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Core Onboard Functions for Crewed Ships Under Hybrid Autonomous Operations with Remote Operation Center Supervision: A Delphi-Based Study

Sujin Jung [1] and Yongjohn Shin [2,*]

[1] Korea Institute of Maritime & Fisheries Technology, Busan 49111, Republic of Korea; emsemsdl0809@gmail.com
[2] Division of Shipping Management, Korea Maritime & Ocean University, Busan 49112, Republic of Korea
* Correspondence: yjshin61@kmou.ac.kr

Abstract

This study examines which onboard human functions remain essential for crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision. As maritime operations transition toward higher levels of autonomy, a critical challenge lies in determining the functional boundary between onboard crews and shore-based control systems. A three-round Delphi method was conducted with 20 maritime experts from five stakeholder domains to identify and validate essential onboard functions. The analysis adopts a function-based perspective, distinguishing core functional responsibilities rather than traditional occupational roles. The Delphi analysis resulted in the validation of four primary onboard function groups: Management, Operation and Control, Maintenance and Recovery, and Automation/ICT/Network. All four groups satisfied the predefined importance and stability criteria in Round 2, with mean importance scores ranging from 4.35 to 4.70 and coefficients of variation ranging from 0.09 to 0.12. In Round 3, all function groups also exceeded the minimum CVR threshold of 0.42, with CVR values ranging from 0.70 to 1.00. Operation and Control showed the highest mean importance score (4.70) and CVR value (1.00), indicating the strongest expert agreement regarding its essentiality under hybrid autonomous operations. These results demonstrate that onboard decision-making authority, manual or override capability, technical recovery, and automation-related system supervision remain non-substitutable despite ROC support. The findings provide quantitative evidence for defining minimum onboard functional requirements and offer a structured basis for future discussions on manning, training, onboard–ROC role allocation, and regulatory frameworks for Maritime Autonomous Surface Ships (MASS). This study contributes to clarifying the functional architecture of hybrid autonomous ship operations and supports safer and more accountable human–automation integration strategies.

Keywords: Maritime Autonomous Surface Ships (MASS); hybrid autonomous operations; function-based manning system; Remote Operation Center (ROC); Delphi method

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1. Introduction

1.1. Background of the Study

The maritime sector is undergoing a structural transformation as digital technologies, including artificial intelligence, autonomous control algorithms, sensor fusion, and

cyber–physical systems, are increasingly incorporated into ship operations. Within this transition, Maritime Autonomous Surface Ships (MASS) have become a central reference point for regulatory development and industrial experimentation [1–3]. However, many near-term applications are not fully unmanned vessels but crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision.

In this study, hybrid autonomous operations refer to an operational state in which qualified crew remain onboard while selected navigation, monitoring, analytical, and decision-support functions are assisted by onboard automation and shore-based ROC support. Rather than treating autonomy as a fixed level label, this study interprets it as a distributed operational configuration involving onboard personnel, automated systems, and shore-based supervisory functions [3–6].

This configuration creates a distributed control architecture in which shipboard personnel retain responsibility for contextual judgment, physical intervention, and safety-critical response, while the ROC provides wide-area monitoring, predictive analysis, and decision support, as illustrated in Figure 1.

