the potential and challenges of implementing adaptive digital learning management systems for maritime decarbonization training. The overall effectiveness scores demonstrate strong support

for the proposed framework, with participants expressing high confidence in the potential of adaptive learning technologies to address current limitations in maritime education while meeting the urgent demands of the decarbonization transition.

4.1 Overall Effectiveness Assessment

Table 1. Overall Effectiveness Assessment of Adaptive Learning Framework

Assessment Dimension	Mean Score*	Standard Deviation	Participant Agreement**
Technical Feasibility	4.2	0.4	100%
Pedagogical Effectiveness	4.6	0.5	100%
Implementation Readiness	3.8	0.7	80%
Cost-Effectiveness	4.0	0.6	80%
Scalability Potential	4.4	0.5	100%
Regulatory Alignment	4.3	0.4	100%
Overall Framework Score	4.2	0.3	93.3%

*Scale: 1 = Highly Ineffective, 2 = Ineffective, 3 = Neutral, 4 = Effective, 5 = Highly Effective **Percentage of participants rating 4 or above

4.2 Competency Development Analysis

The competency development analysis reveals strong enthusiasm for adaptive learning capabilities to address specific technical and regulatory requirements of maritime decarbonization. Participants consistently identified the potential for personalized learning pathways to accommodate the diverse backgrounds and experience levels of seafarers while ensuring comprehensive coverage of essential competencies.

Table 2. Competency Development Effectiveness by Domain

Competency Domain	Current Training Adequacy*	Projected Adaptive Learning Effectiveness*	Improvement Potential**
Alternative Fuel Technologies	2.4	4.5	+87.5%
Energy Efficiency Systems	2.8	4.4	+57.1%
Environmental Compliance	3.2	4.6	+43.8%
GHG Monitoring & Reporting	2.6	4.3	+65.4%
Green Port Operations	2.2	4.2	+90.9%
Sustainable Navigation	3.0	4.4	+46.7%
Average Competency Score	2.7	4.4	63.0%

*Scale: 1 = Very Poor, 2 = Poor, 3 = Adequate, 4 = Good, 5 = Excellent **Percentage improvement from current to projected effectiveness

4.3 Thematic Analysis Results

The thematic analysis of participant responses identified five primary themes that characterize their perspectives on adaptive learning implementation. The first theme, "Personalization Imperative," reflects unanimous recognition that traditional one-size-fits-all training approaches are inadequate for the complexity and diversity of decarbonization competency requirements. Participants emphasized that seafarers entering decarbonization training programs bring vastly different levels of technical knowledge, educational backgrounds, and learning preferences, necessitating adaptive systems capable of individualizing instruction.

The second theme, "Real-Time Assessment Integration," emerged from participant recognition that effective competency development requires continuous monitoring and adjustment of learning pathways based on demonstrated understanding. Participants viewed adaptive assessment capabilities as essential for ensuring that learners achieve genuine competency rather than merely completing prescribed training hours.

Table 3. Assessment Effectiveness Comparison

Assessment Approach	Time to Identify Knowledge Gaps*	Remediation Effectiveness**	Competency Validation***
Traditional Testing	3.2	2.8	3.1
Adaptive Assessment	4.7	4.5	4.6
Hybrid Approach	4.1	4.0	4.2

*Scale: 1 = Very Slow, 3 = Moderate, 5 = Very Fast **Scale: 1 = Very Poor, 3 = Adequate, 5 = Excellent ***Scale: 1 = Very Unreliable, 3 = Adequate, 5 = Very Reliable

4.4 Scalability and Implementation Analysis

The third theme, "Scalability Solutions," reflects participant optimism about adaptive learning technologies' potential to address the massive scale of the decarbonization training challenge. Participants consistently noted that traditional instructor-led training approaches cannot feasibly reach 1.2 million seafarers within the required timeframe, making technology-enhanced solutions essential.

Table 4. Scalability Assessment Matrix

Training Delivery Method	Maximum Annual Capacity*	Quality Maintenance**	Resource Efficiency***
Traditional Classroom	2,400	4.2	2.1
Online Standardized	24,000	3.1	3.8
Adaptive Learning System	240,000	4.5	4.7
Blended Adaptive	120,000	4.8	4.2

*Estimated seafarers per year based on typical institutional capacity **Scale: 1 = Very Poor Quality, 5 = Excellent Quality ***Scale: 1 = Very Inefficient, 5 = Very Efficient

4.5 Regulatory Integration and Sustainability

The fourth theme, "Implementation Complexity," acknowledges significant challenges associated with developing and deploying adaptive learning systems in maritime education contexts. Participants identified multiple barriers including technological infrastructure requirements, faculty development needs, regulatory approval processes, and integration challenges with existing training systems.

The fifth theme, "Regulatory Integration Confidence," reflects participant assessment that adaptive learning systems can be designed to align effectively with IMO frameworks and competency requirements. Participants expressed confidence that technology-enhanced approaches could maintain or enhance compliance with international standards while improving educational effectiveness.

Table 5. Regulatory Alignment Assessment

Regulatory Dimension	Traditional Compliance*	Adaptive System Compliance**	Enhancement Potential***
IMO Competency Standards	4.1	4.4	+7.3%
STCW Certification Requirements	4.0	4.3	+7.5%
Flag State Approval	3.8	4.1	+7.9%
Industry Recognition	3.9	4.2	+7.7%
Average Regulatory Score	3.95	4.25	+7.6%

*Scale: 1 = Very Poor Compliance, 5 = Excellent Compliance **Projected compliance with adaptive learning systems ***Percentage improvement in compliance effectiveness

5. DISCUSSION

The findings of this research provide compelling evidence for the potential of adaptive digital learning management systems to transform maritime decarbonization training, while simultaneously revealing important considerations for successful implementation. The overwhelmingly positive participant assessments, reflected in the overall framework effectiveness score of 4.2 out of 5.0, align strongly with the original research questions regarding the design and implementation of adaptive learning systems for seafarer competency development.

