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Key determinants for the commercial feasibility of maritime autonomous surface ships (MASS)

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ABSTRACT

Maritime Autonomous Surface Ship (MASS) technologies have been developing rapidly in the last decade, but the commercial feasibility and implementation potential of MASS for merchant shipping is still unclear. To unleash the full potential of the technological development, this study investigates the feasibility of possible MASS variants for merchant shipping. We design a multi-criteria decision-making (MCDM) framework incorporating nine key determinants for MASS adoption. Three MASS variants with different degrees of autonomy and two shipping routes are evaluated. Perspectives of relevant maritime professionals were solicited through a web-survey, and the Bayesian Best-Worst Method (BWM) was used for the analysis of the collected data. We find that navigation anti-collision-anti-grounding systems, cybersecurity risks, and capital costs are the three most important criteria for the commercialization of MASS. The analysis further revealed that degree two MASS for intra-European container trade in the Mediterranean and Baltic using small-sized autonomous feeder vessels is considered as the most feasible for the commercialization of the MASS.

1. Introduction

Commercial or merchant shipping comprises several ship types -and corresponding markets- managed and operated by ship crew and shore personnel. Recent technological advances have unlocked the prospect of deploying Maritime Autonomous Surface Ships (MASS) in the shipping industry. MASS relies on the application of technological solutions in the field of autonomous navigation systems (GPS, INS), advanced sensor technology (RADAR, AIS, LIDAR, IR camera, high-resolution sonar, wind, and pressure sensors), machinery, monitoring and control systems automation; and the establishment of advanced Remote Operation Centres (ROCs) [22].

While research and development (R&D) of MASS has been going on for over a decade, adoption of MASS in commercial shipping is yet to take off. MASS R&D has been taking place in countries with a strong maritime cluster tradition such as Norway, Finland, the Netherlands, Poland, Belgium, South Korea, Japan, and China [30]. The three main drivers for the implementation of MASS are cost reduction, improved safety, and seafarer shortage [31]. Other benefits of MASS include reduced emissions and improved reliability of service [28]. Reduced emissions are likely to derive from shifting cargo from road to sea, by developing intermodal last-mile-delivery through smaller MASS [46] and changing propulsion systems to alternative energy sources [51].

Stakeholders in the shipping industry have different interests in MASS. Excluding China, most of the countries supplying seagoing labour (Philippines, Indonesia, Russia, Ukraine, and India), amounting to some 1.9 million seafarers worldwide, have limited interest in MASS development. About 65 % of cadets perceive MASS as a threat to their job, and this percentage goes up to 85 % for cadets coming from Southern Asia [4]. The severe impacts of the recent Covid-19 pandemic on seafarers

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(see [11] and [19]) and the expected future seafarer shortage [3,10] might work as incentives for increased automation and reduced manning in commercial shipping. Moreover, countries in the developing world, particularly densely populated ones, with high regional shipping activities and large number of casualties might benefit the most from MASS [37]. Interestingly, shipowners are not much interested in MASS yet [15].

While there are studies demonstrating the savings from operational cost reductions [1], most of those studies do not include the cost of managing ROCs, dealing with increased cyber security threats in these ROCs, increased maintenance costs and likely changes in insurance premiums. In this regard, Tsvetkova and Hellström [43] argued that MASS can create value for the whole maritime logistics chain, and this needs to be convincingly shown for the successful adoption of MASS.

MASS development has been explored from different perspectives in the academic literature. The majority of the extant literature are on the technical development of MASS [18]. Recently, research on MASS safety has been receiving greater attention with a specific focus on MASS operational risk analysis [8], impact on maritime safety [47], risk governance [16], and safety management [42]. Far less research has been developed dealing with the users' perspective on MASS adoption. Fonseca et al. [15] propose a framework for MASS adoption based on interviews with industry experts and literature synthesis. Their proposed framework considers four major dimensions, namely, economic benefits, technical feasibility, human capital and enabling environment such as social acceptance. When it comes to social acceptance, potential users, particularly of autonomous ferries, are not fond of higher degrees of autonomy [17].

Extant literature provides limited insights into key determinants for the future commercial adoption of MASS. First, discussions in the literature and ongoing debates in the industry reveal that the main drivers of MASS development can also to some extent pose barriers to MASS adoption, as presumed benefits might not be achieved in a real-life commercial setting. In contrast to studies on potential benefits from MASS, Fonseca et al. [15] lean more towards the negative economic outcomes, technical (in)feasibility, and human capital requirements. Second, most studies and ongoing debates fail to clarify the attributes of MASS adoption. In particular, one needs to distinguish between several degrees of autonomy (DOA of MASS), considering the differences between the various shipping sectors. Indeed, the different DOA of MASS might not be equally suitable for all shipping segments and routes. Depending on the segment, the range of shipping needs to be considered as well. The range of shipping in this study refers to shipping route characteristics within the maritime transport network. Considering the MASS discussion outlined above, this study analyzes the key determinants of MASS adoption from a multi-stakeholder perspective while taking into account different DOA as well as different shipping route characteristics. The research questions are as follows: (1) what are the key determinants for MASS adoption in merchant shipping? and (2) which DOA of MASS is the most feasible for merchant shipping and for which route?

The remainder of this study is organised as follows. Section 2 presents the degree of autonomy and shipping route alternatives and develops a set of MASS adoption criteria from the shipping stakeholders' perspective including shipowners, shipbrokers, charterers, seafarers, maritime researchers, and others. Section 3 presents the data collection and multi-criteria decision-making (MCDM) method to assess the identified investment criteria, and also includes the results. Section 4 discusses the main findings, while Section 5 concludes and presents a few avenues for further research.

2. Alternatives and criteria in MASS adoption

2.1. Degrees of autonomy (DOA)

Broadly, a system automation can be expressed by four functions: (1) information acquisition, (2) information analysis, (3) decision selection, and (4) action implementation [36]. In a system, levels of automation (LOA) in each of these functions can vary from low to high level. A system with high LOA in each of these functions is considered a system with higher degree of autonomy (DOA). There exist several classifications of DOA in the context of MASS. Table 1 presents an overview of the DOA classifications by the IMO, Bureau Veritas, Det Norske Veritas (DNV), Lloyd's Register, and ONE SEA.

Classifications presented by IMO, Bureau Veritas, and DNV suggest four DOA, while Lloyd's Register suggests six. The white paper published by ONE SEA [33] synthesized all these DOA and suggested five DOA classifications. Regardless of the DOA classifications by different organizations, the main principles of the DOA are the same. The first degree (D1) ships use advanced artificial intelligence (AI) driven decision support systems, while the highest DOA is a fully autonomous ship. The DOAs in between these two DOAs are ships controlled from a Remote Operation Centres (ROC) with and without seafarers on board. The classification by ONE SEA [33] further includes a category based on human interaction and activity, in terms of the use of hands, eyes, mind, and human supervision. According to their classification, D1 covers assisted operations on a hands-on, eyes-on and mind-on basis; D2 involves partial automation with hands-off (at times), eyes-on and mind-on; D3 implies conditional automation based on hands-off, eyes-off (at times), mind-on; D4 means high level of automation using a hands-off, eyes-off, mind-off (at times) approach; and D5 is the fully autonomous levels involving hands-off, eyes-off, mind-off and human-off. The term mind-on refers to active human attention and intervention, although the ship can perform many functions autonomously.

