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Analysis and Definition of Certification Requirements for Maritime Autonomous Surface Ship Operation

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Abstract: The autonomy of transport systems presents a transformative opportunity to enhance logistics efficiency, improve safety, and support decarbonization. In the maritime sector, the International Maritime Organization (IMO) has been working since 2016 to develop a mandatory regulatory framework for Maritime Autonomous Surface Ships (MASSs), aiming to finalize a comprehensive code. Simultaneously, pilot projects are underway in national waters under the oversight of national administrations. Naval applications of autonomous ships demonstrate their potential, as emerging doctrines highlight their strategic and operational advantages. Although the military sector is not governed at the international level, safely managing interactions between military and commercial MASSs is crucial for ensuring safe navigation. Classification societies play a vital role in achieving high safety standards and ensuring regulatory compliance. This study aims to propose a framework for certifying maritime autonomous vessels. Through a thorough analysis of the existing literature and by identifying gaps, this study outlines a structured pathway to facilitate the certification and operation of MASSs, addressing key technical, operational, and safety considerations. This research contributes to designing a risk-informed approach for the development of autonomous surface vehicles.

Keywords: autonomous ship; MASS; marine certification; safety; IMO MASS Code

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1. Introduction

The development of Maritime Autonomous Surface Ships (MASSs) is primarily driven by the potential for operational cost reduction, improved safety, and enhanced logistical efficiency. Automation aims to reduce human error [1,2], yet it simultaneously introduces new risks, particularly in terms of system reliability, cybersecurity, and regulatory compliance [3]. Recognizing these challenges, the International Maritime Organization (IMO) has undertaken a structured regulatory approach. The regulatory scoping exercise, initiated in 2017 and concluded in 2021 [4], identified key areas where existing maritime conventions need to be adapted to accommodate MASS operations. These adaptations pertain to the roles of onboard and remote operators, liability concerns, and adherence to navigation rules such as COLREGs. The IMO categorizes MASS autonomy into four levels, ranging from automated decision-support systems with onboard crews to fully autonomous operations. However, current IMO regulations mainly focus on cargo vessels, leaving passenger ships and military applications outside the immediate regulatory scope. This classification is vital, as different levels of autonomy impose distinct technical and operational requirements, affecting control systems, risk management strategies, and certification procedures.

Classification societies have introduced interim certification frameworks to bridge regulatory gaps, incorporating risk-based methodologies and goal-based safety standards as part of the Digital Transformation Roadmap (see Figure 1). These efforts align with the ongoing development of the IMO MASS Code, which is set to transition from a non-mandatory framework (2025) to a mandatory code (2032), regulating the operation of maritime autonomous surface ships [5].

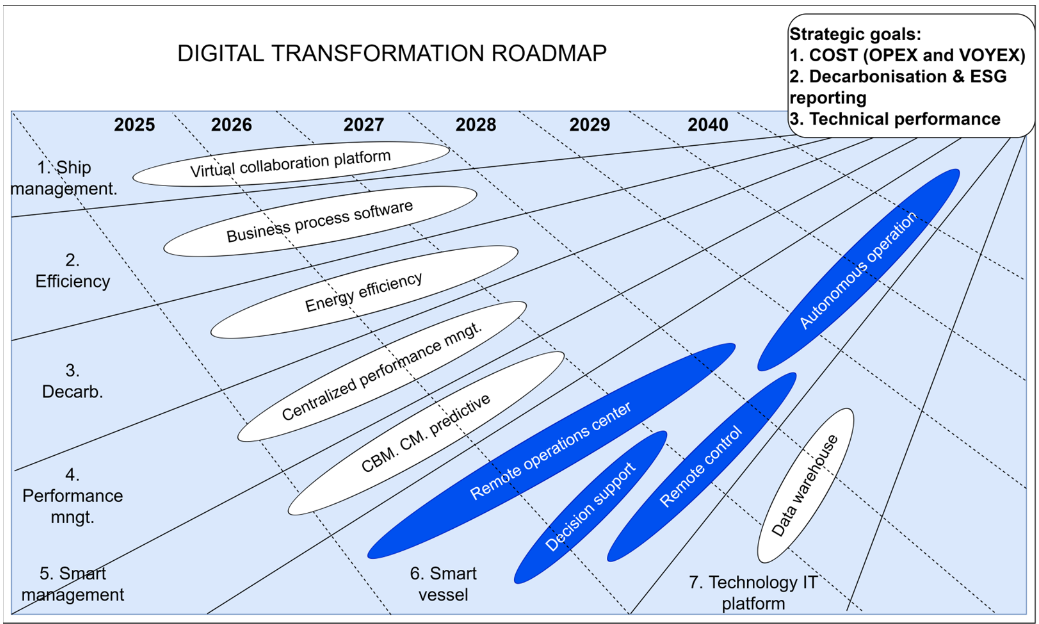

Figure 1. Visualization of the Digital Transformation Roadmap.

Navies are also highly motivated in introducing autonomous vehicles that can be employed in a wide range of missions, reducing human exposure to risks. USVs designed for military applications are generally required to follow in-house Ministry of Defence rules. However, military USVs need to be certified to operate in environments where manned and unmanned ships can operate altogether. The way to manage the interaction between many different in-house rules and future international MASS Codes is, at the moment, not clear.

This paper explores the interaction between these evolving regulations and the feasible challenges faced by MASS developers, emphasizing certification pathways and regulatory adaptation strategies. The goal of this paper is to propose a credible pathway for achieving Class Society certification and obtaining navigation licenses from Flag States. The proposed framework is designed to link rules and technical challenges associated with MASSs, ensuring their safe and efficient integration into maritime operations.

2. Literature Review

The IMO MASS Code will be applicable only to cargo ships; the applicability to passenger ships will be considered at a future stage. For the definition of MASSs, the International Maritime Organization (IMO) has proposed four levels of autonomy [6]:

- Degree 1 (Ship with automated processes and decision support): Seafarers are present on board to operate and manage shipboard systems and functions. While some operations may be automated, seafarers are ready to take control when necessary.

- Degree 2 (Remotely controlled ship with seafarers onboard): The ship is controlled and operated from a different location. Seafarers are present onboard to manage and operate the ship's systems and functions.
- Degree 3 (Remotely controlled ship without crew onboard): The ship is managed and operated from a different location. There are no crew members on board.
- Degree 4 (Fully autonomous ship): The ship's operating system can make decisions and take actions independently.