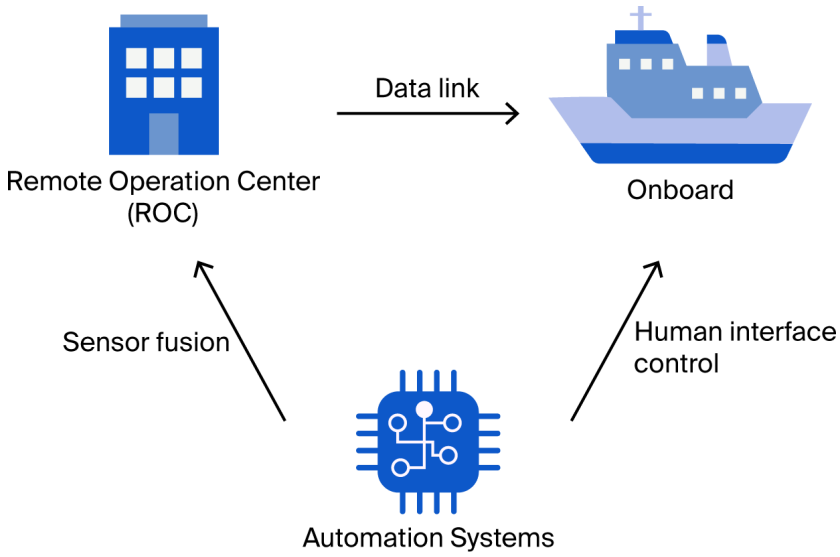


Figure 1. Hybrid operational architecture with distributed interaction between onboard systems and ROC supervision.

A key challenge in this architecture is that the boundary between onboard and shore-based responsibilities remains unclear [7]. ROC operators can integrate traffic, sensor, and environmental data, but they cannot fully reproduce shipboard sensory cues or conduct physical intervention onboard. Consequently, even where automation and ROC supervision reduce routine monitoring demands, onboard functions related to local assessment, manual or override action, technical recovery, and emergency coordination remain operationally significant [4,8,9].

1.2. Need for the Study

International regulatory work on MASS, including the IMO Regulatory Scoping Exercise and the continuing development of the MASS Code, increasingly emphasizes goal-based and function-oriented approaches rather than fixed technical or manning prescriptions [3,10,11]. This regulatory direction makes it important to clarify which onboard functions must remain available in crewed hybrid autonomous operations.

Previous studies have examined human–automation interaction, ROC functions, competency requirements, legal responsibility, and risk in autonomous or semi-autonomous shipping [5,12–14]. These studies generally show that automation reshapes onboard

human roles rather than eliminating them, especially under abnormal, degraded, or emergency conditions.

Nevertheless, existing research has not yet provided an empirically validated classification of core onboard functions that remain non-substitutable under hybrid autonomous operations with ROC supervision. Without such a functional baseline, regulatory authorities and industry stakeholders may either under-specify onboard capabilities or continue to rely on position-based manning structures that do not reflect emerging hybrid operational realities. The Delphi method is therefore appropriate for this study because expert judgment is valuable in an emerging socio-technical domain where large-scale operational evidence remains limited [11,15,16].

1.3. Purpose, Research Questions, and Contributions

Against this background, this study aims to identify and validate the core onboard functions required for the safe operation of crewed ships under hybrid autonomous operations with ROC supervision. Preliminary function groups are derived from regulatory developments, prior research on human–automation interaction and ROC functions, and reported hybrid autonomy scenarios, and are then refined and validated through a structured three-round Delphi process.

To operationalize this objective, the study addresses the following research questions:

RQ1. *Which onboard functions are considered core and operationally indispensable for crewed ships operating under hybrid autonomous operations and ROC supervision?*
RQ2. *To what extent do expert judgments converge on the importance of these onboard functions when evaluated through a structured Delphi process?*
RQ3. *How can the validated onboard functions be interpreted as a minimum functional baseline that informs future discussions on manning, training, and onboard–ROC role allocation under hybrid autonomy?*

The study makes three main contributions.

First, it clarifies crewed hybrid autonomous operations as a distributed operational state involving onboard personnel, automation, and ROC supervision, thereby establishing the operational context in which onboard functions must be reinterpreted.

Second, it provides an empirically validated, function-based classification of core onboard functions, complementing prior studies on competency, risk, and role evolution by identifying what must remain onboard rather than who should perform each task.

Third, it provides an empirically validated functional baseline that supports a transition from traditional position-based manning concepts toward function-oriented governance under hybrid autonomous operations. The findings suggest that future Maritime Autonomous Surface Ships (MASS) governance frameworks may need to reorganize onboard human responsibilities around essential functional capabilities rather than conventional rank- or occupation-based structures. In this respect, the study contributes to future discussions on manning concepts, onboard–ROC responsibility allocation, training frameworks, and regulatory development for hybrid autonomous maritime operations.