The IMO is the highest regulatory body in the maritime industry. The IMO classification has been referred by other international organizations such as UNCTAD [21]. Extant literature on MASS widely refers to the DOA classification by IMO [15,23]. Hence, this study considers the four-degree classification as the alternatives to be assessed. The detailed DOA classification by the IMO is presented in Table 2.

2.2. Shipping route alternatives

According to a survey of seagoing cadets, about 30 % expect MASS commercial operations to take off in less than 10 years, while another 50 % expect MASS adoption in 11–20 years [4]. However, not all DOA classifications of MASS are equally suitable for different shipping segments and routes. Among the shipping market segments, container shipping is considered the most compatible with MASS adoption due to a higher degree of standardization in operations and cargo movement which makes the implementation of robotic systems easier [25]. Other studies suggest that MASS is likely to be more feasible for short-sea shipping operations [1,9]. Still, the potential of long-range MASS has also been identified [32,35]. For the purpose of this study, two route alternatives are considered:

- ROUTE 1 (R1): Container shipping between the Far East and North Europe or Mediterranean using large-scale autonomous vessels. Note that the unit capacity of manned container vessels on this route currently ranges between 12,000 TEU and 24,300 TEU.
- ROUTE 2 (R2): Intra-European container trade in the Mediterranean and Baltic Sea using small-scale autonomous feeder vessels. At present, intra-European container feeder and shortsea operations on these routes depend on manned container ships with a capacity ranging from 500 to around 4000 TEU.

The Far East to North Europe/Mediterranean route is one of the most economically significant shipping routes globally with 24.2 million TEUs transported in 2022 alone [45]. Implementing MASS on this route could lead to substantial cost savings and efficiency improvements, making it a valuable area for testing and deploying advanced shipping

Table 1
Degree of autonomy classifications.

DOA	IMO	Bureau Veritas	DNV	Lloyd's Register	ONE SEA
D0	No automation	Human operated	Manually operated function	Manual	Basic operation
D1	Ship with automated processes and decision support	Human directed	System decision supported function	On-board decision support	Assisted operation
D2	Remotely controlled ship with seafarers on board	Human delegated	System decision supported function with conditional system execution capabilities	On/off board decision support	Partial automation
D3	Remotely controlled ship without seafarers on board	Human supervised	Self-controlled function with human in the loop	Active human in the loop	Conditional automation
D4	Fully autonomous ship	Full automation	Autonomous function usually without human intervention	Human in loop/supervisory	High automation
D5				Fully autonomous- rarely supervised	Autonomous
D6				Fully autonomous – unsupervised	

Source: authors' compilation based on ONE SEA [33], [7], DNVGL [13]

Table 2
MASS degree of autonomy.

Degree	Autonomy	ROC	Unmanned
D1	Conventional ships with automated processes and decision support	No	No
D2	Remotely controlled ships with reduced seafarers on board	Yes	No
D3	Remotely controlled ships without any seafarers on board	Yes	Possible
D4	Fully autonomous ships capable of determining actions and making decisions	When required	Possible

Source: authors' interpretation based on [20]

technologies. The high degree of standardization in container operations facilitates the integration of autonomous technologies. Large-scale autonomous vessels are more feasible on this route due to the availability of advanced port infrastructure and technological support in major ports along the route. This infrastructure can support the operational requirements of large autonomous ships, including handling, maintenance, and cybersecurity measures.

The Mediterranean and Baltic Sea regions are ideal for short sea shipping operations, where small-scale autonomous feeder vessels can efficiently handle regional container trade. The shorter distances and frequent port calls make these regions suitable for testing and deploying smaller autonomous vessels. Intra-European shipping routes involve a network of smaller ports and terminals, which can benefit from the flexibility and efficiency of autonomous feeder vessels. These vessels can enhance the logistical capabilities of regional supply chains by providing more frequent and reliable services.

2.3. MASS investment criteria

To identify relevant determinants or criteria for MASS investment from a shipowner's perspective, a systematic approach was adopted. First, a literature search was conducted in the Web of Science database using the Boolean expression: (("ship* investment*" AND ("autonomous shipping" OR "unmanned ship" OR "autonomous ship" OR "autonomous vessel" OR "Maritime Autonomous Surface Ships")). This search did not return any relevant studies, demonstrating that MASS investment decision-making has not received attention in existing literature. This further justified the relevance of this study. Hence, we decided to proceed with the Boolean expression ("ship* investment*") to identify the criteria that shipowners and other shipping stakeholders would consider in ship investment decisions. This search returned 36 records, of which 32 were journal articles. Subsequently, we screened the full text of the articles manually for their relevance to ship investment decision-making. Nine articles were retained as relevant (see Appendix A for an overview). The studies that were excluded from this shortlist mainly related to risk assessment, ship price forecasting, financial schemes and real options valuation.

The 18 most commonly mentioned criteria, as obtained from the reviewed literature, are listed in Appendix B. In most MCDM methods, the required number of pair-wise comparisons increases significantly with the number of criteria. Hence, to keep the efforts of respondents reasonable in completing the data collection survey, three rounds of semi-structured Delphi [26] were undertaken with two authors of this study and two industry experts working with autonomous ships to obtain a shortlist of determinants for MASS adoption in merchant shipping. The aim of using the Delphi methodology was to narrow down the number of criteria to the most relevant ones that can be used in a decision-making framework. The Delphi exercise resulted in a final consensus list of nine criteria, which are: (C1) Operating costs (OPEX), (C2) Capital costs (CAPEX), (C3) Net present value (NPV), (C4) Remote Operation Centre (ROC), (C5) Navigation anti-collision and anti-grounding system, (C6) Cybersecurity risk, (C7) Technical intervention services, (C8) Compliance with rules and regulations, (C9) Environmental benefits at sea and in port. Criteria C1-C3 are financial, C4-C7 are technical, C8 and C9 represent legal and environmental determinants. The description of each criterion is provided in Table 3.

2.4. MCDM framework

This study employs an MCDM framework for assessing MASS adoption in shipping, linking the DOA and route alternatives to the nine identified criteria. The framework includes a set of nine criteria on the first level, three DOA classifications of MASS on the second level, and two route alternatives on the third level. The MCDM framework is depicted in Fig. 1.

Each DOA comes with varying requirements. For instance, for MASS D2 and D3, ROC setup is a mandatory requirement. For D3, further technical intervention services would be required if no crew is on board. For D3 and D4, higher security including cyber security preparedness will be necessary which will require additional investment. A company that invests and plans for D2 MASS operations cannot suddenly switch to D3 or D4. Further, companies need to consider their shipping route profile when exploring MASS alternatives. Most container shipping companies focus on specific routes. Therefore, shipping companies need to decide which degree of autonomy is most suitable for them based on their financial, technical, legal, and environmental profile.

3. Bayesian best-worst MCDM method

The Bayesian best-worst method (BWM) is adopted in this study to operationalize the proposed MCDM framework for MASS adoption. The BWM method was originally proposed by Rezaei [38]. BWM significantly reduces the number of pairwise comparisons of criteria compared

Table 3
Criteria for commercial MASS adoption.