Most of the new ships may be categorized as Degree 1 but most of the existing ships cannot fall into any degree. Furthermore, the proposed code is intended for international commercial shipping, while passenger ships and military applications remain out of the proposed rules, despite the vast number of possible applications. The main engineering aspects of MASSs can be divided into four main categories: Guidance and Control, Reliability and Availability, Cybersecurity, and Rules [7]. All topics will be addressed in the literature review.

Guidance and Control systems must navigate the ship in all circumstances, avoiding moving and fixed obstacles. Advanced optimization methods (OM) are used to produce optimal trajectories or paths that might include sophisticated characteristics, such as spatiotemporal–optimal, danger level (considered as a collision probability), fuel saving, weather routing, and scheduled missions. The Evolutionary Algorithm (EA) represents a class of artificial intelligence increasingly used in the design of USV path planners. EA can be characterized as an optimization problem with specified constraints. To date, genetic algorithms (GA) are the most widely adopted method for waypoint generation [8]. Due to their expensive computational costs, especially when constraints such as obstacles, USV dynamic limits, and mission constraints must be satisfied, optimization methods are limited for real-time implementation [9,10]. To ensure safe and effective path planning in dynamic and hazardous environments, the hybrid path planning strategy has recently been applied to minimize the risk cost function [11]. In publications [12,13], a hybrid path planning approach is presented, which is constituted by a two-layered architecture combining both global and local path planning functions. Since COLREG regulations were originally devised as navigation rules for seafarers, incorporating and implementing this regulation in a collision avoidance strategy presents a big challenge [14,15], especially for the identification of lights, flags, and horns. A significant number (56%) of collisions at sea are caused by violations of COLREGs [16,17]; therefore, protocol-based collision avoidance algorithms should embed all the applicable COLREG regulations [14]. A modified virtual force field (MVFF) method [15], which complies with COLREG guidelines in a USV simulation, could be employed in another approach. It has also been demonstrated that this method may face greater challenges in scenarios with multiple obstacles. Digital twinning is emerging as a promising tool to design, test, and operate assets, including autonomous vehicles. One pillar of digital twinning is the capability to simulate the behavior of the asset in the relevant operational scenarios: in [18], the authors simulated the propulsion system; in [19], the maneuverability performance was modelled; while in [20], the control system was modelled. Digital twinning is emerging as a promising tool to design, test, and operate assets, including autonomous vehicles [18,19].

Ensuring the reliability and availability of MASSs is critical due to their isolated operations and the potentially severe consequences of system failures. This is particularly true as autonomous vessels operate with minimal human intervention. Established methodologies such as Reliability Block Diagrams (RBD) and Fault Tree Analysis (FTA) are widely used to model system behavior, identify failure modes, and quantify failure probabilities [21–24]. These methodologies can complement existing classification society certification frameworks, bridging gaps between traditional risk models and AI-driven safety assessments [25–28].

MASS certification requires structured risk evaluation methodologies to ensure operational safety and regulatory compliance. The IMO's regulatory framework incorporates Formal Safety Assessments (FSA) as a structured methodology to assess risks, while classification societies utilize Failure Mode and Effects Analysis (FMEA) and Hazard Identification (HAZID) techniques to validate system safety. These methodologies allow regulators and certifying bodies to assess the likelihood of failures, their impact on vessel operation, and mitigation strategies before MASSs can receive certification [29]. These techniques aid in designing fault-tolerant architectures, often leveraging redundancy. However, excessive redundancy introduces challenges such as increased weight and costs, necessitating balanced system configurations. Along with digital twinning technics [30,31] that provide cost-effective autonomous technology testing possibilities, different technological solutions (e.g., sensors and telecommunication, remote control and operation centers, obstacle and collision avoidance systems, cybersecurity, and vessel health management, etc.) [32,33] are under development by different market players (Kongsberg Maritime, Bimco, Navantia, Aivenuatics, etc.) [34]. The solutions currently present on the market, including vessel test cases such as Jara Birkeland, Munin, and Revolt [35–37], are proposing different complex technologies, starting from pathway optimization to the testing of unmanned vessel operations, with different vessel autonomy levels. Although the mentioned projects have utilized MASS technologies, there is still a way to go towards their wide adoption [38]. This indicates the requirement for technology verification and adaptation in the maritime sector.

Cybersecurity remains a fundamental challenge in the certification of MASSs, as regulatory frameworks must account for cyber threats alongside traditional maritime risks. Classification societies, including RINA, ABS, and DNV, have integrated cybersecurity resilience into their MASS certification standards, with a focus on secure remote-control operations, encrypted communication channels, and system redundancy for fail-safe operations. Given the increased reliance on AI-based decision-making, certification protocols must include penetration testing, intrusion detection systems (IDS), and cybersecurity risk assessments as part of their compliance verification, with no crew onboard to address issues in real-time [39,40]. The communication systems linking MASSs to Shore Control Centres (SCC) are particularly vulnerable. Cyberattacks targeting these systems, such as signal manipulation or jamming, could compromise navigation and operational safety. Similarly, reliance on sensors and AI for autonomous decisions creates risks of data manipulation, leading to unsafe actions. Operational technology (OT) systems, which often lack robust security protocols, further amplify the risk of propulsion, steering, or auxiliary system disruptions. To mitigate these threats, cybersecurity must be integrated into the design and operation of MASSs. The essential measures are applying "security-by-design" principles, ensuring redundancy in communication systems, and improving data reliability through advanced sensor fusion. International standards, like those from the IMO and IACS and the Nato Cooperative Cyber Defense Centre of Excellence (CCDCOE) in a workshop, provide critical guidelines for enhancing the resilience of MASSs to cyber threats [41].

As IMO and IACS work toward publishing the first international codes for Maritime Autonomous Surface Ships (MASS), classification societies have anticipated this timeline by developing their own goal-based rules. These early frameworks aim to bridge the regulatory gap, enabling forward-thinking shipowners and shipyards to adopt MASS technology while ensuring safety and compliance. The approach taken by Class Societies balances innovation and regulatory needs. Prescriptive rules typically applied to traditional vessels are complemented by goal-based standards for MASSs, providing the flexibility needed to address rapidly evolving technologies. These standards outline essential requirements for the design, construction, and operation of autonomous ships, emphasizing safety, cybersecurity, and environmental compliance.

