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The human element in autonomous shipping: a study on skills and competency requirements

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Abstract
This study examines the evolving landscape of the shipping industry in the context of Maritime Autonomous Surface Ships (MASS), with a focus on the critical role of Maritime Education and Training (MET). As the sector undergoes rapid transformation, there is a pressing need for MET providers to adapt their curricula and training programs to meet emerging industry standards. Despite growing research interest in future skills and competencies for the MASS workforce, a comprehensive framework for assessing and ranking these skills remains lacking. To address this gap, we propose the application of multi-criteria decision-making (MCDM) techniques, specifically fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to evaluate and prioritise proficiency requirements for MASS. The analysis, based on the responses of 174 experts, yields consistent and robust results, identifying 'Operational Skills', 'Digital Skills', and 'Maritime Competency' as the most crucial skills and competencies for MASS operations. A number of insights and recommendations are provided to guide MET institutions in updating their educational offerings to meet the demands of the evolving maritime industry.

Keywords Autonomous shipping · Maritime education and training · Skills and competencies for MASS · Fuzzy TOPSIS

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1 Introduction

The shipping sector is facing a significant shift driven primarily by increased automation, digitalisation and autonomous technologies. This transition, commonly known as"Shipping 4.0"(Aiello et al. 2020; Kavallieratos et al. 2020; Razmjooei et al. 2023), has the potential to completely transform ship design, operations, and manning. The introduction of Maritime Autonomous Surface Ships (MASS) is a clear demonstration of this transformative change, as exemplified by various initiatives including MUNIN (Maritime Unmanned Navigation through Intelligence in Networks), AAWA (Advanced Autonomous Waterborne Applications), SVAN (Safer Vessel with Autonomous Navigation) and YARA Birkeland which have either been completed or are currently underway (Burmeister et al. 2014; Rolls Royce 2016; Rolls Royce 2018; Yara 2024). These initiatives aim to address the challenges surrounding environmental sustainability, safety and efficiency for maritime transportation.

The International Maritime Organisation (IMO) defines MASS as a ship that can operate independently of human interaction to varying degrees (IMO 2021). The IMO has identified four degrees of autonomy for MASS:

"Degree 1: Ship with automated processes and decision support
Degree 2: Remotely controlled ship with seafarers on board
Degree 3: Remotely controlled ship without seafarers on board
Degree 4: Fully autonomous ship"

These degrees of autonomy illustrate the expected progressive stages of implementing autonomous technology in shipping, from partial automation to fully autonomous operation.

Autonomous shipping offers potential advantages, such as improved safety measures, lowered costs of operation and enhanced productivity. By decreasing human errors, which make up about 75–96% of marine accidents (Allianz 2012; Chang et al. 2021), autonomous ships could enhance shipping safety. The use of autonomous technology can also optimise fuel consumption, decrease crew costs and enhance overall operational efficiency (Ziajka-Poznańska and Montewka 2021). Nonetheless, the implementation of autonomous shipping also faces challenges. Cybersecurity poses a crucial matter since autonomous ships extensively depend on electronic systems and networks, making them susceptible to cyber threats (Tusher et al. 2022; Park et al. 2023). Another issue is the practicality of autonomous shipping due to the significant upfront expenses involved in acquiring the necessary technology and infrastructure (Nakashima et al. 2023). Furthermore, obtaining regulatory approval and establishing suitable legal structures are essential for the successful integration of autonomous shipping (Orzechowski 2024).

As the industry advances towards increased levels of autonomy, the duties and roles of shipboard personnel are anticipated to experience significant changes (Kitada et al. 2019). The traditional crew will slowly be changed by remote operators and on-land supporting teams, causing a fundamental transformation in how vessels operate (Choi and Lee 2022). This change will necessitate a reassessment of key skills and competencies for seafarers, as well as a reshuffling of organisational structure and decision processes.

The role of 'Maritime Education and Training' (MET) within this transition is significant. As the industry progresses, MET providers must adapt their educational curricula and training programmes to match the evolving standards of this era (Demirel 2020). However, these institutions face various challenges in equipping the future workforce for autonomous shipping. A major one is the absence of a comprehensive and standardised framework for preparing autonomous workforce. The IMO has not yet developed a clear set of guidelines and proficiency standards for autonomous shipping, making it challenging for MET institutions to create and establish successful training courses.

Despite the increasing research interest in the skills and competencies required for the future MASS workforce, there continues to be a lack of a comprehensive framework for assessing and ranking these skills. Prior research has mainly focused on identifying specific subsets of skills, typically categorised as hard/soft or technical/non-technical skills and competencies (Kennard et al. 2022; Emad and Ghosh 2023), without considering a holistic set of criteria for determining their significance and viability. Section 2.1 provides a concise overview of the literature. For a comprehensive survey of the relevant literature on skills and competencies, interested readers are referred to Chang et al. (2024b).

To address this gap, this research aims to identify and evaluate the importance of the skills and competencies for MASS. This research proposes the implementation of multi-criteria decision-making (MCDM) techniques in assessing and prioritizing the proficiency requirements for autonomous shipping. In fact, MCDM methods are used to identify, categorise, and rank alternatives based on subjective preferences. They are effective for ranking alternatives as they provide a comprehensive evaluation, especially useful when dealing with conflicting criteria. One specific method is Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), which compares options based on their degree of proximity to ideal and anti-ideal solutions (Hwang and Yoon 1981). TOPSIS has proven effective as a means of ranking alternatives and facilitating decisions in complex situations (Behzadian et al. 2012). TOPSIS, compared to other similar MCDM methods, is particularly advantageous due to its user-friendliness, efficiency, and ability to provide clear rankings. This study uses fuzzy TOPSIS to assess and rank key skills required for autonomous shipping. This method offers distinct advantages over similar techniques. As demonstrated in Section 11.3.3, it produces rankings comparable to other methods, thereby enhancing the robustness of our results. Section 3 provides more information on the selection of the methodology used in this paper.

This study makes novel contributions to the field of MASS and MET by: a) proposing a framework for evaluating and prioritizing the skills and competencies requirements for autonomous ships; b) identifying a set of criteria for assessing the importance and feasibility of skills and competencies; c) ranking the identified skills and competencies based on their relevance and criticality for the future MASS workforce; and d) providing insights and recommendations for MET institutions to adapt their curricula and training programmes, and to policy-makers.

The rest of the paper is structured as follows: Section 2 reviews the relevant literature and identifies a list of future skills and competencies for MASS, along with a set of criteria to evaluate them. Section 3 outlines the methodology employed, and Section 11 details the findings. Section 12 offers a discussion and insights on policy implications, and the paper concludes with potential recommendations for future research in Section 13.

2 Literature review, research gap and problem setting

2.1 Relevant literature and research gap

The introduction of MASS presents a revolutionary change in the industry. However, this transition also brings challenges, especially when it comes to preparing the workforce with the necessary skills and competencies (Sharma and Kim 2022; Koh et al. 2022). Despite the introduction of autonomous and remote shipping, humans will still play a crucial role in complementing new technologies. This shows the significance of preparing for a future-proof workforce (Kennard et al. 2022).

Several reviews have established foundational frameworks for understanding the impact of autonomous shipping on the skills and competencies of seafarers. Li and Yuen (2024) conducted a review of human-centred MASS research, categorising future maritime skills into operational/technical skills (system operation, maintenance, data processing), cognitive/psychological skills (situation awareness, emergency response), social skills (communication, leadership), and continuous learning capabilities. Their work identified certain traditional operational skills becoming redundant, such as magnetic compass usage and manual ship position determination. Cicek et al. (2019) literature review extends this via establishing a structured framework of 33 competencies across four key domains: technical, social, methodological and personal competencies. Emad et al. (2021) highlights that autonomous ships will still require human oversight, whether onboard or remotely, requiring new technical and cognitive competencies. The study identifies critical skills such as remote monitoring, AI-assisted decision-making, cybersecurity awareness and human-automation interaction.