No.	Criteria	Description
C1	Operating costs (OPEX)	Costs related to manning, stores, lubricants, repairs, maintenance and insurance. Lower operating costs from reduced crew size and automation, leading to significant savings.
C2	Capital costs (CAPEX)	Investment into ship purchase plus interest on debt or dividend payments. CAPEX is likely to be higher for MASS in comparison to conventional ships due to advanced technology requirements and the provision of duplicate systems to reduce or eliminate risks in case of technical failure or disruptions. Higher initial capital expense due to advanced technology, but potential long-term efficiency gains.
C3	Net present value (NPV)	The estimated present-day value of future cash flows generated by a ship investment while considering the time value of money. Positive NPV indicates profitability, taking into account the future financial benefits of MASS adoption.
C4	Remote Operation Centre (ROC) infrastructure	Setup a control centre infrastructure at shore or at sea, from where a qualified operator can remotely navigate one or more ships. Centralized control infrastructure reduces crew requirements on individual vessels, enhancing operational efficiency.
C5	Advanced navigation anti-collision and anti-grounding system	Increased safety through use of advanced sensors and radar. These systems reduce the risk of collisions and groundings, thus avoiding accidents and delays.
C6	Cybersecurity risk	Operational hazard due to a hacker taking over ship operations. Being part of intelligent transport systems, MASS is highly vulnerable to cyber threats. Cyberattacks could lead to operational downtime and financial losses.
C7	Technical intervention services	Operational downtime due to human intervention in case an unmanned vessel faces mechanical problems while at sea. Unmanned vessels may face operational downtime, with costs incurred for human intervention and repair services.
C8	Compliance with rules and regulations	Improved adoption in commercial shipping due to adhering to all relevant regulations of local and international agencies in the areas of safety of navigation, ship emissions, Port State Control, pilotage, etc. Non-compliance could result in fines, legal action, or operational delays.
C9	Environmental benefits at sea and in port	Competitive advantage through expected reduction in GHG emissions, noise and pollution at sea and in ports due to MASS deployment. Environmental benefits may lead to cost savings through emissions credits or reduced taxes and enhance the company's reputation.

to Analytic Hierarchy Process (AHP) MCDM method. Later, Mohammadi and Rezaei [27] introduced the Bayesian BWM, which enables probabilistic group decision-making, and reduces the influence of outliers in criteria weights. The input to the Bayesian BWM is the decision-makers rating of the criteria in a pair-wise manner, although different from AHP surveys. Applications of BWM and Bayesian BWM is evident in the autonomous shipping literature in various context such as assessment of MASS for arctic shipping [29], and exploration of cybersecurity risk of MASS [44], respectively. The MCDM framework proposed in this study is more focused on the three degrees of autonomy of MASS and two shipping routes, while Munim et al., [29] did not consider routes and also included conventional vessel for benchmarking. Further, the list of nine criteria in this study is based on a structured literature review and Delphi method.

3.1. Data collection

A BWM survey for data collection differs from typical Likert-scale surveys in that a pair-wise comparison is made with the most important (Best) and least important (Worst) criterion. The structured BWM web-survey was distributed to authors' network through LinkedIn and email communication, targeting only shipping and maritime professionals. A total of 40 responses were received. After cleaning for incomplete responses and straight lining, 34 responses were retained. A summary of the respondents' background is presented in Table 4. Two major respondent groups were seafarers and academics with 26.47 % and 23.53 % of the responses, respectively. The average professional experience in the sample was 13.19 years. The majority of the respondents were geographically located in Europe, particularly in Norway, the United Kingdom and Belgium, which belong to the group of countries at the forefront of MASS development.

3.2. Steps in Bayesian BWM application

The Bayesian BWM can be applied in five steps to identify the most important and the least important criteria based on weights and then utilize those weights to identify the priorities for the route and MASS alternatives. In total nine criteria were evaluated by the 34 maritime experts.

STEP 1: The maritime experts identify the most important and the least important criterion for MASS adoption out of the nine criteria. The respondents were asked: "which of the following criteria is the "most important" for MASS adoption in merchant shipping?" and "which of the following criteria is the "least important" for MASS adoption in merchant shipping?" According to the frequency counts (Fig. 2), (C2) Capital costs (CAPEX) and (C6) Cybersecurity risk have highest frequency for most important with six counts each. (C9) Environmental benefits at sea and in port has highest frequency for least important criterion with nine counts.

STEP 2: In this step, the maritime experts were asked to compare the importance of the most important criterion vis à vis the other eight criteria using a 5-point scale where 1 indicate equal importance and 5 indicate absolutely more importance of the most important criterion, forming the best-to-others (BO) vector (Table 5). The respondents were asked: "how much more important is the "most important criterion" in comparison to the following criteria?" For instance, for Respondent 3 in Table 5, the most important criterion is C1, which is then compared to the other eight criteria. C1 has a value of 5 when compared to C6 indicating that C1 is absolutely more important than C6.

STEP 3: Next, the experts were asked to compare the importance of the eight remaining criteria with respect to the least important criterion using a 5-point scale where 1 indicate equal importance and 5 indicate absolutely more importance of each of the eight criteria over the least important criterion. This forms the other-to-worst (OW) vector (Table 6). The respondents were asked: "how much more important are the following criteria in comparison to the "least important criterion"?" For instance, for Respondent 3 in Table 6, the least important criterion is C5, and the importance of other eight criteria over C5 are rated. C2 has a value of 5 when compared to C5, indicating that C2 is absolutely more important than C5.

STEP 4: To compute the aggregate criteria weights based on the input data from the experts (Tables 5 and 6), the Bayesian BWM algorithm was implemented using MATLAB [27]. Based on the original study by [27], the algorithm can be expressed as in equation (1).

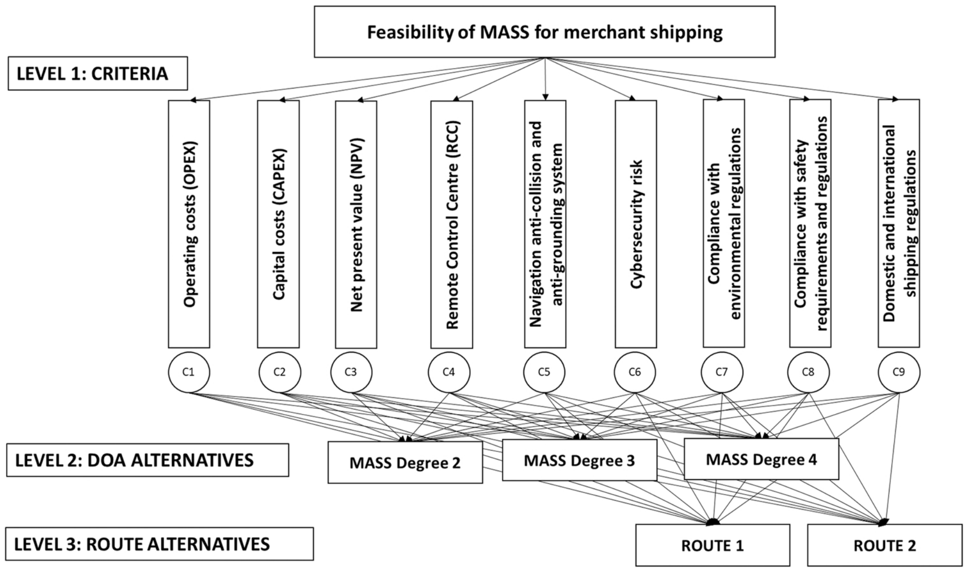


Fig. 1. MCDM framework for MASS feasibility.

Table 4
Respondents' background.