In conclusion, it is essential to ensure that these aspects are integrated into the design and operation of MASSs, allowing a level of safety, security, and environmental protection equivalent to or exceeding that of conventional ship operations. Additionally, MASSs must provide reliable and high-quality services that meet or surpass the standards expected in traditional maritime activities, thereby ensuring the confidence of stakeholders and compliance with evolving regulatory frameworks.

A review of the existing literature on MASS certification reveals two main gaps: first, a limited comprehensive analysis of classification rules specific to MASSs, and second, a lack of detailed studies on how Flag State administrations issue navigation licenses for autonomous vessels. While several works discuss aspects of MASS regulation, no unified framework bridges classification requirements with Flag State authorization processes (Maritime Authorities). Both gaps are critical, as they represent fundamental steps in designing, certifying, and operating Maritime Autonomous Surface Ships (MASSs). This paper aims to address these gaps by proposing a credible pathway for achieving Class Society certification and obtaining navigation licenses from Flag States. The proposed framework is designed to link rules and technical challenges associated with MASSs, ensuring their safe and efficient integration into maritime operations. The structure of this paper is as follows:

- Section 3 describes the research methodology.
- Section 4 explores the requirements set by IMO.
- Section 5 presents Flag States rules.
- Section 6 examines the standards and guidelines developed by classification societies.
- Section 7 discusses naval requirements and their implications for MASS certification.
- Section 8 presents a technical procedure for enabling the operation of MASSs.
- Section 9 introduces future challenges.
- Section 10 concludes the study, summarizing the findings and proposed solutions.

3. Research Methodology

This study employs a structured comparative analysis to evaluate the certification pathways for Maritime Autonomous Surface Ships (MASSs). The methodology is based on three key analytical steps:

- Regulatory Framework Assessment: We systematically review IMO resolutions, the regulatory scoping exercise, and the draft IMO MASS Code to identify key legal adaptations required for autonomous shipping.
- Classification Society Standards Comparison: We analyze classification society certification frameworks, including those from RINA, DNV, Lloyd's Register, and the China Classification Society (CCS), to compare prescriptive and goal-based certification approaches.
- Flag State Authorization Review: We examine national regulatory frameworks from leading Flag States, including Norway, the UK, and Japan, to assess early-stage MASS implementation.

The comparative method highlights commonalities and discrepancies in these frameworks, allowing us to identify challenges in harmonizing international MASS certification. Risk-based methodologies, such as Formal Safety Assessments (FSA) and Failure Mode and Effects Analysis (FMEA), are referenced to evaluate the robustness of certification requirements.

4. International Regulatory Framework Assessment—The IMO Role

The International Maritime Organization (IMO) is at the forefront in developing an international regulatory framework for Maritime Autonomous Surface Ships (MASSs). Following the timeline exposed in the previous paragraph, the non-mandatory version is expected to be finalized by 2025, with the mandatory Code scheduled to take effect in 2032, initially limited to cargo ships. To address the complexities of MASS operations, the IMO has established a joint working group (MSC-LEG-FAL) to examine key legal and operational issues, including the roles and responsibilities of the master and crew [42], both on board and remotely. Additionally, the introduction of Remote Operations Centers (ROCs) has raised challenges related to jurisdiction, command transitions between ROC and MASS, and liability. The IMO emphasizes that the master of a MASS must retain overall responsibility for the vessel, whether physically on board or remotely located. These ongoing efforts aim to ensure that MASS can provide a level of safety, security, and environmental compliance equivalent to or exceeding conventional ships.

The developed IMO Code uses a goal-based approach: a flexible framework aimed at achieving defined safety outcomes without prescribing specific technical solutions. This approach allows innovation while maintaining high safety standards, suitable for rapid advancements in technology. However, as the Norway Administration has highlighted, it poses more challenges in clarity, interpretation, and compliance verification with diverse safety standards [43].

Chapter 5 of the IMO MASS Code will introduce a framework for approving and certifying Maritime Autonomous Surface Ships (MASSs) to ensure compliance with the highest standards of safety, security, and environmental protection.

A key feature of the approval process is the collaborative approach between stakeholders, such as Flag States, classification societies, and the IMO. This approach ensures a balanced and thorough evaluation of technical and operational aspects. However, challenges persist, particularly in aligning innovative autonomous technologies with established regulatory standards, demonstrating equivalent levels of safety, and navigating the complexities of international regulatory frameworks.

5. Flag State Review

Flag States are responsible for enforcing international and national regulations over their vessels, and in the last few years, some administrations have been increasingly facing the problem of authorizing Maritime Autonomous Surface ship operations without a common set of rules already in force. Because the IMO MASS Code is not expected to enter into force before 2032, the most innovative and forward-looking Flag States have been developing specific frameworks to manage the integration of autonomous vessels into their registries, ensuring safety and compliance with applicable and future international standards. In the following subsections, a survey on the existing autonomous shipping activities is provided, and the state lists them in alphabetic order.

A key hazard in the regulatory landscape is the role of Flag of Convenience (FoC) which collectively accounts for a significant share of global ship registrations. Given their tendency to adopt regulatory frameworks that differ from the majority of the Flag States, the integration of MASS certification under FoC jurisdictions may introduce additional complexities. While some Flag States have begun to introduce MASS-specific rules, the extent to which FoC registries will align with emerging international standards remains uncertain.

5.1. Norway

The Norwegian Maritime Authority (NMA) has been actively involved in developing MASS regulations. It has collaborated with key stakeholders like DNV and Kongsberg

Maritime to support projects such as the Yara Birkeland and ASKO sea drones. These initiatives highlight a phased approach to automation, ensuring the gradual integration of autonomous functionalities while maintaining safety standards [43]. For example, the Yara Birkeland, a fully electric autonomous container ship, has transitioned to semi-autonomous operations with automated docking and crossing capabilities. The vessel's operational monitoring is conducted from a Remote Operations Center (ROC). It flies the Norway flag, and the NMA has issued special permits to facilitate sea trials, ensuring a controlled and gradual approach to integrating autonomous technology into a commercial vessel.

