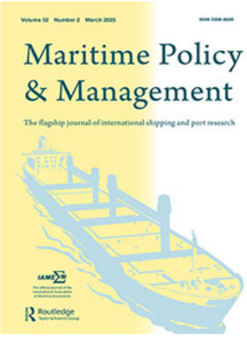
Belabyad, M, Kontovas, C, Pyne, R and Chang, C-H

Skills and competencies for operating maritime autonomous surface ships (MASS): a systematic review and bibliometric analysis



Routledge
Taylor & Francis Group

Maritime Policy & Management

The flagship journal of international shipping and port research

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tmpm20

Skills and competencies for operating maritime autonomous surface ships (MASS): a systematic review and bibliometric analysis

Mehdi Belabyad, Christos Kontovas, Robyn Pyne & Chia-Hsun Chang

To cite this article: Mehdi Belabyad, Christos Kontovas, Robyn Pyne & Chia-Hsun Chang (04 Mar 2025): Skills and competencies for operating maritime autonomous surface ships (MASS): a systematic review and bibliometric analysis, Maritime Policy & Management, DOI: 10.1080/03088839.2025.2475177

To link to this article: https://doi.org/10.1080/03088839.2025.2475177

MARITIME POLICY & MANAGEMENT
https://doi.org/10.1080/03088839.2025.2475177

Routledge
Taylor & Francis Group

ORIGINAL ARTICLE

Skills and competencies for operating maritime autonomous surface ships (MASS): a systematic review and bibliometric analysis

Mehdi Belabyad, Christos Kontovas, Robyn Pyne and Chia-Hsun Chang

Liverpool Logistics, Offshore and Marine Research Institute (LOOM) and School of Engineering, Liverpool John Moores University, Liverpool, UK

ABSTRACT

The emergence of autonomous ships brings a significant transformation, offering operational efficiencies and environmental sustainability through the implementation of intelligent systems. This transition, however, introduces intricate challenges, particularly related to human-machine interaction, highlighting the crucial role of maritime education and training institutions in equipping the future maritime workforce with appropriate skills and competencies. This paper presents a systematic review and bibliometric analysis to offer a comprehensive exploration of the skills and competencies required for the future of autonomous shipping. The skills framework derived from the literature provides a holistic view of the competencies required for the successful operation of maritime autonomous surface ships, encompassing technical and digital proficiency, operational and managerial competencies, higher-order thinking skills, and interpersonal skills. The findings of this study have significant implications for the future of maritime education and training, workforce development, and policymaking. The identified skills framework serves as a foundation for curriculum development and training program design, emphasising the need for a hybrid approach that balances traditional seafaring skills with emerging competencies. The study underscores the importance of lifelong learning, adaptability, and collaboration as key enablers for navigating the complexities of autonomous shipping.

ARTICLE HISTORY
Received 25 October 2024
Accepted 25 February 2025

KEYWORDS
Maritime autonomous surface ships (MASS); maritime education and training (MET); skills; autonomous shipping; automatic; human factor

1. Introduction

Historically, maritime accidents have resulted in severe consequences. Among the documented shipping incidents, human error has been identified as the leading causal factor, accounting for approximately 80–90% of reported accidents (Chang et al. 2021; Heij and Knapp 2018). To deal with the accidents caused by human error, maritime autonomous surface ships (MASS) have been attracting increasing attention in both the maritime industry and academia. The International Maritime Organization (IMO), as the leading regulatory body, defines MASS as *'ships which, to a varying degree, can operate independently of human interaction.'*

According to Chang et al. (2021), MASS offer a range of advantages, including enhanced safety and security, more efficient human resource management, reduced operational costs, and increased eco-friendliness. At the same time, it's important to note that the safety and

CONTACT Chia-Hsun Chang c.chang@ljmu.ac.uk Liverpool Logistics, Offshore and Marine Research Institute (LOOM) and School of Engineering, Liverpool John Moores University 3 Byrom Street, Liverpool L3 3AF, UK

Supplemental data for this article can be accessed online at https://doi.org/10.1080/03088839.2025.2475177

commercial benefits may not be entirely clear. For example, reducing or completely eliminating the crew could result in less maintenance while at sea, but increased time at port to perform these tasks, which might not be overall beneficial for the owners. Nevertheless, several MASS trials and demonstrations have been announced in Norway, China and Japan. Autonomous shipping vessels will have a transformational impact on the industry, however there is still a lack of a clear regulatory environment. Following the introduction of MASS on the IMO's agenda, various entities within the maritime industry have taken steps towards regulating the adoption of autonomy in vessels. A notable instance includes the IMO regulatory scoping exercise (RSE) carried out in 2021. For a recent survey on the relevant regulations and industry codes, reviewing MASS research and development, and collision avoidance navigation systems see Zhang et al. (2021).

The transition towards autonomous vessels in the global maritime sector has gained significant attention, with numerous efforts directed towards adapting regulations and much of the academic research focusing on advancing intelligent technologies for situation awareness and collision avoidance (Chang, Bandara Wijeratne, et al. 2024; Munim and Haralambides 2022) and topics such as risk assessment (Chang et al. 2021).

However, it is anticipated that the most profound impact of MASS would be related to the necessary modifications to skillsets (X. Li and Fai Yuen 2024). The abilities required for navigational and engineering roles in autonomous vessel operations diverge significantly from those in conventional ships. For instance, the International Convention on Standards of Training, Certification & Watchkeeping for Seafarers (STCW) establishes Knowledge, Understanding and Proficiency (KUP) requirements for officers supervising navigational watches on ships. However, many of these competencies may become irrelevant in the context of MASS operations. A crucial question, thus, emerges: *What competencies and skills are required for maritime professionals to operate MASS effectively, and how can maritime education and training (MET) programmes be adapted to align with the evolving guidelines and competency standards established by the IMO?* Addressing this challenge will necessitate updating curricula and ensuring that the MET offerings are industry-aligned, providing students with the essential skills required for a successful career in the evolving maritime landscape.

This paper aims to identify the skill and competency requirements in the context of autonomous ships through an extensive survey of the available literature. By identifying key competencies, the paper underscores the importance of considering human factors in the design of training programs and regulatory guidelines for maritime professionals. Ultimately, by addressing these human-centric aspects, the paper contributes to the advancement of human factors principles within the maritime industry, facilitating the safe and efficient integration of autonomous technologies into maritime operations.

Despite the increasing body of research on MASS (see M. Kim et al. 2020; Munim and Haralambides 2022; Jovanović et al. 2024 for a survey of the relevant literature), there are still few studies focusing on the essential skills needed for the successful implementation of MASS. This gap is highlighted by Sharma and Kim (2022). As previously mentioned, the unique nature of MASS operations sets them apart from conventional ships, requiring a workforce with new and expanded skill sets. While previous studies have surveyed the literature on future skills (e.g. Cicek, Akyuz, and Celik 2019; Emad, Enshaei, and Ghosh 2021; X. Li and Fai Yuen 2024), our study stands out in three ways: (a) using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to ensure transparent and reproducible results, (b) incorporating both academic literature and grey sources from industry and regulatory bodies like the IMO, and (c) mapping the skill landscape using Le Deist and Winterton's (2005) competency framework.

It is also an acknowledged reality that there often exists a disparity between the practical skills demanded by the maritime industry and those acquired by students upon completion of their education. The skills needed for autonomous operation might be fundamentally different (also due to the element of digitalisation) and this underscores the significance of accurately determining the necessary skills and competencies for autonomous operations, which is exactly what the focus of this paper is.

Therefore, this subject is of paramount importance for several reasons which we will list below. Firstly, the potential advantages of MASS are considerable, yet they come with significant risks that demand highly skilled individuals and therefore there is a clear need to identify relevant skills and competencies in a systematic way. Secondly, the advancement and adoption of MASS technology are rapidly progressing, making this research area particularly timely. Thirdly, the fascinating and innovative character of MASS could serve to attract younger generations to maritime industries, potentially addressing the existing shortage of seafarers.

To that end, the contributions of this paper are as follows:

We conduct a systematic literature review using the PRISMA framework. We analyse the gathered literature and use thematic analysis to categorise the identified skills and competencies, placing them under a category—referred to as a 'dimension'—following Le Deist and Winterton's framework. The results emphasise cognitive and functional dimensions in the skills framework, suggesting a strong focus on knowledge, as well as technical and operational aspects.

Finally, we present the significant findings of this study, which have implications for the future of MET, workforce development, and policymaking. These findings can serve as a foundation for curriculum development and training program design. This study also reveals the need for further research to deepen the understanding of human factors in autonomous shipping.

The paper is structured as follows: In Section 2, we discuss our methodology used to identify and analyse the relevant literature and the findings from a bibliometric analysis of relevant academic literature. In Section 3, we present an exhaustive list of required skills for MASS and a detailed exploration of these skills. Finally, Section 4 offers an in-depth discussion and conclusions.

2. Systematic literature review and Bibliometric Analysis

2.1. Systematic literature review

In conducting this study, we adopted the PRISMA framework. This widely recognised methodology provides a comprehensive and transparent approach to reporting systematic reviews, ensuring the quality and replicability of the review process (Page et al. 2021). In recent years, the usage of PRISMA in non-medical disciplines has increased substantially, acknowledging its role in producing high-quality, reliable, and transparent systematic reviews (Methley et al. 2014; Page et al. 2021). Its methodological robustness can contribute significantly to the transparency and replicability of reviews, regardless of the subject matter (Bramer et al. 2017).

The systematic literature review followed a comprehensive and targeted approach in crafting the search query, designed to cover a broad array of literature pertaining to the necessary skills for operating MASS and their equivalents. Guided by the research question of this review: 'What are the necessary skills identified in the literature for effectively operating MASS?,' a combination of keywords and boolean operators were used, as shown in Figure 1.

An initial screening was conducted based on the title, abstract, and keywords of the identified studies. This screening aimed to exclude studies that were evidently not relevant to the research question. Furthermore, specific inclusion criteria were applied to refine this initial selection.

We have gathered studies published in peer-reviewed journals, conference proceedings and industry reports after 2010 (noting here that the earliest identified document was published in 2017).The search was conducted using the Scopus and Web of Science (WoS) databases, as this combination is considered the most suitable for research related to autonomous shipping (Chaal et al. 2023).

Additionally, we have employed the so-called, snowballing, often called as a 'chain-referral' method (Wohlin 2014) which involved going through the reference lists of identified articles, pinpointing and assessing other potential sources that may be pertinent to the

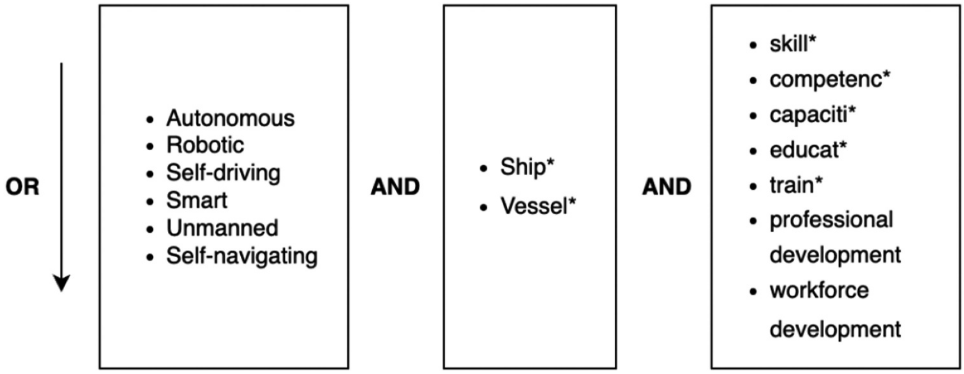


Figure 1. Keywords set for the search.