Ghosh et al. (2024) identify several critical skill areas needed for future seafarers, including: technical competencies (like operating autonomous systems and troubleshooting equipment), non-technical skills (such as communication, leadership, and decision-making), meta-competencies (like computer operation skills), and core ethical values (particularly for emergency decision-making). Their study shows that while the 'International Convention on Standards of Training, Certification and Watchkeeping for Seafarers' (STCW) Code occasionally addresses some behavioural and leadership competencies, it primarily focuses on knowledge-based requirements rather than demonstrated performance abilities. Further research by Ghosh and Emad's (2024a; 2024b) on MASS competency frameworks confirms that existing maritime standards, particularly the STCW Code, are inadequate for the evolving demands of autonomous shipping. They extend the essential competencies needed for MASS operations, covering both technical domains (ICT, AI, electronic engineering) and non-technical areas (communication, leadership, problem-solving), focusing on how these must be defined across different operational levels (Support, Operational, Management). Their research emphasises the importance of creating balanced frameworks that can support both traditional seafaring and autonomous operations during what they anticipate will be an extended transition period.

Further empirical research has also highlighted and validated key future skills and competencies. Seven essential sets of skills and competencies for future sociotechnical systems in autonomous shipping were identified by Hynnekleiv et al. (2020), based on expert workshop discussions, broadly categorised as technical and non-technical competencies. Emad and Ghosh (2023) conducted a qualitative study comprising interviews with 37 participants. They identified five key skill categories that will be crucial: cognitive skills (critical thinking, assertiveness), operational skills (including technical competencies in ICT, AI, and systems integration), leadership and teamwork abilities, decision-making capabilities, and communication skills. Their research indicate that future operators should first obtain traditional seafaring qualifications before specializing in autonomous systems operation, effectively creating a two-tier qualification system. The study also highlighted that while technical skills in areas like information technology, artificial intelligence and satellite communications will be essential, non-technical competencies such as problem-solving and effective communication will become even more critical due to the complex nature of remote ship operations and the need to manage information from multiple sources. Similarly, Sharma and Nazir (2021) concluded future operators should obtain traditional seafaring qualifications before specializing in autonomous systems. Their mixed-methods study found five key technical competencies needed for autonomous ship operators: IT/AI skills, safety/cybersecurity management, basic engine operations knowledge, electronic equipment expertise, and systems integration capabilities. Non-technical skills included were situational awareness and leadership.

Major maritime organizations have also contributed to understanding future skill requirements for MASS operations. The International Association of Maritime Universities (IAMU 2019) published the Global Maritime Professional (GMP) Body of Knowledge, providing a comprehensive framework that identifies critical competencies across cognitive, affective, and psychomotor domains. Their work, particularly on long-term projections, highlights technological awareness, computing skills, adaptability and leadership as crucial competencies for future maritime professionals. This is further supported by the World Maritime University and International Transport Workers'Federation's Transport 2040 project (WMU and ITF 2023), which specifically examined how digitalization and automation will transform maritime competency requirements. Their research mapped global technological trends to identify future maritime competencies, highlighting the growing importance of advanced technological proficiency in AI and automation, cybersecurity awareness, and problem-solving skills. Both organizations emphasise the critical need for continuous learning and adaptability in the context of increasing vessel autonomy.

Among these studies, a limited subset has attempted to assess and rank the identified skills and competencies using MCDM methods. Li et al. (2019) used a fuzzy comprehensive evaluation method to evaluate the competencies of MASS operators across both hard and soft skills. Kim and Mallam (2020) used the Delphi-Analytical Hierarchy Process (AHP) to explore the requirements for leadership competence in the STCW during autonomous maritime operations. They highlighted factors such as situational awareness, decision-making ability and communication prowess in the realm of remote operation. Ceylani et al. (2022) used a fuzzy AHP to rank crucial skills needed for future seafarers in light of digital transformation. Their study revealed that cognitive competencies like reasoning, decision-making, problem-solving and critical thinking were the most essential followed by operational, individual and social ones. Furthermore, Hossain Chowdhury et al. (2023) applied the Best-Worst Method to identify top-ranked crucial skills for seafarers for the future.

It is important to note that this paper does not include a comprehensive literature review on the topic, as this has been thoroughly covered in other works, such as Belabyad et al. (2025). This study presents an analysis of skills and competencies required for autonomous ship operations and a systematic approach to their ranking based on the finding presented in Chang et al. (2024b). We employ a widely recognised MCDM technique, namely fuzzy TOPSIS, to prioritise the identified skills and competencies based on their relevance and importance for the future MASS workforce.

This analysis provides preliminary insights and recommendations for MET institutions to adapt their curricula and training programs accordingly. We anticipate that this research will stimulate further exploration of the topic and contribute to the enhancement of MET programs in addressing these emerging skill requirements.

2.2 Problem setting

The rapid advancement of autonomous shipping technology has brought about a shift in the maritime industry, necessitating a re-evaluation of the skills and competencies required for the future workforce. These needs go beyond simply identifying which ones are needed, to realistically assessing and prioritising them considering a wide range of criteria. Without such a framework, MET institutions may struggle to develop effective and efficient training programmes that meet the needs of the autonomous shipping industry.

In this study, our goal is to offer recommendations, so the skills and competencies are outlined in general terms. To accomplish this, we identify the key skills and competencies related to Maritime Autonomous Surface Ships (MASS), referred to as ‘alternatives’ in MCDM terminology, through a literature review (see Section 2.3 for more details). MCDM methods have been employed to select a preferred alternative, categorise alternatives, and/or rank them based on subjective preferences. For a comprehensive overview of the classical and fuzzy TOPSIS methodologies, including their applications, benefits, and main challenges, the interested reader can refer to the surveys by Behzadian et al. (2012) and Salih et al. (2019).

In our research, we employ a fuzzy TOPSIS approach and validate our methodology by comparing our results with those obtained from alternative methods. As demonstrated by Ceballos et al. (2017), numerous approaches often yield similar, if not identical, rankings. Our sensitivity analysis, detailed in Section 11.3.3, confirms this finding for our case study, comparing ranks produced by various methods. This consistency is crucial, as our study utilises fuzzy TOPSIS to rank multiple alternatives to provide valuable managerial insights. The observed congruence across different methodologies reinforces the robustness of our results and, consequently, lends credibility to our recommendations (see Section 12).

In summary, a literature review (see Section 2.3) and discussions with experts have helped to identify eleven skill categories relevant to the operations and management of autonomous ships. Additionally, four criteria for evaluating these skills were identified and are discussed in greater detail in the subsequent section. Figure 1 depicts the hierarchical structure and shows the relationship between the identified criteria and the measures or strategies to be assessed.

2.3 Skills and competencies related to autonomous ships

As the maritime industry moves towards autonomy, the skills and competencies required by the workforce are evolving. A systematic literature review was conducted to identify the skills required for MASS. Below is a description of the relevant skills. For a detailed literature review on the skills and competencies to be ranked, refer to Chang et al. (2024b). Additional relevant literature is discussed in Section 2.1.

2.3.1 Digital skills

Digital skills, including cybersecurity, data analytics, cloud technology and software engineering are becoming more significant (Koh et al. 2022; Bolbot et al. 2022; Ceylani et al. 2022). Cybersecurity is specifically emphasised in the literature as it is essential for the remote functioning of self-operating ships (Maritime UK 2020; Park et al. 2023). The future workforce must have strong cyber hygiene

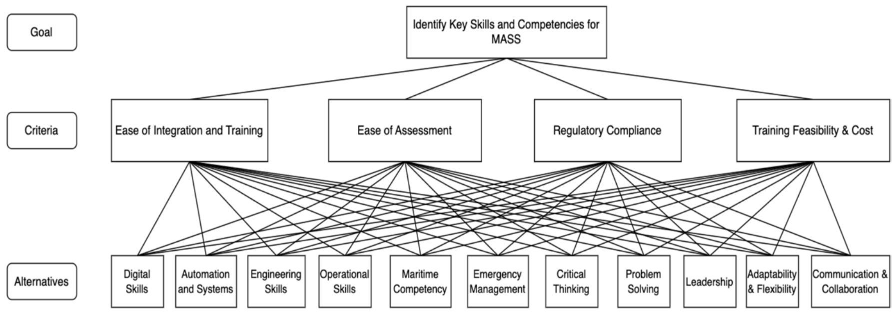


Fig. 1 Hierarchy of skills and competencies ranking for MASS

and continuously evaluate threats and vulnerabilities within onboard networks and remote command centres.