5.2. United Kingdom

The UK's Maritime and Coastguard Agency (MCA) has developed a code of practice for an autonomous vessel's safe design, construction, and operation [44,45]. Developed with the support of the industry and some Recognized Organizations (ROs), including Lloyd's Register and Bureau Veritas, it is a goal-based standard that covers all the aspects of a MASS, starting with the identification of the kind of MASS, the examination and certification, the registration up to requirement about maintenance procedure, and record-keeping practices. One chapter is implemented for the requirements of environmental protection. The code of practice in recent years has been successfully applied to several projects of different dimensions. The Maritime Autonomy Surface Testbed (MAST) is a USV built for the Royal Navy, for which, the MCA provides the regulatory framework and guidance necessary for conducting trials within the testbed area [46]. Considering the testing area, MCA played an important role in the establishment of the UK's proving area for testing and developing cutting-edge products for the marine sector, including the MASS: the Smart Sound Plymouth [47]. MCA is currently involved in several projects with local industries (i.e., Rolls-Royce, SeaBot Maritime, Konsberg Maritime, Ltd.. . .) and another important project in which the codes of practice were successfully applied, the Mayflower [48].

5.3. France

France has advanced its regulatory framework for USV by implementing a two-tiered system to facilitate the integration of autonomous technologies. The framework, established under legislation enacted in October 2021, distinguishes between smaller unmanned maritime devices ("maritime drones") and larger autonomous surface ships. A case-by-case authorization regime has been developed for MASS, requiring comprehensive risk assessments and safety evaluations performed by the "Commission centrale de sécurité des navires". The flag certification process is like the IMO MASS Code, Chapter 5. Once approved, vessels are issued operational certificates valid for two years [49].

5.4. Japan

Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has prioritized the development of autonomous shipping as part of its broader maritime strategy. MLIT established in December 2020, "Safety Design Guidelines of Maritime Autonomous Surface Ships" also applied to the project of the "Nippon Foundation MEGURI2040 Fully Autonomous Ship Program" aimed at the development of a demonstration testing of fully autonomous coastal navigation. Through the success of this testing, it seeks to create further opportunities for technological development in this field [50].

5.5. China

The China Ministry of Transport has developed and issued guidelines for the construction, testing, and operation of autonomous vessels in collaboration with the CCS (China Classification Society) [51]. China established the Wanshan Marine Test Field, one of the world's largest testing grounds for autonomous ships, located in the South China Sea.

This test field covers an area of 771 km^2 and is equipped with state-of-the-art facilities to support the research and development of MASS technologies. It serves as a hub for both commercial and military autonomous vessel projects [52]. Many projects of MASSs in the navy sector are classified, but China is working on several autonomous cargo ship projects, such as the "Jin Dou Yun 0 Hao", which is a fully electric autonomous cargo ship designed for inland waterways.

5.6. Republic of Korea

One of the Republic of Korea's main projects has focused on developing and implementing the KASS (Korean Autonomous Surface Ship project) Autonomous Navigation System, integrating advanced features such as collision detection, avoidance, and economic navigation [53]. Extensive sea trials, including those on the 25 m Haeyangnuri-ho and 1800 TEU container vessels, have validated the system under real-world conditions. Regulatory efforts include detailed Hazard Identification studies, which analyse risks across key subsystems like voyage planning, situational awareness, and vessel control. The Autonomous Ship Verification & Evaluation Research Centre surveyed these trials, employing digital twin technology and simulation environments. The system is progressing towards full operational deployment by 2025 [54].

5.7. Russia

As in other countries, Russia has also made advancements in experimenting with MASSs, supported by a government-led regulatory framework established in 2020. The Russian Maritime Register of Shipping (RMRS) has developed a classification system for autonomous and remotely controlled ships, enabling the certification of vessels such as the dual-fuel ferries Marshal Rokossovsky and General Chernyakhovsky. These ships operate in the Baltic Sea under remote control capabilities, with fallback manual operation supported by decision-making tools for confined waters [55,56].

5.8. Italy

Another active flag in this sector is the Italian Maritime Administration, actively aligning its regulations with the standards set by the IMO and taking part in the working group of the IMO MASS Code. Italy is participating in various EU-funded projects aimed at advancing maritime autonomy, such as the OCEAN2020 Project [57]. These projects often involve collaborations between the Italian Flag State and universities, research institutes, and private sector companies, focusing on the technological and regulatory challenges of integrating autonomous ships into existing maritime operations. Italy's approach to regulating autonomous ships is closely linked with broader European Union initiatives. Italy participates in the EU's efforts to create a unified regulatory framework for autonomous ships, ensuring that Italian-flagged vessels can operate seamlessly across European waters.

5.9. European Union

In recent years, the European Union has supported the development of MASSs through innovative projects and regulatory efforts [58,59]. The AUTOSHIP Project [60], supported by the Horizon 2020 program, focused on developing and demonstrating autonomous technologies, including two remotely operated vessels for short-sea and inland waterways shipping. The project focused on digital integration, advanced sensors, and cybersecurity, aiming to create a foundation for greener and more efficient maritime logistics. Similarly, some years before, the MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) [35,61] project explored the potential of unmanned merchant ships, addressing energy efficiency and operational safety while showcasing significant reductions in crew dependency and fuel consumption. The H2020 MOSES initiative further enhanced this vision by integrating automation into short-sea shipping and inter-modal transport, emphasizing sustainability and advanced cargo handling. Apart from these technological projects, the SARUMS (Safety and Regulations for Unmanned Maritime Systems) initiative, coordinated by the European Defense Agency (EDA) [62,63] has focused on regulatory frameworks, addressing gaps in safety standards, collision avoidance, environmental compliance, and interoperability. All these efforts demonstrate the EU's commitment in supporting the innovation and harmonizing regulations in the maritime sector, ensuring the seamless integration of MASSs into global operations.

6. Classification Societies

Some classification societies, with the aim of anticipating the mandatory IMO MASS Code entry into force (estimated in 2032), have developed a set of rules to provide a service to "forward-thinking" shipowners and shipyards. The early rules have been developed in parallel with the first MASS prototype/projects in the North Sea area and Far East region: Lloyd's Register (2017) [64], DNV-GL (2018) [65], CCS (2015, 2018), Korean Register (2019) [66], RINA (2021), ABS (2021) [67].

The choice between developing "prescriptive rules" and "goal-based rules" primarily hinges on factors such as the maturity of the technology, the need for innovation in the systems or solutions, and the complexity of the aspects being regulated. Prescriptive rules are most suitable for certifying a project when established technologies or practices are employed, particularly for projects where "best practices" are well-understood and broadly accepted (i.e., in the traditional shipping industry).