Frequency distribution of respondents' profession		
Profession	Frequency	Percentage
A charterer	2	5.88 %
A seafarer	9	26.47 %
A shipbroker	1	2.94 %
A shipowner	4	11.76 %
Working in a shipping company	5	14.71 %
Working in an academic institution	8	23.53 %
Other	5	14.71 %
Grand Total	**34**	**100.00 %**
Average Years of experience		
Profession	Avg. Years of experience	Standard deviation
A charterer	5.50	0.71
A seafarer	15.78	3.49
A shipbroker	5.00	0.00
A shipowner	18.50	9.81
Working in a shipping company	19.00	7.52
Working in an academic institution	19.75	10.44
Other	8.80	3.03
Grand average	**13.19**	**5.00**
Country of residence		
Country	Frequency	Percentage
Norway	7	20.59 %
United Kingdom	3	8.82 %
Belgium	3	8.82 %
Denmark	2	5.88 %
Malaysia	2	5.88 %
United States of America	2	5.88 %
Bangladesh, Brazil, Bulgaria, Chile, China, Czech Republic, Estonia, Germany, Greece, the Netherlands, Nigeria, Poland, Sweden, Turkey, Ukraine	15*	44.12 %
Grand Total	**34**	**100.00 %**

* One respondent per country.

$$A_B^k|w^k \sim multinomial\left(\frac{1}{w^k}\right), \quad \forall k = 1, \ldots, k$$

$$A_w^k|w^k \sim multinomial(w^k), \quad \forall k = 1, \ldots, k$$

$$w^k|w^* \sim Dir(\gamma \times w^*), \quad \forall k = 1, \ldots, k$$

$$\gamma \sim gamma(0.1, 0.1)$$

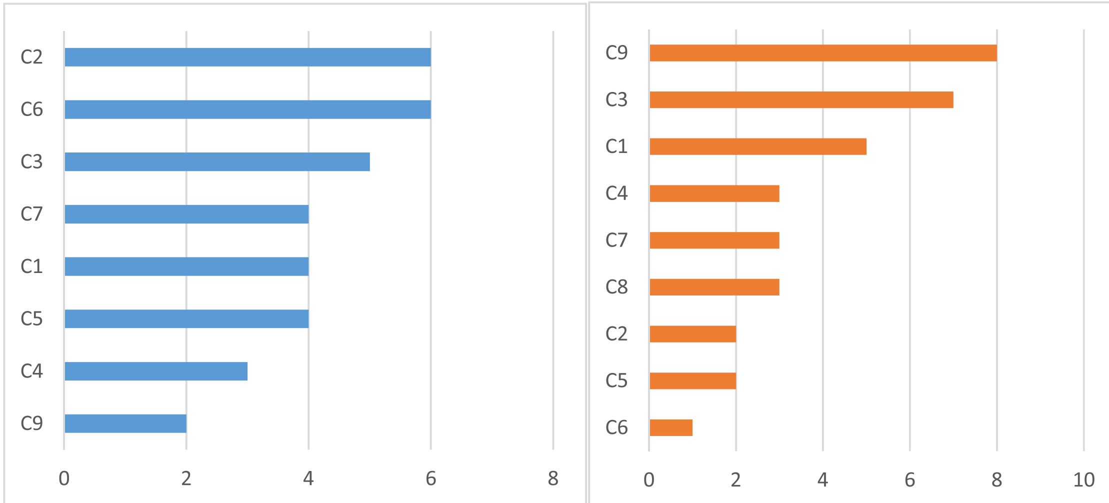
$$w^* \sim Dir(1) \tag{1}$$

Here, A_B^k represents the preference of the most important criterion (B) over the other criteria for respondent k, while A_w^k represents the preference of the other criteria over the least important criterion (W) for respondent k. The weights w^k correspond to the decision criteria weights for respondent k and w^* is the aggregated weight vector across all respondents. *multinomial* denotes a multinomial distribution and *Dir* a Dirichlet distribution. These weights follow a Dirichlet distribution $Dir(\gamma \times w^*)$, where γ~gamma (0.1,0.1). The prior weight vector w^* is assumed to follow a Dirichlet distribution $Dir(1)$.

The outcome is the credal ranking of the criteria reported in Fig. 3. The most important criterion for MASS adoption was (C5) Navigation anti-collision and anti-grounding system and the least important is (C9) Environmental benefits at sea and in port. The second and third most important criteria were (C6) Cybersecurity risk and (C2) Capital costs (CAPEX), respectively.

The values in the edges of Fig. 3 correspond to confidence scores (see full matrix in Appendix C), which indicate superiority of one criterion over another [27]. In the context of MASS feasibility, a confidence score higher than 0.90 could be interpreted as strong superiority, 0.70–0.90 as moderate, and below 0.70 as weak. For instance, C5 has a weak superiority (0.61) over C6, while moderate (0.74) over C2. Similarly, C2 has weak superiority over C7 (0.52), while strong over C9 (0.93).

STEP 5: Finally, using the weights obtained for the nine criteria through the Bayesian BWM estimation, the priorities of the DOA of MASS and route alternatives can be calculated. To calculate priorities, in Phase 1, the rating of the DOA and route alternatives was required under each criterion. The respondents were asked: "considering the following criteria, how feasible are the following route and MASS alternatives?". Feasibility ratings under each criterion were recorded using a 5-point scale where (1) referred to *not feasible at all* and (5) to *absolutely feasible*. The aggregate value of the feasibility ratings under each



(a) Count of most important criteria (b) Count of least important criteria

Fig. 2. Frequency of the most and least important criteria *(C1) Operating costs (OPEX), (C2) Capital costs (CAPEX), (C3) Net present value (NPV), (C4) Remote Operation Centre (ROC), (C5) Navigation anti-collision and anti-grounding system, (C6) Cybersecurity risk, (C7) Technical intervention services, (C8) Compliance with rules and regulations, (C9) Environmental benefits at sea and in port.*

Table 5
Best-to-Others (BO) vector.

Respondent	Most important	C1	C2	C3	C4	C5	C6	C7	C8	C9
1	C1	1	2	2	3	3	2	3	3	3
2	C9	1	1	2	3	3	2	1	1	1
3	C1	1	3	2	3	3	5	3	3	4
4	C1	1	1	3	3	2	4	3	4	5
5	C2	2	1	2	1	1	3	1	3	5
6	C3	3	2	1	1	1	4	3	4	3
7	C5	3	2	2	2	1	2	2	3	3
8	C6	4	2	2	3	3	1	4	2	2
9	C6	4	2	2	4	4	1	4	4	3
10	C6	2	2	5	4	3	1	3	2	5
11	C9	5	5	5	5	1	3	5	3	1
12	C6	5	3	3	3	3	1	2	5	2
13	C1	1	1	1	2	2	2	2	1	1
14	C2	2	1	3	2	2	1	1	2	2
15	C2	3	1	2	2	2	2	2	1	1
16	C7	3	3	2	2	2	2	1	3	3
17	C3	4	3	1	3	5	5	3	2	5
18	C6	2	4	5	5	1	1	3	1	1
19	C6	2	2	1	2	1	1	2	2	3
20	C7	5	5	5	2	1	1	1	1	3
21	C7	2	4	4	2	1	2	1	1	5
22	C3	2	2	1	3	3	3	3	3	3
23	C3	2	2	1	2	2	2	2	2	2
24	C5	2	2	2	3	1	1	2	4	2
25	C5	4	3	3	5	1	5	5	4	2
26	C7	3	4	2	2	2	1	1	3	3
27	C2	1	1	1	3	3	4	2	2	3
28	C2	2	1	2	2	3	2	2	2	2
29	C2	2	1	2	3	2	4	2	2	4
30	C3	1	1	1	3	3	3	3	2	3
31	C4	3	2	3	1	4	4	4	4	4
32	C4	2	2	4	1	2	2	2	4	3
33	C4	5	5	5	1	4	4	3	3	5
34	C5	5	5	5	5	1	5	4	5	5

criterion were calculated using the geometric mean approach as expressed in Eq. (2), where n represents the sample size of 34 and c the set of nine criteria.