2. Prior Research

2.1. Hybrid Autonomy as an Operational State in Contemporary Shipping

Recent developments in autonomous and semi-autonomous shipping increasingly emphasize operational configurations rather than fixed autonomy labels. While early regulatory discussions relied on level-based categorizations such as those introduced in the IMO Regulatory Scoping Exercise (RSE), contemporary industrial trials and regulatory drafts increasingly describe autonomy in terms of how functions are distributed between onboard systems, shipboard personnel, and shore-based entities [1,5,10]. In this context,

the operational state commonly associated with hybrid autonomous operations can be characterized as a crewed vessel operating with automated functions under continuous or conditional Remote Operation Center (ROC) supervision, rather than as a discrete technological stage.

This hybrid operational state differs fundamentally from both conventional fully crewed ships and higher autonomy concepts in which the onboard crew is absent. Shipboard personnel remain physically present and retain legal and practical responsibility for safety-critical decisions, while automation and ROC support assume substantial portions of monitoring, analysis, and advisory functions [2,9,10]. Legal and regulatory studies further emphasize that, under existing international law and flag State responsibilities, accountability for seaworthiness and safe navigation remains closely tied to onboard command authority, even where navigational authority and operational responsibility are no longer exclusively exercised onboard, challenging traditional interpretations of flag State obligations [15,17–20]. As a result, safety and performance emerge from cooperation among humans, automation, and shore-based systems rather than from a single command locus.

Several studies have emphasized that hybrid autonomy introduces a qualitatively different operational regime in which authority, responsibility, and situational awareness are distributed across multiple nodes [3,10,15,21]. This distribution challenges traditional assumptions embedded in position-based manning systems, which presuppose that decision making, monitoring, and intervention are co-located onboard [13]. Consequently, understanding hybrid autonomy requires analytical frameworks that move beyond static autonomy levels and instead examine the functional roles and responsibilities across onboard and shore-based actors, a shift that is increasingly reflected in recent regulatory and academic discourse [6,8,10].

2.2. Human–Automation Interaction and Shared Control in Hybrid Maritime Operations

A substantial body of literature has examined human–automation interaction in maritime contexts, frequently drawing on concepts of shared control, supervisory control, and human in the loop or human on the loop architectures. Early foundational work in supervisory control established that automation is most effective when humans retain oversight authority rather than being fully removed from control loops [22,23]. Within the maritime domain, subsequent studies have adapted these principles to ship and Remote Operation Center (ROC) environments, emphasizing that automation performs well in routine, data-intensive tasks such as continuous monitoring, pattern recognition, and optimization, whereas humans remain essential for contextual interpretation, ethical judgment, and adaptive decision making under uncertainty [5,8,9,14,23,24].

In hybrid autonomous operations, automation typically manages nominal navigation and machinery control, while humans intervene during abnormal, unexpected, or degraded conditions [9,14,25]. This division of labor reflects a broader consensus across safety-critical domains that full substitution of human judgment is neither technically feasible nor operationally desirable in complex, open environments such as maritime navigation [23,26,27]. Studies on joint cognitive systems further emphasize that safety performance emerges from coordinated human–automation interaction rather than from isolated human or machine capabilities [26].

Importantly, shared control models also highlight risks associated with unclear authority boundaries, particularly during transitions between automated and manual control modes. Classical and contemporary safety research has identified such mode transitions as a recurrent source of operational accidents and near misses, often linked to out-of-the-loop performance degradation and delayed human intervention [28,29]. While these studies provide valuable insights into interface design, workload management, and error prevention,

they rarely translate interaction principles into a concrete classification of which onboard functions must be retained under hybrid autonomy. As a result, the question of how human–automation interaction insights should be operationalized within function-based manning structures remains insufficiently addressed [5,14,27].

2.3. Remote Operation Centers and Shore-Based Supervisory Functions

Parallel to advances in onboard automation, significant attention has been devoted to the development of Remote Operation Centers (ROCs) for autonomous and semi-autonomous ships. ROC-focused studies describe shore-based facilities that integrate wide-area traffic information, sensor feeds, and environmental data to provide supervisory oversight, predictive risk analysis, and decision support [2,9,10,30]. In certain configurations, ROCs may also assume limited teleoperation capabilities during emergencies or transitional phases; however, such capabilities are generally framed as supplementary rather than as replacements for onboard control and responsibility [3,18].

