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Original Paper

Navigating the Digital Tide: Drivers, Key Factors, and Challenges in Maritime Education and Training for the Digital Era

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Abstract

Digital transformation (DT) is fundamentally reshaping the maritime industry, where the critical bottleneck has shifted from technology availability to human capital readiness. Despite extensive attention to maritime technology, systematic investigation into the digital transition of Maritime Education and Training (MET) remains underdeveloped. Here, we conduct a comprehensive systematic literature review employing the Technology-Organization-Environment (TOE) framework to identify and structure the drivers, key factors, and challenges underpinning MET digitalization. Analyzing 101 publications from five major academic databases (2015–2025) alongside supplementary sources, we identify 7 drivers, 11 key factors, and 9 challenges. Our analysis reveals that while technological advancements initiate digitalization, organizational capabilities (digital leadership, departmental collaboration, dynamic training objectives) and environmental conditions (policy support, career planning, ecological pressure) predominantly determine transformation effectiveness. Critical barriers including conservative educational models, difficulty in quantifying digitalization outcomes, and uneven distribution of digital resources transcend purely technical solutions. These findings demonstrate the necessity of a fundamental paradigm shift from technology-centric to people-oriented approaches in MET transformation. We propose an integrative analytical framework that prioritizes seafarer career development and cognitive skill cultivation, providing structured guidance for future scholarly research and institutional planning in navigating MET's digital transition toward a sustainable maritime future.

Keywords

Maritime Education and Training (MET), Digital Transformation, Digital Era, Drivers, Key Factors,

Challenges, TOE Framework

1. Introduction

Digital transformation (DT) is now among the strongest forces shaping economic systems globally [1-4]. Maritime industry that carries over 80% of global trade, a key pillar for international economy, is being impacted by this digital wave [5,6]. Once thought of as conservative with an aversion for new technologies, the industry has undergone a transformation towards digital integration driven by increasing demands around efficiency, safety, sustainability, and regulatory compliance [7,8]. With rapid advancements in technology, the main barrier preventing its effective use is not a lack of access to technology, it's a matter of preparing and equipping our workforce for operation within such digital environments [9,10]. The modern mariner is expected to combine traditional nautical skills with digital competencies such as data driven decision making, cybersecurity literacy, and collaborating effectively with automated or intelligent systems [11,12]. The growing capability gap puts Maritime Education and Training (MET) in the heart of the transformation of the maritime industry, where it is not only a limitation but also an essential enabler for successful digital implementation [13].

The MET includes diverse types of learning: from formal degrees provided at maritime universities or academies; to vocational training provided in special centers; certification paths, competency based assessments and continuous professional development (CPD), which promote lifelong learning during one's maritime career [14]. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), first adopted in 1978 and amended on several occasions—forms the basis of international regulation of MET with defining minimum competency requirements for seafarers in all signatory states [15]. Although influential in scope, the STCW framework (including the 2010 Manila Amendments) has failed to keep up with the fast moving competency demands of digital transformation [16,17]. Emerging critical skills (e.g., data literacy; interpreting algorithmic outputs; managing human–machine interfaces; cybersecurity competence; operating remote/shore based control systems) are only partly or indirectly represented in current competency tables [18].

The notion of the "Digital Era in MET" encompasses two interrelated yet analytically distinct dimensions that must be clearly articulated. The first concerns the need to cultivate maritime professionals equipped with the digital competencies required by an increasingly technology-driven maritime industry. The second dimension pertains to the internal digital transformation of MET institutions themselves, which involves modernizing governance structures, administrative workflows, pedagogical practices, assessment systems, and quality assurance processes [19,20]. Although these dimensions influence one another, they do not necessarily evolve in parallel. An institution may integrate digital teaching technologies without adequately preparing students for digitally intensive maritime workplaces; conversely, programmers may emphasize digital competencies while retaining outdated instructional or organizational models.

Research into maritime digitalization and automation has increased significantly in the last decade as technology changes accelerate within the sector. The research covers various themes ranging from using AI and machine learning for navigation support or collision-avoidance systems, predictive maintenance [21–23]; integration of IoT-enabled sensing technologies and big data analytics for enhanced vessel performance monitoring and operational optimization [20,24]; the progression of autonomous and remotely controlled ships [25,26]; as well as the rise of digital platforms and shared data infrastructures that aim at enhancing maritime logistics and supply-chain coordination [9,27]. Other works investigated the technical foundations of e-Navigation architectures, the application of blockchain in document handling and cargo visibility as well as increased cybersecurity threats due to increasing connectivity in maritime systems [28]. However, an interesting trend emerges in all these contributions; despite considerable focus on technological innovations and regulatory developments there is little systematic work done regarding how maritime digitalization transforms competency frameworks and the skills needed by the future workforce.

MET has built up a significant amount of scholarly literature that examines fundamental pedagogical practices and institutional processes. There has been considerable focus placed upon curriculum development and competency based education (CBE) with many studies which examine how MET programmers articulate their learning outcomes, map curricula to the STCW framework and assess the achievement of prescribed competencies [3,12]. Another well established research stream is simulator based training where there has been a lot of work in terms of fidelity of simulators, transfer of learning, scenario construction as well as reliability of simulation based competency assessment [29,30]. The research into quality assurance and accreditation also looked at ways in which MET institutions ensure that they comply with international regulatory standards, whilst maintaining consistent and robust training provision [19,31].