$$\left(\prod_{i=1}^{n} x_{ic}\right)^{\frac{1}{n}} = \sqrt[n]{x_{1c} * x_{2c} * x_{3c} * \ldots * x_{34c}} \quad , c = \quad [1, 2, 3, \quad \ldots, \quad 9] \qquad (2)$$

In phase 2, the normalized values of the geometric means under each criterion were calculated by dividing them with the highest value. In phase 3, the normalized values are multiplied by their respective criteria weights to calculate priority values of each alternative. Priority calculations in phases 1–3 are reported in Tables 7 and 8 for DOA and ROUTE alternatives, respectively. By calculating the average values of Phase 3 in Tables 7 and 8, priorities of DOA and ROUTE alternatives are calculated (Fig. 4a). Among the alternatives, D2 and route 2 were found most feasible. The final priorities were calculated by multiplying the priorities

Table 6
Others-to-Worst (OW) vector.

Respondent	Least important	C1	C2	C3	C4	C5	C6	C7	C8	C9
1	C9	2	2	2	2	2	2	2	2	1
2	C4	2	2	2	1	2	2	2	2	2
3	C5	3	5	4	4	1	4	4	2	3
4	C5	5	3	3	4	1	3	5	3	4
5	C3	3	5	1	3	3	5	4	3	5
6	C2	5	1	5	2	3	5	5	4	4
7	C3	3	2	1	1	4	3	2	4	4
8	C1	1	3	3	1	1	1	2	2	2
9	C1	1	1	1	5	5	5	5	5	5
10	C9	4	4	2	3	3	5	3	3	1
11	C1	1	1	1	3	5	3	3	3	5
12	C8	5	5	5	5	3	5	5	1	3
13	C3	2	2	1	2	2	2	2	2	2
14	C3	3	4	1	2	2	1	2	2	2
15	C6	3	4	3	2	2	1	2	2	2
16	C2	2	1	2	4	5	4	5	3	2
17	C8	4	3	5	5	5	5	3	1	4
18	C4	4	5	4	1	5	5	4	4	5
19	C9	2	2	3	2	3	3	2	2	1
20	C3	2	5	1	5	5	5	5	5	5
21	C9	4	2	2	4	5	4	5	5	1
22	C4	3	3	4	1	2	2	2	2	2
23	C7	3	3	3	3	3	3	1	3	3
24	C3	1	1	1	3	4	4	3	2	4
25	C9	3	3	2	4	5	5	5	4	1
26	C1	1	1	2	3	3	5	5	4	2
27	C7	5	5	4	3	3	2	1	3	2
28	C9	4	4	4	4	4	4	2	3	1
29	C9	3	4	3	3	3	2	2	3	1
30	C9	4	4	5	2	3	3	2	1	1
31	C1	1	3	2	5	4	4	4	5	5
32	C3	3	3	1	4	3	3	3	3	3
33	C7	5	5	5	4	4	4	1	5	2
34	C8	3	3	3	4	5	3	4	1	5

of DOA and route alternatives (Fig. 4b). The most feasible MASS alternatives would be D2 in route 2, that is, intra-European container trade in the Mediterranean and Baltic using small-sized autonomous feeder vessels. Next, D3 MASS on route 2 or D2 MASS on route 1 come with equal priority.

4. Discussion

The findings reveal that reliability of advanced (C5) Navigation anti-collision and anti-grounding system is the most important criterion for MASS adoption in shipping, followed by (C6) Cybersecurity risk and (C2) Capital costs (CAPEX). This further confirms that the most important driver of MASS adoption is related to safety. Hence, this might explain why the majority of published research indeed focuses on safety issues, particularly collision avoidance [18,28]. [23] mapped the safety challenges for MASS, particularly when various DOA of MASS will be sailing in a mixed environment; as expected the extent of risk increases when higher DOA MASS are operating. For instance, D3 and D4 MASS sailing in the same waters represents a higher risk than D2 and D3. The highest risk occurs when all degrees of MASS sail simultaneously in the same waters. The operational phase and area in navigational waters are two most critical factors determining maritime accident risk [5]. The issue of risk assessment in a mixed environment needs further attention in future research.

With the increased use of digital technologies, MASS is likely to be more exposed to cyber threats. [44] assessed the core systems and their sub-systems in MASS operations. Navigation systems such as Global Navigation Satellite Systems (GNSS), Electronic Chart Display and Information System (ECDIS), and communication devices in ROC were found most vulnerable to cybersecurity breaches. Future studies should investigate cybersecurity risk mitigation strategies and develop concrete cybersecurity risk management plans for navigation and ROC systems [41].

The true capital cost of MASS is unknown. Although some studies indicate 10–30 percent increase in capital costs compared to identical conventional vessels, such estimates require caution. The majority of economic analyses of MASS investment seems to be unreliable. [50] provides a good overview of the relevant costs. Capital costs include vessel purchase through own equity or loan, loan repayments and depreciation allowances, vessel registration fees, and taxes. With an account of detailed operating expenses and revenue potential, net present values of the MASS investment can be calculated. [24] found that increase in CAPEX is a less significant cost factor, whereas shore crew costs are the most uncertain among the cost factors. More in-depth costs-benefit studies are required to get more reliable estimates. New business models may emerge to capitalize on increasing costs due to advanced technological requirements of MASS.

The ranking of the MASS adoption criteria might vary depending on the stakeholder concerned. Fig. 5 presents the ranking for four different stakeholder groups. According to the *academic* sub-sample (Fig. 5a), the most important criterion for MASS adoption is *(C2) Capital costs (CAPEX) followed by (C4) Remote Operation Centre (ROC), and (C1) Operating costs (OPEX)*. *(C6) Cybersecurity risk* is the most important for *seafarer* and *shipping management* sub-samples, followed by *(C5) Navigation anti-collision and anti-grounding system* and *(C7) Technical intervention services* interchangeably in second and third positions (Fig. 5b-c). For the *others* sub-sample (Fig. 5d), the most important criterion is *(C5) Navigation anti-collision and anti-grounding system,* followed by *(C6) Cybersecurity risk, and (C8) Compliance with rules and regulations*. The *others* group mainly includes consultants and maritime law professionals. The first four criteria are identical in the seafarer and shipping management sub-samples; hence, these need to be prioritized the most by the MASS builders and policy makers.