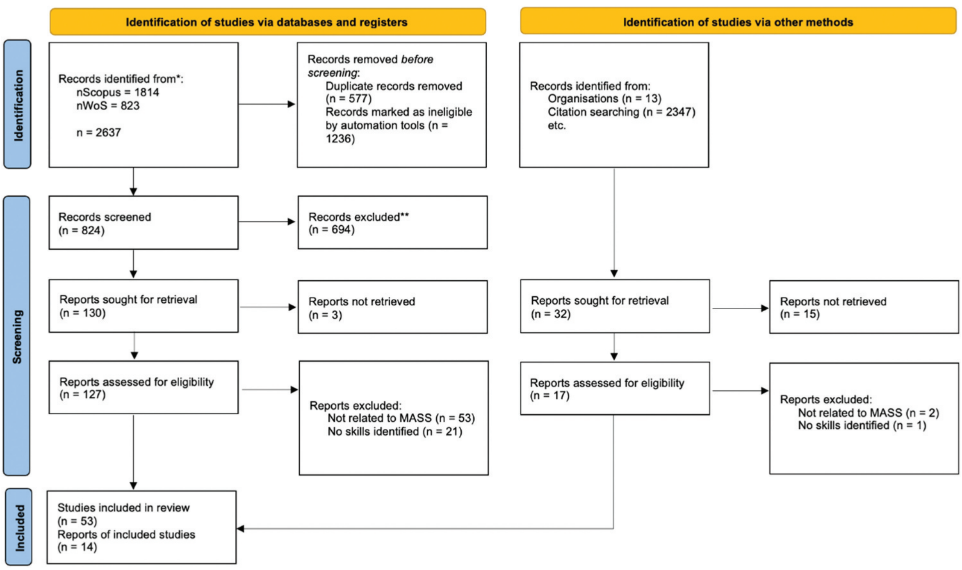


Figure 2. PRISMA flow chart for the selection process. Source: developed by the authors using PRISMA framework.

research query (Greenhalgh and Peacock 2005). Our hybrid search strategy was complemented with the 'berry picking' approach (Bates 1989) to retrieve grey literature, particularly industry and policy reports. For this, we directly gathered literature using Google Scholar but also collecting several documents submitted to the IMO, as these are relevant in setting policies for MASS.

Figure 2 provides the PRISMA flow diagram illustrating the process. After collecting the studies following the search strategy outlined above, and screening them by reading titles, abstracts, and full text as necessary, 67 studies were identified as eligible.

2.2. Bibliometric analysis

After collecting the data, we carried out a bibliometric analysis. Bibliometric analyses are powerful tools for examining the structure and dynamics of scientific research, allowing for the identification of key trends, influential publications and collaborative networks. In this study, the bibliometric

Table 1. Dataset descriptive statistics.

DATA	DESCRIPTION	RESULTS
MAIN INFORMATION ABOUT DATA	Timespan	2017:2023
	Sources (Journals, Books, etc)	45
	Documents	53
	Annual Growth Rate (%)	41.42
	Document Average Age	3.13
	Average citations per doc	8.604
	References	1684
DOCUMENT CONTENTS	Keywords Plus (ID)	216
	Author's Keywords (DE)	149
AUTHORS	Authors	140
	Authors of single-authored docs	10
AUTHORS COLLABORATION	Single-authored docs	10
	Co-Authors per Doc	3.04
	International co-authorships (%)	16.98

analysis was performed using the Bibliometrix package in the R statistical programming language (Aria and Cuccurullo 2017).

The bibliometric analysis below focuses on the academic publications in our dataset ($n = 53$), which is around 79% of the total studies collected through the search process, see Table 1 for a summary.

It is worth noting that our research primarily concentrated on publications released after 2010, however, the first academic papers discussing skills and competencies associated with MASS appeared around 2017. While there may be earlier works, especially in automation, the principal discussions on MASS began around 2017 and this likely aligns with the commencement of discussions at the IMO in February 2017 and the launch of a scoping study to investigate how MASS could be integrated into IMO instruments; for more details, please refer to Section 3.6. The number of contributions has been increasing since then. The number of articles grew from 1 in 2017 to 15 in 2022; suggesting a field that is gaining momentum. Figure 3 presents the number of citations and publications per year.

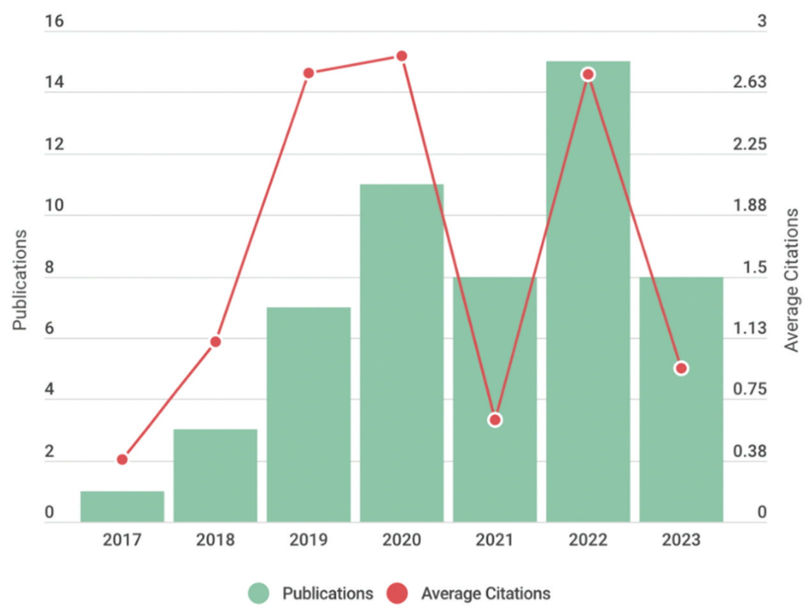


Figure 3. Academic publication and average citation trends.

The WMU Journal of Maritime Affairs emerges as the leading publication outlet, with 4 articles on the topic. Other important journals -noting that this is still an emerging field with limited published items- include Ergonomics, the Australian Journal of Maritime and Ocean Affairs, and Maritime Policy and Management, each with 2 articles. The research output is relatively scattered across various sources, with no single publication venue dominating the discussion on the skills for MASS. This is characteristic of emerging research areas where the body of knowledge is still developing, and the research community is yet to coalesce around a set of core themes, methodologies, and seminal works.

Certain countries are dominant in terms of research output and impact. This also intersects with countries where trials are performed. Norway leads both in frequency of research output and in total citations, which suggests a strongly funded, high-quality research environment. The average citations per article are substantially higher than other countries, indicating that Norwegian research is very impactful. Norwegian research landscape gained high momentum for future skills for MASS after 2019 that is increasing yearly. This is followed by Australia which, despite fewer publications than Norway, Australia's research exhibits high impact.

2.3. Thematic analysis and research trends

To identify important themes and key areas of research effort of the published literature, a frequency analysis of keywords, abstracts, and titles from the 53 reviewed papers was conducted, with the results presented in Table 2. While this analysis yields limited novel insights, as the most frequently occurring words are largely related to the original search parameters (i.e. words included in the search string), several observations can be made. Firstly, the prominent appearance of 'automation' suggests its significance as a core component of autonomous vessels. Secondly, the frequent use of the term 'future' in titles and abstracts implies that MASS are not presently viewed as mainstream, but rather as a prospective/future development anticipated by the industry. Lastly, an increasing tendency to refer to autonomous vessels as MASS is observed, as evidenced by the frequency of the term 'surface,' which is obviously attributed to the emergence of MASS as a concept in the IMO discussions.

2.4. Thematic map

Thematic analysis is crucial for bibliometric reviews, as emphasised by Aria and Cuccurullo (2017). This method enhances the review's comprehensiveness by identifying and tracking key themes within a specific research domain. By categorising literature into themes through co-word analysis, which analyses keyword frequency and co-occurrence, researchers can uncover main topics and trends. Themes are defined by two key parameters: density, which indicates the level of

Table 2. Most frequent words in keywords, abstracts and titles of the selected papers (occurrences).

	AUTHORS' KEYWORDS PLUS		ABSTRACTS		TITLE	
	Words	#	Words	#	Words	#
1	ships	15	maritime	132	maritime	34
2	automation	8	autonomous	114	autonomous	28
3	shipping	6	ships	98	future	20
4	surface ship	6	seafarers	83	education	16
5	maritime education	5	training	78	ships	16
6	personnel training	5	industry	64	training	15
7	human	4	future	62	shipping	12
8	human engineering	4	shipping	58	seafarers	10
9	maritime industry	4	education	52	skills	7
10	ship	4	human	47	surface	7

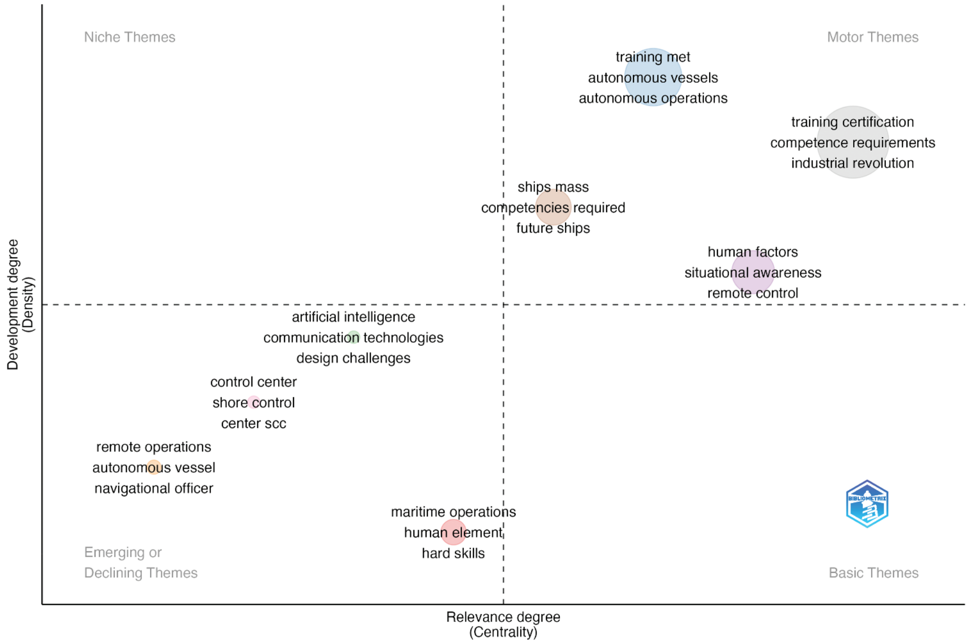


Figure 4. Thematic map – produced using the Bibliometrix software.

development, and relevance, which measures their significance. These parameters are plotted on a thematic network, with density on the vertical axis and relevance on the horizontal axis.

Following Aria and Cuccurullo (2017), the thematic map is divided into four quadrants based on two dimensions, as illustrated in Figure 4. 'Motor Themes' (high density and high relevance) are themes that are well-developed and crucial to the research field. On the other hand, 'niche themes' (upper left) are well-developed but not central to the field, and 'basic themes' (bottom right) are fundamental and cross-cutting, providing a basis for further research.