More recently, digital learning technologies have become a prominent focus within MET scholarship. Investigations of virtual reality (VR) and augmented reality (AR) have highlighted their potential to deliver immersive learning experiences and support the development of practical skills and knowledge retention [18,32]. The rapid expansion of online and blended learning—accelerated by the disruptions caused by the COVID-19 pandemic—has also generated significant research interest, prompting MET institutions around the world to adopt digital and remote learning strategies on an unprecedented scale [7,33]. Studies examining learning management systems, massive open online courses (MOOCs), and mobile learning applications have expanded understanding of how digital platforms can support maritime education [34].

Although there are many advances in this area, one enduring problem is that most of this research focuses on the effectiveness of particular tools or pedagogical innovations within existing institutional structures; therefore, our understanding about what MET institutions need to do to reorganize, adapt, and transform at an institutional and systemic level to address the needs of the digital era remains relatively underdeveloped.

An emerging body of literature has begun to outline the digital competency requirements for maritime professionals in increasingly technology-intensive operational environments. However, these contributions remain largely fragmented and have not yet converged into a coherent or comprehensive competency framework. Several scholars emphasize data literacy—particularly the ability to interpret, evaluate, and use data generated by sensor-rich maritime systems—as a foundational competence in digitalized shipping [18]. Knowledge and skills in cybersecurity are also considered vital due to increased vulnerabilities of interconnected ships, ports, and maritime infrastructures against cyberattacks [8,35]. Although such contributions exist, there are inconsistencies in terms used for describing maritime digital competencies as well as different categorizations without standard descriptors or assessment criteria.

Our previous analysis identifies multiple interconnected gaps in the existing literature which form the basis of our study's rationale: (1) While there is increasing interest on maritime digitalization[8,35] and digital transformation in general education domains [36,37], we lack any comprehensive and systematic review focusing exclusively on the digital transformation of MET. There exists no synthesis of the drivers, key success factors, and challenges shaping MET's transition into the digital era; (2) Current research rarely addresses MET digitalization as a dual layered phenomenon – while the development of digital competencies for maritime operations and internal digital transformation of MET institutions are usually treated separately with little regard to their interdependency. To understand MET's digital evolution it is necessary to integrate both aspects instead of considering them as independent or unrelated issues; (3) Although many scholars have identified emerging digital competency needs, we lack an operationalized and consistent set of competency classifications and assessment metrics cutting across technological domains, occupational categories, and levels of seniority; (4) Much of the existing literature is descriptive and backward looking providing little guidance on what future evolution of MET systems should look like over the next decade.

In order to fill in such gaps, we conduct a systematic literature review which aims at identifying and synthesising the drivers, key factors and challenges related to MET's digital transformation. In addition, our study will propose an integrative analytical framework for academics as well as practitioners' decision-making. Specifically, we are interested in answering the following questions:

RQ1: What drivers are propelling the digital transformation of MET?

RQ2: What key factors enable MET institutions to adapt effectively to the digital era?

RQ3: What challenges impede the digital transformation of MET?

The rest of this paper is structured as follows: In section 2 we explain in detail our systematic review methodology (searches, inclusion/exclusion criteria) and analysis techniques; Section 3 contains the empirical results concerning the identified drivers, key factors, and challenges related to MET digitalization. Section 4 draws on those findings, elaborates an integrative framework, proposes forward-looking scenarios and discusses their implications for policy, institutional practices and future research. Finally, Section 5 closes the paper by summarising its main contributions and acknowledges its limitations.

2. Methodology

A systematic literature review was conducted to deepen understanding of digitalization trends in MET and to identify the research factors relevant to MET. The overall methodological design is presented in Figure 1. 5 major academic databases—Web of Science, SpringerLink, IEEE Xplore, ScienceDirect and Google Scholar—served from 2015-2025 as the primary sources of data. Searches were performed using a series of targeted keyword combinations, including:

• Digitalization AND maritime

• Digitalization AND education

• Digitalization AND maritime education

• Digitalization AND maritime training

• Digitalization AND maritime education and training

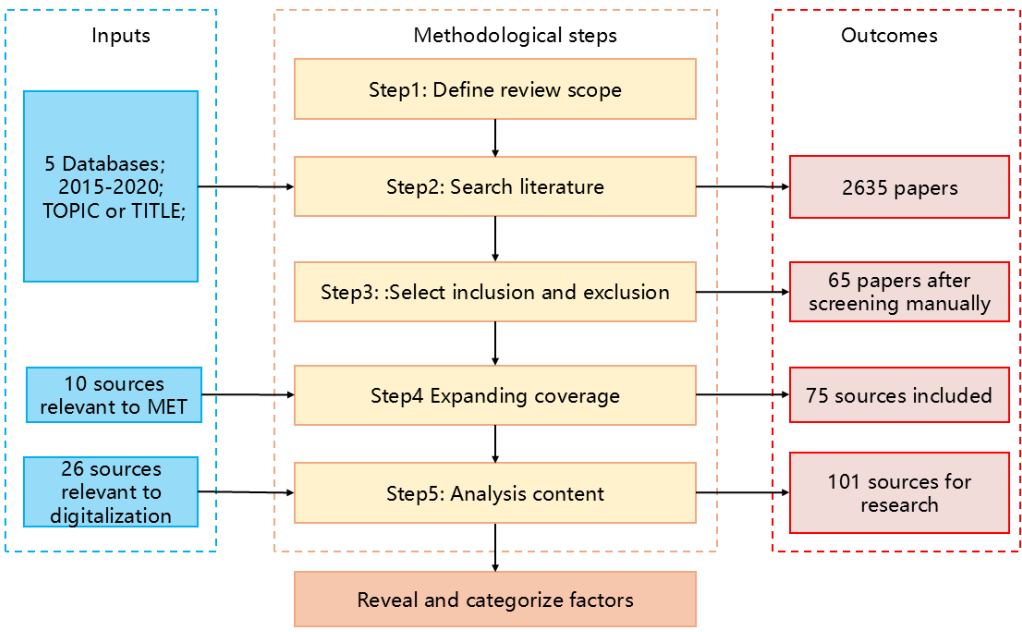

Figure 1. The Flowchart of Methodology

Both "Topic" and "Title" fields were used as inclusion criteria. 65 publications meeting both condition and demonstrating relevance to the research objectives were retained for further examination. In parallel, 15 additional materials only relevant to MET and 26 sources only relevant to digitalization were reviewed to fill conceptual or contextual gaps not fully covered by the initial search. The final dataset comprised 101 core documents.

2.1 Inclusion and Exclusion Criteria

Scope for the literature review is guided by clear inclusion/exclusion criteria. Due to a small amount of direct studies addressing the digitalization of MET we have extended our search to other areas such as MET and the wider digital maritime sector which allowed us to gather valuable insights (although not directly focused on digital of MET) contributing in an important way towards understanding its digital transition.

2.2 Sources Used in the Study

In order to better close the research gap for MET scholarship, we used various sources beyond traditional journal articles and conference papers; our final corpus comprised books, doctoral/master's theses, editorial commentaries as well as institutional/industry reports that provide different views on MET digitalization. We present a complete list of all source categories in Table 1.

Table 1. Sources Used in the Research

Sources from database		**Additional sources**	
Journal papers	36	Journal papers	25
Conference papers	10	Conference papers	5
Dissertations	2	Dissertations	2
Doctoral or master’s theses	2	Magazine articles	1
Editorial commentaries	7	Official Web Pages	3
Books	2		
Working papers	3		
Report	3		
Total	65		36

2.3 Analysis of the Identified Literature and Other Sources

The initial stage of analysis concentrated on academic publications that included the terms “digitalization” and “maritime education and training (MET)” within their titles or topics. In alignment with the study’s objective of identifying drivers, key factors, and challenges, a detailed content analysis was conducted on the selected documents. Targeted searches using the keywords “driver(s),” “key factor(s),” and “challenge(s)” helped guide the coding and extraction of relevant information.

Once we isolated those core components, we then reviewed various illustrative case studies in order to explore the wider significance of MET digitalization. We collected additional insight from relevant online resources as well as professional materials on MET's digitalization practices. In addition to this, for richer context, we also looked at supplementary scientific literature within the maritime transport sector (even if our search terms did not appear), so that we could capture adjacent developments affecting MET's digital transformation.

3. Result

The present study aims at identifying the drivers, key factors, and challenges underlying the digital transformation of MET by means of an extensive systematic literature review. A structured taxonomy comprising 7 drivers (2 technological, 3 organizational, and 2 environmental); 11 key factors (2 technological, 6 organizational, and 3 environmental); and 9 challenges (4 technological, 2 organizational, and 3 environmental) was developed based on the TOE framework for a holistic and multidimensional understanding of MET digitalization.

3.1 Drivers

Drivers can be understood as either internal or external stimuli which trigger, start or speed up changes in MET systems. From our systematic literature review we have identified 7 different drivers. We synthesize these factors by analyzing 76 relevant sources into a table (Table 2).

Table 2. Drivers of DT in MET

NO	Categories	Description	Sources
1	Drivers related to technologies	**Emergence of technologies (58)** = Unification of technologies that breaks the boundaries between the physical, digital, and biological worlds	[11,12,18,19,21,32,34,38,38–88]
2		**Maturation of technologies (38)** = Increased technical readiness and economic feasibility of systems making them relatively cheaper, more compact, portable, and accessible than traditional tools	[11,12,18,21,38,40–43,47–55,57,58,60–62,64,66,67,69–71,74,75,78,80,81,83,85–87]
3	Drivers related to organization	**Job requirements (27)** = The changes in the field of seafarers' jobs brought by digitalization	[11,12,19,21,34,38,41,42,45,47,48,50,52,53,55,62,63,66,68,69,74,81,83,86,87,89,90]
4		**Efficiency improvement (16)** = Reducing costs and emissions and optimizing vessel performance through the implementation of digital technologies	[34,39,42,43,50,53,59,64,65,68,73,76,87,88,90,91]
5		**Spatial constraints (7)** = Relating to the ship as a closed working and living environment far from shore	[49,64,73,76,84,87,92]