The most feasible alternative is D2 MASS deployed on a short-range

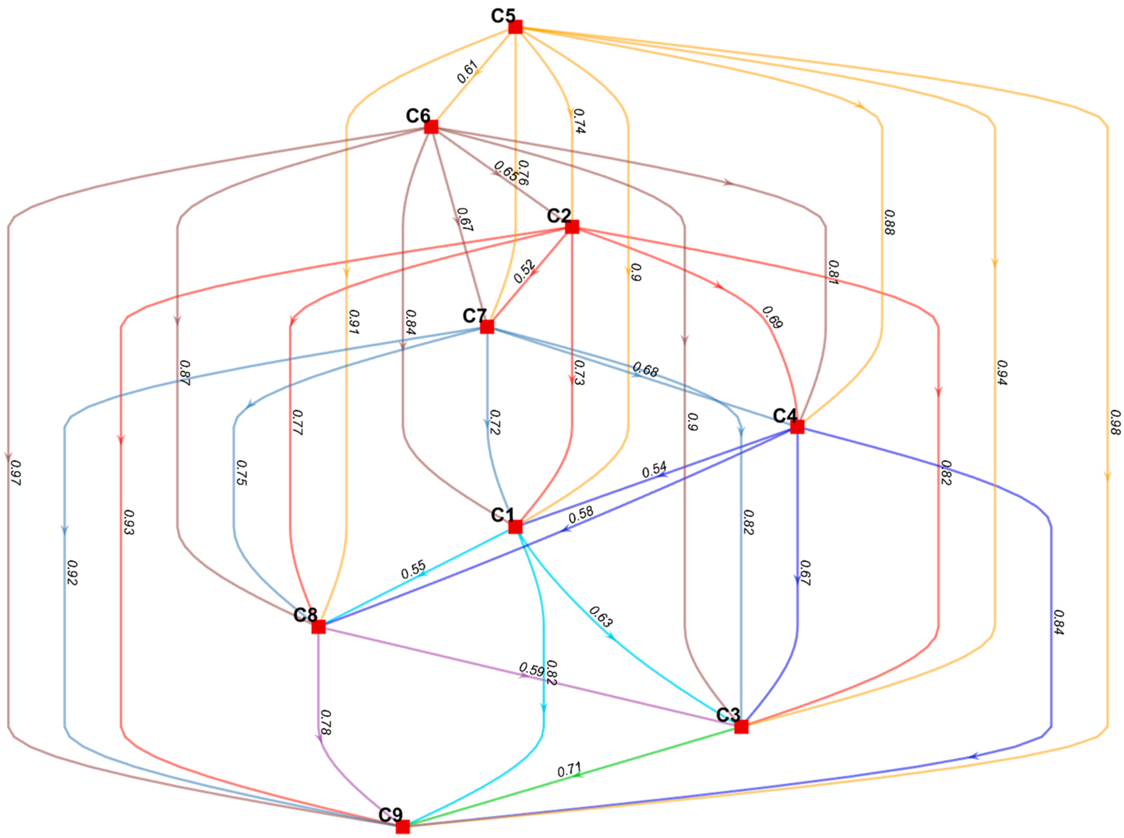


Fig. 3. Priority of criteria for MASS adoption. *(C1) Operating costs (OPEX), (C2) Capital costs (CAPEX), (C3) Net present value (NPV), (C4) Remote Operation Centre (ROC), (C5) Navigation anti-collision and anti-grounding system, (C6) Cybersecurity risk, (C7) Technical intervention services, (C8) Compliance with rules and regulations, (C9) Environmental benefits at sea and in port.*

Table 7
DOA feasibility under each criterion.

DOA alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9
Criteria weights	0.108	0.115	0.104	0.109	0.124	0.120	0.115	0.107	0.098
Phase 1: Geometric mean of DOA feasibility ratings									
MASS D2	3.490	3.106	2.529	2.910	3.153	2.936	3.327	3.152	2.809
MASS D3	2.434	2.248	2.083	2.417	2.407	2.376	2.452	2.554	2.378
MASS D4	1.716	1.775	1.785	1.786	1.952	1.868	2.051	2.135	2.067
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Phase 2: Normalized values									
MASS D2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
MASS D3	0.697	0.724	0.824	0.830	0.763	0.809	0.737	0.810	0.847
MASS D4	0.492	0.572	0.706	0.614	0.619	0.636	0.617	0.678	0.736
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Phase 3: DOA priority calculation									
MASS D2	0.108	0.115	0.104	0.109	0.124	0.120	0.115	0.107	0.098
MASS D3	0.075	0.083	0.086	0.091	0.094	0.097	0.085	0.087	0.083
MASS D4	0.053	0.066	0.074	0.067	0.076	0.076	0.071	0.072	0.072

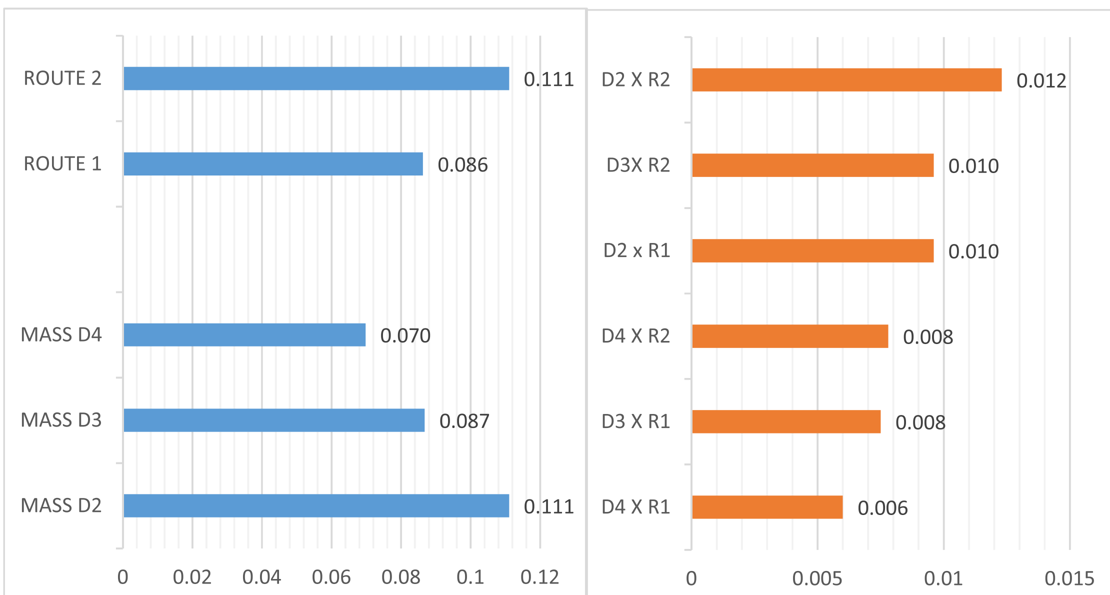
route. This is what we observe in the ongoing projects, particularly with ZULU in Belgium and Asko in Norway. The D2 and D3 MASS are found in the final priority of MASS adoption. Both are remotely controlled; D2 with reduced crew and D3 without crew on-board. This implies more attention needs to be dedicated to the role and functioning of ROCs. According to Størkersen [42], ROC personnel might face a heavy burden in handling and responding to planned and unplanned situations and being capable of making rapid decisions. The degree of burdensomeness would largely depend on the functions of the ROC operator and the number of vessels each operator has to manage. Hence, the workload of ROC operators needs to be carefully designed. Experimental studies can be conducted with MASS of varying DOA under an operator to test their workload-stress capabilities. Also, the competence requirements for ROC operators still remains to be further explored and should be clearly defined.

5. Implications for policy

The findings of this study lead to several policy recommendations to support the adoption and integration of MASS into the commercial shipping industry. Technological advancements, particularly in navigation and anti-collision systems (C5), were found to be the most critical factors in determining the feasibility of MASS (Fig. 3). Governments should provide incentives for research and development (R&D) in these

Table 8
ROUTE feasibility under each criterion.

