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Safety assurance and standardization of MASS: a comparative analysis of classification societies

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Abstracts
The rapid advancement of Maritime Autonomous Surface Ships (MASS) necessitates the development of coherent and robust regulatory frameworks. While classification societies have pioneered their own sets of rules, a universally accepted international standard is still absent. This paper provides a comparative analysis of the main MASS guidelines issued by leading classification societies and discusses them in relation to the ongoing work of the International Maritime Organization (IMO). The comparison is based on three main aspects: definitions and classification of autonomy, risk assessment and equivalent safety approaches, and the governance of remote operation centres (ROC) and human involvement. The results show that although all societies follow a risk-based safety approach, there are clear differences in how autonomy is defined, how risk assessment is used in approval processes, and how remote operators are treated within the regulatory framework. In some cases, risk assessment is mainly used to justify alternative designs, while in others it is more closely connected to system qualification and verification. Approaches to ROC governance also vary, from general responsibility models to more detailed technical requirements. Overall, the study shows that while safety goals are similar, the structure and implementation of safety assurance are not yet fully aligned. The paper highlights several areas where further harmonization is needed, including autonomy classification, ROC governance, and the integration of risk assessment methods, in order to support the safe and practical deployment of MASS.

Keywords: Autonomous ships, safety assurance, classification societies, comparative analysis.

1. Introduction

Autonomous ships are developing at an unprecedented pace and have become one of the most discussed topics in the maritime industry (Goerlandt 2020). With rapid advancements in artificial intelligence, sensor technologies, machine learning, and communication systems, vessels are increasingly capable of operating with limited or even no human intervention. This shift promises to improve operational efficiency, reduce human errors, enhance safety, and lower environmental impacts, which are major concerns for modern shipping. As a result, autonomous ships are attracting attention not only from researchers and technology developers but also from shipowners, regulators, and insurers who are trying to understand their potential and implications (IMO 2021).

Despite these technological innovations, autonomous ships still require classification, just like conventional vessels. Classification societies have traditionally been responsible for verifying that ships meet structural, mechanical, and operational standards. They assess designs, oversee construction, and certify vessels to ensure they are seaworthy and safe to operate. For autonomous ships, the role of classification societies becomes even more critical because these vessels integrate complex automated and cyber-physical systems, which challenge traditional safety frameworks and risk management approaches. Classification societies are now providing guidelines and notations specifically addressing autonomy, cybersecurity, and operational safety to help bridge this gap (Cefor 2018). At the international level, the International Maritime Organization (IMO) has conducted regulatory scoping exercises and is developing a MASS Code, but binding global regulations are not yet in force (Goerlandt 2020). This situation has resulted in multiple classification societies independently developing their own MASS frameworks. While these frameworks share common objectives, they differ in terminology, autonomy definitions, risk methodologies, and human oversight models.

However, a structured comparison of these frameworks remains limited. Existing discussions often focus on individual societies or technical aspects, without systematically analyzing their governance logic and safety assurance mechanisms. To address this gap, this paper presents a comparative analysis of leading classification society guidelines for MASS. The study focuses on three core dimensions: (1) definitions and classification logic of autonomy, (2) risk assessment and equivalent safety approaches, and (3) remote operation center governance and human factors. By identifying areas of convergence and divergence, the paper aims to clarify the current state of standardization and highlight priorities for future regulatory harmonization.

2. Classification Societies and Document Scope

2.1. *Selection of Classification Societies*

To ensure representativeness and industry relevance, the classification societies included in this study were selected based on their 2024 global gross tonnage (GT) rankings (IACS 2024). Gross tonnage provides a widely accepted quantitative indicator of a society's market share and influence within the international shipping industry. By selecting societies with the highest total classed tonnage, this study focuses on organizations that exert substantial technical and regulatory impact on global maritime practice. Based on this criterion, the analysis includes DNV, ABS, Lloyd's Register (LR), ClassNK (NK), China Classification Society (CCS), Bureau Veritas (BV), Korean Register (KR), refer to Fig. 1. These societies account for the majority of the world's classified fleet and therefore play a decisive role in shaping emerging standards for MASS.