Data analytics and processing skills are essential for MASS workforce, as autonomous ships produce extensive data from different systems (Jo et al. 2020). To gain operational knowledge, the future MASS workforce must possess a profound understanding of this data and use relevant tools (Emad and Gosh, 2023; Fan and Yang 2023). Furthermore, software engineering and programming are essential for coding automation features, integrating systems and executing upgrades (Mallam et al. 2019).

2.3.2 Automation and systems skills

Automation and Systems skills relate to understanding and operating automated maritime systems and technologies, such as fault identification, systems understanding and autonomous systems (Saha 2021; Sharma and Kim 2022; SkillSea 2020). This is especially important because automation touches upon core operations aspects such as navigation, propulsion and cargo handling, which makes it crucial for the future workforce to have a deep understanding of these systems (Saha 2021).

The future MASS workforce must be able to monitor, control and optimise integrated ship systems (Yoshida et al. 2020; Saha 2021). This involves interpreting system data, detecting anomalies, discerning performance metrics and pinpointing aspects for enhancement. Furthermore, troubleshooting skills are also emphasised, as the workforce must be able to diagnose system malfunctions and anomalous sensor outputs (Sharma and Kim 2022; Emad and Ghosh 2023).

2.3.3 Technical proficiency

Engineering skills (i.e., electrical and electronic engineering) include both the understanding of interconnected sensors and data networks and the practical applications in monitoring electrical operations and troubleshooting (Future Federation 2018). Furthermore, mechanical engineering skills are also very important, with the future workforce needing to understand mechanical systems like propulsion and steering to identify problems noted in sensor logs and initiate maintenance or repairs (Bolbot et al. 2022; Sharma and Kim 2022).

2.3.4 Operational skills

Operational skills such as monitoring and analysing data, as well as switching between tasks and recognising limitations are important to ensure the security of autonomous operations (Li et al. 2019; Ceylani et al. 2022). In addition, the future MASS workforce needs to have robust knowledge of engine room operations, this includes alert handling and maintenance skills (Sharma and Kim 2022).

From the operations perspective, multi-tasking skills are essential, reflecting an operator's ability to manage different and various operational aspects without compromising on performance (Veitch et al. 2020; Bogusławski et al. 2022).

2.3.5 Maritime competency

Several studies have highlighted that traditional maritime competency should remain important for autonomous shipping (Li et al. 2019; WMU and ITF 2019; Kennard et al. 2022; Chang et al. 2024a). This includes, for example, an understanding of the 'Convention on the International Regulations for Preventing Collisions at Sea' (COLREG) for the safe navigation of vessels (including skills related to route planning, situational awareness, communications etc.) radar operations and the functions of the 'Electronic Chart Display and Information System' (ECDIS). In addition, understanding the levels of automation and relevant regulatory implications is also important (Maritime UK 2020).

2.3.6 Emergency and safety management

Emergency management skills encompass situational and safety awareness, which involve perceiving, comprehending, and predicting evolving situations, particularly in complex or rapidly changing environments that heavily rely on sensors, data streams, and automation systems. This includes perceiving, understanding, and predicting developing emergency circumstances (Bolbot et al. 2022; Kennard et al. 2022). Additionally, crisis handling involves executing risk assessments, a crucial skill set that not only focuses on recognising potential risks but also on anticipating them in advance, adapting to unexpected obstacles, and learning from past incidents (Sharma and Kim 2022; Maritime UK 2022).

2.3.7 Critical thinking

Critical thinking is an important skill for the future MASS workforce, involving analysing scenarios, identifying issues and devising solutions for different situations in MASS activities, relying on vast datasets and sensor information from various autonomous systems (Jo et al. 2020; Sharma and Kim 2022).

2.3.8 Decision-making and problem-solving skills

Problem-solving skills are essential in navigating the challenges that can arise within autonomous shipping settings. This can include addressing unknown and complex issues, requiring extensive knowledge and proficiency in both the technology and maritime settings, combined with critical thinking (Sharma and Kim 2022; Emad and Ghosh 2023).

2.3.9 Leadership and influence

Leadership skills are important for leading teams and making decisions. 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 (Kim and Mallam 2020). In particular, motivation, inspiration and stakeholder management have been emphasised as key leadership attributes (Sharma and Kim

2022). Leaders must inspire trust and confidence in their teams, especially in an environment where reliance on technology might lead to apprehension.

2.3.10 Adaptability and flexibility

Individual adaptability and flexibility, which encompass a professional's resilience and ability to adjust to changing scenarios and also the technology changes, were also highlighted as necessary skills for MASS. The literature places significant emphasis on self-learning motivation and the drive for life-long learning and improvement (Fan and Yang 2023; Bachari-Lafteh and Harati-Mokhtari, 2021).

2.3.11 Communication and collaboration

Communication and Collaboration skills are necessary for sharing information and working cooperatively with others (Emad et al. 2021). Teamwork, communication and emotional intelligence are key components of these skills. Notably, clear communication between ship and shore workers is critical as crews, operators, engineers and other stakeholders collaborate remotely.

2.4 Assessment criteria

After identifying several key skills and competencies, the next step involves determining a set of criteria to evaluate them. This approach is typical in MCDM problems, where different alternatives (in this case, the skills mentioned in Section 2.3) are assessed against a set of criteria to compare the alternatives. The chosen criteria, along with the relevant literature that suggests or supports their use, are presented below.

2.4.1 Regulatory compliance

Ensuring compliance with regulations is necessary in evaluating the feasibility of adopting new skills and competencies to align with new technologies for MASS vessels. Given that the maritime sector is strictly regulated, it becomes important to evaluate the skills and competencies necessary for navigators operating under MASS operations, adhering to requirements laid out by global standards like the STCW and the IMO collision regulations COLREG (Sharma and Kim 2022; Chang et al. 2024a).

2.4.2 Ease of integration into training

The ease of integrating a new skill into existing maritime training programs is a crucial consideration. Maritime Education and Training (MET) is a highly complex and time-intensive process, requiring careful planning and implementation of any changes (Mallam et al. 2019). Therefore, it is essential to evaluate whether the incorporation of new skills and competencies can fit within the current course structure or necessitates significant modifications (Maritime UK 2021). Skills and competencies that require minimal revisions are more likely to be embraced by both students and MET institutions. Thus, any new skills must be introduced in a way that minimises disruption to the learning process. This may involve adapting current course structures or creating new ones that can seamlessly integrate into the existing curriculum (Emad and Roth 2008). Additionally, the level of integration is closely linked to the preparedness and willingness of MET institutions and educators to accept change (Aboul-Dahab 2021). Kataria and Emad (2022) emphasised that fostering an environment that promotes continuous learning and flexibility within MET institutions is vital for effectively incorporating new skills and competencies. This includes providing training opportunities for instructors to gain the necessary expertise and proficiency in teaching emerging technologies and capabilities efficiently (Yuen et al. 2022).

2.4.3 Training feasibility (including cost-effectiveness)

The feasibility of providing training in new skills and competencies for MASS ships is a crucial criterion that evaluates the ability of MET institutions to efficiently and affordably teach these skills without overburdening their resources or the learners. The high costs associated with developing maritime skills present a challenge to training viability (CINEA 2020).