Goal-based rules are more suitable for certifying projects that utilize new or rapidly evolving technologies. Additionally, when proven technology is employed in new contexts and scenarios, goal-based rules are better suited for solutions tailored to specific situations. This certification approach easily accommodates innovation and technological advancement, providing the flexibility that the industry needs to explore various methods. For these reasons, all of the following rules issued by IACS members for certifying the MASSs fall under Goal-based Standards:

- Lloyd's Register Unmanned Marine Systems Code.
- DNV Class Guidelines for Autonomous and Remotely Operated Vessels.
- Korean Register Guidelines for Autonomous Ships.
- RINA Guidelines for the Classification OF Maritime Autonomous Surface Ships.
- ABS Guidelines for Autonomous and Remote-Control Functions.
- BUREAU VERITAS Guidelines for Autonomous Shipping.
- CLASS NK Guidelines for Autonomous Ships.

The China Shipping Register (CCS) has issued somewhat different rules for intelligent ships. Intelligent ships can monitor and collect data and information regarding the ship itself, the external environment, logistics, and the port by utilizing sensors, communication, the Internet, and other technical means. All these inputs work together to enable intelligent operations in navigation, management, maintenance, and cargo transportation based on big data processing and analysis technologies, making the ship more environmentally friendly and economically efficient. The CCS rules feature a primarily goal-based structure but have also been partially developed to include prescriptive solutions.

6.1. RINA Approach

The RINA's certification framework identifies the applicable rules and class characteristics of a MASS starting from the vessel's Concept of Operation (ConOps). The set of applicable rules for the certification of the "traditional aspects" of the vessel could be defined starting from the technical specification and the characteristics of the vessel. For a commercial autonomous vessel, the RINA rules for the Classification of Ships [68] can be used, or in the case of a fast small autonomous patrol boat, the most suitable Rules will be the RINA rules for Fast Patrol Vessel or the RINAMIL [69], depending on the vessel's characteristics. The applicable rules are related to the vessel's typology, with unmanned capability considered an additional class notation.

The RINA Guidelines for MASSs (GUI 35) [7] provide a technical background for assessing the autonomous capabilities throughout all three main phases of the project: design, construction, and testing. The first step involves studying the impact of the "MASS Technology" and its scope in the application, analyzing the ConOps, and implementing the Operational Design Domain (ODD) that defines the operating conditions specifically managed by a MASS technology. The guidelines outline three main tasks required for completing the technical evaluation of a MASS:

- Navigation (Collision and grounding avoidance; Route management; Speed, draught, and trim control)
- Machinery management
- Communication function

For each task, a risk assessment should be carried out to demonstrate that risks related to the use of proposed MASS technologies have been mitigated and made as low as reasonably practicable (ALARP). The output from this process will be the explication of the functional and performance requirements, as well as the definition of the tests and evaluation criteria for the vessel. Upon satisfactory approval of the documents and successful testing activities, a Statement of Compliance is issued by RINA with a validity of 3 years. The possible degree of autonomy considered in the MASS additional class notation (RINA Rules for the Classification of Ships, Pt. A, Ch. 1, Sec. 2, [6.14.55]) [68] are the following:

- MASS-ADS: Ship with Automated Processes and Decision Support: seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and, at times, be unsupervised, but with seafarers on board ready to take control.
- MASS-RCM: Remotely Controlled Manned ship: the ship is controlled and operated from another location. Seafarers are available on board to take control of and operate the shipboard systems and functions.
- MASS-RCU: Remotely Controlled Unmanned ship: the ship is controlled and operated from another location. There are no seafarers on board.
- MASS-FAS: Fully Autonomous Ship: the operating system of the ship can make decisions and determine actions by itself.

Below is an example of certification of a small remote-operated unmanned patrolling ship (see Figure 2) without any navigation restriction, as detailed in Table 1, that could be eligible for the assignment of the class with the following characteristics:

PC ✠ ; Patrol; unrestricted navigation

with the following additional class notations:

MASS—RCM

where

- PC—The main class symbol for vessels classed in accordance with the RINA Rules for Fast Patrol Vessels or equivalent.

- ✠—The construction mark assigned when the vessel has been surveyed by the society during its construction in compliance with the new building procedure.
- Patrol—A ship intended for patrolling operations.
- Unrestricted navigation—The navigation notation assigned when the vessel is designed for unrestricted navigations.
- MASS—RCM—The additional class notations MASSs are assigned having the degree of autonomy of Remotely Controlled Manned ship.

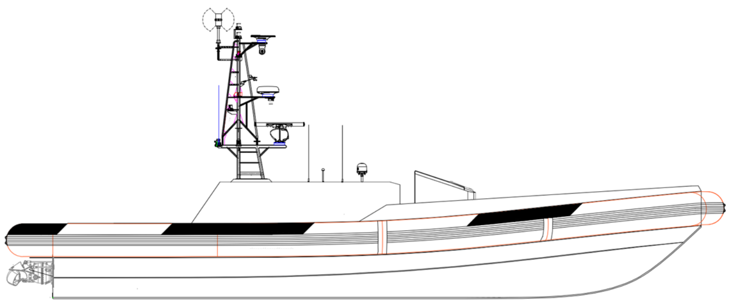

Figure 2. A case study of naval unmanned vessel (UNV-S).

Table 1. Technical specification of the UNV-S.

Technical Specification UNV-S	
Length	20.00 m
Beam	5.00 m
Immersion	1.10 m
Displacement	30 t
Material	Aluminium alloy
Range	600 nm
Endurance	over 14 days
Installed power	1600 kW

Other additional class notations or service notations could be added to highlight some features of the unmanned vessel. Apart from the class notation, the regulatory framework of a commercial MASS will include all the applicable international conventions (i.e., SOLAS, ILCC, BWM, AFS, MARPOL. . .).

6.2. The CCS Rules for Intelligent Ships

While European classification societies have developed sets of goal-based rules for the certification of a MASS, CCS rules are an exception by which the unmanned vessel certification is a chapter of the rules for intelligent ships [51]. With these rules, CCS has classified more than 200 units up to the end of 2023. As for other Class Society regulations, every ship that is classified by CCS receives a primary classification notation that includes a general indication of the ship's type, construction, and overall compliance with CCS-applicable rules. Ships can receive additional notations that describe special features, capabilities, or compliance with specific regulations or technological advancements. For intelligent and autonomous ships, CCS provides a set of notations that describe the level of automation and the ship's ability to perform specific functions autonomously as follows: *i-Ship* (*Ai*, *Ri*, *Nx*, *Hx*, *Mx*, *Ex*, *Cx*, *I*) where *Ai* and *Ri* are the functional notation for autonomous operation and remote control, the "*i*" is an integer number for describing the degree of control and autonomous operation (*Nx*), intelligent hull (*Hx*), intelligent machinery (*Mx*), intelligent energy efficiency management (*Ex*), intelligent cargo management (*Cx*), and the "*x*" is an additional notation for optional functions.