This selection approach ensures that the comparative analysis reflects mainstream regulatory developments rather than isolated or niche initiatives. Although smaller classification societies may also publish relevant guidelines, their global influence remains comparatively limited. Therefore, focusing on the leading societies allows the study to capture dominant regulatory trends and standardization trajectories in the MASS domain.

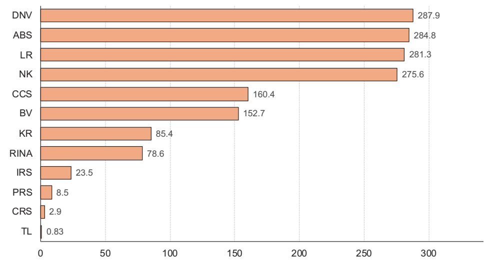

Fig. 1 Ratings of class societies by total gross tonnage in 2024 (IACS 2024).

2.2. *Document Scope*

To understand the evolution of safety assurance approaches, the major MASS-related documents issued by each selected classification society were mapped chronologically, as illustrated in Fig. 2. The timeline demonstrates that regulatory engagement with autonomous shipping accelerated significantly after 2017, coinciding with rapid technological developments and increased international policy attention. Early documents primarily focused on exploratory guidance and unmanned marine systems, while later publications evolved toward more structured frameworks addressing autonomy levels, risk-based approval, ROC, cybersecurity, and system qualification.

The timeline also highlights differences in regulatory maturity and strategic orientation among societies. Some organizations adopted an early exploratory approach, issuing conceptual guidelines before IMO regulatory developments, whereas others aligned their frameworks more closely with the IMO regulatory scoping exercises and the anticipated MASS Code.

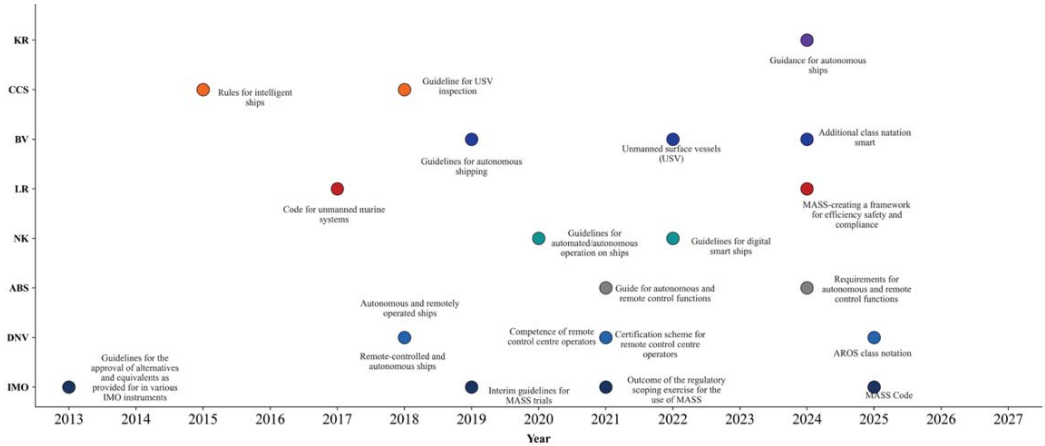

Fig. 2. Timeline of MASS guidelines issued by IMO and Classification Societies

3. Comparative analysis

3.1. *Terminology and Scope*

Given the diversity of regulatory approaches, a clear understanding of terminology and scope is necessary before comparing detailed safety requirements. Table 1 presents a structured comparison of how leading classification societies define autonomy, specify its scope. The table reveals significant differences in classification logic, ranging from graded autonomy levels to function-based or modular frameworks. These conceptual variations underpin the divergent safety assurance approaches analyzed in the subsequent sections.

3.2. *Risk Assessment and Equivalent Safety Across Classification Societies*

Risk assessment and the demonstration of equivalent safety constitute the central regulatory mechanism enabling the approval of unmanned and autonomous ships. While all major classification societies adopt a risk-based philosophy, significant differences exist in how risk assessment is triggered, how equivalence is demonstrated, and how deeply risk considerations are integrated into the approval process.

To clarify these differences, the comparison can be structured along five analytical dimensions:

(1) the trigger for risk assessment,

(2) the mechanism for demonstrating equivalence,

(3) the reference methodology adopted,

(4) the treatment of fallback or degraded operational states, and

(5) the degree of integration between risk assessment and system approval.