The concentration of themes in the 'motor' quadrant (upper right) highlights the dominance of developed and relevant research topics (Figure 4). These findings suggest a strong research focus on human factors, and MET in the context of industrial revolution and autonomous shipping.

Clusters containing themes such as 'artificial intelligence,' 'communication technologies,' 'shore control,' 'remote operations' and 'hard skills' are positioned at the lower left quadrant, representing emerging themes. We could therefore assume that these themes represent developing research areas that are undergoing a shift in research interest. Their presence points to future directions for research, such as exploring the changing roles and responsibilities of maritime professionals in the era of autonomous shipping, focusing increasingly more on remote operators.

2.5. Discussion and implications of the bibliometric analysis

The bibliometric analysis of the literature on future skills and competencies for autonomous shipping presents a comprehensive picture of a rapidly evolving and multifaceted research landscape. The exponential growth in research output, particularly since 2019, highlights the increasing attention and urgency surrounding this topic, as the maritime industry grapples with the disruptive potential of autonomous technologies (Sharma, Tae-Eun, and Salman 2021).

The geographic distribution of research output and collaboration patterns reveals a concentration of activity in countries with strong maritime traditions, such as Norway, Australia, and the UK, reflecting their proactive approach and strategic investments in autonomous shipping (Theotokas, Lagoudis, and Raftopoulou 2024). However, the low level of international collaboration and the scarcity of research from developing countries underscore the need for a more inclusive and collaborative approach to ensure the global realisation of the benefits of autonomous shipping (Lau and Ng 2015).

The thematic analysis uncovers a research landscape characterised by distinct clusters focusing on technological systems, human factors, education, and regulatory aspects, highlighting the transformative nature of autonomous shipping and the need for a paradigm shift in the skills and competencies of maritime professionals (Mallam, Nazir, and Sharma 2020; Sharma and Kim 2022). The dominance of motor themes related to maritime education, autonomous ships, and human factors suggests a maturing research area, while the presence of emerging themes, such as artificial intelligence and remote operations, points to future research directions and the need for interdisciplinary collaborations (Kobyliński 2018).

Despite the promising trends and potential future directions revealed by the analysis, the research on future skills and competencies for autonomous shipping is still in its early stages, with a fragmented publication landscape and a lack of consensus on key concepts and methodologies (Sharma, Tae-Eun, and Salman 2021). This calls for more conceptual and empirical work to establish a solid foundation for the field, including the development of comprehensive frameworks for the identification, assessment, and development of the required skills and competencies. In the next section, we present a framework to categorise the skills and competencies that are related to autonomous ships as identified in the relevant academic literature.

3. Systematic review of skills and competencies for MASS

The terms 'skills,' 'competencies,' and 'competence' are often used interchangeably, leading to potential confusion. Hoffmann's (1999) seminal work on the 'chaotic' nature of competency definitions remains relevant, noting that the concept of competency suffers from *'definitional inconsistency and conceptual ambiguity'*. However, precise definitions are crucial for this study, to ensure consistency and suggest effective education and training recommendations for the future maritime workforce. Therefore, this study primarily uses the terms 'skills' and 'competencies,' with a deliberate focus on 'competency' rather than 'competence.' In our study, we carefully distinguish between 'competence' and 'competency' based on recent literature in maritime education and human resource development. As suggested by Teodorescu (2006) and further applied to maritime education by Fan and Yang (2023), 'competence' refers to the overall state or quality of being adequately qualified and able to perform a task, while 'competency' denotes specific, identifiable characteristics such as knowledge, skills, mindsets, and thought patterns that contribute to successful performance. Consequently, we have chosen to use the term 'competency' (plural: 'competencies') throughout this paper to emphasise the specific, identifiable attributes.

Skills and competencies, while often used interchangeably, have distinct meanings in our study:

(1) Skills: These are specific, observable abilities that can be taught, learned, and measured. Skills are typically task-oriented and form the building blocks of broader competencies.
(2) Competencies: These are broader, more complex attributes that integrate multiple skills with knowledge, attitudes, and behaviours. Competencies are context-specific and relate to successful performance in a particular role or situation.

A thematic analysis is used to categorise the identified skills and competencies in the various documents gathered during the literature review, while a multi-dimensional framework developed by Le Deist and Winterton (2005) is applied for their assessment. The latter presents a model which describes four dimensions: cognitive (knowledge), functional (know-how), social (attitudes and behaviours) as well as meta (learning abilities including reflection).

We should note here that the term 'competency' is a widely used one both in professional context and academia; however, its definition has been subject to numerous debates (Hoffmann 1999; Stoof et al. 2002). Besides being multifaceted, there is no agreed upon theoretical basis for understanding what constitutes a competency (Mulder et al. 2009; Winterton, Delamare Le Deist, and Stringfellow 2006). Le Deist and Winterton's framework is used to recognise the holistic aspect of this concept.

3.1. Classification of skills and competencies

Breaking down the skills and competencies into these four dimensions we could obtain useful insights into the varying significance of the different components in shaping curriculum design. This categorisation can assist MET institutions in distributing attention and resources across these identified dimensions.

To that extent, every skill and competency assessed was placed under one or more categories called 'dimensions,' derived from the Le Deist and Winterton's framework, according to its nature; thus, some skills and competencies might have fallen under several groups while others could fit perfectly well within just one category. We then categorised all skills and competencies along dimensions using a coding technique. This allowed us to create a typology of skills and

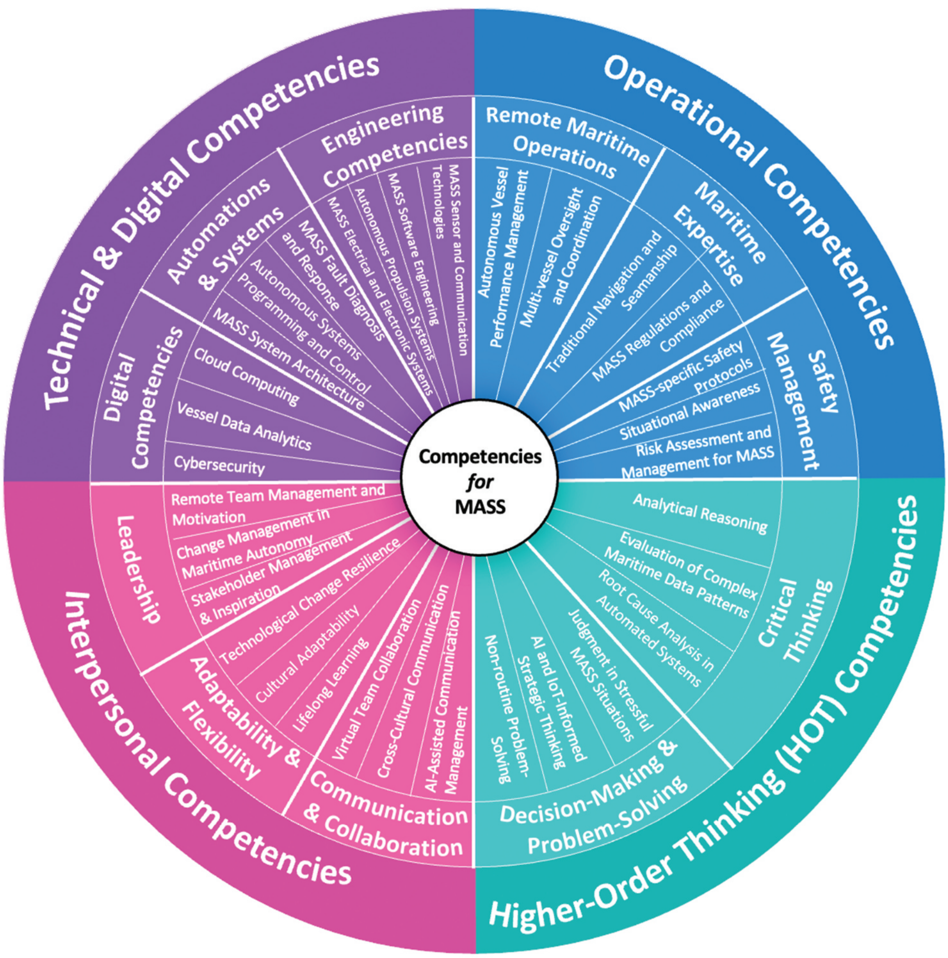


Figure 5. The skills and competencies framework.

competencies based on their respective dimensions, enabling us to move from a simple listing to a multi-dimensional analysis of the future skills and competencies needed for MASS.

The framework (Figure 5) is organised hierarchically, moving from broad to specific. The outer ring represents the four main competency categories: Technical & Digital, Operational, Higher-Order Thinking (HOT), and Interpersonal Competencies. Each of these broad competencies is then broken down into more specific competency areas in the middle ring. Finally, the innermost ring presents the individual skills that contribute to each specific competency. This structure allows for a comprehensive view of the skills required for MASS operations, from broad competency areas down to specific, actionable skills. The details of each skill are presented below.

Figure 6 shows the analysis of the prevalence of each skill across the publications reviewed that uncovers a strong emphasis on digital competencies (43 papers) and communication & collaboration (38 papers), highlighting the increasing importance of technological proficiency and effective teamwork for the effective operations for MASS. Automation & systems (30 papers) and leadership (23 papers) also emerge as crucial competencies. Furthermore, the findings suggest that traditional maritime expertise (20 papers) is still important in the mix of competencies for MASS. Furthermore, there is a balanced distribution of competencies and skills across critical thinking (17 papers) and problem-solving (17 papers), followed by Engineering competencies (16 papers), adaptability & flexibility (15 papers), Safety Management (15 papers) and remote maritime operational competencies (14 papers).

In the Sections below we discuss the main competencies identified in the literature. The Supplementary material includes a table listing additional literature that we couldn't discuss in the main body due to space constraints.

3.1.1. Technical and digital competencies

3.1.1.1. Digital competencies. Developing digital literacy and competency emerged as critical skills for the future autonomous shipping workforce across the literature. These skills cover both cognitive (knowledge and understanding) and functional (practical abilities) dimensions.

Figure 6. Competencies prevalence among publications.

Numerous sources have highlighted the critical importance of cybersecurity skills for the safe remote operation of autonomous vessels (see for example Bolbot et al. 2022; Ceylani, Kolçak, and Solmaz 2022; Park et al. 2023). These skills are underscored both in terms of cognitive dimension, involving an understanding of the theoretical foundations of cyber threats and protective measures (Maritime 2020), and functional dimension, encompassing practical abilities such as anomaly detection, system isolation, and network recovery (Bolbot et al. 2022). The increasing interconnectivity of systems via automation, the internet, and data networks heightens cyber risks. Therefore, future seafarers and operators must maintain robust cyber hygiene and possess the ability to continuously evaluate threats and vulnerabilities in digitised onboard systems and remote command centres according to WMU (2019).

Data analytics and processing skills were also consistently highlighted, both from a cognitive and functional competency perspective. Seafarers and remote operators need to understand (cognitive) and effectively process and organise (functional) the vast data generated by autonomous ships. This would require data analytics and processing skills and competencies to process and organise this vast data as highlighted in various project reports (WMU 2019) and academic papers (Bartusevičienė 2020). Data science skills are then required to apply techniques like machine learning, statistical analysis and modelling to derive operational insights from the collated data, allowing for continuous monitoring and optimisation of autonomous ship performance (Fan and Yang 2023).