The issue of who bears the training expenses is a critical factor. Some businesses are willing to fund their crew's education, regardless of position, and help them achieve mastery. However, others are hesitant to do so (MacIntyre 2023). This disparity in employer support could hinder seafarers'opportunities to enhance or acquire new skills and competencies for the rise of MASS.

To address this challenge, it is essential to recognise that skills and competencies are assets in which investments can be made. The costs and benefits should be shared among three main parties: individuals, government, and employers (GMCA 2017). Each party has a vested interest in developing a skilled maritime workforce, as it can lead to improved safety, efficiency, and employability of seafarers (Caesar 2024). MET institutions can facilitate this by enabling cost-sharing agreements among these stakeholders.

Additionally, the presence of qualified instructors is a critical aspect of evaluating the feasibility of training. The technological advancements in the maritime sector require continuous professional development for instructors to ensure they have the necessary expertise and proficiency to teach new competencies (Sharma and Nazir 2021).

2.4.4 Ease of assessment

The ease and effectiveness of assessing proficiency in new skills and competencies can influence the capacity of MET institutions to upskill and reskill efficiently the maritime workforce for MASS. Current MET practices may not fully address the new expertise required for autonomous shipping (Ghosh et al. 2014). Therefore, it is essential to evaluate whether a skill is suitable for accurate and convenient assessment techniques that align with existing MET structures.

Ease of assessment is characterised by clear and measurable learning outcomes that can be evaluated using practical and technology-enhanced approaches (Mallam et al. 2019; Koh et al. 2022). MET institutions would be able to prioritise skill development with well-defined learning outcomes which can then be translated into assessment criteria and performance measures for consistently fair judgments of students' knowledge, skills and abilities.

3 Methodology

As previously mentioned, this paper focuses on evaluating and prioritizing the skills and competencies required for autonomous ships. We assess and rank these skills and competencies to identify the most important ones according to expert opinions. This research is vital as it helps the maritime industry and educational institutions concentrate on the most critical skills and competencies, as perceived by stakeholders. MCDM methods have been utilised to identify a preferred alternative, categorise alternatives, and/or rank them based on subjective preferences (Tzeng and Huang 2011). These techniques are particularly effective for ranking alternatives as they offer a comprehensive evaluation, which is especially beneficial when decisions involve multiple conflicting criteria. Designed to tackle complex decision problems with numerous alternatives and criteria, MCDM methods can incorporate both quantitative and qualitative data. Their structured approach ensures transparency in the decision-making process, allowing decision-makers to justify their choices through systematic evaluation of criteria and alternatives.

The proposed fuzzy TOPSIS method, which builds on the classical approach by Hwang and Yoon (1981), is briefly described below.

3.1 Classical TOPSIS

TOPSIS is a traditional method that ranks alternatives based on the principle that *"the best alternative should have the shortest distance from the positive ideal solution (PIS) and the longest geometric distance from the negative ideal solution (NIS)"* (Hwang and Yoon 1981; Hwang et al. 1993). It is a well-established method; for a comprehensive review of TOPSIS applications, see Behzadian et al. (2012).

3.2 Fuzzy TOPSIS

In the classical TOPSIS approach, performance ratings and the weights of the various criteria are given as exact values (crisp numbers). This paper employs the fuzzy TOPSIS approach, as first described by Chen (2020), which recognises that human judgment cannot be easily expressed by precise numbers. In fact, the use of fuzzy sets allows to incorporate *"unquantifiable information, incomplete information, non-obtainable information and partially ignorant facts into decision model* " (Dağdeviren et al. 2009). Some advantages of TOPSIS and its fuzzy extension, over other MCDM methods include its user-friendliness, effectiveness in handling complex decisions, and its ability to provide clear and easily understandable rankings for decision-makers (Hwang and Yoon 1981; Dağdeviren et al. 2009; Pandey et al. 2023).

Extending TOPSIS to a fuzzy environment is straightforward, with the main difference being the use of fuzzy numbers instead of precise numbers; see Section 3.3 for details.

3.3 Introduction to Fuzzy Theory and basic arithmetic

Fuzzy models, such as those utilising triangular fuzzy numbers, have proven highly effective in addressing decision-making problems where information is imprecise. Below, we outline some fundamental definitions of fuzzy sets and fuzzy arithmetic, per Dağdeviren et al. (2009) and mainly following the notation used in Chen (2000).

Definition 1. "A fuzzy set $\widetilde{A}$ in a universe of discourse X is characterised by a membership function that assigns a real number in the interval [0;1] to each element x."

Definition 2. A triangular fuzzy number $\tilde{a}$ is defined by a triplet $\tilde{a} = \left(a_1, a_2, a_3\right)$ as shown in Fig. 2.

The membership function for a triangular fuzzy number is defined as follows:

$$\mu_{\overline{\alpha}}(x) = \begin{cases} 0, & x < a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_2 \geq x \geq a_1 \\ \frac{x-a_3}{a_2-a_3}, & a_3 \geq x \geq a_2 \\ 0, & x > a_3 \end{cases}$$

where a_2 is the value for which $\mu_{\overline{\alpha}}\left(a_2\right) = 1$, and a_1 and a_3 are the extreme values on the left and right of the fuzzy number $\tilde{a}$, respectively, with $\mu_{\overline{\alpha}}\left(a_1\right) = \mu_{\overline{\alpha}}\left(a_3\right) = 0$.

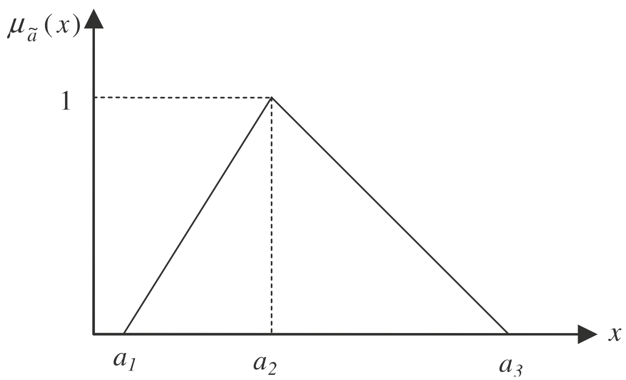


Fig. 2 Triangular fuzzy number

Definition 3. Operations involving fuzzy numbers, $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$, such as addition, subtraction, multiplication and division, can be represented as follows:

$$\begin{aligned}
&\tilde{a} \oplus \tilde{b} = (a_1, a_2, a_3) \oplus (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \\
&\tilde{a} \ominus \tilde{b} = (a_1, a_2, a_3) \ominus (b_1, b_2, b_3) = (a_1 - b_3, a_2 - b_2, a_3 - b_1) \\
&\tilde{a} \otimes \tilde{b} = (a_1, a_2, a_3) \otimes (b_1, b_2, b_3) = (a_1 \cdot b_1, a_2 \cdot b_2, a_3 \cdot b_3) \\
&\tilde{a} \oslash \tilde{b} = (a_1, a_2, a_3) \oslash (b_1, b_2, b_3) = \left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right) \\
&k\tilde{a} = k(a_1, a_2, a_3) = (ka_1, ka_2, ka_3).
\end{aligned}$$

Definition 4. The (Euclidean) distance between two triangular fuzzy numbers $\tilde{a}$ and b is calculated as:

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]}$$

Linguistic variables Source: Chen (2020)

3.4 Fuzzy TOPSIS: methodology steps

The fuzzy TOPSIS-based methodology in our study consists of the steps illustrated in Fig. 3 and described below.