3.2.1. *Trigger Conditions for Risk Assessment*

At the regulatory level, the IMO requires risk assessment primarily when alternative designs or arrangements are proposed. In this context, risk assessment serves as a justification mechanism to demonstrate that a novel design achieves an equivalent level of safety compared to prescriptive requirements.

A similar approval-oriented trigger can be observed in CCS, where risk assessment becomes mandatory when new technologies exceed the scope of existing rules. In such cases, equivalence must be demonstrated through risk analysis combined with testing evidence.

In contrast, DNV and ABS embed risk assessment earlier in the lifecycle. DNV requires

Table 1. Defination of autonomy across class societies.

Organization	Level of Autonomy
IMO	*Degree One*: 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. *Degree Two*: Remotely controlled ship with seafarers on board. The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions. *Degree Three*: Remotely controlled ship without seafarers on board, the ship is controlled and operated from another location. There are no seafarers on board. *Degree Four*: Fully autonomous ship. The operating system of the ship is able to make decisions and determine actions by itself.
DNV	DNV defines maritime autonomy through a structured, four-tier framework focusing on the level of system independence and human involvement. The Autonomous and Remotely Operated Ships (AROS) class notation family categorizes autonomy as: *AROS-NAV* (Autoremote Navigation), *AROS-ENG* (Autoremote Engineering), *AROS-SAFE* (Autoremote Safety), *AROS-OPS* (Autoremote Operations), details refer to (DNV 2024).
ABS	*Smart:* System augmentation of human functions. The system provides passive decision support, such as in the form of health or performance anomaly detection, diagnostics, prognostics, decision/action alternatives, and/or recommendations. *Semi-Autonomy:* Human augmentation of system functions. System operation builds upon a smart foundation and is governed by a combination of system and human decisions and actions. *Full Autonomy*: No human involvement in system functions. The system makes decisions and takes actions autonomously. Humans perform a supervisory function solely, and have capability to intervene and override actions made by the system.
ClassNK	ClassNK doesn´t establish fixed autonomy levels, it defines three operation conditions based on the extent to which decision-making subtasks are executed by computer systems and/or from remote locations (ClassNK 2022). *Automated Condition* means a condition where computer systems take charge of execution of some or all of the decision-making subtasks which compose the target task. *Remote Operation System* means a system that allows remote operation of some or all of the decision-making subtasks that compose the target task. *Autonomous Condition* means a condition where all decision-making subtasks composing the target task are automated without limitations of Operation Design Domain (ODD) and fallbacks are also wholly automated.
CCS	*Remote Control Ships* means that the ship can be controlled by remote control stations or positions other than the ship to achieve the operation of the ship. *R1*- The main function of the ship is controlled by the remote control station. Seafarers on board monitor the ship's condition, take over the operation of the ship in an emergency or when necessary, and operate the non-remotely controlled system and equipment according to the ship's operational scenario determined by the design. *R2*- The ship is controlled remotely without seafarers on board. *Autonomous Operation Ships*: The ship can realize autonomous operation from anchorage to anchorage, with remote control and monitoring. When necessary, the remote control station can remotely control the ship. *A1*-The ship is operated by crew and / or pilots when entering and leaving the port and during berthing. *A2*-The ship is operated by remote control station when entering and leaving the port and during berthing. *A3*-The ship can realize autonomous operation from berth to berth, with remote control and monitoring. When necessary, the remote control station can remotely control the ship (CCS 2025).
LR	*AL 0 Manual*: No autonomous function. All action and decision-making performed manually. *AL 1 On-board Decision Support*: All actions taken by human Operator, but decision support tool can present options or otherwise influence the actions chosen. Data is provided by systems on board. *AL 2 On & Off-board Decision Support*: All actions taken by human Operator, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or off-board. *AL 3 'Active' Human in the loop*: Decisions and actions are performed with human supervision. Data may be provided by systems on or off-board. *AL 4 Human on the loop, Operator/ Supervisory*: Decisions and actions are performed autonomously with human supervision. High impact decisions are implemented in a way to give human Operators the opportunity to intercede and over-ride. *AL 5 Fully autonomous*: Rarely supervised operation where decisions are entirely made and actioned by the system. *AL 6 Fully autonomous*: Unsupervised operation where decisions are entirely made and actioned by the system during the mission.
BV	The degree of automation represents the degree of decision making (authority) deferred from the human to the system. A0 human operation, crew is on board; A1 human directed, crew is/not on board; A2 human delegated, crew is/not on board; A3 human supervised, crew is/not on board; A4 full automation, crew is/not on board (BV 2019).
KR	AL1 Decision-making and action are made by operator AL2 Decision-making is made by operator (system/remote) and action is made by operator AL3 Decision-making is make by system/remote (operator) and action is made by operator AL4 Decision-making and action are made by system (Operators are constantly monitored for decision-making and action) AL5 Decision-making and action are made by system