5.1 Theoretical Implications and Literature Alignment

The analysis of competency development effectiveness reveals a striking improvement potential of 63.0% across all domains when comparing current training approaches to projected adaptive learning effectiveness. This finding directly addresses the research question

concerning how intelligent tutoring systems can be designed for green shipping technologies, with participants expressing particular optimism about the potential for adaptive systems to address complex technical competencies such as alternative fuel technologies and green port operations (Keen et al., 2021; Lacetera et al., 2023).

The identification of alternative fuel technologies as the domain with the highest improvement potential (+87.5%) underscores the critical need for personalized learning approaches in areas where traditional training methods have proven inadequate. These findings align closely with existing literature on adaptive learning effectiveness in technical education contexts, while extending research by demonstrating specific applications in maritime environmental compliance training.

5.2 Implementation Challenges and Success Factors

The cross-group comparison analysis reveals nuanced differences in perspective that provide important insights for implementation strategy development. Technical specialists demonstrated higher optimism regarding technological feasibility (4.8) but lower attention to implementation caution (3.5), while educational experts showed the opposite pattern with higher emphasis on pedagogical rigor (4.9) and greater implementation caution (4.2). This finding suggests that successful adaptive learning implementation in maritime contexts requires careful integration of technical capabilities with educational expertise.

The regulatory alignment assessment provides particularly significant insights that differentiate maritime applications from other adaptive learning contexts (Lin & Fu, 2022). The finding that participants project improved regulatory compliance through adaptive learning systems (+7.6% average improvement) contrasts with literature that often treats regulatory requirements as constraints on technological innovation. This suggests that adaptive learning systems, when properly designed, can enhance rather than complicate compliance with international maritime standards.

5.3 Scalability and Practical Implications

The scalability assessment results offer perhaps the most significant contribution to addressing the research questions regarding predictive models for seafarer learning outcomes and data-driven personalization in maritime e-learning platforms. The projected capacity increase from 2,400 seafarers annually through traditional classroom methods to 240,000 through adaptive learning systems represents a 100-fold improvement that directly addresses the scale challenge of training 1.2 million seafarers by 2030.

The thematic analysis of "Personalization Imperative" aligns with existing research on adaptive learning effectiveness in diverse educational contexts, while extending previous work by identifying specific personalization requirements in maritime professional education. The emphasis on accommodating diverse technical backgrounds, educational experiences, and learning preferences reflects the unique characteristics of the global seafarer workforce and suggests that adaptive learning algorithms must be specifically calibrated for maritime contexts.

5.4 Future Research Directions and Limitations

The research fills important gaps in existing literature by providing the first comprehensive investigation of adaptive learning applications specifically designed for maritime decarbonization training. While previous studies have explored digital transformation in maritime education generally or adaptive learning in other technical domains, this research addresses the unique intersection of environmental technology competencies, international regulatory requirements, and global workforce characteristics that characterize maritime decarbonization training.

The practical implications of these findings are significant for multiple stakeholder groups. For maritime educational institutions, the results suggest that investment in adaptive learning capabilities could substantially enhance training effectiveness while addressing scalability challenges that threaten institutional capacity to meet decarbonization training demands. For shipping companies, the improved competency development outcomes and regulatory compliance projections suggest that adaptive learning approaches could reduce compliance risks while enhancing operational effectiveness of trained personnel.

6. CONCLUSION

This research provides compelling evidence for the transformative potential of adaptive digital learning management systems in addressing the urgent challenges of maritime decarbonization training. The study reveals strong support among maritime education professionals for implementing AI-powered adaptive learning frameworks that can personalize instruction, enhance competency development, and achieve the scale necessary to train 1.2 million seafarers by 2030.

The overall effectiveness score of 4.2 out of 5.0 and projected improvement potential of 63.0% across competency domains demonstrate that adaptive learning systems offer viable solutions to current limitations in maritime education approaches. The research successfully addresses its primary objectives by demonstrating how intelligent tutoring systems can be designed for green shipping technologies, revealing opportunities for predictive models in seafarer learning outcomes, and identifying requirements for digital assessment frameworks that maintain regulatory compliance.

The thematic analysis reveals five critical dimensions for successful implementation: personalization imperative, real-time assessment integration, scalability solutions, implementation complexity management, and regulatory integration confidence. The projected capacity increase from thousands to hundreds of thousands of trained seafarers annually addresses the critical scale challenge of the decarbonization transition while maintaining educational quality and regulatory compliance.

However, the research also acknowledges important implementation challenges including technological infrastructure requirements, faculty development needs, and integration complexity with existing systems. The lower implementation readiness score (3.8) compared to other effectiveness dimensions indicates that successful deployment requires careful attention to practical considerations beyond technological capabilities.

The practical implications extend across multiple stakeholder groups, offering maritime educational institutions pathways to enhance effectiveness while managing scalability demands, providing shipping companies with improved competency assurance, and enabling regulatory bodies to maintain standards while supporting innovative educational approaches. For the broader maritime industry, the research suggests that adaptive learning systems can facilitate the workforce transformation essential for achieving decarbonization objectives while maintaining operational safety and effectiveness.

Future research should focus on pilot implementations, broader stakeholder engagement, and development of detailed technical specifications that can guide institutional adoption of adaptive learning approaches. The research establishes a foundation for continued investigation into how emerging technologies can address critical challenges in professional education within safety-critical industries facing rapid technological transformation.

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