Cloud computing knowledge is also important, particularly on the cognitive level. As autonomous ships have more sensors and data-generation sources, cloud-based data storage and processing will likely be used. Understanding cloud architecture, virtualisation, networking and how to leverage Infrastructure/Platform/Software-as-a-Service cloud models enables seamless remote oversight of ships and their vast data as stated by Belev et al. (2021).

3.1.1.2. Automations & systems. Operating and overseeing automated systems and processes onboard autonomous vessels emerged as another critical technical skillset from the literature, covering both cognitive and functional competencies.

A deep cognitive competency is reflected in the understanding of automation engineering principles, emphasised by several studies (Lynch et al. 2022; Saha 2023; Sharma and Kim 2022). With the rise in automation spanning navigation, propulsion, and cargo handling, it is crucial for future seafarers, especially remote operators, to have a deep understanding of foundational elements such as sensors, actuators, and controllers as highlighted by Saha (2023). Complementing this cognitive foundation, functional aspect manifests in the ability to program automation workflows and adapt control logic, enabling effective supervision of automated maritime operations (Sharma and Kim 2022).

Monitoring, controlling and optimising integrated ship systems, as underscored by multiple sources (Ceylani, Kolçak, and Solmaz 2022; Saha 2023; WMU 2023), reflect both cognitive and functional dimensions. Operators must interpret system data, exercise in cognitive understanding, and then apply functional skills to detect anomalies, discern performance metrics, and pinpoint aspects for enhancement. This extends to initiating actions like emergency stops and equipment modifications during autonomous tasks (Yoshida et al. 2020).

Meta-dimension, the ability to reflect on and improve practices, is evident in the emphasised troubleshooting skills. As physical access diminishes, the workforce, both seafarers and remote operators, requires a reflective and adaptive approach to diagnose system malfunctions and anomalous sensor outputs, as highlighted by several studies (Emad and Ghosh 2023; Saha 2023; Yoshida et al. 2020). Another vital functional competency is the capability to respond to alarms and system faults. Future maritime professionals need to adeptly decode alarm alerts, assess the gravity of issues, and execute corrective measures (Maritime 2020; Yoshida et al. 2020). This prevents minor disruptions from spiralling into significant system breakdowns.

3.1.1.3. Engineering competencies. The literature underscores the importance of specialised technical competencies for the future seafarers and operators supporting autonomous shipping. These are mainly related to engineering skills and competencies.

Electrical and electronic engineering expertise is particularly highlighted, encompassing both cognitive (understanding the theoretical aspects of interconnected controls, sensors, and data networks) and functional levels (practical applications in monitoring electrical operations and troubleshooting) (Maritime 2020; SkillSea 2020). Sharma and Kim (2022) specifically noted the need for hands-on expertise in instrumentation and controls. Furthermore, mechanical engineering skills also provides key support (Bolbot et al. 2022; Maritime 2020). Operators should understand mechanical systems like propulsion and steering (cognitive) to identify problems noted in sensor logs and initiate maintenance or repairs (functional) as highlighted by Sharma and Kim (2022). These competencies support performance optimisation as per Skillsea (2020).

Software engineering has emerged as a vital competency, at both the cognitive and functional competencies levels. Autonomous ships heavily depend on programmed command and control systems, making software the heart of the operation. Knowledge of programming languages, systems design, testing and debugging will be essential, on a cognitive level, while on a functional level, hands-on software development skills to code automation features, integrate systems, and implement upgrades will be necessary (Ceylani, Kolçak, and Solmaz 2022). This will allow remote operators to monitor, troubleshoot and optimise onboard software and digital infrastructure.

On the other hand, systems engineering skills allow effective integration of automation, navigation, power/propulsion and other systems (Sharma and Kim 2022; Yoshida et al. 2020). This reflects both cognitive (grasping the interconnectedness of various systems) and functional dimensions (optimising performance). With multiple complex and interlinked systems on autonomous ships, a systems-level perspective helps optimise the ship's performance according to Yoshida et al. (2020). This stresses that operators should not only understand how various subsystems interconnect but also continually assess and refine their performance, highlighting the meta aspect related to the ability not just to operate within the system but to reflect upon its operations, learn from them, and make improvements.

In addition, sensor and data engineering skills are also important. Remote operators rely heavily on data, requiring cognitive competencies like understanding sensor technology and data networking and functional ones to ensure sensor and data network uptime (Bolbot et al. 2022).

3.1.2. Operational competencies

3.1.2.1. Remote maritime operations. The autonomous shipping environment necessitates the confluence of a range of operational skills that are both traditional and emergent in nature. The review identified three key operational skills as pivotal for the future workforce in this domain: (a) operations monitoring and analysis, (b) multi-tasking and (c) operational limitations awareness.

Operations monitoring and analysis skills and competencies involve the continuous assessment of system performance, detection of anomalies, and ensuring that the vessel operates within defined parameters. Multiple studies underscored the importance of this skill, emphasising its role in maintaining the efficiency and safety of autonomous operations (Ceylani, Kolçak, and Solmaz 2022; SkillSea 2020). Particularly, WMU (2019) stressed on advanced digital operations monitoring and analysis of physical entities like cranes and winches given the evolving remote nature of shipping, as well as robotics, cognitive and AI-driven robots. Sharma and Kim specifically highlighted the need for future seafarers to have robust knowledge about engine room operations (alert handling and maintenance skills). Operations monitoring and analysis is a blend of cognitive and functional skills and competencies, where the former is about understanding the system and the latter involves applying this understanding to ensure smooth operations.

Given the multi-dimensional nature of autonomous shipping operations, multi-tasking skills emerged as a crucial competency (Kennard, Zhang, and Rajagopal 2022). This reflects an individual's ability to manage various operational aspects without compromising on performance. In the environment of MASS, multitasking would likely refer to the simultaneous monitoring and management of multiple ship systems and processes. This skill can be categorised as meta, signifying the ability to learn and adapt in real-time environments.

Additionally, recognising the limitations of autonomous vessels, and more importantly, operating within them, is crucial to prevent overburdening the system and ensuring safety (Maritime 2020). This operational limitation awareness skill, deeply embedded in the cognitive level, requires a comprehensive understanding of the system's capacities and boundaries.

3.1.2.2. Maritime expertise. Traditional maritime skills continue to be a vital part of the skill set needed for the autonomous shipping workforce; this will be outlined in the MASS Code as well. The shift to autonomous operations doesn't lessen the value of traditional maritime knowledge. Instead, it calls for an integrated approach where traditional and new skills coexist.

Maritime competency, in the traditional sense, covers a wide range of cognitive and functional skills. These include a deep understanding of the Convention on the International Regulations for Preventing Collisions at Sea (COLREG), radar operations, and the functions of the Electronic Chart Display and Information System (ECDIS). These foundational skills ensure that the basics of safe and efficient seafaring are maintained, even in a digital environment (Kennard, Zhang, and Rajagopal 2022; Saha 2023). Skills related to sea awareness and handling remain as crucial as ever.

Understanding the levels of automation is another key cognitive skill (Maritime 2020). As ships become more technologically sophisticated, operators need to understand the varying levels of autonomy, from partial to full automation. They need to know how these levels affect decision-making, safety protocols, and overall operations.

Legal and regulatory knowledge adds another layer of complexity to the cognitive skills needed for MASS operations. As international maritime conventions and recommendations adapt to accommodate autonomous operations, the future workforce must be skilled at navigating these regulatory changes. They need to ensure operations remain compliant while taking full advantage of automation (Bolbot et al. 2022; T.-E. Kim and Mallam 2020; Maritime 2020).

3.1.2.3. Safety management. Navigating the complexities of autonomous shipping requires a robust framework for emergency and safety management. The literature identified three key skills and competencies in this category: (a) knowledge of safety protocol for autonomous operations, (b) situational and safety awareness and (c) risk assessment execution.

First, knowledge and understanding of safety protocols and management tailored to autonomous operations, a cognitive competency, is essential (Veitch and Andreas Alsos 2022). These protocols offer theoretical guidelines that consider the unique challenges of operations with minimal human intervention (Maritime 2020). Similarly, the knowledge of regulatory compliance, which ensures the operation of MASS aligns with global safety standards, is also rooted in cognitive understanding.

Second, situational and safety awareness was highlighted by numerous scholars (Bolbot et al. 2022; Kennard, Zhang, and Rajagopal 2022; Yoshida et al. 2020). This functional competency to perceive, comprehend, and predict evolving situations, especially during complex or rapidly changing environments, will rely heavily on sensors, data streams, and automation systems. This is not just about viewing data but understanding its implications in real time. For instance, if sensors pick up an unexpected obstacle or change in weather conditions, operators need to quickly comprehend the data, understand its implications, and predict how it might affect the ship's operations. A quick response would also be needed; see HOTS below.

However, beyond these tangible skills lies an essential meta competency. Risk assessment execution, for instance, is not just about identifying risks but proactively anticipating them, adapting to unforeseen challenges, and learning from past incidents (Sharma and Kim 2022). The draft MASS code (see Section 4.6) highlights the '*ability to apply the risk assessment on any operation* *of the MASS*' as a key competency requirement for both seafarers on board MASS and remote control operators (RCOs).

3.1.3. Higher-order thinking skills (HOTS)

3.1.3.1. Critical thinking. The reviewed literature emphasised analytical and logical thinking as a key cognitive competency for the autonomous shipping workforce. Sharma and Kim (2022) and Ceylani, Kolçak, and Solmaz (2022) identified critical thinking as vital for navigating complex autonomous operations. Fan and Yang, (2023) stated analytical reasoning aids interpretation of data patterns. Ceylani et al. (2022) identified critical thinking and reasoning as the most important skills needed in the future for seafarers.

Among these critical thinking skills, evaluating options and evidence competencies were also highlighted. Mallam, Nazir, and Sharma (2020) emphasised abilities in analysing large information sets from autonomous systems. Yoshida et al. (2020) discussed evaluating sensor data to recognise hazards. Kennard, Zhang, and Rajagopal (2022) noted skills in scrutinising data from multiple autonomous ship systems. These skills will help future seafarers and operators confirm the accuracy of the information obtained from restricted ship sense, radar display, and other items at remote control centres (RCCs) (Yoshida et al. 2020). Root cause analysis was additionally noted. Cicek, Akyuz, and Celik (2019) and Emad and Ghosh (2023) highlighted troubleshooting abilities to identify faults in automated systems.

3.1.3.2. Decision-making and problem-solving skills. The literature highlighted strong judgement and decision-making abilities as a cognitive skill and competency critical for the autonomous shipping workforce (T.-E. Kim and Mallam 2020; SkillSea 2020; Yoshida et al. 2020). Specifically, this can cover competencies such as determining appropriate actions and making sound judgements under stress. Determining appropriate actions was noted by multiple papers. Yoshida et al. (2020) described the ability to choose suitable responses to alarms or abnormalities. In particular, Chowdhury et al. (2023) pinpointed the significance of data-driven decision-making, again emphasising the cognitive domain. To facilitate decision-making, knowledge of artificial intelligence, Internet of Things, and big data is essential (Skillsea 2020).

Additionally, problem-solving, a cognitive skill and competency, emerged as one of the most recurrent themes in the reviewed literature (Ceylani, Kolçak, and Solmaz 2022; Cicek, Akyuz, and Celik 2019; Emad and Ghosh 2023; Kennard, Zhang, and Rajagopal 2022; Saha 2023; SkillSea 2020; Yoshida et al. 2020). This includes solving unfamiliar and non-routine problems. Addressing these problems demands a deep understanding of both the technology and the maritime environment, coupled with the ability to think critically and creatively.