ROUTE alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9
Criteria weights	0.108	0.115	0.104	0.109	0.124	0.120	0.115	0.107	0.098
Phase 1: Geometric mean of ROUTE feasibility ratings									
ROUTE 1	2.121	2.108	2.052	2.169	2.228	2.173	2.248	2.554	2.580
ROUTE 2	3.003	2.799	2.555	2.999	2.775	2.709	3.100	3.161	2.960
	C1	C2	C3	C4	C5	C6	C7	C8	C9
Phase 2: Normalized values									
ROUTE 1	0.706	0.753	0.803	0.723	0.803	0.802	0.725	0.808	0.872
ROUTE 2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Phase 3: ROUTE Priority calculation									
ROUTE 1	0.076	0.087	0.084	0.079	0.099	0.096	0.083	0.086	0.086
ROUTE 2	0.108	0.115	0.104	0.109	0.124	0.120	0.115	0.107	0.098



(a) DOA and ROUTE priority (b) Final priority

Fig. 4. Priority of MASS alternatives.

areas to accelerate innovation. Furthermore, public-private partnerships could help bridge the gap between technological development and real-world application.

Cybersecurity risks (C6) were the second most important concerns raised by stakeholders (Table 3, Fig. 3). Autonomous vessels, particularly those with higher DOAs, are more susceptible to cyber threats due to their higher reliance on digital systems. To safeguard operations, robust cybersecurity measures, including advanced threat detection systems, must be put in place. Regular updates to protocols, as well as collaboration with cybersecurity experts, will enhance the resilience of the MASS vessels.

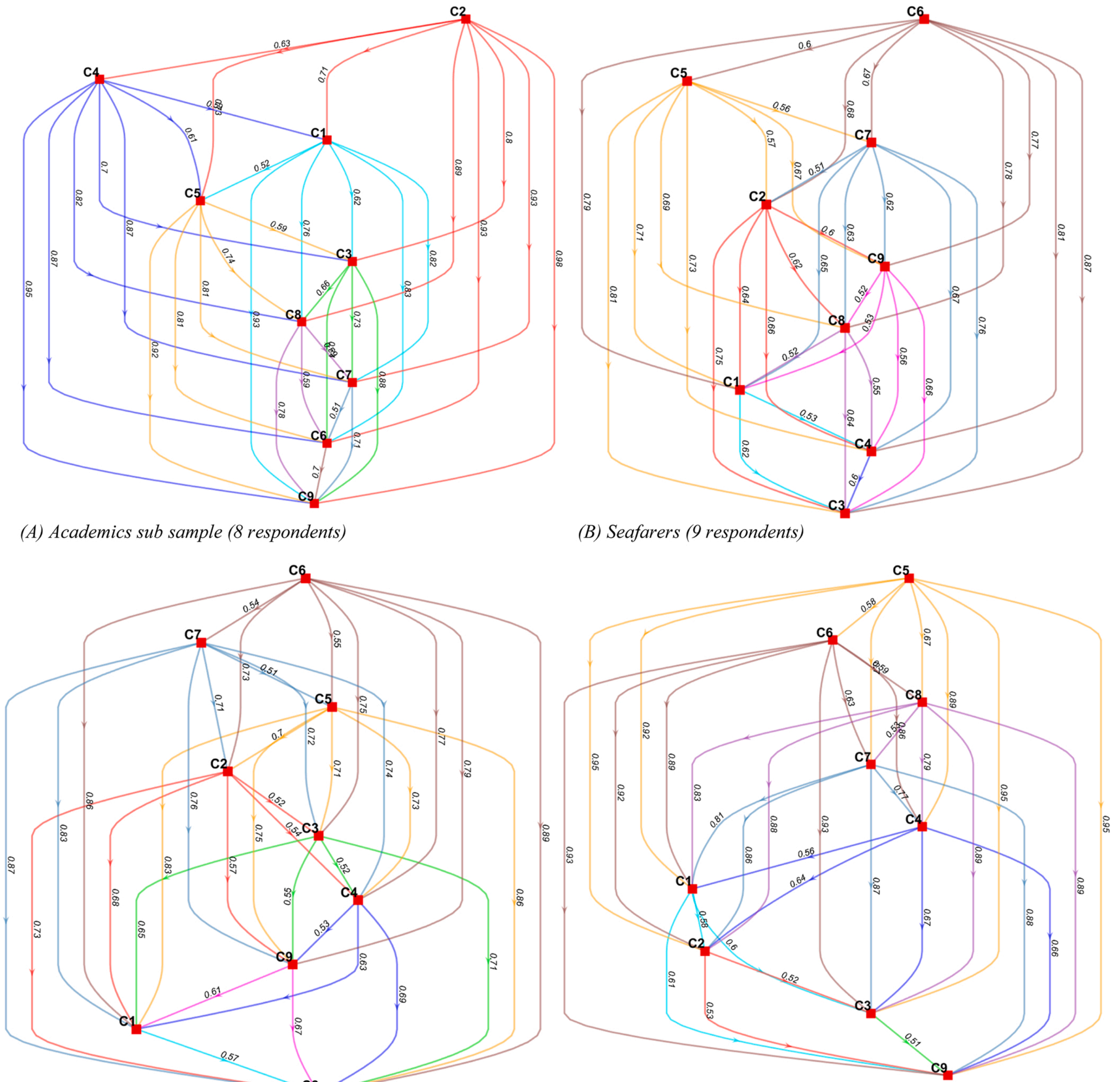
Economic factors, particularly capital costs (C2) and operating costs (C1), are too key determinants of MASS adoption (Table 7, Fig. 3). Financial incentives such as subsidies and tax benefits for stakeholders investing early in MASS could facilitate commercial adoption. Additionally, insurers are encouraged to adjust premiums for vessels demonstrating increased safety due to autonomous technologies.

Further, as autonomous vessels shift to reduced or no crew (in D2, D3, and D4), policy makers as well as various stakeholders including maritime education and training institutions must invest in both infrastructure and personnel. This includes ROC operator training to equip them with the skills necessary to handle real-time decision-making under both routine and emergency scenarios, which are crucial as the operational burdens of ROCs might be unpredictable in the early stages. Moreover, regulatory and policy making bodies need to account for the dynamic nature of MASS DOA. For instance, ships could transition between different levels of autonomy (refer to Table 2) depending on operational requirements. The environmental benefits of adopting autonomous vessels, although ranked lower in stakeholder priorities (Fig. 3), should not be overlooked. Stricter emissions standards for autonomous ships can drive innovation in cleaner energy solutions and contribute to the shipping industry's decarbonization efforts.

Lastly, the successful adoption of MASS requires the active engagement of all stakeholders, from shipowners to regulatory bodies. Involving stakeholders in policy development ensures that diverse concerns are addressed, which is particularly important for the social acceptance of MASS technologies.