Step 1. Problem definition and data collection

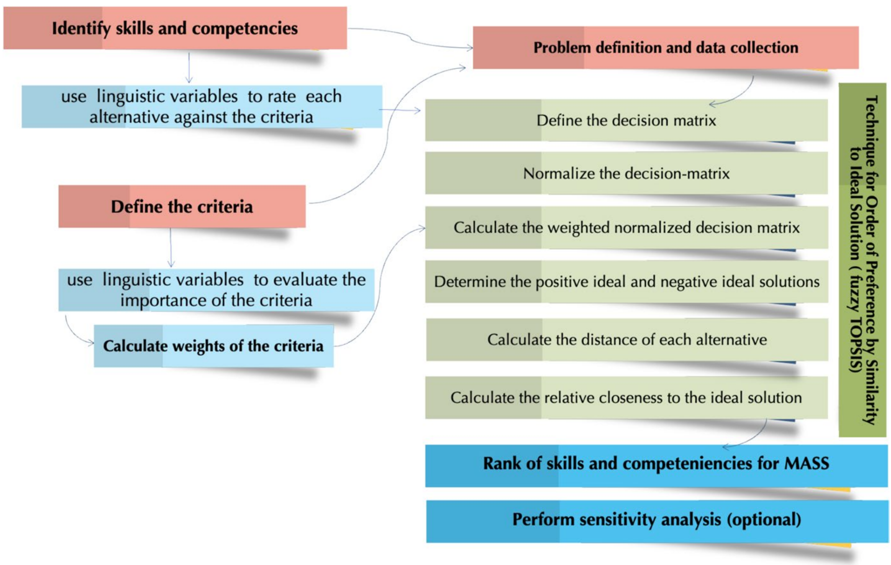


Fig. 3 The fuzzy TOPSIS methodology employed in this study

In this step, we define the problem by identifying the alternatives (in our case study, the required skills and competencies for MASS) and the criteria for assessing them (see Fig. 1). This was achieved through a literature review and expert judgment (refer to Section 2.1 and Section 2.2 for more details).

Next, we gather all the necessary data to solve the problem. As with most multi-criteria decision analysis methodologies, the inputs include a set of alternatives, a set of criteria/parameters, the weights of each criterion (wj) and the rating (xij) of alternative Ai with respect to criterion Cj.

3.5 Aggregation of the importance of the criteria—weighting

The importance of each criterion/attribute can be determined using various methods, such as direct assignment (as done in this study) or indirectly through, for example, pairwise comparisons, as used in the Analytic Hierarchy Process (AHP) method. In this work, following Chen (2000), a group of experts provided their opinion on the importance of each criterion using linguistic variables; these were then converted to triangular fuzzy number using the definitions presented in Table 1.

Assuming a group of K decision makers (or experts), the importance of the criteria can be calculated as the simple average:

$$\widetilde{w}_j = \frac{1}{K}\left[\widetilde{w}_j^1 (+) \widetilde{w}_j^2 + \cdots + \widetilde{w}_j^K\right] \tag{1}$$

where $\widetilde{w}_j^K$ is the importance weight (represented as a fuzzy triangular number) of the K-th decision-maker.

3.6 Aggregation of the ratings

Experts provide their ratings for each alternative (in our study a skill or competency) using the linguistic terms, which are then converted into triangular fuzzy number using Table 2. Assuming a group of K experts, the rating of alternatives with respect to each criterion can be calculated as follows:

Table 1 Linguistic variables for the importance weight of each criterion

Linguistic Variable	Fuzzy number
Very low (VL)	(0, 0, 0.1)
Low (L)	(0, 0.1, 0.3)
Medium low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
Medium high (MH)	(0.5, 0.7, 0.9)
High (H)	(0.7, 0.9, 1)
Very high (VH)	(0.9, 1, 1)

Table 2 Linguistic variables for the ratings

Linguistic Variable	Fuzzy number
Very Poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium Poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium Good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very Good (VG)	(9, 10, 10)

$$\widetilde{x}_{ij} = \frac{1}{K}\left[\widetilde{x}_{ij}^{1}(+)\widetilde{x}_{ij}^{2} + \cdots + \widetilde{x}_{ij}^{K}\right] \tag{2}$$

where $\widetilde{x}_{ij}^{k}$ is the rating of the kth decision maker for alternative A_i with respect to criterion C_j.

Step 2. Define the decision matrix

Given the above information, the fuzzy multicriteria group decision-making problem can be expressed in a matrix format as follows:

$$\widetilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_n \end{array} \\ \begin{bmatrix} \widetilde{x}_{11} & \widetilde{x}_{12} & \ldots & \widetilde{x}_{1n} \\ \widetilde{x}_{21} & \widetilde{x}_{22} & \ldots & \widetilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \widetilde{x}_{m1} & \widetilde{x}_{m2} & \vdots & \widetilde{x}_{mn} \end{bmatrix} \end{array}, i = 1,2,\ldots,m; j = 1,2,\ldots,n \tag{3}$$

where $A_1, A_2, \ldots, A_m$ are the alternatives, $C_1, C_2, \ldots, C_n$ are the criteria, and $\tilde{x}_{ij}$ are the fuzzy numbers that indicate the rating of the alternative A_i with respect to criterion C_j.

Step 3. Normalisation of the decision matrix

In several MCDM methods, including fuzzy TOPSIS, data are normalised to eliminate deviations caused by different measurement units and scales. Normalization adjusts the values to conform to a standard, resulting in values between 0 and 1. In our work, we use linear scale transformation to make the various criteria scales comparable. For more information on different normalization techniques, refer to Ploskas and Papathanasiou (2019).

The normalised fuzzy decision matrix is calculated as follows:

$$\tilde{\boldsymbol{R}} = \left[\tilde{r}_{ij}\right]_{m\times n}$$

where B and C are the benefit and cost criteria, respectively, and

$$
\begin{aligned}
\tilde{r}_{ij} &= \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B \\
\tilde{r}_{ij} &= \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C \\
c_j^* &= \max_i c_{ij} \text{ if } j \in B \\
a_j^- &= \min_i a_{ij} \text{ if } j \in C.
\end{aligned}
$$

Step 4. Calculate the weighted normalised decision matrix

The weighted normalised decision matrix $\tilde{P} = \left[\tilde{p}_{ij}\right]_{\mathrm{mxn}}$ is then calculated by multiplying the normalised decision matrix by the fuzzy weights.

That is, the value $\tilde{p}_{ij}$ is calculated as: $\tilde{p}_{ij} = w_i \tilde{x}_{ij}$ with $i = 1, \ldots, m$, and $j = 1, \ldots, n$

.

Step 5. Determine the positive and negative ideal solutions

The PIS A^+(benefits) and NIS A^-(costs) are calculated as follows:

$$
\begin{aligned}
A^+ &= \left(\tilde{p}_1^+, \tilde{p}_2^+, \ldots, \tilde{p}_m^+\right) \\
A^- &= \left(\tilde{p}_1^-, \tilde{p}_2^-, \ldots, \tilde{p}_m^-\right)
\end{aligned}
$$

where $\tilde{p}_{\mathrm{j}}^+ = (1,1,1)$ and $\tilde{p}_j^- = (0,0,0), j = 1,2, \ldots, n$.

Step 6. Calculate the distance of each alternative

The distance of each alternative A_i from the ideal solutions are calculated as follows:

$$
\begin{aligned}
d_i^+ &= \sum_{j=1}^{n} d\left(\tilde{p}_{ij}, \tilde{p}_j^+\right), i = 1,2, \ldots, m \\
d_i^- &= \sum_{j=1}^{n} d\left(\tilde{p}_{ij}, \tilde{p}_j^-\right), i = 1,2, \ldots, m
\end{aligned}
$$

where the distance $d\left(\tilde{p}_{ij}, \tilde{p}_j^+\right)$ is defined in Definition 4.

Step 7. Calculating the relative closeness to the ideal solution and scoring the alternatives

n this step, the relative closeness ξ_i for each alternative A_i with respect to the positive ideal solution is calculated as:

$$
\xi_i = \frac{d_i^-}{d_i^+ + d_i^-}.
$$

The alternatives are then ranked based on their relative closeness. The best alternatives are those with higher ξ_i values, indicating they are closer to the PIS.