3.1.4. Interpersonal skills

3.1.4.1. Communication & collaboration. Teamwork and collaboration were emphasised extensively in the literature. Mallam, Nazir, and Sharma (2020) highlighted that autonomous operations require enhanced collaboration between onshore operators and onboard crews, necessitating competencies in virtual teaming. Ceylani, Kolçak, and Solmaz (2022) and IAMU (2019) also identified teamwork skills as one of the top social skills required for MASS. T.-E. Kim and Mallam (2020) noted that effective coordination and cooperation in dispersed teams enable safe autonomous operations, while Sharma and Kim (2022) emphasised the importance of the ability to establish trust in teams.

Enhanced communication was frequently emphasised across sources, as both a social and functional skill and competency. Clear communication between ship and shore workers is critical as crews, operators, engineers, and other stakeholders collaborate remotely, as highlighted by Mallam, Nazir, and Sharma (2020). Ceylani, Kolçak, and Solmaz (2022) identified communication as a top skill and competency, while Sharma and Kim (2022) noted the importance of verbal abilities. Some studies noted specifically English and multi-language communication skills (SkillSea

2020). Furthermore, the rise of Artificial Intelligence, specifically Large Language Model (LLMs), with the particular example of SeaGPT,[1] also calls for future seafarers and remote operators to have Communication Automation skills through generative AI, which refers to a subset of artificial intelligence focused on creating new content. This entails the use of generative Artificial intelligence (AI) tools like SeaGPT to automate communication processes between crew managers and port agents (Economist Impact 2023).

Emotional intelligence, a social skill and competency, was cited as well, with Fan and Yang (2023) stating that empathy, social awareness, and relationship building are key for autonomous shipping teams.

Finally, the ability to negotiate, persuade, and resolve conflicts is vital (Ceylani, Kolçak, and Solmaz 2022; Sharma and Kim 2022; SkillSea 2020). These skills, essential for aligning diverse interests and ensuring harmonious operations, resonate with the social dimension.

3.1.4.2. Adaptability & flexibility. Adaptability to new technologies is emphasised across several studies. As the maritime sector integrates advanced technologies like AI-driven systems, Internet of Things, Virtual or Augmented Reality, and advanced data analytics, future MASS workforce needs to understand, adopt, and effectively use these innovations (Chowdhury et al. 2023).

Cultural adaptation was also identified as an important social skill and competency by several studies. Cicek, Akyuz, and Celik (2019) and Sharma and Kim (2022) stated that understanding cultural differences allows effective team interactions in global autonomous shipping operations. Given the global nature of maritime operations, professionals often interact with diverse cultures, necessitating an understanding and respect for varied cultures. Thus, Ceylani, Kolçak, and Solmaz (2022) and Chowdhury et al. (2023) also noted the growing need for cross-cultural cooperation abilities as operations become more diverse.

The ability to adapt and be flexible is also seen as a vital skill for MASS. This includes a professional's resilience and their capacity to adapt to changes (IAMU (2019); Ceylani, Kolçak, and Solmaz 2022, Chowdhury et al. 2023). This skill, which is deeply rooted in cognitive and meta competencies, guarantees that maritime professionals can continue to perform effectively amidst uncertainty and change.

Lastly, the literature emphasises self-learning motivation and the drive for lifelong improvement (Ceylani, Kolçak, and Solmaz 2022; Fan and Yang 2023). In an industry that's at the forefront of technological evolution, the intrinsic motivation to learn and upskill is crucial. This aligns with the meta domain where the emphasis is on self-regulation, learning to learn, and the motivation to continually advance one's competencies.

3.1.4.3. Leadership. Leadership and influence are central in ensuring the effective operation of autonomous shipping. As the maritime sector transitions to autonomous operations, the nature of leadership roles transforms.

At the forefront, leadership, management, and guidance are essential for steering teams and operations (IAMU (2019); T.-E. Kim and Mallam 2020, Chowdhury et al. 2023). With the integration of advanced technologies, leaders in the maritime sector need to not only guide teams but also ensure that they effectively interface with technological systems. This demands a deep understanding of both human dynamics and technical intricacies, reflecting a cognitive domain where professionals demonstrate the ability to integrate knowledge and skills in complex situations. More specifically, T.-E. Kim and Mallam (2020) have outlined a set of skills and competencies for effective leadership in the age of autonomous shipping. In addition to technical and digital skills and competencies, they emphasised on participative involvement, task and workload management, caring and supporting, controlling and enforcing and effective resource management. Sharma and Kim (2022) noted that leadership skills, as they are currently incorporated into STCW requirements, are still needed for autonomous shipping but would have to be updated as the industry transitions.

Motivation, inspiration, and stakeholder management have been emphasised as key leadership attributes. Leaders must inspire trust and confidence in their teams, especially in an environment where reliance on technology might lead to apprehension. Motivating teams, ensuring their well-being, and managing diverse stakeholders, from technology providers to regulatory bodies, is a testament to the social competencies required in leadership roles. Effective stakeholder management, in particular, is critical to ensure smooth operations and adherence to global standards and regulations.

3.2. Future skills for MASS: dimensions typology

The framework of skills and competencies derived from the review was examined using the dimensions outlined in Le Deist and Winterton (2005). This classification offers a view of competencies by grouping them into four categories: cognitive, functional, social and meta.

The cognitive aspect covers skills and competencies that entail knowledge, comprehension and other mental processes. In the context of MASS, this can involve understanding automation systems, familiarity with frameworks and knowledge of cybersecurity principles. The functional dimension relates to skills and competencies that require the application of knowledge and expertise. In our context, this includes operating and maintaining systems proficiently, troubleshooting issues and making decisions based on data insights. The social dimension includes abilities connected to communication interactions and teamwork efforts. As identified in our skills and competencies framework, future seafarers or MASS operators are expected to work with AI systems communicate effectively within diverse teams and exhibit leadership skills in challenging situations. Finally, the meta aspect concerns to abilities that empower individuals to learn, adapt and regulate their performance. In the context of MASS, this includes fostering a culture of life-long learning, engaging in creative thinking and developing resilience to navigate rapid technological advancements.

The results emphasise cognitive and functional dimensions in the skills framework suggesting a strong focus on knowledge, as well as technical and operational aspects. Nevertheless, the inclusion of social and meta skills and competencies shows a growing acknowledgement of the value of interpersonal skills for MASS and lifelong learning.

Additionally, it was observed that several skills and competencies in the framework span different dimensions. For instance, activities such as monitoring and analysing MASS operations require a blend of understanding (system knowledge) and functional application (implementation). Furthermore, to effectively work alongside AI systems, individuals must possess a mix of social (interacting with others) and cognitive (comprehending AI principles) skills.

This typology has implications for MET. It suggests that MET programs should take an integrated approach to developing skills competencies addressing all aspects in a rounded and context specific manner. This could suggest combining teaching, hands-on practice, social learning opportunities and reflective methods.

Figures 7 and 8 provide the typology of the competencies and skills categories identified highlighting the prevalence of dimensions within the typology. It appears that the framework derived from the literature is primarily composed of cognitive and functional dimensions which suggest a strong emphasis on technical knowledge and practical skills within the MASS sector (Figure 7).

The presence of social and meta dimensions, though less prevalent, indicates the importance of attitudes, behaviours, and the ability to acquire new skills in this field. This is perhaps areas where future research could focus on.

The technical and digital competencies cover the cognitive and functional dimensions providing the technical knowledge and skills necessary for MASS operations. While the Operational and managerial skills and competencies are mainly cognitive and functional, they also include meta-competencies. Higher-Order Thinking Skills (HOTS) are essentially cognitive skills. Lastly, cognitive skills are a mix of all dimensions with an emphasis on social skills (Figure 8).

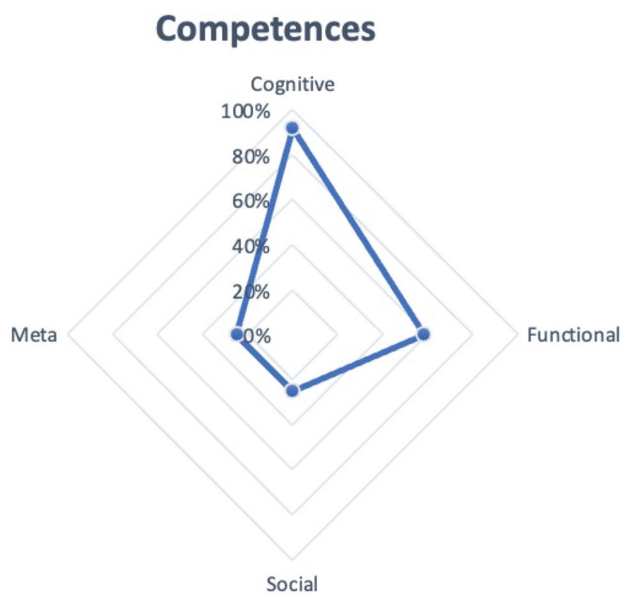


Figure 7. Typology of the framework's skills and competencies dimensions.

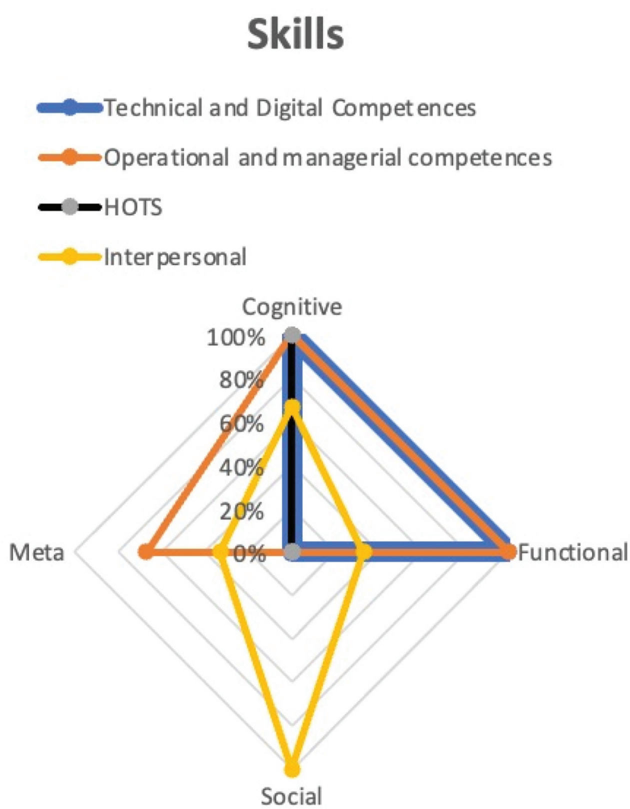


Figure 8. Typology of each skill and competency category dimensions.

3.3. IMO and MASS: what skills are on the radar of the regulators?

The IMO has been actively engaged in developing the goal-based MASS code that is aimed to establish a robust safety regime for MASS. This is expected to be adopted as a mandatory Code under SOLAS in the short term. As part of this, IMO is in the process of identifying and developing guidelines for the necessary skills and qualifications of MASS operators.

While a final version of this code is not available until around 2025, many submissions to the IMO and particularly the Maritime Safety Committee (MSC), the work by the Intersessional Working Group on Autonomous Surface Ships (ISWG/MASS), and the recent draft of the MASS Code (MSC 109/5[2]) can provide a clear picture on the essential skills and competencies necessary for MASS operators that are being discussed. In fact, Chapter 15 of the MASS Code considers the 'Human Element,' which will contain provisions related to training and practical skill development and competencies both for the crew on board the MASS and operators in a Remote Operations Centre (ROC).