6	Drivers related to environment	**Policy promotion (9)** = The mandatory international and regional regulatory frameworks that drive the continuous need for training updates and operational compliance	[39,61,64–66,87,89,91,93]
7		**Market competition (9)** = Socio-economic and labor market pressures arising from globalization and competition	[34,38,45,46,60,64,73,87,94]

Technological drivers encompass 2 primary elements: **Emergence of new technologies** and **Maturation of technologies**. MET is currently undergoing a significant period of transition as Maritime 4.0 technologies become increasingly embedded across the sector [49]. Researcher Tijan mapped the expanding technological landscape in maritime transport and highlighted 8 major digital domains, including autonomous systems, AI, Big Data, VR, AR, IoT, cloud platform [95]. Autonomous navigation and AI are developing rapidly and are widely viewed as pivotal to MET's future direction (**Emergence of new technologies**) [77]. At the same time, the continued maturation of VR, AR, IoT, and cloud technologies has expanded their applicability within MET [18]. Unlike traditional full-mission simulators, these emerging tools offer advantages such as lower cost, smaller physical footprints, greater mobility, and improved accessibility—features that collectively support new models of distributed, flexible, and ubiquitous learning (**Maturation of technologies**) [87].

The main organizational drivers include: **Job requirements**, **Efficiency improvement**, and **Spatial constraints**. According to researcher Matt, DT triggers fundamental changes in business processes, organization structure, and management approach across industries [2]. This can be seen in the changing competency needs related to digital maritime work within MET, thus requiring an institution's restructuring and curriculum redesign (**Job requirements**). **Efficiency improvement** as one of the key drivers of digital transformation, reflected in our findings; MET institutions adopt digital technology to enhance their training effectiveness, streamline their learning process, and maximize utilization of limited resources [4]. **Spatial constraints** represent a unique driver in the maritime industry wherein traditional face to face instruction presents considerable logistical, time, and financial challenges to institutions and seafarers alike. Digital platforms overcome such constraints through flexible, location independent learning, transforming the operational landscape of MET and allowing it to serve diverse and geographically dispersed learners [85].

Environmental drivers include **Policy promotion** and **Market competition**. The STCW Convention – and its subsequent amendments – has been the main international regulation that governs seafarer training over many years [40], while the latest review in 2020 added specific provisions regarding digital competencies as it was necessary to adjust training requirements according to advances in maritime technologies [51]. Meanwhile, the IMO's revision of the 2023 Greenhouse Gas (GHG) Strategy, mandating a 40% reduction in carbon intensity by 2030 and aiming at net zero emissions by 2050, adds further pressure to the industry to improve the quality and relevance of MET (**Policy promotion**) [12]. However, ongoing difficulties within the global seafarer labor market characterized by decreasing number of workers and high turnover rate amongst experienced personnel intensifies competition for skilled maritime professionals [65] forcing MET institutions to deliver graduates with advanced digital and operational competencies but also to increase the attractiveness of maritime careers. Improving talent development pipelines and enhancing the perceived value of maritime work are now crucial aspects of MET's strategic response to both regulations and market demands (**Market competition**) [48].

3.2 Key Factors of Digitalization in MET

Key factors: The fundamental conditions for effectively digitalizing MET. A total number of 11 factors was identified based on our systematic review; 80 relevant sources are summarised in Table 3.

Table 3. Key Factors of DT in MET

NO	Categories	Description	Sources
1	Key factors related to technologies	**Integrate ICT technology with maritime scene（11）** = Elements of ICT are matched with real maritime scenarios to support the digital transformation, thereby improving operational efficiency, safety and sustainability	[12,42,43,46,54,64,65,72,77,81,96]
2		**Match practical tools with pedagogical methods（15）** = MET institutions must use technical tools as supplements and auxiliary tools to traditional methods, adapting to teaching methods and learning objectives to support experiential and interactive learning	[12,19,40,41,43,45,48,52,53,56,58,59,65,71,96]
3	Key factors related to organization	**Departmental collaboration（11）** **=** Designing, developing, and integrating new digital applications and curricula with industry and regulatory organizations to share knowledge and resources and bridge theory and industry demands.	[12,38,39,44,47,49–51,55,57,89]
4		**Traceable teaching system（5）** = Enhance the quality of MET through the collection and	[18,34,75,83,90]

		management of student progress data, facilitating ongoing	
5		**Dynamic training objectives**（7） = Adapting quickly to technology and talent needs in Industry 4.0 and avoiding outdated curriculum content in practice.	[44,45,48,56,58,91,92]
6		**Digital leadership**（8） = Digital thinking and capabilities that adapt to the shipping industry's digital and develop practitioners' post-digital leadership skills.	[40–42,44,45,48,56,91]
7		**Communication skills**（13） = Key bridges - language or non-verbal skills used for cross-cultural adaptation, coordination, teamwork, and problem-solving in restrictive environments	[52,68–70,80,81,83,85,90,94,97–99]
8		**Maritime experience**（4） = The practical knowledge and abilities acquired while serving in ships industry.	[32,73,78,80]
9	Key factors related to environment	**Policy support**（4） = Strategic, flexible, and forward-looking regulatory frameworks, recommendations, and economic incentives from states and international organizations like the IMO and UN	[11,38,39,63]
10		**Career planning**（4） = Considering economic, family, and work pressures and enabling seafarers to establish clear career advancement tracks and sustain continual training	[58–60,65]
11		**Ecological Pressure**（2） = Ship activities create pollution and carbon dioxide emissions that hurt marine ecosystems and the environment.	[12,91]