4 Questionnaire design, analysis and results

4.1 Data collection

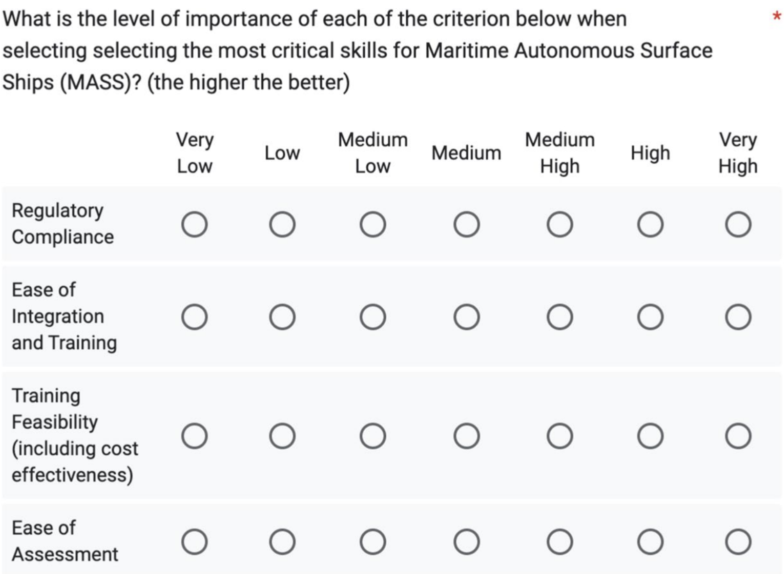
The data necessary for our analysis were gathered using an online questionnaire divided into three sections. The first section requested respondents to provide details about their professional background, work experience, and region. In the second section (see Fig. 4), experts were asked to rate the importance of each criterion (ranging from 'very low' to 'very high') for selecting the key skills and competencies for MASS; see Section 2.4.1 for a detailed description.

In the final section, we gathered the ratings for the identified skills and competencies (refer to Section 2.3) using seven linguistic terms ranging from 'very poor' to 'very good'.

For instance, Fig. 5 illustrates the question concerning the rating of the alternatives (skills) based on their ease of integration and training.

4.2 Profile of the respondents

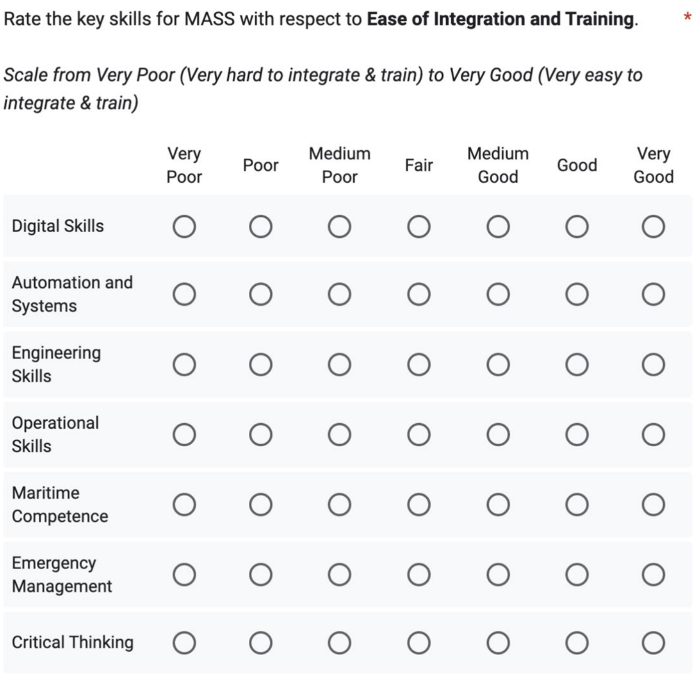
A total of 178 responses have been received; of which 174 were used in our analysis. 4 responses were excluded from our analysis due to either incomplete



What is the level of importance of each of the criterion below when selecting selecting the most critical skills for Maritime Autonomous Surface Ships (MASS)? (the higher the better) *

	Very Low	Low	Medium Low	Medium	Medium High	High	Very High
Regulatory Compliance	○	○	○	○	○	○	○
Ease of Integration and Training	○	○	○	○	○	○	○
Training Feasibility (including cost effectiveness)	○	○	○	○	○	○	○
Ease of Assessment	○	○	○	○	○	○	○

Fig. 4 Questionnaire: Importance of criteria


Rate the key skills for MASS with respect to **Ease of Integration and Training**. *

Scale from Very Poor (Very hard to integrate & train) to Very Good (Very easy to integrate & train)

	Very Poor	Poor	Medium Poor	Fair	Medium Good	Good	Very Good
Digital Skills	○	○	○	○	○	○	○
Automation and Systems	○	○	○	○	○	○	○
Engineering Skills	○	○	○	○	○	○	○
Operational Skills	○	○	○	○	○	○	○
Maritime Competence	○	○	○	○	○	○	○
Emergency Management	○	○	○	○	○	○	○
Critical Thinking	○	○	○	○	○	○	○

Fig. 5 Questionnaire: Rating of skills example. (Note: 7 out of 11 skills are presented here due to space considerations)

data or deemed as extreme outliers (i.e., values were outside two standard deviations from the mean values).

Table 3 presents their professional background, work experience, geographic location, seagoing experience and familiarity with MASS.

The survey gathered responses from 174 participants with diverse professional backgrounds, work experience, and geographic locations within the maritime industry. The majority of respondents are professional seafarers (36%), followed by maritime researchers and educators (22%), ship-owning/operating companies (17%), and maritime training institutes/providers (10%).

Over half of the respondents (57%) have more than 15 years of work experience, while the remaining have varying levels of experience. Geographically, the respondents were primarily from East Asia (39%) and Europe (26%), with smaller representations from other regions such as South Asia, Southeast Asia, and Sub-Saharan Africa.

Furthermore, 70% of the respondents had seagoing experience, bringing valuable insights to the survey. However, when it comes to familiarity with autonomous shipping technologies, only 20% considered themselves very or extremely familiar, while 33% were slightly familiar and 25% were not familiar at all.

Table 3 Respondents' background

		N	Percentage
Professional Background	Ship Owning/Operating Company	30	17%
	Maritime Training Institute/Provider	17	10%
	Maritime Research (e.g., Academic Researchers, Analysts) and Education (from University)	38	22%
	Professional Seafarer (e.g., Master, Chief Officer, Chief Engineer)	62	36%
	Regulator (e.g., Maritime Authorities, IMO)	11	6%
	Other	16	9%
Work Experience	$<=5$ year	30	17%
	6–10 years	17	10%
	11–15 years	28	16%
	>15 years	99	57%
Geographic Location	Australasia (Australia, New Zealand)	8	5%
	Central & South America (including the Caribbean)	3	2%
	East Asia (China, Japan, South Korea, etc.)	68	39%
	Europe (including the EU, UK, and other European countries)	45	26%
	Middle East & North Africa	8	5%
	North America (USA, Canada)	3	2%
	South Asia (India, Pakistan, Bangladesh, etc.)	13	7%
	Southeast Asia (Indonesia, Malaysia, Philippines, etc.)	8	5%
	Sub-Saharan Africa	8	5%
	No Answer	10	6%
Seagoing Experience	Yes	122	70%
	No	52	30%
Familiarity with autonomous shipping technologies	Not familiar at all	43	25%
	Slightly familiar	57	33%
	Moderately familiar	38	22%
	Very familiar	25	14%
	Extremely familiar	11	6%

4.3 Results

The expert opinions regarding the weights and the ratings have been aggregated using simple means per the classical approach of Chen (2000); see Eqs.1 and 2.