A submission by the United Kingdom (MASS-JWG 2/3) notes that Remote Operators are distinct from traditional seafarers due to their shore-based role, necessitating specialised training and certification that may overlap with seafarers' curricula. The designation of remote operators of MASS as seafarers involves two distinct aspects: qualifications under the STCW and labour conditions under the Maritime Labour Convention (MLC) (MSC 107/5/1). This reaffirms the need to consider new and updated provisions for the training of Remote Operators.

To this end, the Correspondence Group on Development of a goal-based instrument for MASS differentiates between MASS crew/seafarers and Remote operators. They provided initial considerations in terms of the human elements in MASS. Seafarers and RC operators must possess a shared foundational knowledge, including an understanding of the MASS Operational Design Domain (ODD), manual intervention skills for system malfunctions, and managerial capabilities to mitigate over-reliance on automation; see IMO doc. MSC 108/4 for more. They must ensure continuous communication, conduct regular maintenance, and have a comprehensive knowledge of MASS operations and technology. In addition to these, RC operators require specialised skills to interpret data from onboard systems, manage transitions between operational modes, and receive training in both practical scenarios and simulations. Their training should also emphasise behavioural competencies crucial for remote operation, such as decision-making, situational awareness, and stress management.

It's worth noting that the drafted IMO MASS code makes a distinction between the competency standards for seafarers operating on board MASS and those working in remote centres. At the time of writing this paper, and following the latest MSC meeting (MSC 109), several issues remain unresolved in the MASS Code concerning skills and competencies. For instance, there is ongoing discussion about 'Supplementary Competencies, Training, and Familiarisation,' and whether the Remote Operator of a MASS should meet the competency and experience standards of an officer qualified under the appropriate STCW requirements, or if regulatory bodies (i.e. States) can accept 'equivalent' competencies and experience. Additionally, the applicability of STCW for remote operators is still under debate.

Furthermore, a submission by the Republic of Korea (MSC 109/INF.13) provided details on a simulator setup for remote operations. It identified the functional requirements for remote operation simulators used for training and qualifying remote operators. This was based on comparing the competencies outlined in the STCW Convention (for conventional navigators) with those required for remote operators and MASS remote operation simulators.

While there are currently similarities in the competency requirements for both roles, differences exist in their respective duties and familiarisation provisions. As these roles evolve, there may arise a need for distinct sets of skills and competencies. This analysis could serve as a foundation for researching the skills and competencies applicable to RCOs as well.

Table 3. IMO MASSPeople competency standards for MASS operators (IMO doc. MSC/ISWG/MASS 2/3/1).

	LEVEL		
FUNCTION	*Support*	*Operational*	*Management*
Equipment Operation	MASS systems, operation, and troubleshooting	MASS automation, intervention, advanced operation, and troubleshooting	System monitoring, maintenance, integration, and assessment
MASS Manoeuvring	Basic manoeuvring, passage planning, and situational awareness	Navigational systems, planning, data evaluation, and advanced manoeuvring	Passage planning, approval, strategic thinking, and risk management
Maintenance and Repair	Basic software, propulsion, and troubleshooting	Software, propulsion maintenance, diagnostic, and maintenance procedures	Software, propulsion management, long-term planning, and resource allocation
Communication maintenance	Command-and-control structure and communication system maintenance	Environmental impact on communications, diagnostic, and maintenance procedures	Command-and-control system operation, leadership, and team coordination
Safety and security	Cyber security, anti-piracy measures, and implementation	Cyber-attacks, piracy response, risk assessment, and management	Cyber-attack, piracy response strategies, and security measure implementation
Emergency and Abnormal Operation	Vessel monitoring, alarms, and initial emergency response	Critical systems, failure modes, emergency response, and leadership	Emergency procedure management, leadership, decision-making, and crisis management
Vessel and ROC Operations	ROC role, legislation, collaboration, and adaptability	ROC organisation, security, planning, and monitoring	Best practices in ROC and MASS operations, personnel, and legislation management
Use of AI and Advanced Technologies	Human-Machine teaming, AI basics, and working with AI systems	Human-Machine Teaming, AI models, analytical thinking, and problem-solving	AI integration, validation processes, critical thinking, and analytical skills

To facilitate the international community's work on reskilling and upskilling the maritime workforce for MASS operations, the IMO created the MASSPeople international competency standards working group, formed in early 2021; see www.masspeople.org for more. The group presented a set of competency standards for MASS operators across three functional levels as shown in Table 3.

So far, this is the most advanced progress by the IMO groups to clarify MASS remote operators' roles and functions, and by extension the necessary knowledge, skills and abilities. This is anticipated to be used for the development of Chapter 15 of the coming goal-based MASS code.

The emphasised skills can be broadly categorised into technical, operational, and managerial competencies. Technical skills focus on the understanding and operation of MASS systems, software, propulsion, and advanced technologies such as AI and Human-Machine Teaming. Operational skills involve manoeuvring, situational awareness, communication, risk assessment, and emergency response. Managerial skills include strategic thinking, long-term planning, resource allocation, leadership, and decision-making.

Table 3 also reveals a progression of skills from the Support to Management levels, with each level requiring a deeper understanding of the systems, processes, and decision-making involved in MASS operations. This suggests the need for a structured training and career development framework to ensure operators acquire the necessary competencies as they advance in their roles. Across all levels, there is a strong emphasis on the understanding and application of AI and Human-Machine Teaming concepts.

A comparative analysis of the IMO's progress on skills for MASS operators and the findings from our systematic review show several key areas of convergence and divergence. Both emphasise the importance of a blend of technical, operational, and managerial skills, with a focus on digital competencies, traditional maritime knowledge, and the ability to work with AI and advanced technologies.

However, the systematic review findings place a stronger emphasis on Higher-Order Thinking Skills (HOTS), such as critical thinking, decision-making, and problem-solving. The review also highlights the crucial role of interpersonal skills, including communication, collaboration, adaptability and leadership, which are not given the same level of prominence in the IMO's work. Yet, it is important to note that IMO aims to provide a regulatory framework for the safety of MASS, and work on the human element section is ongoing. At the same time, IMO's intent is not to produce an 'STCW for MASS operators,' but rather to establish high-level safety standards and guidelines that ensure the integration of human factors into MASS operations, setting the scene for future training and certification protocols to be developed in alignment with these standards.

4. Discussion and conclusions

4.1. Key findings and discussion

There is a clear upward trend in research interest for future skills related to autonomous ships from 2018 onwards, balanced between industry and academic contributions, with a notable peak in 2020 and 2022. Our systematic review has identified 11 competencies across four categories. The most prominent of these are digital competencies and communication & collaboration, followed by automation & systems and leadership. The literature also highlighted the importance of traditional maritime competency, and Higher Order Thinking competencies including problem-solving and critical thinking. Engineering competencies, adaptability & flexibility, safety management and remote operation competencies also emerged as critical for MASS, though not as prevalent in the literature as the previous ones.

The emergent competencies and skills framework derived from the literature offers a typology of knowledge, skills and abilities necessary for training future seafarers or operators for MASS. This framework, predominantly cognitive and functional, highlights the technical demands of MASS. Sharma and Kim (2022) and Chang, Lin, et al. (2024) highlighted the necessity for maritime professionals to possess technical proficiency and a comprehensive understanding of automated systems. This aligns with Murai et al. (2022) which underscores the importance of skilled operator-level recognition in ship manoeuvring situations, an essential skill in MASS operations. Moreover, Y. Li, Duan, and Liu (2019) emphasised the need for 'smart seafarers' who are adept in artificial intelligence, big data, cybersecurity, and digital systems, further illustrating the multifaceted nature of required competencies in this field. Concurrently, the framework emphasises the social and meta aspects through the need for adaptability, continuous learning, and strong interpersonal interactions (Ceylani, Kolçak, and Solmaz 2022; Chowdhury et al. 2023). Overall, the adoption of these skillset can lead to enhanced operator capabilities, which could also compensate for the risks of autonomous vessels, thus, increasing their overall safety. This is for example in line with example Meir, Grimberg, and Musicant (2024) which propose that the risks of autonomous vehicles' operations, particularly in tele-driving, can be compensated by the capabilities of the operator and the system.

This study's findings reveal a significant paradigm shift in the maritime sector, emphasising the integration of human intelligence with advanced machine capabilities. This transition, crucial in the context of MASS, brings into focus the increasing cognitive load on maritime professionals as they manage complex automated systems, requiring a balance of technical expertise, mental agility, and stress management skills (Murai et al. 2022).

Notably, the rise of RCCs and RCOs in the literature marks a transformative shift in operations discussions, maintaining the relevance of traditional maritime skills in this new context (Kennard, Zhang, and Rajagopal 2022; Saha 2023). While streamlining operations and reducing human onboard presence, MASS creates a demand for a new kind of maritime professional: the Remote Operator (RO). These professionals, stationed ashore, play a pivotal role in monitoring and controlling the ship's position and parameters. These operators might control more than one vessel; in the relevant IMO discussion of Remote Operation Management companies stated that companies might control more than one

RCC. These developments not only reflect the integration of technology in maritime operations but also suggest a redefinition of maritime roles, where traditional skills are merged with advanced technological competencies, creating a hybrid domain of expertise that is both innovative but also rooted in established maritime knowledge (Emad and Ghosh 2023).

The above literature review, combined with the interpretation of our key findings, has led to the identification of three important themes. These offer an exploration into the future skills and competencies required for autonomous ships and could serve as potential avenues for further research exploration.

4.1.1. Theme 1 - a hybrid competency model: balancing traditional seafaring skills with new competencies

It is important to strike a balance between traditional seafaring and the new competencies required for autonomous shipping. While many current seafaring competencies, both technical and non-technical, will remain relevant, there is a growing need for operators to upskill and adapt to working with autonomous ships and shore-based stations. First, as highlighted in the discussions on the MASS Code, there is a necessity for familiarity with 'advanced technological tools;' this is underscored by the need for a strong emphasis on digital competencies presented as emphasised in Section 3.1. For instance, traditional seamanship skills, such as navigation, and engine operation skills would need to be enhanced to incorporate the digital aspect, such as incorporating AI systems and data analytics into navigation, and skills relevant to remote operations.

Additionally, as discussed in Section 3.3, a key difference might be that remote operators do not need to have only traditional seafaring skills. Instead, they need to possess what the drafted MASS Code refers to as 'supplementary competencies.' Instead of the conventional competency to 'plan a voyage and conduct navigation,' remote operators might need to 'understand and operate intelligent navigation systems of autonomous ships.' In emergency situations, they might require the competency to 'understand and execute emergency responses using the emergency response system of a MASS,' rather than the traditional skill of 'coordinating search and rescue operations' (MSC 109/INF.13).

The competencies and skills framework derived from this systematic review suggests that future maritime personnel should ideally have a foundation in traditional seafaring before acquiring the necessary skills to work with autonomous systems (Emad and Ghosh 2023; Kennard, Zhang, and Rajagopal 2022). This highlights the significance of developing a comprehensive training and education framework that seamlessly integrates traditional and emerging skills.