Technological key factors consist of 2 essential elements: **Integrate ICT technologies with maritime scene** and **Match simulated tools with pedagogical methods**. **Integration ICT with maritime scenarios** requires that digital tools be embedded within realistic maritime contexts rather than adopted as generic instructional add-ons. This emphasis aligns with findings from VR and AR research in MET [13,32,42,46], which consistently show that immersive technologies are most effective when they accurately mirror real-world operational settings and are tightly coupled with established training workflows. Equally important is **Match practical tool with pedagogical methods**. When sophisticated simulators are inserted into traditional, lectured driven teaching models without corresponding pedagogical adaptation, their capacity to enhance learning is significantly diminished. Effective simulation-based training therefore requires deliberate instructional planning, clear learning outcomes, and integration with competency-based assessment strategies [21,96].

Key organizational factors include: **Departmental collaboration**, **Traceable teaching system, Dynamic training objectives**, **Digital leadership**, **Communication skills**, **Maritime experience**.

Factors of **Departmental collaboration** and **Traceable teaching systems** illustrate that institutional integration is key to MET's digital transformation. Digitalization does not happen by isolated technology uptake from individual departments but rather calls for **Departmental collaboration** between all academic divisions, training centers, simulation units, and administrative services [43,50,71]. **Traceable teaching systems** – capable of tracking learning trajectories, monitoring competency development, and enabling data-driven refinement – are foundational to such interconnectedness. This resonates with the emphasis on organizational integration as a fundamental condition for successful digital transformation across sectors by Verhoef [3].

The dynamic nature of **training objectives** is critical. Moving beyond seafaring roles, there are now various career paths including shore-based maritime data analysts, intelligent vessel system maintenance engineers, and maritime cybersecurity specialists—digitalization constantly spawns new job profiles. Consequently, curricula must evolve not just with technological advancement or regulatory update, but also to meet an expanding demand for a broader set of skills required across this expanded range of occupations [19,81,83]. A similar view can be found within competency-based education (CBE) frameworks which are highlighted in MET literature [14]: Programming fundamentals for data analysis; Maritime cybersecurity protocols to protect interconnected vessel systems; Interdisciplinary collaboration skills: all these have become non-negotiable requirements.

The significance of **Digital leadership, Communication skills, Maritime experience** within MET correspond closely with insights from the broader digital transformation literature. **Digital leadership** and **Communication skills** represent an evolution of traditional competencies: they require upgrading conventional leadership and communication frameworks to adapt to digital collaboration scenarios and technology-driven decision-making processes [45,100]. Notably, **Maritime experience** retains irreplaceable value even in the digital age; the unique nature of maritime operations—characterized by complex and unpredictable marine environments—means that practical experience remains critical to ensuring operational safety and economic efficiency, which cannot be substituted by digital technologies alone [62].

The environmental key factors include 3 major components: **Policy support, Career planning, and Ecological pressure**. The **policy support** provided by the IMO and national maritime administrations sets the regulatory expectations and funding signals for institutional priorities. Without a clear policy direction and adequate financial mechanisms, there are significant challenges faced by MET institutions when pursuing digital transformation [67,74].

Another prominent organizational element specific for digital era seafarer's distinct generations, especially Generation Z (Gen Z) maritime professionals, are **career plans**. The Gen Z seafarers emphasize work-life balance (strong focus on family connectivity), seamless digital access, and personal career advancement – all elements that characterize their career expectations in the digital age. In order to meet these preferences, MET institutions have two options: design training systems according to this preference or establish robust and transparent career planning frameworks which link digital skills acquisition with defined progression paths ranging from entry level roles up to specialized digital maritime positions. Integration of attraction and development via generation-specific career support is not only a recruitment tool, it is a defining characteristic when nurturing digitally competent seafarers who will thrive in an ever-changing maritime ecosystem [60,76].

Meanwhile, intensifying **Ecological pressures** embodied are transforming MET's curricular content and strategic focus: a move towards alternative fuels, enhanced vessel energy efficiency, and compliance with ever stricter environmental regulations require new technical and operational expertise [93,98].

3.3 Challenges of Digitalization in MET

From our literature review we identify several challenges hindering the digitalization of MET: Overall there are 9 challenges (4 technological; 2 organizational; 3 environmental) which can be found in Table 4.