4.3.1 Weights of criteria

The weights are presented as fuzzy triangular numbers (i.e., in the format that they will be used in the fuzzy TOPSIS methodology); their crisp values using the so-called graded mean integration are also shown in Table 4. Based on the responders'

Table 4 Weights of criteria

	Regulatory Compliance	Ease of Integration into Training	Training Feasibility (incl. cost-effectiveness)	Ease of Assessment
Fuzzy Weights	(0.71,0.87,0.94)	(0.70,0.86,0.95)	(0.71,0.87,0.95)	(0.65,0.82,0.93)
Crisp values	0.2537	0.2517	0.2542	0.2404

opinion the most important criteria in the selection of the most important skills and competencies for MASS are ‘Training Feasibility’ (see Section 2.4.4) and ‘Regulatory Compliance’ (Section 2.4.2). We should note though that based on our analysis all factors appeared to be almost equally important.

4.3.2 Rank of skills and competencies for MASS

The decision matrix is presented in Table 5. The eleven alternatives (i.e. skills and competencies) are presented in detail in Section 2.3.

The decision matrix and the fuzzy weights constitute the primary inputs for the fuzzy TOPSIS methodology detailed in Section 3. Subsequently, the relative closeness to the ideal solutions was determined, and the alternatives (skills and competencies) were ranked accordingly, as illustrated in Table 6.

Based on the above results the experts believe that the most important skills related to MASS are ‘*Operational Skills* (A4), followed by ‘*Digital Skills*’ (A1) and ‘*Maritime Competency*’ (A5).

4.3.3 Robustness of the results and sensitivity analysis

It is important to note that the results of all MCDM methods, including our approach, are sensitive to the weights and specific methodologies employed. In classical approaches, sensitivity analysis is typically conducted; this is straightforward in classical TOPSIS, where weights can be slightly adjusted to examine their impact

Table 5 Decision matrix

	Regulatory Compliance	Ease of Integration into Training	Training Feasibility (incl. cost-effectiveness)	Ease of Assessment
A1	(6.40,8.10,9.20)	(6.40,8.10,9.10)	(6.00,7.70,8.90)	(6.40,8.10,9.10)
A2	(6.20,7.90,9.00)	(6.30,8.00,9.10)	(6.00,7.80,8.90)	(6.20,7.90,9.00)
A3	(6.00,7.70,8.90)	(6.30,8.00,9.00)	(6.00,7.70,8.90)	(6.10,7.80,8.90)
A4	(6.40,8.10,9.10)	(6.40,8.10,9.20)	(6.30,8.00,9.10)	(6.10,7.80,9.00)
A5	(6.50,8.20,9.20)	(6.30,8.10,9.20)	(6.10,7.80,8.90)	(6.10,7.90,9.10)
A6	(6.10,7.70,8.80)	(5.80,7.50,8.70)	(6.10,7.70,8.80)	(6.00,7.70,8.90)
A7	(5.80,7.40,8.60)	(5.40,7.10,8.30)	(5.40,7.00,8.30)	(5.80,7.50,8.70)
A8	(5.80,7.40,8.60)	(5.60,7.30,8.50)	(5.70,7.40,8.50)	(5.80,7.60,8.80)
A9	(5.70,7.40,8.60)	(5.50,7.20,8.50)	(5.70,7.40,8.60)	(5.80,7.50,8.70)
A10	(6.10,7.80,8.90)	(5.70,7.40,8.60)	(5.60,7.30,8.50)	(5.80,7.60,8.80)
A11	(6.30,7.90,9.00)	(5.90,7.60,8.80)	(5.80,7.50,8.70)	(6.00,7.80,9.00)

Table 6 Relative closeness to the ideal solutions and score of the alternatives

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
Distance from PIS	1.35	1.38	1.4	1.35	1.36	1.44	1.55	1.51	1.52	1.49	1.4
Distance from NIS	2.97	2.94	2.92	2.98	2.98	2.87	2.74	2.78	2.79	2.82	2.9
Relative closeness	0.69	0.68	0.68	0.69	0.69	0.67	0.64	0.65	0.65	0.65	0.7
Rank	**2**	4	5	**1**	**3**	7	11	10	9	8	6

Legend: *A1*, Digital Skills; *A2*, Automation and Systems Skills; *A3*, Technical Proficiency; *A4*, Operational Skills; *A5*, Maritime Competency; *A6*, Emergency and Safety Management; *A7*, Critical Thinking; *A8*, Decision-Making and Problem-Solving Skills; *A9*, Leadership and Influence; *A10*, Adaptability & Flexibility; *A11*, Communication & Collaboration

on the final rankings. In our study, consistent with similar research (e.g., Yan et al. 2017; Emovon and Aibuedefe 2020), validation is performed by comparing our results with those obtained using similar fuzzy MCDA methods (see Table 7 for details). The interested reader is referred to Tzeng and Huang (2011) and Alinezhad and Khalili (2019) for a discussion of these various MCDA methods.

Table 7 presents the results for fuzzy TOPSIS using both vector and linear normalization. Our study employs a linear scale transformation (see methodology in Section 3) to standardise the criteria ratings into a comparable scale. Additionally, we include results for Multi-Objective Optimization based on Ratio Analysis (MOORA), VIšekriterijumsko KOmpromisno Rangiranje (VIKOR) with a v parameter (reflecting the decision maker's preference for consensus) set at 0.5, and Weighted Aggregated Sum Product Assessment (WASPAS) with a (\lambda) parameter, which combines the weighted sum model (WSM) and the weighted product model (WPM), also set at 0.5.

Table 7 Rank of skills and competencies produced by different methods

Alternatives	Fuzzy MMOORA	Fuzzy TOPSIS (Vector normalisation)	Fuzzy TOPSIS (linear normalisation) *This study*	Fuzzy VIKOR (v = 0.5)	Fuzzy WASPAS (lambda = 0.5)
A1	**3**	**3**	**2**	**2**	**2**
A2	4	4	4	4	4
A3	5	5	5	5	5
A4	**1**	**1**	**1**	**1**	**1**
A5	**2**	**2**	**3**	**3**	**3**
A6	7	7	7	7	7
A7	11	11	11	11	11
A8	10	10	10	9	10
A9	9	9	9	10	9
A10	8	8	8	8	8
A11	6	6	6	6	6

Legend: *A1*, Digital Skills; *A2*, Automation and Systems Skills; *A3*, Technical Proficiency; *A4*, Operational Skills; *A5*, Maritime Competency; *A6*, Emergency and Safety Management; *A7,* Critical Thinking; *A8*, Decision-Making and Problem-Solving Skills; *A9*, Leadership and Influence; *A10*, Adaptability & Flexibility; *A11*, Communication & Collaboration

Our analysis produced consistent and robust ranking results, identifying the most critical skills and competencies for Maritime Autonomous Surface Ships (MASS) operations.’Operational Skills’(A4) are identified as the top priority, followed by’Digital Skills’(A1) and’Maritime Competency’(A5).

Notably, all methodologies used in our sensitivity analysis unanimously place A4 on the top. The subsequent positions are occupied by either A1 or A5, with slight variations depending on the specific method used. While we acknowledge the potential limitations of our approach, which are elaborated in Section 13, the validation process we have undertaken reinforces our confidence in the robustness of these results.

Drawing from these findings, Section 12 presents insights and recommendations aimed at guiding Maritime Education and Training (MET) institutions. These suggestions are designed to assist in the adaptation of educational curricula and training programs to effectively address the evolving demands of the maritime industry, particularly in the context of autonomous shipping.

4.4 Comparison between subgroups

Finally, while we felt this analysis to be a potential avenue for future research, we applied the MCDA techniques to the entire sample and various subgroups, including non-academics, academics, and those with exclusively seafaring experience; see Table 8 for the results. The purpose of this analysis was to identify potential differences in opinions among these subgroups regarding the importance of various skills and competencies. It would be particularly intriguing to investigate whether the ranking of essential skills and competencies would differ when considering only the responses of those with seafaring experience, and whether the ranking derived from the sample of academics working in MET institutions would diverge from the ranking obtained from non-academics.