Within the CCS rules, intelligent navigation means obtaining all the information necessary for ship navigation through advanced perception and sensing information fusion technology, using computers and control technology to carry out analysis and processing, and providing aided navigation decision-making suggestions or autonomous capabilities. In the case of manned vessels, this additional class notation refers to optimizing the management of the vessel's speed and route, enhancing vision, predicting a collision or grounding, and planning an avoidance strategy.

Autonomous navigation capability considers two scenarios: open water or during the entire navigation, including manoeuvring in port or channel and berthing. General high-level performance requirements (i.e., the ability of manoeuvrability and propulsion, the communication capabilities. . .) and detailed equipment to be installed on board (i.e., type of certificate for each main component of the system, some minimal technical performance. . .) are reported. Finally, it is required to test all the systems and capabilities but without any criteria or technical prescription, only to demonstrate that such systems work properly. Chapters 8 and 9 of the rules for intelligent ships [51] are specifically related to remote-controlled ships and fully autonomous vessels. The remote-control capability is subdivided into two scenarios: with crew onboard or a fully unmanned vessel. All the operational capabilities of the remote-control station and the design requirements are defined, such as the capabilities to continue to operate in case of a single failure of a component, the segregation of the server, or the requirement for an emergency control station in case of a complete loss of the main one (i.e., fire, flooding. . .). In case of the presence of crew on board, the possibility of taking control over the automation and manually operating the vessel at any moment should be assured.

The "design" section is a collection of performance requirements and some prescriptions about the system philosophy (redundancy, segregation, transfer of rights. . .). It also analyzes the architecture and the requirements of the navigation system: an augmented visual system allows obtaining real-time video rendering in poor visibility conditions based on information perceived by electronic charts, radar, AIS, GPS, and CCTV by using twin technology and visual reconstruction technology. The system should at least have a visual range of 6 nautical miles, within an angle of view from right ahead to 112.5° on each side of the MASS in the horizontal direction at any time. It is required that the MASS should be equipped with enough bandwidth to communicate with the other vessel and have the possibility to give audible, visual, and shape signals according to COLREG [16]. The performance requirements for the communication capabilities between the MASS and the remote-control station are also defined. For unmanned vessels, the bell, the gong, and the shape handling are required to operate electronically. In the case of a crewed remotely operated vessel, the machinery installation must follow the rules for ships, and the essential parameters and alarms must be reported to the control station. The alarm must be noticed both in local and remote-control stations, and the alarm silence should be independent. For unmanned vessels, the safety, reliability, and availability of machinery installations and systems in the engine room are not to be lower than the level of a manned ship, and all the emergency operations (i.e., emergency stopping, boiler shutdown cutting off/shutting down) specified in the CCS Rules for Classification of Steel Ships are to be realized from the remote-control station. All the activities of periodical maintenance, such as the cleaning of the filters, and the return of the relief devices used for overpressure protection, must be automatic. Also, the mechanical connection mechanism (if any) for emergency operations could be remotely controlled at the remote-control station so that the ship can still have a certain navigation capability in case of failure.

All the essential auxiliary systems must be duplicated unless it is demonstrated through a Failure Mode and Effect Analysis (FMEA) that a single failure will not lead to the total failure of the propulsion system. This might be considered the possible failure of the static component and effective measures are to be adopted to reduce the risk of leakage in the piping of essential systems for propulsion and steering. Pumps, valves, and air vent-closing appliances installed in essential space/systems are to be capable of automatic operation in accordance with procedures. Another requirement is the installation of automatic sensors to measure the fluid level in the tanks and to be able to detect any fuel or oil leakage. A condition monitoring and health assessment system is to be installed for the main propulsion machinery, electrical power generation, boilers, essential auxiliary systems, etc. It is also required to have a reliable electrical power supply to essential and safety equipment, always ensuring communication between the MASS and the control station.

Environmental protection should be guaranteed in each operative condition, and the MARPOL requirements should be applied as far as possible to the MASS. The MASS also must comply with all the applicable rules for stability and hull scantling and be equipped with a real-time hull monitoring system capable of transmitting all the data to the control station for a real-time analysis and evaluation of the safety of the hull. Chapter 9 relates to autonomous operation ships, which can be assigned different class notations based on their level of independence from human interaction. An algorithm that meets basic requirements for intelligent ships conducts comprehensive analysis and decision-making using situational awareness data, controlling propulsion, maneuvering, communication, and signaling for autonomous navigation. It avoids collisions by making decisions based on real-time navigation scenarios in compliance with COLREG. The onboard signal equipment automatically sends signals (audible, visual, and shape) as per these regulations. The algorithm monitors and controls all the onboard systems and is capable of detecting a failure in a connected system and evaluating the seaworthiness of the ship to make decisions to continue or abort the mission. The autonomous ship is to be able to guarantee the essential functions in case of a single failure. In general, the vessel is to be designed to have a fail-safe mode: if the seaworthiness is affected and it is also impossible to remote control, the vessel ensures the safety of the other vessels and the environment. The requirements for the machinery and system installation are the same for the remotely operated vessels, while additional rules are defined for autonomous anchoring decision-making and system capabilities. The same documents required in Chapter 8 must be submitted, with some additional requirements for the tests required for the assessment of autonomous algorithm capabilities.

6.3. Comparison Between RINA and CCS Rules

The two previously analyzed classification rules, even though they are both goal-based standards, show several differences that need to be analyzed. The CCS rules for intelligent ships are applicable to several aspects, not only for "MASS", and CCS has specific functional notations (R1, R2) for remote control and (A1, A2, A3) for autonomous operations. The RINA guidelines are applicable to all four typologies of MASSs as defined by IMO, considering broader categories and risk levels, without such detailed notations (only the difference between manned vessel, remoted operated, or fully autonomous). Both are goal-based standards, even if the CCS rules present some prescriptive requirements, with an emphasis on ensuring safety, security, and environmental protection. CCS rules, in some cases, offer a discretization of the main goal inside general, performance, and operative requirements with some prescriptions, while RINA provides a structured approach to certification involving risk assessments, system validation, and verification procedures tailored to MASSs.