Table 4. Challenges of DT in MET

NO	Categories	Description	Sources
1	Challenges related to technologies	**High cost（20）** = Acquisition and maintenance of digital technologies, including full mission simulators, virtual reality systems, modern classrooms, the Green Digital Shipping Corridor (GDSC), and crew training, necessitate significant capital investment.	[11,12,19,38,41,43,44,46,47,49, 52,54,56,57,59,61,63,67,71,100]
2		**Cybersecurity risks（6）** = External malicious intrusions, digital attacks, or cyber	[73,75,76,79,96,98]

		threats, supply chain disruptions, damage to critical operations, substantial economic losses, and technical disasters.	
3		**Technological iteration**（5） = Evolving, and updated to maintain the sustainability and efficacy of digital tools.	
4		**Inconsistent framework**（4） = The lack of unified regulatory strategies, standardized structures, and theoretical and methodological agreement	[51,54,56,57]
5	Challenges related to organization	**Conservative education model**（4） = The model that inflexibility and unable to adapt the rapid changes	[85,86,88,90]
6		**Difficulty of quantifying digitalization**（7） = Non-technical indicators must deal with subjective evaluations, which are imprecise and unclear and may limit explanations for outcomes fluctuation.	[39,40,42,45,48,89,92]
7	Challenges related to environment	**Uneven distribution of digital resources**（13） = Remote learning options and education quality vary by country and region due to resources, technology, and access disparities.	[46,47,52–55,57,58,60–62,91,92]
8		**Insufficient trust within the industry**（6） = Encompassing both untrust in technology and interpersonal	[81,82,84,86,94,99]
9		**Cultural differences**（10） = diverse backgrounds in their daily living and working habits	[32,68–73,75,76,97]

The technological challenges include **High costs, Cybersecurity risks**, **Technological iteration**, and **Inconsisitent frameworks**. **High cos**t continues to be a primary concern, consistent with Gausdal's emphasis on financial burden being one of the main impediments for digital transformation within the maritime sector [27]. Procurement, operation, and maintenance of advanced simulation systems and digital infrastructure requires significant long term investment; many MET institutions – particularly those located in resource constrained regions – struggle to mobilize sufficient funds [32,38,52]. **Cybersecurity risks** are becoming an increasing concern as MET institutions embrace more connected and data driven systems. Kessler emphasized the growing attack surface across maritime digital infrastructures, and MET has similar vulnerabilities embedded into their learning management platforms, simulator networks, and repositories of sensitive student information [101]. Challenges associated with **Technological iteration** and **Inconsistent frameworks** complicate digital transformation. Emerging technologies can change within months whereas the MET curricula often take years before undergoing comprehensive revisions [67,87]. This temporal gap leads to chronic curriculum obsolescence where graduates do not necessarily possess the competencies required to operate in the digitally advanced maritime environments that they enter. There exists a fragmented standard, incompatible system, and lack of interoperability within the current ecosystem of maritime technologies.

Organizational challenges: **Conservative educational models**, and **Difficulty of quantifying digitalization**. MET institutions with long standing maritime traditions and strong regulatory compliance cultures are particularly susceptible to this kind of conservatism which makes it harder to transform pedagogy [73,80,94]. Lack of robust assessment metrics complicate curriculum design, hinder quality assurance processes, and create uncertainty about training outcomes (**Conservative educational models**). A deeper structural conflict remains as well between the STCW Convention's minimum standards paradigm vs. cultivating forward looking, dynamic competency frameworks in MET institutions (**Difficulty of quantifying digitalization**) [54,68,102].

Environmental challenges: **Uneven distribution of digital resources**, **Insufficient trust within the industry,** and **Cultural differences**. **Uneven distribution of digital resources** has an adverse effect on seafarers from developing countries that constitute a large part of the global maritime workforce; they often have access to training institutions lacking technological capacity [53,63,84]. **Insufficient trust within the industry** is characterized by untrust in technology and interpersonal trust within digital environments. Lack of intentional effort to build technological and interpersonal trust may result in resistance towards digital tools and reduced operational effectiveness in highly automated maritime environments [69,70]. **Cultural differences** arise due to the inherent multinational nature of maritime crew and underscore the importance of culturally adaptable approaches within MET. Progoulaki and Theotokas [103], provide examples of how cultural diversity impacts communication patterns, decision making styles, and interpersonal dynamics on board which give rise to misunderstandings or coordination difficulties. Such differences also affect engagement with digital systems as well as each other in technologically mediated environments.

4. Discussion

The objective was to thoroughly identify the drivers, key factors, and challenges associated with the digital transformation of MET using TOE framework. A structure categorization comprising of 7 drivers, 13 key factors, and 9 challenges has been identified (Figure 2). Although we have categorized and described them in our Results section; here in discussion part we will go for an in-depth analysis from the three main aspects of the TOE framework – technology, organization, and environment.