A consistent finding across this literature is that ROC-based situational awareness differs fundamentally from shipboard situational awareness. While ROCs benefit from aggregated, high-level information and advanced analytical tools, they lack direct access to local sensory cues and the ability to perform physical intervention onboard [4,9,14]. Consequently, most studies emphasize that ROCs are best suited for macro-level supervision and advisory functions rather than for replacing onboard capabilities entirely, a position that is also reflected in recent regulatory frameworks and draft provisions [3,10,31].

Despite increasingly detailed discussions of ROC roles and shore-based supervisory functions, the literature largely treats onboard functions implicitly as residual tasks that remain after remote functions are assigned, rather than explicitly identifying and validating them. From a systems safety perspective, such implicit treatment of onboard functions is problematic, as it obscures how critical human and technical functions are redistributed and potentially fragmented across socio-technical boundaries [13,32]. This ambiguity makes it difficult to determine which onboard functions are truly non-substitutable and which could, in principle, be shifted ashore under different technological or regulatory assumptions, underscoring the need for an explicit, function-based articulation of core onboard capabilities under hybrid autonomy.

2.4. Competency Frameworks, Risk Analyses, and Manning Implications

Existing research on autonomous and semi-autonomous shipping has examined competency requirements for future seafarers and remote operators using a variety of analytical and consensus-based approaches, including AHP/ANP, Delphi techniques, and system-oriented risk assessment methods. These studies provide valuable insights into skill prioritization, safety-critical competencies, and operational readiness under increasing levels of automation [12,14]. However, most competency-oriented frameworks begin with predefined roles or capability sets and implicitly assume the continued availability of appropriate onboard personnel, rather than explicitly questioning which onboard functions must exist as a prerequisite for safe operation under hybrid autonomy.

Complementary risk-oriented studies further demonstrate that hybrid autonomous operations introduce new failure modes associated with sensor reliability, software integrity, communication links, and the interaction between human operators and automated systems [14,33,34]. Such analyses emphasize the importance of timely diagnosis, safe fallback, and recovery actions in preventing accident escalation. Nevertheless, these risk analyses typically focus on hazard pathways and control effectiveness and do not translate their findings into a validated taxonomy of core onboard functions. As a result, the func-

tional implications for onboard staffing are often treated as given, rather than systematically derived from risk and operational requirements [33].

Similarly, studies addressing the impact of automation on crew size and manning arrangements indicate that automation reshapes human roles rather than eliminating them, particularly in non-routine and safety-critical situations [13]. While these findings highlight the persistence of human involvement, they stop short of defining a minimum onboard functional baseline that could serve as a stable reference for regulatory design, manning principles, and training frameworks. From a systems safety perspective, the absence of such an explicit functional baseline obscures how responsibilities are distributed across human, technical, and organizational elements and limits the ability to evaluate trade-offs between onboard and shore-based functions in a transparent and defensible manner [32].

2.5. Gap Identification and Positioning of the Present Study

Synthesizing the preceding strands of literature reveals a clear and persistent gap. Contemporary research has extensively examined human–automation interaction, ROC capabilities, competency evolution, and risk profiles in autonomous and semi-autonomous shipping. However, despite this breadth of work, no consensus-based and empirically validated framework currently exists that explicitly identifies which onboard functions are core and non-substitutable for crewed ships operating under hybrid autonomous operations and ROC supervision [12–14].

This gap persists in part because existing studies are fragmented across disciplinary boundaries, including engineering, human factors, safety science, policy, and maritime education and training. Moreover, many analyses implicitly assume traditional position-based manning structures when discussing automation impacts, competency requirements, or risk mitigation strategies [13,32,33]. As a result, the fundamental question of "what must remain onboard" is often addressed indirectly, treated as residual, or left unresolved in both technical and regulatory discussions [15].