4.1.2. Theme 2 - balancing technological expertise and fundamental maritime skills: striking a balance

The question of whether future seafarers/operators of autonomous ships should have IT specialist skills is crucial. The literature underscores the importance of technological expertise (refer to Section 3.1 for more details), indicating a distinct move towards more sophisticated IT systems on MASS. One side argues for a clear separation of roles between system users, operators, and IT specialists, stressing the importance of focusing on the core operational and navigational skills (see Section 4.2) (Lützhöft and Earthy 2023). On the other hand, the increasing complexity of autonomous systems and the need for operators to engage with, manage, and possibly troubleshoot these complex systems offer a contrasting viewpoint. This view suggests that a higher degree of IT expertise is essential for the future workforce. In fully autonomous vessels (Degree Four), the ability to scrutinise decisions made by the operating system of the ship, as highlighted in the reviews, suggests a need for a deeper comprehension of the technologies driving autonomous operations.

4.1.3. Theme 3 - METs: integrating knowledge, skills, and attitudes within a 'learning to learn' framework

The skills framework derived from the systematic review which we presented above (see also Figure 6), when analysed through the lens of Le Deist and Winterton's (2005) competency dimensions, offers MET institutions strategies for optimising their curricula for the MASS era. Given the predominance of cognitive (knowledge) and functional (know-how) aspects in the framework, MET institutions should prioritise the development of curricula that provide a robust foundation in the knowledge and practical skills necessary for MASS operations. This might involve a greater focus on subjects such as automation, cybersecurity, data analytics, and software engineering. Furthermore, the presence of social competencies in the framework underscores the importance of developing students' interpersonal skills such as communication, collaboration, leadership, and cultural awareness.

The identification of meta skills and competencies also suggests that MET institutions should focus on developing students' ability to learn, adapt, and self-regulate in the face of rapid technological change and uncertainty. By emphasising the development of these competencies, MET institutions can foster a *'learning to learn'* ability among their students, which is essential for lifelong learning and adapting to new challenges (Bogusławski et al. 2022; Nikolov et al. 2021). Incorporating problem-based learning (PBL), reflective methods, and social learning opportunities can significantly enhance seafarers' learning. PBL immerses seafarers in real-world maritime challenges, fostering critical thinking and self-directed learning. Reflective methods encourage self-awareness and continuous improvement by prompting seafarers to evaluate their experiences and strategies. Social learning opportunities, such as peer interactions and feedback—which is how most seafarers learn and gain experience—offer diverse perspectives and motivation, creating a dynamic and supportive learning environment.

4.2. Implications and future research

The findings of this systematic review have significant implications for the future of the maritime sector. The study contributes to the evolution in MET practices by providing a clear set of essential skills and identifying key themes. Here we discuss the implications for stakeholders and offer recommendations to address the challenges and opportunities presented by the advent of autonomous shipping.

MET institutions are key players in equipping the next generation of maritime professionals. This study proposes a skills framework that advocates for a paradigm shift in curriculum development and training programme design. MET institutions should adopt a hybrid model, blending traditional seafaring skills with modern competencies required by the introduction of autonomous vessels. To meet the changing demands of the maritime sector, a bold reimagining of traditional curriculum is crucial. This includes the integration of new topics such as automation, cybersecurity, data analytics and software engineering into maritime education. Additionally, through hands-on training using advanced technologies like simulations and virtual reality along with real-world case studies, bridging the gap between theory and application can be achieved. It's essential that METs foster a culture promoting lifelong learning and adaptability among students to thrive in an era where technology evolves rapidly. Collaborations with industry partners are necessary to facilitate the creation of relevant curricula and responsivity to the evolving needs of the maritime sector.

At the same time, as we move towards the implementation of fully autonomous systems in maritime operations, a new education specialisation will likely emerge; that for remote operators. In the short term, there may be a transitional phase where seafarers can be retrained to take on onshore roles. However, as technology continues to evolve and the demands of MASS operations become more complex and vessels fully automated, the required skill set for these new roles may diverge significantly from those currently possessed by seafarers. Thus, in the long term, a separate role may emerge, requiring a distinct education and training program.

For the maritime workforce, the implications are far-reaching, underscoring the need for continuous upskilling and reskilling to stay ahead of technological advancements. To remain competitive, maritime professionals must take personal responsibility for their learning and actively pursue opportunities to acquire new skills. Those who can combine traditional seafaring with emerging technologies will have a clear advantage; younger seafarers may find this easier as they are more familiar with modern tools and devices. Equally important is the cultivation of strong interpersonal skills, particularly in communication, collaboration, and leadership. As autonomous shipping operations become more complex and distributed, the ability to work effectively in diverse, cross-functional teams will be a critical success factor. Furthermore, having a willingness and mindset for ongoing learning and adaptation is no longer just an option but a necessity for succeeding in this new era of maritime operations (see Theme 3).

Policymakers and regulators have an essential role in creating an enabling environment for the adoption of autonomous shipping technologies. The findings emphasise the importance of establishing a forward-looking, adaptive regulatory framework. This latter should balance between encouraging innovations and progress and ensuring the safety and security of autonomous shipping operations. To achieve this balance, clearly defined guidelines for designing, constructing and managing autonomous vessels are crucial, standards for crew training and certification. There is no single path to autonomous shipping. It requires a collective effort between stakeholders. Collaboration among MET institutions, industry partners, policymakers and international organisations is necessary for creating a shared vision for the evolution of the maritime sector.

Finally, this study also reveals the need for further research to deepen the understanding of the human factors in autonomous shipping. This research should focus on developing empirical evidence to validate and refine the skills framework identified in this study and could involve conducting large-scale surveys or interviews with maritime professionals, educators, and industry stakeholders to assess the relevance and importance of specific competencies. At the same time, we could perhaps look at the experience gained in other sectors such as unmanned aerial vehicles; see Lynch et al. (2022).

Additionally, while the current study provides a comprehensive framework of the broad categories of skills and competencies, a more granular exploration of the specific roles and responsibilities of MASS operators is necessary. This could involve conducting detailed job analyses and task inventories to map out the precise activities and functions performed by operators in different scenarios, such as remote monitoring, system maintenance, and emergency response.

By breaking down the roles of MASS operators into their constituent tasks and activities, researchers can develop a more fine-grained understanding of the knowledge, skills, and abilities required for each function. This could lead to the development of detailed competency profiles or job specifications that outline the specific technical, cognitive, and interpersonal requirements for different operator roles.

Finally, as previously mentioned, there are presently shared competency standards for positions both on board MASS and in RCCs. Nonetheless, as roles continue to evolve, there will be a growing demand for unique skill sets and competencies. Consequently, this analysis could lay the groundwork for investigating the skills and competencies pertinent to RCOs.

Notes

1. Sea GPT is an AI chatbot developed by Greywing, a Singapore-based maritime intelligence platform, and based on Open AI's GPT4 model for automating crew changes. It aims to streamline the communication process, like drafting emails with important questions and extracting the most essential information from port agency replies for specific crew members.
2. In this paper we cite IMO documents submitted the Maritime Safety Committee (MSC) using the standard code: MSC x/y/z, where x is session, y is agenda item, and z is document number of agenda item. IMO documents do not appear in the reference list and are part of the 'grey' literature.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by the International Association of Maritime Universities.

ORCID

Mehdi Belabyad http://orcid.org/0009-0001-3807-6962
Christos Kontovas http://orcid.org/0000-0001-9461-6436
Robyn Pyne http://orcid.org/0000-0003-4661-1651
Chia-Hsun Chang http://orcid.org/0000-0002-7351-8471

References

Aria, M., and C. Cuccurullo. 2017. "Bibliometrix: An R-Tool for Comprehensive Science Mapping Analysis." *Journal of Informetrics* 11 (4): 959–975. https://doi.org/10.1016/j.joi.2017.08.007.

Bartusevičienė, I. 2020. "Maritime Education and Training as a Tool to Ensure Safety at Sea in the Process of Introduction of Maritime Autonomous Surface Ships in Shipping." *Proceedings of the 24th International Scientific Conference Transport Means*, Dubna, Russia, 2020: 368–374.

Bates, M. J. 1989. "The Design of Browsing and Berrypicking Techniques for the Online Search Interface." *Online Review* 13 (5): 407–424. https://doi.org/10.1108/eb024320.

Belev, B., A. Penev, Đ. Mohović, and A. Perić Hadžić. 2021. "Autonomous Ships in Maritime Education Model Course 7.01." *Pomorstvo* 35 (2): 388–394. https://doi.org/10.31217/p.35.2.20.

Bogusławski, K., M. Gil, J. Nasur, and K. Wróbel. 2022. "Implications of Autonomous Shipping for Maritime Education and Training: The Cadet's Perspective." *Maritime Economics & Logistics* 242 (2): 327–343. https://doi.org/10.1057/s41278-022-00217-x.

Bolbot, V., O. Methlouthi, M. Chaal, O. Valdez, A. Bahootoroody, A. Tsetkova, M. Hellström, J. Saarni, and S. Virtanen. 2022. *Identification and Analysis of Educational Needs for Naval Architects and Marine Engineers in Relation to the Foreseen Context of Maritime Autonomous Surface Ships (MASS)*, Aalto University SCIENCE + TECHNOLOGY. https://urn.fi/URN:ISBN:978-952-64-0826-2 .

Bramer, W. M., M. L. Rethlefsen, J. Kleijnen, and O. H. Franco. 2017. "Optimal Database Combinations for Literature Searches in Systematic Reviews: A Prospective Exploratory Study." *Systematic Reviews* 6 (1): 245. https://doi.org/10.1186/s13643-017-0644-y.

Ceylani, E., İ. Ç. Kolçak, and M. S. Solmaz. 2022. "A Ranking of Critical Competencies for Future Seafarers in the Scope of Digital Transformation." In *Proceedings of the International Association of Maritime Universities Conference*, Batumi, Georgia.

Chaal, M., X. Ren, A. BahooToroody, S. Basnet, A. V. Victor Bolbot, and P. van Gelder. 2023. "Research on Risk, Safety, and Reliability of Autonomous Ships: A Bibliometric Review." *Safety Science* 167 (November): 106256–56. https://doi.org/10.1016/j.ssci.2023.106256.

Chang, C.-H., I. Bandara Wijeratne, C. Kontovas, and Z. Yang. 2024. "COLREG and MASS: Analytical Review to Identify Research Trends and Gaps in the Development of Autonomous Collision Avoidance." *Ocean Engineering* 302 (April): 117652. https://doi.org/10.1016/j.oceaneng.2024.117652.

Chang, C.-H., C. Kontovas, Q. Yu, and Z. Yang. 2021. "Risk Assessment of the Operations of Maritime Autonomous Surface Ships." *Reliability Engineering and System Safety* 207 (March): 107324. https://doi.org/10.1016/j.ress.2020.107324.

Chang, C.-H., C.-C. Lin, Z. Yang, and C. Kontovas. 2024. "Evaluating the Social Acceptance of Autonomous Ferries: An Observation from Passengers' Boarding Willingness." *Transport Policy* 159 (October): 83–94. https://doi.org/10.1016/j.tranpol.2024.10.012.

Chowdhury, H., M. Mojahid, H. Rashid Askari, and R. Tauhid Bushra. 2023. "Revisiting Seafarers' Skills in the Twenty-First Century: A Modified Delphi-BWM Approach." *Australian Journal of Maritime & Ocean Affairs* 16 (2): 141–161. https://doi.org/10.1080/18366503.2023.2214429.

Cicek, K., E. Akyuz, and M. Celik. 2019. "Future Skills Requirements Analysis in Maritime Industry." *Procedia Computer Science* 158:270–274. https://doi.org/10.1016/j.procs.2019.09.051.