CCS asks for a list of specific documents and information to be submitted for approval, with the explicit possibility for the society to ask for more documentation whenever it is found necessary. RINA requires a submission for approval of a Concept of Operations (CONOPS), an Operational Design Domain (ODD), details on human role and relative location, documentation demonstrating compliance with the applicable functional and performance requirements, and a risk assessment, including cyber security risks. One of the first steps for the classification of a MASS according to the RINA rules is to agree on the class regulatory framework applicable to the corresponding tasks in conventional ship operations, the application of which is required. One of the outputs of the RINA process is the testing and sea trials procedure, in accordance with risk analysis and design approval. The CCS rules require the designer to prepare a testing procedure and send it to the CCS for approval, but in the rules, there are no prescriptive requirements to allow the technician to approve or reject the Factory Acceptance Test or Sea Acceptance Test (FAT/SAT) procedures.

A critical component of MASS certification is system validation, which ensures that autonomous vessels meet operational and safety benchmarks before deployment. CCS, along with other classification societies, mandates a three-tier validation approach:

- Laboratory Testing: Component-level validation, including sensor accuracy, AI-based collision avoidance performance, and redundancy testing.
- Simulated Trials: Digital twin simulations to assess system behavior under various environmental and operational conditions.
- Real-Scale Trials: Sea acceptance tests (SAT) conducted under controlled conditions to validate compliance with safety and performance requirements.

Certification processes require MASSs to demonstrate fail-safe mechanisms, compliance with collision avoidance protocols (COLREGs), and system resilience under unexpected failures. In both sets of rules, upon satisfaction with the technical requirements and after successful testing activities and sea trials, it is possible to issue an additional class notation, which will be part of the vessel's class certificate. For some kinds of vessels (i.e., military vessels and governmental vessels not used for commercial purposes), the class certificate is not mandatory, and a Statement of Compliance according to GUI35 could be issued by the RINA with a validity of 3 years.

7. Unmanned Naval Vehicles (UNV)

The increasing adoption of Surface and Underwater Unmanned Naval Vehicles (UNV-S and UNV-U) in various defense operations symbolizes the advancements made in automation, artificial intelligence (AI), and robotics within the navy sector. Around the world, navies are adapting to a new category of autonomous or semi-autonomous vessels that can be employed in a wide range of missions, including intelligence gathering, surveillance, reconnaissance, anti-submarine warfare, mine countermeasures, and maritime security. USVs are particularly suited for missions categorized as "dull, dirty, or dangerous", thus reducing human exposure to risks. While commercial standards ensure safety and environmental protection, USVs designed for military applications require additional features, such as long-term reliability, modular payload capabilities, and advanced damage control systems [70,71].

NAVSEA's approach (U.S. Navy) to certifying the Machinery Control Systems (MCS) for autonomous unmanned naval surface vessels (UNVs) involves a certification scheme that ensures reliability, automation, and suitability for extended unmanned operations [72]. It consists of a tiered strategy:

- Tier 1: Baseline Commercial Standards. This tier provides foundational requirements for unattended engine rooms based on existing classification society rules (e.g., ABS ACCU Notation). These include automated safety functions like pump changeovers, fuel transfer, and propulsion safety shutdowns, typically allowing 24 h unattended operations.
- Tier 2: Guidance for Unmanned and Autonomous Systems. Expand Tier 1 to include features specific to autonomous vessels, such as enhanced sensor suites, remote operation capabilities, fault-tolerant designs, and cybersecurity. Standards also address higher autonomy levels, including remote and fully autonomous operations and compliance with maritime regulations (e.g., COLREGS for navigation).
- Tier 3: Military-Specific Enhancements (NAVSEA Guidance). The full certification covers prolonged military missions and addresses gaps in commercial standards. It includes advanced automation for machinery alignment, casualty recovery, and damage control (e.g., fire suppression and flooding response). Robust systems for diagnostics, mission consequence analysis, and redundancy are critical. Features such as automated decision-making systems ensure mission continuity under adverse conditions.

Together, these tiers ensure that UNV designs meet operational, safety, and mission-specific requirements, enabling NAVSEA to certify US Navy systems for autonomous naval operations.

Several European Navies (Belgium, Germany, Finland, France, Italy, the Netherlands, and Sweden) took part in the development of the Safety and Regulations for Unmanned Maritime Systems (SARUMS BPG) [62] published for the first time in 2018 and updated in 2022 by the European Defense Agency. The SARUMS Best Practice Guide provides a structured framework focused on risk management and compliance with international conventions, primarily SOLAS and UNCLOS. This approach involves identifying and mitigating risks using the ALARP (As Low As Reasonably Practicable) principle, supported by comprehensive safety management systems that address programmatic, design, and operational dimensions. Certification relies on rigorous verification processes, including simulations, trials, and environmental assessments, overseen by national authorities and subject to periodic reviews to ensure ongoing compliance. SARUMS promotes interoperability and standardization, facilitating the safe and reliable deployment of UMS across various maritime contexts.

Some navies use the SARUMS approach to certify their MASS. One of the developers of best practice is the Italian Navy, which has planned a new acquisition program for UNVs to embark on their vessels, which are used as motherships of the unmanned systems. The new 105 m long major oceanographic vessel (NIOM) will be equipped with some ROVs, AUVs, and a 5 m long diesel electric autonomous surface vehicle vessel for scientific research [73]. The future frigate for the Italian Navy, FREMM EVO [74], will be equipped with drones operating in all three dimensions (aerial, surface, and underwater).

8. A Pathway for Flag State Authorization for a MASS

There are many studies addressing the MASS approval process by Flag State, analyzing questions ensuring MASS compliance with different international rules and instruments [75–78]. In those studies, the development of a roadmap towards transition to MASS is recommended; however, no methodology for MASS approval by Flag States has been found.

The main goal of this paragraph is to identify a possible approach to allow a Flag State to authorize a MASS to operate, issuing a “flag state approval” and flagging the vessel. The main principle is to identify a solution that guarantees an equivalent level of safety between the “manned” and “unmanned” configurations.

The risk associated with MASS operation can be considered as a function of various parameters, such as area of operativity, traffic in that area, degree of autonomy of the MASS, and the momentum of the vessel [79–82]. The greater the risk, the higher the level of certification required.

The operation of traditional vessels is authorized by a Flag administration or Recognized Organization following satisfactory inspection of the following aspects:

- Hull structure and interior layout.
- Buoyancy, stability, and maximum load line.
- Propulsion and steering.

