



Transforming Maritime Education and Training Systems to Enhance Seafarers' Competence in the Digital Shipping Era: A Mixed-Methods Study

Tri Iriani Eka Wahyuni¹, Joe Alend Seniza Bokau¹, Joe Ronald Kurniawan Bokau^{1*}

¹Politeknik Pelayaran Barombong, Makassar, Sulawesi Selatan, Indonesia

*Email: joeronald.kb@gmail.com

Abstract. The rapid digital transformation of the global maritime industry has reshaped the competency requirements of seafarers and has created new expectations for Maritime Education and Training (MET) institutions. This study analyzes how MET systems can be transformed to enhance seafarer competence in the digital shipping era. An explanatory sequential mixed-methods design was employed. Quantitative data were collected from 210 respondents consisting of cadets, active seafarers, and instructors, and were analyzed using descriptive statistics and partial least squares structural equation modeling (PLS-SEM). Qualitative data from interviews, observations, and document review were used to interpret and contextualize the quantitative findings. The results indicate that digital transformation has a significant positive effect on MET transformation, while MET transformation has a stronger direct effect on seafarer competence than digitalization alone. The model explains 64% of the variance in seafarer competence. Technical and safety competence were rated highly, whereas digital competence remained at a moderate level, indicating a persistent skills mismatch between maritime education outcomes and the operational demands of technology-intensive shipping. The study further identifies a dual competency gap: experienced seafarers tend to demonstrate stronger technical and safety competence, whereas younger respondents show relatively stronger digital competence. The study proposes an integrative MET transformation model combining adaptive competency-based curricula, technology-supported learning, simulator-based assessment, instructor capacity development, and industry collaboration. These findings contribute to MET literature by positioning maritime education as the mediating mechanism through which digital transformation is converted into operational competence and global workforce readiness.

Keywords: *Maritime Education and Training; seafarer competence; digital transformation; simulator-based learning; PLS-SEM; maritime human resources*

1. INTRODUCTION

The maritime sector remains a strategic backbone of global trade, with a substantial proportion of international cargo transported by sea. This role makes seafarer competence a critical determinant of safe, efficient, and sustainable shipping operations

[1]. In parallel with this economic significance, the maritime industry is undergoing a profound technological transition. Digital platforms, artificial intelligence, the Internet of Things, big data analytics, remote monitoring, and the development of Maritime Autonomous Surface Ships (MASS) are changing how ships are operated, monitored, and managed [2], [3].

These developments require seafarers to possess a broader set of capabilities than those traditionally emphasized in maritime training. Modern seafarers are expected not only to operate machinery and navigation systems but also to interpret digital information, supervise automated systems, manage technology-supported decision making, and maintain safety under increasingly complex operational conditions [4]. Consequently, seafarer competence in the digital era should be understood as a multidimensional construct that includes technical, digital, cognitive, and safety-related dimensions.

The transformation of shipping also intersects with the sustainability agenda. Regulatory pressure related to emissions reduction, energy efficiency, and green shipping has expanded the knowledge and skill requirements for maritime personnel [5]. Digitalization and environmental transition therefore create a double challenge for MET institutions: they must preserve the foundations of safe seamanship while also preparing learners for technology-intensive and sustainability-oriented operations.

Maritime Education and Training (MET) institutions have responded to these demands through the introduction of simulators, e-learning platforms, virtual learning environments, competency-based curricula, and industry-informed training models. However, studies continue to report mismatches between MET curricula and the evolving needs of the maritime labor market [6], [7]. Many institutions still rely heavily on conventional classroom delivery, while the integration of digital learning, advanced simulation, and data-driven training remains uneven [8], [9].

The challenge is not limited to infrastructure. Instructor readiness, institutional policy, curriculum flexibility, and collaboration with shipping companies also shape whether technology can be translated into meaningful learning outcomes. Without systematic integration, technology risks becoming an add-on rather than a core component of professional competence development. Moreover, rapid technological change may generate technostress and resistance among seafarers, particularly when training systems do not sufficiently support psychological adaptation to new digital work environments [10].

This study addresses the need for a more integrated understanding of MET transformation. Rather than treating digitalization as an isolated technological issue, the study examines how digital transformation, MET system reform, and seafarer competence are interrelated. Specifically, the study seeks to answer two research questions: (1) How does digital transformation influence the transformation of MET systems? (2) How does MET transformation affect the development of seafarer competence in the digital shipping era?