risk analysis already at the concept stage and links it iteratively to the Concept of Operations (CONOPS). ABS triggers risk assessment based on an assigned Risk Category Level, which determines the depth of verification and validation activities.

KR introduces an explicit autonomy-level threshold, requiring formal risk assessment reports for higher autonomy levels (e.g., AL3 and above), while BV mandates hazard identification particularly for USVs and alternative arrangements.

This distinction reveals two principal trigger logics: exemption-driven risk assessment (IMO, CCS), and design-integrated risk assessment (DNV, ABS, KR).

3.2.2. *Mechanisms for Demonstrating Equivalent Safety*

Although all societies refer to "equivalent level of safety," their demonstration mechanisms differ. The IMO framework emphasizes structured documentation, including hazard identification, risk evaluation criteria, and risk control options. CCS adopts a similar logic by explicitly allowing exemptions or alternative arrangements if supported by risk analysis and test evidence.

DNV formalizes equivalence through gap analysis and focused risk analysis when existing rules are challenged. A distinctive feature of DNV's framework is the requirement to define a Minimum Risk Condition (MRC), or fallback state, ensuring safe degradation under abnormal conditions.

ABS, on the other hand, operationalizes equivalence through a risk-informed validation model. The assigned risk category determines verification rigor rather than serving merely as a justification for rule deviation.

LR adopts a goal-based approach, where performance requirements may be satisfied through risk-based assessment when prescriptive rules are unavailable.

Thus, equivalence may function either as: a regulatory justification tool, or an engineering validation mechanism, depending on the society.

3.2.3 *Risk Methodologies and Technical Depth*

The methodological references also differ in explicitness. IMO defines a general risk assessment framework but does not prescribe specific techniques.

CCS refers to recognized FSA methodologies and national or international standards.

DNV explicitly references recognized methods such as FMEA/FMECA and requires traceability of risk mitigation measures.

ABS structures risk evaluation through a matrix combining supervision level and consequence category.

KR embeds risk within a lifecycle-based design approval process.

BV emphasizes hazard identification and redundancy analysis.

3.2.4 *Fallback States and Degraded Operation*

One of the most technically differentiating aspects concerns fallback or degraded operational capability.

DNV explicitly requires the definition and verification of a fallback state (formerly MRC), particularly when the ship operates outside its Operational Design Domain (ODD). This fallback logic forms a cornerstone of DNV's equivalent safety argument.

ABS addresses degraded operation indirectly through supervision levels and risk categorization.

KR and BV emphasize redundancy and degraded mode capability as part of approval requirements.

In contrast, IMO and LR articulate fallback more conceptually within goal-based compliance rather than as a defined engineering construct.

3.2.5 *Integration with Approval and Verification*

The degree of integration between risk assessment and system approval varies significantly.

In IMO and CCS frameworks, risk assessment primarily supports exemption approval.

In DNV's framework, risk assessment is tightly embedded within concept qualification (CQ) and system qualification (SQ).

In ABS, risk category assignment directly determines the depth of V&V activities.

In LR, risk assessment supports performance-based compliance verification.
In KR, risk reports are formally required before approval for higher autonomy levels. This reveals a structural spectrum shown in Table 2.

Table 2 Governance models of safety assurance in MASS classification frameworks.