The present study addresses this gap by adopting a function-based perspective and applying a structured Delphi methodology to validate core onboard functions for the hybrid operational state. Building on established applications of the Delphi method in maritime safety, hazard analysis, and policy-oriented research, the study focuses on identifying a minimum functional baseline rather than prioritizing, weighting, or optimizing functions [11,15,16]. This baseline is defined as the set of onboard functions that remain necessary regardless of automation support or ROC supervision, while explicitly acknowledging boundary conditions related to vessel type, operational profile, and technological maturity as reflected in current MASS regulatory developments [3,10]. In doing so, the study complements existing competency- and risk-oriented research by shifting the analytical focus from traditional position-based manning assumptions toward function-oriented operational governance under hybrid autonomy. The validated function set provides an empirically grounded reference point for subsequent quantitative analyses, onboard–ROC responsibility allocation, and future regulatory discussions concerning Maritime Autonomous Surface Ships (MASS).

3. Methodology

3.1. Analytical Scope and Definitions

3.1.1. Research Design and Analytical Scope

This study employs a structured Delphi methodology to identify and validate core onboard functions for crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision, as this approach is particularly suitable for addressing complex and exploratory problems where empirical data are limited and expert

judgment is essential. The primary methodological objective is to establish a minimum onboard functional baseline, rather than to prescribe vessel-specific manning levels, competency standards, or detailed operational procedures. This objective is consistent with prior maritime safety and policy research addressing emerging socio-technical systems, in which empirical operational data remain limited and expert judgment plays a critical role in early stage validation [11,15,16,32].

Figure 2 illustrates the hybrid operational structure assumed in this study, clarifying the functional separation between onboard responsibilities and shore-based ROC support, and reflecting the current regulatory understanding of hybrid autonomous operations in which onboard personnel retain responsibility for safety-critical functions while automation and shore-based systems provide varying degrees of support, supervision, and decision assistance, thereby establishing the functional context for identifying core onboard functions in this study [3,10].

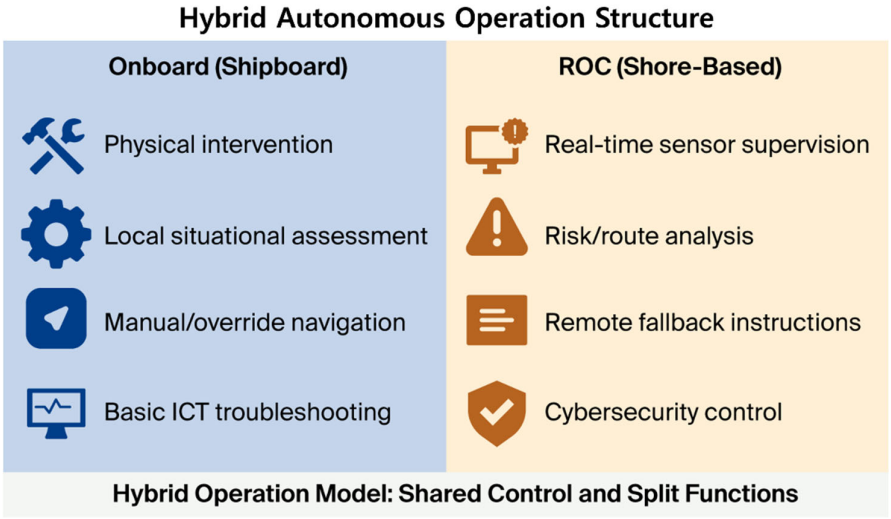


Figure 2. Operational structure of a crewed hybrid autonomous operation model with ROC supervision.

The research design follows an exploratory–confirmatory structure aligned with the Delphi methodology, which is widely regarded as appropriate for early-stage validation in complex and evolving domains where empirical operational evidence remains limited. In the exploratory phase, a broad set of onboard functions is identified to avoid premature exclusion of safety-critical responsibilities. In the confirmatory phase, these functions are refined and validated through iterative expert consensus using a combination of qualitative judgment and quantitative screening criteria, consistent with established applications of the Delphi method in maritime research [11,16].