2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

MET refers to the professional education and training system designed to produce competent maritime personnel through a combination of theoretical instruction, practical training, simulator exercises, assessment, and certification. MET supports safe

navigation, ship operation, emergency response, environmental protection, and professional conduct in the maritime workplace [7]. The scope of MET includes nautical studies, marine engineering, maritime management, safety and security training, and the development of non-technical skills such as leadership, teamwork, communication, and decision making.

Internationally, MET is anchored in the Standards of Training, Certification and Watchkeeping for Seafarers (STCW), which provides minimum competency standards for seafarer education, training, certification, and watchkeeping [13]. Although STCW remains essential for harmonizing global competence requirements, the pace of technological change has raised questions about whether existing standards are sufficiently responsive to digitalization, automation, and emerging shipboard roles [2], [11].

Competence is generally understood as the integrated application of knowledge, skills, and attitudes required to perform tasks effectively and safely. In maritime operations, competence has traditionally emphasized technical proficiency, compliance with safety procedures, and operational experience. However, modern shipping increasingly requires digital competence, cognitive flexibility, and the ability to supervise automated systems [4].

Technical competence includes navigation, machinery operation, cargo handling, and the practical application of maritime procedures. Safety competence involves risk awareness, emergency response, regulatory compliance, and the prevention of human error. Cognitive competence includes problem solving, situational awareness, information interpretation, and decision making under uncertainty. Digital competence includes the ability to operate electronic systems, interpret data, use digital platforms, and adapt to new technologies [3], [9].

Digital transformation in shipping changes both the operational environment and the learning environment. In ship operations, digital technologies enable real-time monitoring, integrated decision support, predictive maintenance, and smarter logistics. In education, digital tools enable flexible learning, virtual simulation, scenario-based assessment, and data-supported feedback [3], [15].

However, the presence of technology alone does not guarantee competence development. The effectiveness of digital learning depends on curriculum design, instructor capability, assessment methods, institutional support, and industry relevance [6], [8]. Therefore, MET transformation should be conceptualized as a systemic process involving adaptive curricula, technology-supported learning, simulation, instructor development, and stronger collaboration between education providers and industry stakeholders.

Previous studies have examined maritime non-technical skills, digital learning, autonomous shipping, and industry collaboration, but many remain partial in scope. A more holistic model is required to explain how digital transformation can be translated into seafarer competence through MET transformation. This study therefore proposes that MET is not merely an educational context but a mediating mechanism connecting digital industry change to competence development. H1: Digital transformation has a positive effect on MET transformation. H2: MET transformation has a positive effect on seafarer competence. H3: Digital transformation has a positive direct effect on seafarer competence. H4: MET transformation mediates the relationship between

digital transformation and seafarer competence. Table 1 presents the selected research gaps.

Table 1. Summary of Selected Research Gaps

Source	Focus	Main contribution	Limitation	Gap addressed in this study
Mallam et al. [7]	Seafarer skills	Emphasizes non-technical skills	Limited discussion of digital competence	Integrates digital, cognitive, technical, and safety competence
Ghosh [9]	MET and industry	Identifies competence mismatch	Does not develop an integrated model	Develops a transformation model
Kitada et al. [8]	Industry collaboration	Highlights education-industry linkage	Limited operationalization for digital MET	Positions collaboration as a model component
Zhang et al. [3]	Digital learning	Shows benefits of digital education	Focuses mainly on technology implementation	Links technology to competence through MET
Bogusławski [2]	Autonomous shipping	Explains changing seafarer roles	Limited connection to MET systems	Connects automation to MET reform
Gekara [6]	Digital workforce skills	Shows MET adaptation challenges	Does not test a competence model	Tests MET transformation empirically

3. METHODOLOGY

3.1 Research Design

This study employed an explanatory sequential mixed-methods design. Quantitative data were collected and analyzed first to test the proposed relationships among digital transformation, MET transformation, and seafarer competence. Qualitative data were then gathered through interviews, observations, and document review to explain and enrich the statistical findings [16].

The quantitative component used a cross-sectional survey design because the objective was to capture current perceptions of MET transformation and competence development at a particular period. The qualitative component provided contextual

insight into implementation challenges, curriculum adaptation, technology use, and industry alignment.

3.2 Participants and Sampling

The study involved 210 respondents consisting of maritime cadets, active seafarers, and instructors. Participants were selected using purposive sampling because they had direct experience with MET systems or maritime operations. For the qualitative phase, informants were selected using snowball sampling until the information obtained became sufficiently repetitive and no major new themes emerged, as shown in Table 2 and Table 3.