Governance Model	Representative Societies
Regulatory equivalence-based	IMO, CCS
Engineering-integrated lifecycle risk	DNV
Risk-tiered validation model	ABS
Goal-based integrity framework	LR
Level-triggered risk approval	KR
Redundancy-focused safety assurance	BV

3.3. Remote Operation Centres and Human Governance

The governance of ROC, or shore-based control centres, represents one of the most structurally differentiating aspects among classification societies in the context of MASS. While all societies acknowledge the continued importance of human oversight, they diverge significantly in how deeply ROC governance is integrated into their regulatory and technical frameworks (Kilinc 2025).
A primary distinction concerns the legal and classification status of the ROC. At the conceptual level, the IMO does not formally define ROC as a classified entity, and human responsibility remains governed under existing conventions such as COLREG and STCW. LR follows a similar approach, emphasizing accountability and regulatory compliance without prescribing detailed ROC engineering requirements. In these models, the ROC functions primarily as an operational extension of the vessel rather than as a separately governed technical system.
In contrast, DNV adopts the most structurally embedded approach. The Remote Operations Centre is treated as an integral component of the autonomous system, with explicit requirements addressing layout, situational awareness, alarm management, communication redundancy, and cybersecurity. Moreover, DNV establishes a dedicated certification scheme for remote operators, extending classification principles beyond vessel systems to include operator competence. This represents the highest level of human governance integration among the societies reviewed.
Between these two ends of the spectrum lie hybrid models. ABS integrates human oversight into its risk-tiered validation framework through defined supervision levels that directly influence verification depth. KR links remote supervision requirements to autonomy levels, requiring formal risk assessment reports for higher autonomy classes. In these cases, human involvement operates primarily as a risk control parameter within the safety assurance process.
CCS, ClassNK, and BV adopt a system-functional perspective. Remote operation is recognized within the ship's technical configuration—often through modular notations or task-level definitions—but without detailed ergonomic prescriptions or standalone operator certification schemes. The emphasis remains on system reliability, redundancy, and communication integrity rather than formalized human-factor governance.
To summarize these structural differences, Table 3 compares the classification status of ROC, operator competence requirements, and the degree of integration with risk-based approval frameworks

Table 3 Comparative approaches to ROC governance and human oversight.

Society	ROC Classification Status	Operator Certification	Integration with Risk Framework	Governance Model Type
IMO	Not formally classified	No	Conceptual responsibility under existing conventions	Regulatory responsibility model
LR	Not formally classified	No	Compliance-oriented	Goal-based responsibility model
DNV	Treated as classified system component	Yes (dedicated scheme)	Fully embedded in lifecycle qualification	Engineering-integrated governance
ABS	Functionally defined	No standalone scheme	Supervision level linked to risk categories	Risk-tiered supervision model
KR	Recognized in approval framework	No standalone scheme	Higher autonomy levels trigger formal RA	Level-triggered risk model
CCS	System-functional integration	No	Linked to system reliability requirements	System-integrated model
ClassNK	Defined as Remote Operation System (ROS)	No	Embedded in task-level logic	Task-based functional model
BV	Functional remote arrangement	No	Emphasis on redundancy and communication reliability	Engineering-focused assurance model

4. Conclusion

This paper presented a comparative analysis of the principal MASS frameworks developed by leading classification societies in the absence of binding international regulations. By examining terminology and scope, risk and equivalent safety mechanisms, and ROC governance, the study highlights both convergence and divergence in current safety assurance practices.

The findings show that while all societies adopt a broadly risk-based philosophy, their governance structures differ significantly. Autonomy is variously defined through graded levels, modular notations, or task-based conditions, reflecting different classification logics. Although the objective of demonstrating equivalent safety is common across frameworks, the role of risk assessment ranges from regulatory justification for rule exemptions to deep integration within lifecycle qualification and verification processes. These differences illustrate that safety assurance for MASS is not yet standardized in structure, even if aligned in principle.

The treatment of ROC and human oversight reveals the most pronounced divergence. Some societies regard remote operation primarily as an extension of existing regulatory responsibility, while others integrate ROC more explicitly into classification and, in certain cases, extend governance to operator competence. This spectrum of approaches reflects varying interpretations of how human factors should be embedded within autonomous ship safety architecture.

Overall, the current regulatory landscape demonstrates partial convergence in safety objectives but fragmentation in implementation pathways. As the IMO progresses toward a MASS Code, greater alignment in autonomy definitions, risk integration mechanisms, and ROC governance models will be essential to support interoperability and scalable deployment. Continued coordination among classification societies and regulators will play a decisive role in shaping a coherent and robust safety framework for future autonomous shipping.

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