Surprisingly, the results reveal a consistent consensus regarding the top three skills essential for autonomous shipping: operational skills, maritime competency, and digital skills.

5 Discussion and recommendations

In the previous section, we presented the most essential skills and competencies relevant to autonomous shipping, including those for various sub-groups (see Section 11.4). To validate our approach, we employed a variety of methods (Section 11.3.3).

The results reveal a consistent consensus regarding the top three skills and competencies essential for autonomous shipping: operational skills, maritime competency, and digital skills. This resonates with the growing recognition of the importance of traditional maritime competency to be integrated with new technological proficiency. In the existing literature, several scholars have emphasised that autonomy in shipping does not mean that traditional seafaring skills will be redundant; some traditional skills would be kept, and others shifted (Ceylani et al. 2022; Kennard et al. 2022; Li and Yuen 2024).

Table 8 Rank of skills and competencies for different sub-groups

Alternatives	ALL ($n = 174$)	Seagoing experience ($n = 122$)	Academics ($n = 55$)	Non-Academics ($n = 119$)
A1	**2**	**3**	**3**	**2**
A2	4	4	4	4
A3	5	6	6	5
A4	**1**	**1**	**2**	**1**
A5	**3**	**2**	**1**	**3**
A6	7	7	5	8
A7	11	10	10	11
A8	10	10	11	9
A9	9	9	9	10
A10	8	8	8	7
A11	6	5	7	6

Legend: *A1*, Digital Skills; *A2*, Automation and Systems Skills; *A3*, Technical Proficiency; *A4*, Operational Skills; *A5*, Maritime Competency; *A6*, Emergency and Safety Management; *A7*, Critical Thinking; *A8*, Decision-Making and Problem-Solving Skills; *A9*, Leadership and Influence; *A10*, Adaptability & Flexibility; *A11*, Communication & Collaboration

The position of operational skills at the top of the list shows their vital role in guaranteeing the safe and efficient functioning of autonomous vessels. This aligns with previous scholarship stressing the significance of human intervention amidst automation (Pazouki et al. 2018). As vessels become increasingly self-sufficient, the ability to monitor, troubleshoot, and maintain complex systems will remain paramount (Emad and Ghosh 2023). The importance of operational skills highlights the need for a workforce capable of adapting to the unique challenges posed by the fusion of traditional seafaring with advanced automation, ensuring the smooth operation of autonomous ships in dynamic maritime environments.

The high ranking of digital skills across all subgroups is unsurprising. With vessels relying heavily on advanced sensors, data analytics and communication systems, proficiency in these areas will be a key differentiator for the workforce (Mallam et al. 2019). The consistently high ranking of digital skills across subgroups highlights the need for targeted training programmes that teach digital literacy and cybersecurity awareness, equipping maritime professionals with the tools to thrive in an increasingly connected and data-driven industry.

The findings of this research could offer valuable insights into the future of the autonomous shipping workforce. They can provide guidance for Maritime Education and Training (MET) institutions in developing curriculum content aligned with the necessary skills and competencies. By promoting a balance between traditional maritime knowledge and advanced operational and digital skills, these institutions can prepare a well-equipped workforce to operate safe and efficient future autonomous ships.

Moreover, this study has the potential to shape strategic choices and regulatory structures within the maritime field. As autonomous navigation remains a rapidly growing field, it is essential for authorities to set protocols and standards that emphasise nurturing the identified skills and competencies (Hopcraft and Martin 2018). The recent draft

MASS Code (see MSC 108/WP.7, Annex 1) by the IMO plays a critical role in providing guidance to policymakers who are formulating regulations for autonomous shipping. Our research findings support the Code's emphasis on a well-defined approval process that includes detailed risk assessments, documentation of design, rigorous testing and verification procedures..Even though the draft acknowledges the importance of human involvement in MASS operations (see Chapter 15 of the MASS Code draft-MSC 108/WP.7, Annex 1), our research shows a need for policymakers to further prioritise this factor. The differences in skill priorities among various stakeholders highlight the necessity for customised training and competency standards that cater to each specific role within the framework of MASS operations. It is imperative for policies to mandate implementing design principles centred around humans during development of control systems and human-machine interfaces, as made evident by our study's emphasis on competencies in both maritime and operational aspects, along with digital skills that contribute to interaction between humans & automation.

6 Conclusions and future work

This study employed a fuzzy TOPSIS analysis to prioritise the skills and competencies required for the successful operation of autonomous ships, as perceived by various stakeholders within the maritime industry. The results reveal a consensus, with operational skills, maritime competency, and digital skills consistently emerging as the top three competencies across all respondent subgroups (Section 11.3.2). The importance of these skills and competencies highlights the necessity for a workforce capable of combining traditional maritime knowledge with modern technological and digital abilities. As the field adapts to the major change towards autonomy, stakeholders must acknowledge the ongoing significance of practical seafaring experience, situational awareness and regulatory compliance, while also promoting advancement in technological and digital awareness. Indeed, much of the current research has focused on situational awareness and the navigational aspect (Kim et al. 2022 and Chan et al. 2022).

To summarise, this study establishes a foundation for understanding the key skills and competencies necessary in the safe and efficient operations of autonomous vessels. Emphasizing operational skills, maritime competency and digital skills while acknowledging different viewpoints from different individuals involved will enable the maritime sector to navigate the opportunities and challenges posed by autonomy in the sector. Ongoing research and collaboration among industry, academia and policymakers will be essential to ensure that the workforce is well-equipped for future autonomous vessels while maintaining the highest standards of safety, efficiency and sustainability.

6.1 Future research

However, the subjectivity inherent in the fuzzy TOPSIS approach, as the final rankings are determined by the viewpoints (i.e. ratings) of participants, is a notable limitation. Future research could apply our evaluation framework and analyse the data using various MCDA techniques such as MOORA and VIKOR (which we included in our sensitivity analysis but did not describe in detail), or other methods such as PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) and ELECTRE (Elimination and Choice Translating Reality). Additionally, future research can explore possible extensions of the presented fuzzy TOPSIS technique, particularly concerning the normalisation step of the distance measures. While we used linear normalisation (see Section 3.4, Step. 3), other methods such as vector, logarithmic, or Markovic normalisation can be applied. Similarly, alternative distance metrics, like Manhattan or Tchebycheff, can be used to obtain the final rank. These variations in the fuzzy TOPSIS method might yield different rankings; for more alternative approaches, see Ploskas and Papathanasiou (2019).

Moreover, the sample size of this research may not fully be representative of the maritime sector despite its diversity (see Section 11.2 for more). Future studies can increase participant representation to validate our findings or test them in other areas such as the comparison of regions, departments, size and types of companies, etc. by using analysis of variance (ANOVA) or multivariate analysis of variance (MANOVA).

Comparative studies examining the differences in skill prioritisation among various stakeholder groups, such as seafarers, ship operators and policymakers, could provide valuable insights into the perspectives and needs of different actors within the industry. We have conducted a brief analysis, see Section 11.4, but we feel that this is an interesting area for further investigation. These insights may inform the development policies that can be effectively adopted by all parties involved.

Finally, this study aims to provide high-level recommendations, so that the skills and competencies are described in broad terms. As we progress from Degree 1 to Degree 2 and ultimately to fully autonomous ships, the required skills and competencies will change. Our respondents seem to be considering more Degree 1 and Degree 2 scenarios, anticipating that seafarers will still be onboard vessels in the near future. For example, the skillset for individuals working exclusively at Remote Operations Centres (ROCs) might not require much seamanship skills. Therefore, it would be useful to conduct a similar analysis focusing specifically on seafarers on remotely controlled vessels and a separate one focusing only on remote operators.

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Data availability For data requests, please contact the corresponding author.

Declarations

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