6. Conclusion

This study employed a MCDM framework to analyse the key determinants of MASS adoption in shipping. The framework was operationalized by data collected from maritime industry experts, with the objective of carrying out a multi-stakeholder evaluation of MASS



(A) Academics sub sample (8 respondents)

(B) Seafarers (9 respondents)

(C) Working in shipping company(5 respondents), shipowner(4 respondents), broker(1 respondent) and charterer (2 respondents); total 12 respondents

(D) Others (5 respondents)

Fig. 5. Sub-sample-wise ranking of criteria (C1) Operating costs (OPEX), (C2) Capital costs (CAPEX), (C3) Net present value (NPV), (C4) Remote Operation Centre (ROC), (C5) Navigation anti-collision and anti-grounding system, (C6) Cybersecurity risk, (C7) Technical intervention services, (C8) Compliance with rules and regulations, (C9) Environmental benefits at sea and in port.

adoption for different DOAs and shipping sectors. The Bayesian BWM method was used for analysis. The most important criterion for MASS adoption was shown to be *(C5) Navigation anti-collision and anti-grounding system,* followed by *(C6) Cybersecurity risk* and *(C2) Capital costs (CAPEX)*. Some variations in criteria ranking were found while conducting a sub-sample analysis. The most feasible alternative appeared to be D2 MASS deployed on a short-range route (Fig. 4b). The least prioritized alternative was D4 MASS deployed on a long-distance route.

Future research might replicate the study in a larger geographic context to increase validity of the findings. Also, qualitative exploration into ranking of criteria and priority of alternatives are recommended. The level of autonomy of MASS might not be fixed during a particular voyage and change during different operating phases. For instance, a D3 MASS might be fully autonomous during clam sea environment. The complexities of switching the degree of autonomy needs further exploration. The adoption of MASS with higher DOA on long-distance routes such as the Europe-Far East trade might be influenced by the propulsion technology, port infrastructure readiness, human-capital readiness, insurance premiums, and shippers' willingness to accept a longer lead time. These factors need further exploration too. Role of ROC operators and their operational burden is crucial for safety management, particularly in mixed operational environment with conventional shipping. Future research should also investigate the impact of MASS on freight rates dynamics. Are the freight rates going to be more stable for MASS? Are the newbuilding prices likely to be more stable? The cost of operating MASS and its financial feasibility considering the vessel lifetime needs more investigation.

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CRediT authorship contribution statement

Halvor Schøyen: Writing – review & editing, Validation, Data curation. **Hercules Haralambides:** Writing – review & editing, Validation. **Theo Notteboom:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Ziaul Haque Munim:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization, Project administration.

Appendix A

Table A9
Nine studies on shipping investment decision-making

NO	Study	Market segment	Relevant criteria
1	Sahin et al.,[40]	Bulk	Ship price, return on investment, loss probability, ship capacity, energy consumption, speed, engine power, crane existence.
2	Akgul and ÇETİN [2]	Not specified	Market condition, payback period, technical features, financing capacity, risk perception.
3	Yao et al. [49]	Bulk	Cost, ship design and compliance, environmental performance, economic performance, vessel productivity, incentive mechanism, public appraisal and branding, technology maturity.
4	Park et al.,[34]	Bulk	Financial capacity and funding, ship type and size, international market condition, fleet productivity, freight rate fluctuations, shipping tax benefit, domestic and international regulations, ship registry.
5	Fan and Luo [14]	Container	Global container throughput, fleet management capacity, market share, time-charter index, average vessel size.
6	Duru et al.,[12]	Bulk	Return on equity, fuel consumption, loss probability, loaded draught, ship speed, cargo crane existence.
7	Bulut et al.,[6]	Bulk	All from Duru et al. [12] plus ship size, fleet size, profitability, fleet age, crew cost, service quality, ship management experience.
8	Rousos and Lee [39]	Bulk, Tanker	Net present value, internal rate of return, capital requirement, freight rate fluctuations, second hand price, ship category management experience, environmental performance, 3rd party involvement.
9	Xu and Yip [48]	Not specified	Shipbuilding contracts, global fleet size, orderbook, trade demand, freight market, shipbuilding price, second-hand price.

Appendix B

Table 10
Finalizing the criteria for MASS deployment (C: costs, M: market, F: financial, T: technological, E: environmental, R: regulatory)

Sub-criteria	Criterion from literature	1st round	2nd round	Final round Confer Table 3
(C1) Operating costs (OPEX)	YES			KEEP
(C2) Voyage costs		ADDED		DROP
(C3) Cargo handling costs		ADDED		DROP
(C4) Periodic maintenance costs		ADDED		DROP
(C5) Capital costs (CAPEX)	YES			KEEP
(M1) Average time-charter earnings	YES			DROP
(M2) New building prices	YES	DROP		
(M3) Second hand-prices	YES	DROP		
(M4) New building orders	YES			DROP
(M5) Scrapping volume	YES			DROP
(F1) Net present value (NPV)	YES			KEEP
(F2) Internal rate of return (IRR)	YES		DROP	
(F3) Payback period (price/earnings ratio)	YES			DROP
(T1) Propulsion and power supply system	YES			DROP
(T2) Average service speed of the ship	YES			DROP
(T3) Remote Operation Centre (ROC)		ADDED		KEEP
(T4) Survey and inspections services		ADDED		DROP
(T5) Navigation anti-collision and anti-grounding system		ADDED		KEEP
(T6) Technical intervention services			ADDED	KEEP
(T7) Cyber security risk				ADDED
(E1) Environmental benefits at sea and in port	YES			KEEP
(E2) Reduced GHG emissions	YES			DROP
(E3) Shift in Cargo transport from road to sea			ADDED	DROP
(R1) Compliance with safety requirements and regulations	YES			REVISED to "Compliance with rules and regulations"
(R2) Compliance with design requirements and regulations	YES			
(R3) Domestic and international shipping regulations	YES			
(R4) Ship registration benefits	YES			DROP

Appendix C

Table 11
Confidence scores of the nine criteria based on the full sample

Criterion	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0.000	0.267	0.629	0.461	0.102	0.162	0.284	0.545	0.820
C2	0.733	0.000	0.822	0.690	0.257	0.354	0.522	0.768	0.935
C3	0.371	0.178	0.000	0.334	0.057	0.099	0.182	0.414	0.714
C4	0.539	0.310	0.666	0.000	0.119	0.188	0.317	0.579	0.836
C5	0.898	0.743	0.944	0.881	0.000	0.607	0.760	0.911	0.984
C6	0.838	0.646	0.901	0.813	0.393	0.000	0.667	0.873	0.974
C7	0.716	0.478	0.818	0.683	0.240	0.333	0.000	0.752	0.924
C8	0.455	0.232	0.586	0.421	0.089	0.127	0.248	0.000	0.784
C9	0.180	0.065	0.286	0.164	0.016	0.026	0.076	0.216	0.000

Appendix D. List of acronyms

AI-Artificial Intelligence
AIS-Automatic Identification System
BWM-Best-Worst Method
CAPEX-Capital Expenses
DOA-Degree of Autonomy
DNV-Det Norske Veritas
ECDIS-Electronic Chart Display and Information System
GHG-Greenhouse Gas
GPS-Global Positioning System
GNSS-Global Navigation Satellite System
IMO-International Maritime Organization
INS-Inertial Navigation System
LIDAR-Light Detection and Ranging
MASS-Maritime Autonomous Surface Ships
MCDM-Multi-Criteria Decision-Making
NPV-Net Present Value
OPEX-Operating Expenses
RADAR-Radio Detection and Ranging
R&D-Research and Development
ROC-Remote Operation Centre
TEU-Twenty-foot Equivalent Unit
UNCTAD-United Nations Conference on Trade and Development

Data Availability

Data is published in the manuscipt.

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