Table 2. Respondent Profile by Category

Category	n	Percentage
Cadets	110	52.4%
Active seafarers	60	28.6%
Instructors	40	19.0%
Total	210	100%

Table 3. Respondent Profile by Experience

Experience	n	Percentage
< 2 years	85	40.5%
2-5 years	70	33.3%
> 5 years	55	26.2%

3.3 Instruments and Data Collection

Questionnaire items were developed from the conceptual dimensions of digital transformation, MET transformation, and seafarer competence. Responses were measured using a five-point Likert scale. The instrument was piloted to ensure item clarity and initial reliability before full distribution.

Semi-structured interviews were conducted with selected cadets, seafarers, instructors, and industry-related informants. Observations focused on the use of simulators, digital platforms, classroom practices, and the interaction between instructors and learners. Document review covered curricula, training modules, institutional policies, and relevant international standards.

3.4 Data Analysis

Quantitative data were analyzed using descriptive statistics and PLS-SEM. PLS-SEM was selected because it is suitable for predictive modeling, relatively flexible with non-normal data, and appropriate for moderate sample sizes [17]. The measurement model was evaluated through indicator reliability, convergent validity, discriminant

validity, Cronbach's alpha, and composite reliability. The structural model was assessed using path coefficients, t-statistics, R-square, predictive relevance, and mediation interpretation.

Qualitative data were analyzed using thematic analysis. Coding involved identifying meaningful units of information, grouping them into categories, and developing themes related to curriculum transformation, technology integration, instructor readiness, industry collaboration, and competence gaps [18]. Trustworthiness was enhanced through triangulation of sources and methods, member checking, and systematic documentation of the research process.

4. RESULTS

4.1 Descriptive Findings

The overall profile of respondents indicates that the study captured perceptions from learners, practitioners, and educators. Cadets formed the largest group, reflecting the importance of understanding how future seafarers perceive the readiness of MET systems. Respondents also varied in experience, enabling comparison between younger and more experienced maritime personnel. Table 4 shown the competence scores.

Table 4. Seafarer Competence Scores

Competence dimension	Mean	Interpretation
Technical competence	4.12	High
Digital competence	3.65	Moderate
Cognitive competence	3.88	High
Safety competence	4.20	Very high

The results show that technical competence and safety competence were rated highly, while digital competence remained moderate. This finding suggests that conventional maritime competence remains relatively strong, but digital capabilities are not yet fully aligned with the technological demands of modern shipping. Table 5 shown the perceived effectiveness of the MET system.

Table 5. Perceived Effectiveness of the MET System

Indicator	Mean	Interpretation
Competency-based curriculum	3.75	Good
Learning methods	3.60	Fair
Technology use	3.45	Fair
Simulator facilities	3.90	Good

The MET system was perceived positively in terms of curriculum and simulator facilities, but technology use and learning methods were only rated as fair. Gap analysis

indicated that the largest difference between expected and perceived conditions occurred in technology integration, followed by learning methods and curriculum implementation. This suggests that MET reform may be adequate in design but less mature in practical implementation.

4.2 Structural Model Result

The PLS-SEM results support the proposed relationships. Digital transformation had a positive effect on MET transformation, indicating that technological changes in the maritime industry create pressure for educational reform. MET transformation had the strongest direct effect on seafarer competence, suggesting that education and training systems play a central role in converting technological change into practical competence. The model explained 64% of the variance in seafarer competence, which indicates substantial explanatory power for a behavioral and educational model as shown in Table 6.

Table 6. Structural Path Coefficients

Path	Coefficient	t-statistic	Result
Digital transformation -> MET transformation	0.68	8.45	Significant
MET transformation -> seafarer competence	0.72	9.10	Significant
Digital transformation -> seafarer competence	0.55	6.20	Significant

The findings also support a partial mediation interpretation. Digital transformation can influence competence directly, but its stronger and more sustainable effect occurs through the transformation of MET systems. This means that digital technologies do not automatically produce competent seafarers; rather, competence emerges when technologies are embedded in curricula, learning scenarios, assessment, and institutional practice.

4.3 Qualitative Findings

The qualitative findings support the quantitative results in three main ways. First, respondents described curriculum transformation as ongoing but incomplete. Digital topics have been introduced, yet they are often treated as supplementary rather than structurally embedded in competence-based learning. Second, respondents emphasized the importance of simulators for bridging theory and practice, particularly for emergency scenarios, navigation decision making, and the reduction of operational learning curves. Third, instructors and industry respondents highlighted the need for stronger collaboration so that learning outcomes reflect current shipboard technology and operational procedures. Table 7 shown maturity levels.