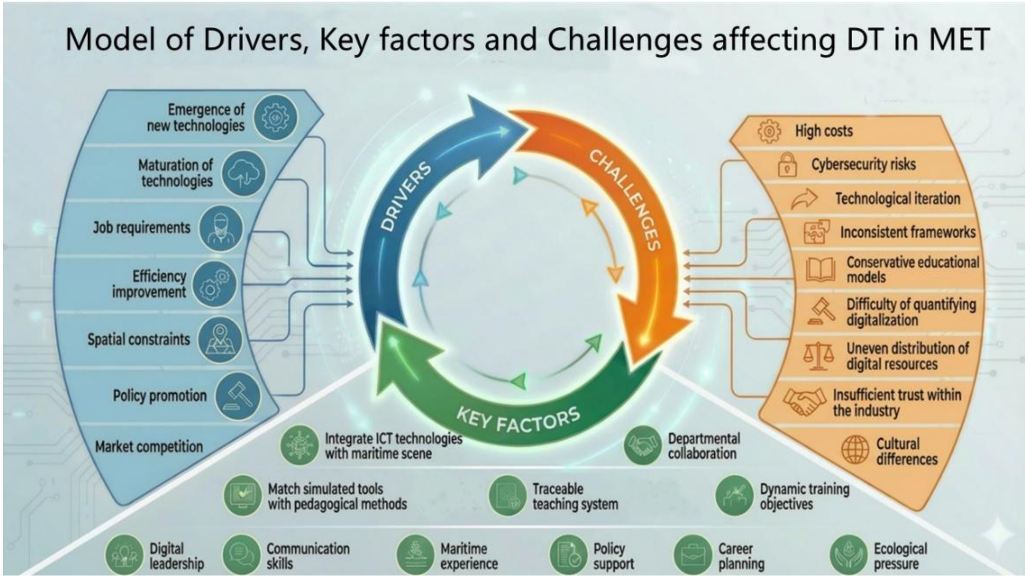

Figure 2. Model of Drivers, Key Factors and Challenges Affecting DT in MET

4.1 Technological Factors of MET Digitalization

Technological Dimension of MET Digitalization includes 2 drivers, 2 key factors, and 4 challenges that together represent the complexity of technology's role during this transformation. The maritime sector today sees an ongoing development and maturing of Maritime 4.0 technologies; this technological evolution profoundly impacted the cultivation of traditional maritime skills – the paradigm shift from manual operation to intelligent decision making, and from experience-based judgment to data-driven analysis has disrupted the longstanding model for seafarer training, transforming the industry worldwide inevitably.

Notably, the value of these technologies in MET is not inherently determined by their technical sophistication, but hinges on two core prerequisites: **Integrate ICT technology with maritime scene** and **Match practical tools with pedagogical methods**. Failure to meet these prerequisites may amplify the identified technological constraints—such as **High costs**, **Technological iteration** leading to curriculum obsolescence, **Cybersecurity risks**, and **Inconsistent framework**—ultimately hindering rather than advancing the sector's digitalization[59,67,91].

In sum, there is dualism in the technological aspect; on one hand, it acts directly as a driver to overcome traditional training limitations but also presents inherent risks which can hamper progress. The need for targeted governance and rational use emerges from this duality: MET institutions should adopt selectively new technologies, focus their attention on compatibility with professional needs, create adaptable systems to face technological changes, thus maximizing the transformative value of technology while minimizing its possible drawbacks.

4.2 Organizational Factors of MET Digitalization

In contrast to the technological aspect providing an external impetus, organizational factors (consisting of 4 drivers, 6 key factors, and 2 challenges) are a core determinant for the direction, pace, and quality of MET digitalization—dominant not only by its number but also by its intrinsic guiding role in transformation practice.

From the perspective of organizational drivers, **Job requirements** and **Efficiency improvement** (derived from technological upgrading) indeed serve as initial triggers for MET reform. However, the results highlight that the essence of organizational digitalization lies in the cultivation of human capital rather than passive adaptation to technical changes [55,58]. Among the organizational-key factors, **Digital leadership** and **Communication skills** emerge as core competencies for future maritime professionals: digital leadership enables the interpretation of digital trends and the formulation of adaptive training strategies, while communication skills adapted to digital collaboration scenarios break through the limitations of traditional on-board information transmission [34,61]. Notably, these modern competencies do not replace but synergize with practical **Maritime experience**—only the integration of digital literacy and time-honored navigation expertise can cultivate talents who meet the dual requirements of intelligent operations and safety assurance [47,90,97].

Effective cultivation of these composite talents depends upon the support from an organization's infrastructure in MET institutions. **Departmental collaboration** and **Traceable teaching systems** are two basic guarantees for this process: The digital transformation is not possible through individual departmental efforts but needs cross-departmental synergy between academic, training, simulation, and administrative units as part of a unified digital training chain. On the other hand, traceable teaching systems that track learning trajectories and monitor competency development offer data support for optimizing training programs and evaluating digital literacy, providing a solid basis for systematic talent cultivation.

A notable organizational key factor is the formation of **Dynamic training objectives** responding to the changing landscape of the maritime industry. Digital era breaks **Spatial constraints** focused on ship navigation, leading to a variety of new positions like maritime data analyst, intelligent vessel maintenance engineer or maritime cybersecurity specialist. It requires MET institutions to break out from rigid curriculum framework and form flexible training objectives corresponding to an enlarged occupational spectrum so that their graduates are able to adapt to diversification development need of the maritime sector [39,88]. In light of it, the organization challenges revealed by our results (**Conservative educational models** and **Difficulty in quantifying digitalization effects**) also emphasize the urgency of organizational reform; breaking the inertia of traditional teaching and establish scientific assessment systems have become necessary conditions to release the value of organizational factors [72,75].