The analytical scope of this study is explicitly restricted to a hybrid operational state characterized by the following conditions: (i) qualified crew remain physically present onboard; (ii) selected navigation, monitoring, and analytical tasks are supported by onboard automation; (iii) a shore-based Remote Operation Center (ROC) provides continuous or conditional supervisory support; and (iv) immediate safety critical intervention, emergency response, and physical recovery actions remain the responsibility of onboard personnel. This scope reflects contemporary regulatory discussions and reported pilot operations in the context of partial autonomy and shared control arrangements [3,12,35], and ensures that the analysis remains focused on operationally realistic and currently relevant hybrid configurations. Accordingly, the findings are not intended to apply to fully unmanned vessels or to conventional ships operating without autonomous support.

3.1.2. Definition of Key Terms

To ensure conceptual clarity and consistency throughout the analysis, several key terms used in this study are explicitly defined as follows.

Hybrid autonomous operations refer to an operational state in which qualified crew remain physically present onboard while selected navigation, monitoring, and analytical functions are supported by onboard automation and shore-based Remote Operation Center (ROC) supervision. This study does not treat autonomy as a fixed level or discrete technological stage, but rather as a distributed operational configuration involving human operators, automated systems, and remote supervisory functions.

Core onboard functions are defined as operationally indispensable functional responsibilities that must remain available onboard to ensure navigational safety, system integrity, and effective emergency response under the defined hybrid operational state. These functions are identified based on their non-substitutability by automation or remote supervision, particularly under abnormal, degraded, or emergency conditions.

Non-substitutability refers to the condition in which a function cannot be fully replicated, replaced, or reliably executed by automated systems or shore-based operators due to requirements for physical presence, contextual judgment, real-time intervention, or direct system interaction.

Remote Operation Center (ROC) denotes a shore-based operational entity that provides monitoring, data integration, predictive analysis, and decision support functions within the defined hybrid autonomous operational framework of this study. While ROCs may support or augment onboard operations, they do not replace onboard responsibility for safety-critical decision-making or physical intervention within the scope of this study.

Finally, the functional baseline identified in this study represents a minimum set of onboard capabilities required for crewed ships operating under hybrid autonomous operations with ROC supervision. It does not prescribe crew size, organizational structure, or competency levels, but instead defines the functional boundary conditions within which such decisions may be made.

3.2. Function-Based Conceptual Framework

A function-based perspective was adopted as the central analytical framework of this study because hybrid autonomous operations redistribute operational responsibility across onboard crew, automated systems, and shore-based ROC support in ways that cannot be adequately captured by traditional position-based manning categories. In this study, functions are defined as operationally meaningful sets of responsibilities that directly contribute to navigational safety, system integrity, and emergency response, regardless of whether they are performed by a specific shipboard rank or supported by automation and remote supervision. This definition is consistent with systems-oriented safety research, which emphasizes functional contributions to overall system performance rather than organizational titles, hierarchical roles, or conventional occupational boundaries [8,32].

This approach responds to the growing recognition that position-based manning logic inadequately captures operational realities under hybrid autonomy, where responsibilities are redistributed across human operators, onboard automation, and shore-based systems [3,10,12,13]. In such configurations, authority and responsibility are no longer fully co-located onboard, and traditional role boundaries are increasingly blurred by shared control and supervisory arrangements involving Remote Operation Centers (ROCs) [4,5,9]. By focusing on functions rather than job titles, the study explicitly addresses the foundational question of what must remain onboard before considering who performs these functions or how many personnel are required.

Within this framework, onboard functions were systematically evaluated using non-substitutability as the primary analytical criterion, whereby each function was assessed in terms of whether it could be reliably replaced by automation or remote supervision, particularly under abnormal, degraded, or emergency conditions. Prior studies consistently indicate that responsibilities requiring contextual judgment, physical presence, and immediate intervention remain fundamentally dependent on onboard human capability, even when advanced automation and ROC support are available [14,36]. This criterion provides the conceptual basis for distinguishing core onboard functions from those that may be partially or conditionally supported by autonomous or shore-based systems.