Table 7. Technology Maturity Levels in MET Implementation

Level	Description
Level 1	Traditional system with minimal technology use
Level 2	Technology used as a learning support tool
Level 3	Technology integrated into curriculum, learning, and assessment
Level 4	Fully digital, data-supported, and adaptive MET ecosystem

Most institutions represented in the study appear to be between Level 2 and Level 3. They have adopted certain technologies, particularly simulators and e-learning platforms, but integration remains uneven. A fully digital MET ecosystem would require data-supported learning analytics, performance-based simulator assessment, instructor development, and sustained industry input.

5. DISCUSSION

The findings confirm that MET transformation is a key mechanism for improving seafarer competence in the digital shipping era. While the maritime industry may introduce advanced systems rapidly, the competence of seafarers depends on how effectively education and training institutions translate these systems into learning outcomes. This supports the argument that technology must be pedagogically and institutionally integrated rather than merely provided as equipment [3], [6].

The moderate level of digital competence is an important warning for MET institutions. High safety and technical scores indicate that traditional training strengths remain valuable, but they must now be complemented by digital literacy, data interpretation, automation supervision, and system-thinking capabilities. This result is consistent with the changing role of seafarers from manual operators to supervisors of integrated cyber-physical systems [2], [4].

The study also identifies a dual competency gap. Experienced seafarers tend to have stronger practical, technical, and safety competence, while younger respondents show stronger familiarity with digital tools. This gap should not be interpreted as a weakness of either group. Instead, it indicates the need for intergenerational learning models in which practical seamanship and digital fluency are deliberately integrated. Mentoring, simulator-based collaborative tasks, and scenario-based learning can support this integration.

The role of simulators is particularly significant. Simulator-based learning allows learners to experience complex, high-risk, and emergency situations without exposing actual vessels or crews to danger. However, the value of simulators depends on scenario design, frequency of use, instructor competence, and performance-based assessment. Without these elements, simulators may become demonstration tools rather than transformative learning instruments [19].

The results have implications for regulators, maritime institutions, and shipping companies. Regulators should support digital competence standards and infrastructure development. MET institutions should redesign curricula around integrated competence outcomes, not simply add digital topics. Shipping companies should

participate more actively in curriculum review, simulator scenario development, internships, and competence assessment so that training remains aligned with operational realities.

6. PROPOSED INTEGRATIVE MET TRANSFORMATION MODEL

Based on the empirical findings and literature synthesis, this study proposes an integrative MET transformation model. The model positions MET as an ecosystem connecting curriculum, technology, instructors, learners, industry, and regulatory standards. Its core assumption is that competence development requires alignment between what is taught, how it is taught, how it is assessed, and what the industry actually requires. The proposed model for MET transformation can be seen in the Table 8.

Table 8. Proposed Model for MET Transformation

Component	Conventional system	Transformed MET system
Curriculum	Theory-oriented and content-heavy	Competency-based, digitally integrated, and industry-informed
Learning method	Teacher-centered lectures	Blended, problem-based, simulator-supported, and scenario-based learning
Competence focus	Basic technical competence	Integrated technical, digital, cognitive, and safety competence
Assessment	Written examinations	Performance-based assessment using simulation and practical tasks
Technology	Limited and supplementary use	Embedded e-learning, simulator, analytics, and AI-supported systems
Instructor role	Primary source of knowledge	Facilitator, mentor, assessor, and learning designer
Industry role	Occasional involvement	Continuous collaboration in curriculum, training, and assessment
Learning orientation	Static qualification model	Lifelong learning and continuous professional development

The proposed model has four main contributions. First, it integrates educational, technological, and industrial dimensions in one framework. Second, it aligns MET development with global competence expectations and STCW-based safety principles. Third, it recognizes digital adaptation and technostress as human-factor issues rather than purely technical issues. Fourth, it provides a practical basis for curriculum development, policy formulation, and future empirical testing across maritime education institutions.

7. CONCLUSION

This study examined the transformation of Maritime Education and Training systems and their effect on seafarer competence in the digital shipping era. The findings show that digital transformation significantly influences MET transformation and that MET transformation has a strong positive effect on seafarer competence. The results also indicate that MET partially mediates the relationship between digital transformation and competence development.

Technical and safety competence remain strong, but digital competence is still moderate. This demonstrates that maritime education must move beyond conventional training models and adopt a more integrated approach that combines adaptive curriculum design, technology-supported learning, simulator-based assessment, instructor capacity building, and industry collaboration.

The proposed integrative MET transformation model offers a practical and theoretical contribution for strengthening seafarer readiness in a rapidly changing industry. Future research should test the model across different maritime institutions and countries, use longitudinal designs to assess competence development over time, and examine additional factors such as organizational culture, leadership, policy support, and learner motivation.

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