4.3 Environmental Factors of MET Digitalization

The environmental aspect is composed by 2 drivers, 3 key factors and 3 challenges that form an integrated system of external normative constraints and internal demand-driven forces for MET digitalization. They dynamically interact with each other in shaping the contextual foundation of transformation where policy, market and ecological changes are the three core pillars.

First, **Policy promotion** emerges as the most dominant environmental factor. MET operates primarily under the framework of the STCW Convention. As a key enabling factor, clear **Policy suppor**t (including targeted funding guidance and unified technical standards) reduces institutional uncertainty and lowers the threshold for digital transformation [11,86,92]. On the other hand, policy can evolve into a constraint: the STCW Convention's inherent focus on minimum competency standards may conflict with the dynamic, forward-looking training needs of digital talent cultivation, thereby limiting the flexibility of MET's digital reform initiatives [64,79].

Second, the **Market competition** has become a dual-sided driver and constraint. Digitization has fundamentally reconstructed the competitive landscape of the maritime labor market: the global shortage of skilled seafarers, coupled with the emergence of new digital roles has intensified competition for high-quality talents, pushing MET institutions to optimize their talent cultivation outputs [57,68,78,89]. A more notable shift lies in the occupational expectations of contemporary maritime learners—compared with those born in the 1980s and 1990s, young learners today exhibit greater diversity and uncertainty in their **Career planning**, no longer confining their professional goals to traditional ship navigation roles. This generational shift demands that MET practitioners re-examine and proactively address **Cultural differences** among learners to design more targeted and inclusive training programs. However, the market environment also faces prominent unfavorable factors: **Uneven distribution of digital resources**—particularly in developing countries, which are major sources of the global maritime workforce—creates a "digital divide" in access to high-quality MET. Additionally, **Inadequate trust within the industry**, manifesting as both skepticism toward the reliability of digital technologies and weakened interpersonal trust in digital collaboration scenarios, further exacerbates market constraints, reducing the willingness of institutions and learners to engage in digital transformation [56,56,77,93].

Third, **Ecological Pressure** changes have emerged as an imperative and non-negotiable driver for MET digitalization. The escalating global focus on environmental protection has imposed stringent requirements for "zero-carbon and low-sulfur" operations in the maritime sector. This shift demands that MET integrate content such as alternative marine fuels, vessel energy efficiency optimization technologies, and environmental regulation compliance into digital training curricula, making ecological pressure a key environmental factor that directly shapes the content and direction of digital training [41,59].

4.4 Summary

The current systematic review revealed that MET digitalization requires coordinated efforts in technological, organizational, and environmental dimensions. Organizational factors being predominant as key success elements supports our main argument; successful MET transformation requires shifting from technology-centric towards people-oriented approach by focusing on seafarer career development, cognitive skills, and holistic professional growth.

5. Conclusion

A systematic literature review was conducted in order to answer our three research questions. Based on an analysis of academic publications as well as policy documents and industry reports from 2015 until 2025 we developed a comprehensive taxonomy for drivers, key factors and challenges which were systematically classified with the Technology–Organization–Environment (TOE) framework. One important finding of this synthesis is that the success of MET digitalization depends largely on organizational instead of technological aspects. While digital tools and infrastructures are essential, the strength of organizational capacity – encompassing leadership, institutional culture, operational processes and human capabilities – ultimately determines the effectiveness and sustainability of MET's digital transformation.

Our study makes some interesting theoretical contributions in the context of maritime education, as well as digital transformation literature.

1. It offers the first comprehensive and integrated analytical framework designed exclusively to understand MET's digital transformation. Thus addressing an important gap in existing scholarship as maritime technology studies and maritime education research have developed in parallel without engaging each other.

2. Applying the TOE framework to the MET domain allows us to provide a categorisation which supports systematic analysis and cross contextual comparison. Our finding regarding the dominance of organizational factors as the categories of key success elements is a seminal concept; it challenges the long-standing technology centric assumptions that shape maritime digitalization debates.

3. The proposed framework integrates disparate body of works such as research on intelligent shipping, sustainable and green shipping, emerging seafarer competency needs, and innovations in educational practice into a cohesive structure. It thus helps achieve a holistic understanding of the transformation landscape of MET.

4. Articulation of testable propositions about the relationship between drivers, key factors, and challenges sets up a strong basis for further empirical investigation. Such propositions can be used by researchers using qualitative, quantitative, and mixed methods approaches to validate, expand, or refine our proposed framework.

Despite these contributions, there are also limitations with this study: first, using only a systematic literature review (without including any primary empirical data) restricts capturing tacit knowledge/experiential insights/emerging practices which have not yet been documented within academic/industry publications; secondly due to the fast rate of technological changes in the maritime domain, some results could be time-sensitive and need revisions when new technologies/regulatory developments/training practices arise; thirdly, most of the literature reviewed was written in English language and does not necessarily represent regional differences regarding MET digitalization especially for non-English-speaking regions where innovations/challenges might be underreported.

It is time for future research to validate and expand this framework with empirically based approaches: surveys, interviews, ethnographic studies or in-depth case analyses on MET institutions, regulators and industry stakeholders could offer valuable insights into the relative importance of identified drivers, key factors and challenges within a particular context of operation.

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