Economist Impact. 2023. Global Maritime Trends 2050. https://impact.economist.com/ocean/global-maritime-trends-2050/downloads/Global%20Maritime%20Trends%202050%20Report.pdf.

Emad, G. R., H. Enshaei, and S. Ghosh. 2021. "Identifying Seafarer Training Needs for Operating Future Autonomous Ships: A Systematic Literature Review." *Australian Journal of Maritime & Ocean Affairs* 14 (2): 1–22. https://doi.org/10.1080/18366503.2021.1941725.

Emad, G. R., and S. Ghosh. 2023. "Identifying Essential Skills and Competencies Towards Building a Training Framework for Future Operators of Autonomous Ships: A Qualitative Study." *WMU Journal of Maritime Affairs* 22 (4): 427–445. April. https://doi.org/10.1007/s13437-023-00310-9.

Fan, S., and Z. Yang. 2023. "Analysing Seafarer Competencies in a Dynamic Human-Machine System." *Ocean & Coastal Management* 240 (June): 106662. https://doi.org/10.1016/j.ocecoaman.2023.106662.

Greenhalgh, T., and R. Peacock. 2005. "Effectiveness and Efficiency of Search Methods in Systematic Reviews of Complex Evidence: Audit of Primary Sources." *BMJ* 331 (7524): 1064–1065. https://doi.org/10.1136/bmj.38636.593461.68.

Heij, C., and S. Knapp. 2018. "Predictive Power of Inspection Outcomes for Future Shipping Accidents – an Empirical Appraisal with Special Attention for Human Factor Aspects." *Maritime Policy & Management* 45 (5): 604–621. https://doi.org/10.1080/03088839.2018.1440441.

Hoffmann, T. 1999. "The Meanings of Competency." *Journal of European Industrial Training* 23 (6): 275–286. https://doi.org/10.1108/03090599910284650.

IAMU (International Association of Maritime Universities). 2019. *Global Maritime Professional (GMP) Body of Knowledge*, Tokyo: IAMU. https://iamu-edu.org/wp-content/uploads/2019/09/IAMU_GMP-Body-of-Knowledge.pdf.

Jovanović, I., M. Perčić, A. BahooToroody, A. Fan, and N. Vladimir. 2024. "Review of Research Progress of Autonomous and Unmanned Shipping and Identification of Future Research Directions." *Journal of Marine Engineering & Technology* 23 (2): 82–97. https://doi.org/10.1080/20464177.2024.2302249.

Kennard, A., P. Zhang, and S. Rajagopal. 2022. "Technology and Training: How Will Deck Officers Transition to Operating Autonomous and Remote-Controlled Vessels?" *Marine Policy* 146 (December): 105326. https://doi.org/10.1016/j.marpol.2022.105326.

Kim, M., T.-H. Joung, B. Jeong, and H.-S. Park. 2020. "Autonomous Shipping and Its Impact on Regulations, Technologies, and Industries." *Journal of International Maritime Safety, Environmental Affairs, and Shipping* 4 (2): 1–9. https://doi.org/10.1080/25725084.2020.1779427.

Kim, T.-E., and S. Mallam. 2020. "A Delphi-AHP Study on STCW Leadership Competence in the Age of Autonomous Maritime Operations." *WMU Journal of Maritime Affairs* 19 (2): 163–181. https://doi.org/10.1007/s13437-020-00203-1.

Kobyliński, L. 2018. "Smart Ships – Autonomous or Remote Controlled?" *Scientific Journals of the Maritime University of Szczecin 53*. https://repository.am.szczecin.pl/handle/123456789/2465.

Lau, Y.-Y., and A. K. Y. Ng. 2015. "The Motivations and Expectations of Students Pursuing Maritime Education." *WMU Journal of Maritime Affairs* 14 (2): 313–331. https://doi.org/10.1007/s13437-015-0075-3.

Le Deist, F. D., and J. Winterton. 2005. "What is Competence?" *Human Resource Development International* 8 (1): 27–46. https://doi.org/10.1080/1367886042000338227.

Li, X., and K. Fai Yuen. 2024. "A Human-Centred Review on Maritime Autonomous Surfaces Ships: Impacts, Responses, and Future Directions." *Transport Reviews* 44 (4): 1–20. https://doi.org/10.1080/01441647.2024.2325453.

Li, Y., Z. Duan, and Z. Liu. 2019. "Study on Risk-Based Operators' Competence Assessment of Maritime Autonomous Surface Ships." *2019 5th International Conference on Transportation Information and Safety (ICTIS)*, IEEE Xplore. https://doi.org/10.1109/ictis.2019.8883599.

Lützhöft, M., and J. Earthy. 2023. *Human-Centred Autonomous Shipping*. Abingdon: Routledge.

Lynch, K. M., V. A. Banks, A. P. J. Roberts, S. Radcliffe, and K. L. Plant. 2022. "Maritime Autonomous Surface Ships: Can We Learn from Unmanned Aerial Vehicle Incidents Using the Perceptual Cycle Model?" *Ergonomics* 66 (6): 1–19. https://doi.org/10.1080/00140139.2022.2126896.

Mallam, S. C., S. Nazir, and A. Sharma. 2020. "The Human Element in Future Maritime Operations – Perceived Impact of Autonomous Shipping." *Ergonomics* 63 (3): 334–345. https://doi.org/10.1080/00140139.2019.1659995.

Maritime, U. K. 2020. Labour Market Intelligence Scoping Report. https://www.maritimeuk.org/priorities/people/skills-commission/projects/labour-market-intelligence-scoping-report/.

Meir, A., E. Grimberg, and O. Musicant. 2024. "The Human-Factors' Challenges of (Tele)drivers of Autonomous Vehicles." *Ergonomics* (May): 1–21. https://doi.org/10.1080/00140139.2024.2346552.

Methley, A. M., S. Campbell, C. Chew-Graham, R. McNally, and S. Cheraghi-Sohi. 2014. "PICO, PICOS and SPIDER: A Comparison Study of Specificity and Sensitivity in Three Search Tools for Qualitative Systematic Reviews." *BMC Health Services Research* 14 (1): 1–10. https://doi.org/10.1186/s12913-014-0579-0.

Mulder, M., G. Judith, B. Harm, and W. Renate. 2009. "The New Competence Concept in Higher Education: Error or Enrichment?" Edited by Johathan Winterton." *Journal of European Industrial Training* 33 (8/9): 755–770. https://doi.org/10.1108/03090590910993616.

Munim, Z. H., and H. Haralambides. 2022. "Advances in Maritime Autonomous Surface Ships (MASS) in Merchant Shipping." *Maritime Economics & Logistics* 24 (May): 181–188. https://doi.org/10.1057/s41278-022-00232-y.

Murai, K., H. Tamaru, R. Shoji, E. Saito, M. Minami, and K. Kokubun. 2022. "Characteristics of Professional Sharp-Lookout Skills Towards Maritime Autonomous Surface Ships." *2022 World Automation Congress (WAC)*. https://doi.org/10.23919/wac55640.2022.9934189.

Nikolov, I., I. Colmorn, C. Hluchy, and R. Garcia-Bernal. 2021. "The Journey Towards Autonomous Ships and the Role of Seafarers in the Future: A Bibliographical Perspective." *Poster presented at the 21st Annual General Assembly – AGA 2021*, Alexandria, Egypt, October 26–28.

Page, M. J., J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, et al. 2021. "The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews." *The British Medical Journal* 372 (71). https://doi.org/10.1136/bmj.n71.

Park, C., C. Kontovas, Z. Yang, and C.-H. Chang. 2023. "A BN Driven FMEA Approach to Assess Maritime Cybersecurity Risks." *Ocean & Coastal Management* 235:106480. https://doi.org/10.1016/j.ocecoaman.2023.106480.

Saha, R. 2023. "Mapping Competence Requirements for Future Shore Control Center Operators." *Maritime Policy & Management* 50 (4): 415–427. https://doi.org/10.1080/03088839.2021.1930224.

Sharma, A., and T.-E. Kim. 2022. "Exploring Technical and Non-Technical Competencies of Navigators for Autonomous Shipping." *Maritime Policy & Management* 49 (6): 831–849. https://doi.org/10.1080/03088839.2021.1914874.

Sharma, A., K. Tae-Eun, and N. Salman. 2021. "Implications of Automation and Digitalization for Maritime Education and Training." In *Sustainability in the Maritime Domain*, edited by R. Lozano, S. Afionis, and C. Desha, 223–233. Springer. https://doi.org/10.1007/978-3-030-69325-1_11.

SkillSea. 2020. "Future Skills and Competence Needs." https://www.skillsea.eu/images/Public_deliverables/del2022/D%201.1.3_Future%20skills%20and%20competence%20needs_final_28%20April%202022.pdf.

Stoof, A., R. L. Martens, J. J. G. van Merriënboer, and T. J. Bastiaens. 2002. "The Boundary Approach of Competence: A Constructivist Aid for Understanding and Using the Concept of Competence." *Human Resource Development Review* 1 (3): 345–365. https://doi.org/10.1177/1534484302013005.

Teodorescu, T. 2006. "Competence versus Competency: What is the Difference?" *Performance Improvement* 45 (10): 27–30. https://doi.org/10.1002/pfi.4930451027.

Theotokas, I. N., I. N. Lagoudis, and K. Raftopoulou. 2024. "Challenges of Maritime Human Resource Management for the Transition to Shipping Digitalization." *Journal of Shipping and Trade* 9 (1). https://doi.org/10.1186/s41072-024-00165-0.

Veitch, E., and O. Andreas Alsos. 2022. "A Systematic Review of Human-AI Interaction in Autonomous Ship Systems." *Safety Science* 152 (August): 105778. https://doi.org/10.1016/j.ssci.2022.105778.

Winterton, J., F. Delamare Le Deist, and E. Stringfellow. 2006. *Typology of Knowledge, Skills and Competences: Clarification of the Concept and Prototype*, European Centre for the Development of Vocational Training. https://www.cedefop.europa.eu/files/3048_en.pdf.

WMU (World Maritime University) and ITF (International Transport Workers' Federation). 2019. "Transport 2040: Automation, Technology, Employment - the Future of Work." World Maritime University. https://commons.wmu.se/cgi/viewcontent.cgi?article=1071&context=lib_reports.

WMU (World Maritime University) and ITF (International Transport Workers' Federation). 2023. "Transport 2040: Impact of Technology on Seafarers - the Future of Work." World Maritime University. https://commons.wmu.se/cgi/viewcontent.cgi?article=1091&context=lib_reports.

Wohlin, C. 2014. "Guidelines for Snowballing in Systematic Literature Studies and a Replication in Software Engineering." *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE, 14*: 1–10. https://doi.org/10.1145/2601248.2601268.

Yoshida, M., E. Shimizu, M. Sugomori, and A. Umeda. 2020. "Regulatory Requirements on the Competence of Remote Operator in Maritime Autonomous Surface Ship: Situation Awareness, Ship Sense and Goal-Based Gap Analysis." *Applied Sciences* 10 (23): 8751. https://doi.org/10.3390/app10238751.

Zhang, X., C. Wang, L. Jiang, L. An, and R. Yang. 2021. "Collision-Avoidance Navigation Systems for Maritime Autonomous Surface Ships: A State of the Art Survey." *Ocean Engineering* 235 (September): 109380. https://doi.org/10.1016/j.oceaneng.2021.109380.