In the case of a MASS, in addition to the previous aspects, the reliability of the autonomous systems must be ensured to guarantee an equal level of safety with respect to a similar manned vessel. The certification of autonomous capabilities should include the following:

- Navigation system
- Propulsion system
- Communication system
- Safety and fire protection
- Auxiliary systems and integration

At the preliminary design stage, an expected hazardous level is assigned, based on a few parameters, such as the operating area, the presence of traffic, the control and communication mode, and the momentum of the vessel. Figure 3 illustrates the MASS regulatory framework developed by the authors, which can be used as a reference by Flag States to support the approval process of such vessels.

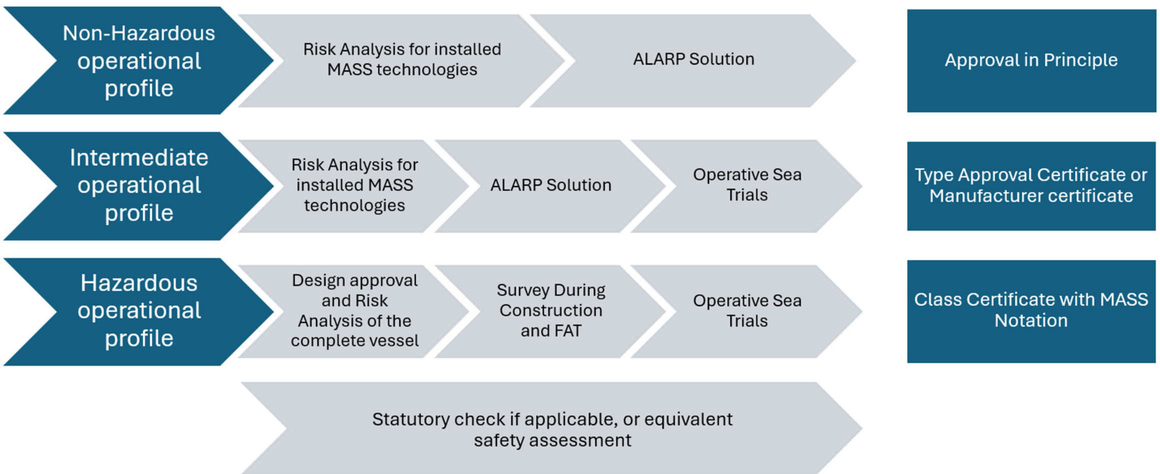

Figure 3. Proposed MASS regulatory framework.

Depending on the level of operational hazards, ranked as low, medium or high, a proposal for a regulatory framework is presented:

- A risk analysis should be carried out for a “Non-hazardous” operational scenario. This analysis should demonstrate that the operational risk associated with the “unmanned” configuration has been mitigated and reduced to the ALARP (As Low As Reasonably Practicable) level [83].
- “Intermediate” operational scenario: In addition to the risk analysis, the design should be checked, and a specific test should be carried out to demonstrate the vessel’s seaworthiness in the ConOps operative conditions. Eventually, if the test results

are satisfactory, the prototype could be eligible for an approval certificate, and the following vessel could be deemed enough for a manufactural certificate.

- In a "Hazardous" operational scenario, Flag State authorization should be achieved upon the previous presentation of a class certificate issued by a delegated Recognized Organization with an additional notation related to autonomous capabilities according to the vessel's degree of autonomy. In addition, the administration will verify all safety aspects typically related to international conventions (e.g., STCW and land-based crew training).

The applicable regulations should be integrated with additional certification, which may also include naval and military capacity, regarding the type of vessel, the type of functions, and ConOps.

The risk-based assessment proposed by EMSA can be used as a valuable tool [84].

9. Next Challenges

Future challenges in implementing certification schemes for Maritime Autonomous Surface Ships (MASSs) arise from the evolving legal and operational complexities associated with autonomous and remote operations. A critical topic is the definition of the roles and responsibilities of the master and crew, which now include both traditional onboard crew and "remote crew" operating from Remote Operations Centres (ROCs). Although the International Maritime Organization (IMO) has maintained that the role of the master remains analogous to that on conventional ships [42], the nuanced requirements of MASS operations necessitate the reconsideration of "command" and "control". This involves determining scenarios where the master may not need to be physically onboard and whether a single master can responsibly oversee multiple MASSs, particularly in high-risk situations such as congested waterways or ecologically sensitive areas.

The legal implications of ROCs are equally complex, which may operate MASSs across varying territorial jurisdictions during a single voyage. Ensuring compliance with international conventions like UNCLOS while addressing jurisdictional overlaps and the seamless transfer of operational control between ROCs requires innovative regulatory frameworks. Additionally, defining the master's role within the ROC structure, especially when delegating responsibilities across multiple remote operators, introduces further intricacies. The integration of MASSs into naval operations adds another layer of complexity. Up to now, many of the operating MASSs are often considered extensions of their deploying motherships, with their operational responsibility falling under the ship's master. Establishing clear boundaries for liability and delegation within naval contexts will require specialized certification mechanisms adapted to both civilian and military applications.

10. Conclusions

The increasing adoption of MASSs represents a fundamental transformation in the maritime industry, offering significant opportunities for improved efficiency, safety, and environmental sustainability. However, regulatory fragmentation and inconsistencies in certification processes remain key obstacles to MASS deployment. This study proposes a structured certification framework that systematically integrates IMO regulatory requirements, classification society standards, and Flag State authorization processes. Unlike prior research that examines these elements separately, our approach bridges the gap between regulatory compliance and technical certification, offering a unified pathway for MASS approval. By applying a comparative methodology, we identify regulatory challenges and propose a harmonized certification strategy that can be adopted by classification societies and Flag State administrations. This structured approach contributes to the early-stage certification of MASSs, ensuring a balance between safety, regulatory compliance, and technological innovation. By building upon existing international guidelines, such as those developed by the International Maritime Organization (IMO) and classification societies, this research highlights the essential steps needed to harmonize technological innovation with robust safety standards.

However, disparities among Flag State administrations remain a critical barrier to international harmonization. The proposed certification pathway integrates classification and Flag State requirements, providing a clear, adaptable framework for MASS approval.

Future research should focus on refining certification models through practical case studies and real-world testing, ensuring that the proposed framework remains adaptable to evolving regulatory and operational landscapes, the validation of the certification framework through pilot projects, ensuring its adaptability across diverse regulatory jurisdictions. It should also focus on the real-world implementation of this framework, leveraging pilot projects to validate certification methodologies and ensure their applicability across diverse regulatory jurisdictions.

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