3.3. Identification of Preliminary Onboard Function Groups

Based on a comprehensive review of IMO regulatory developments, research on human–automation interaction, studies focusing on Remote Operation Centers (ROCs), and evidence reported in hybrid autonomy pilot and demonstration projects, the authors identified a set of preliminary onboard function groups to serve as an exploratory analytical baseline [3,4,10,11,14]. Rather than being derived from expert input at this stage, these preliminary groups were systematically constructed through a structured synthesis of responsibility domains recurring across regulatory documents, academic literature, and reported operational scenarios, followed by their reorganization into function-oriented categories independent of traditional shipboard positions.

The resulting preliminary onboard function groups were intentionally broad and inclusive, reflecting the exploratory objective of the first Delphi round and avoiding premature exclusion of potentially safety-critical responsibilities. In particular, the grouping was designed to capture (i) command and responsibility structures emphasized in IMO regulatory discussions, (ii) human intervention points identified in human–automation interaction and supervisory control research, (iii) ship–shore role boundaries highlighted in ROC studies, and (iv) operational, technical, and recovery-related responsibilities observed in hybrid autonomy trials. On this basis, six preliminary onboard function groups were identified:

- Management and command-related functions;
- Navigation and machinery Operation and Control;
- Maintenance and recovery;
- Safety and emergency response;
- Cargo and deck-related operations;
- Automation, ICT, and network-related functions.

At this preliminary stage, safety and emergency response were deliberately retained as an independent function group to ensure that emergency preparedness, crisis, and response coordination were not implicitly diluted or subsumed under other operational categories. This decision is consistent with regulatory and legal interpretations emphasizing the continued responsibility of onboard personnel for safety-critical and emergency response under hybrid autonomous operations [15].

Similarly, automation, ICT, and network-related functions were treated as a separate preliminary group to capture onboard responsibilities associated with supervising autonomous systems, verifying sensor and data integrity, maintaining ship–shore communication links, and conducting first-level troubleshooting that cannot be fully resolved through remote intervention alone. Prior studies have identified cyber–physical dependencies, communication integrity, and data reliability as distinct sources of operational risk in hybrid autonomous operations, particularly under abnormal or degraded conditions [10,36].

Cargo and deck-related operations were also retained as a preliminary group to ensure that cargo-related safety implications—such as stability effects, cargo behavior, and abnormal cargo conditions—were explicitly considered rather than excluded a priori.

Existing research indicates that automation does not eliminate the need for onboard human involvement in managing cargo-related risks, especially in dynamic or safety-critical scenarios [13,33].

The conceptual boundaries of all preliminary onboard function groups were deliberately left open to refinement through expert feedback in subsequent Delphi rounds, thereby enabling a transparent and iterative validation process through which the structure evolves toward a final set of core onboard functions grounded in expert consensus rather than prescriptive assumptions.

3.4. Structure of the Delphi Process

The Delphi process was conducted in three sequential rounds, each with a distinct analytical purpose and predefined decision logic, comprising exploratory identification in Round 1, quantitative evaluation of importance and stability in Round 2, and final validation of essentiality using CVR in Round 3. This multi-round structure was designed to support a clear progression from exploratory identification to confirmatory validation, while ensuring transparency, reproducibility, and resistance to post hoc modification of inclusion criteria. Such an approach is consistent with established applications of the Delphi method in maritime safety research and hazard analysis, where expert judgment is iteratively refined under controlled and explicitly defined procedures [11,15,16,21,37].

Figure 3 provides an overview of the Delphi procedure adopted in this study, illustrating the sequential flow of the three rounds and the corresponding analytical objectives associated with each stage of the validation process.

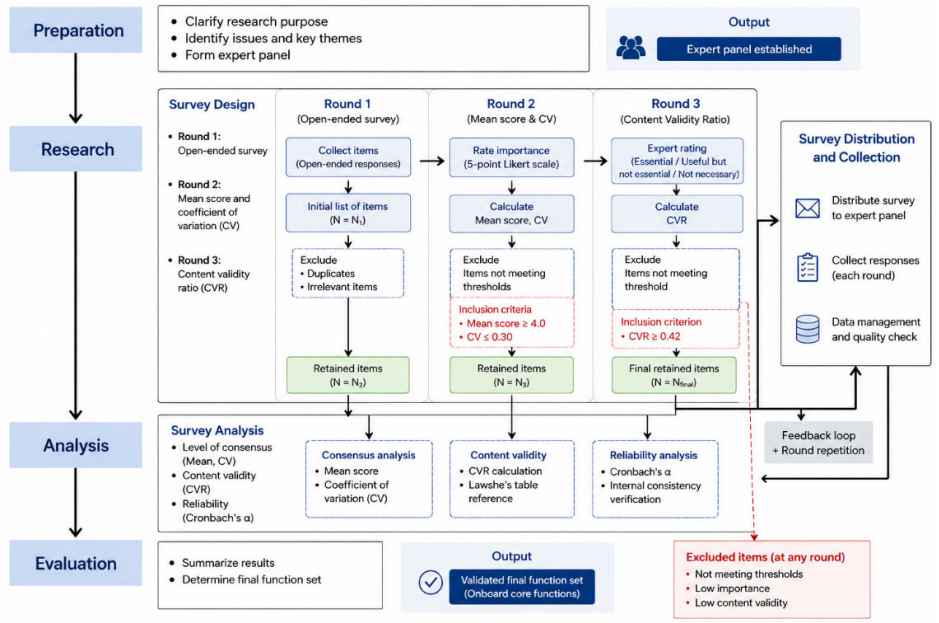


Figure 3. Multi-round Delphi procedure for identifying and validating core onboard functions.

3.4.1. Round 1: Qualitative Exploration and Functional Integration

The first Delphi round employed open-ended questions to elicit expert perspectives on core onboard functions for crewed ships operating under hybrid autonomous operations and Remote Operation Center (ROC) supervision. The full questionnaire used in the Delphi survey across all rounds is provided in Appendix A. Experts were invited to identify indispensable onboard functions, comment on overlap or redundancy among the preliminary function groups, and suggest conceptual integration where appropriate.

Three consistent qualitative outcomes were systematically identified from this exploratory round through thematic analysis of expert responses. First, experts showed

strong convergence on the view that safety and emergency response activities are intrinsic components of onboard management and command authority. Emergency preparedness, real-time crisis, prioritization under uncertainty, and coordination of onboard response were consistently described as inseparable from management responsibility under conditions of hybrid autonomous operations and shared control [15,18]. On this basis, safety and emergency response functions were conceptually integrated into the Management function based on consistent expert convergence and the functional criterion of non-substitutability under hybrid autonomous operational conditions.

Second, traditional navigation and machinery watchkeeping were consistently reframed within a broader Operation and Control function based on expert convergence and the functional requirement for integrated supervisory control under hybrid autonomous operations. Experts emphasized that despite increasing levels of automation and ROC supervision, onboard personnel remain indispensable for supervising automated behavior, interpreting contextual cues unavailable to shore-based systems, and executing manual or override actions during degraded, unexpected, or emergency conditions [3,9].

Third, experts consistently identified automation, ICT, and network-related responsibilities as a distinct onboard function that cannot be fully substituted by remote supervision alone. First-level troubleshooting of autonomous systems, verification of sensor and data integrity, and maintenance of ship–shore connectivity were regarded as core onboard tasks, particularly in scenarios involving communication degradation or system malfunction [10,36].

With respect to cargo-related activities, experts indicated that cargo condition monitoring and basic cargo management should not be treated as a standalone onboard function under hybrid autonomy. Instead, cargo state awareness was described as an operational input supporting vessel control, stability assessment, and emergency response. This perspective supported the integration of cargo-related considerations within the Operation and Control function rather than their retention as an independent functional category, based on their role as supporting operational inputs rather than non-substitutable core functions under hybrid autonomous conditions [4,33].

3.4.2. Round 2: Importance and Stability Assessment

In the second Delphi round, experts evaluated the refined onboard function groups using a five-point Likert scale (1 = not important, 5 = very important). The assessment focused on the perceived importance and operational relevance of each function within the defined hybrid operational state involving onboard automation and Remote Operation Center (ROC) supervision.

Two quantitative screening criteria were applied a priori to assess both relevance and convergence of expert judgments: (i) a mean importance score of 4.0 or higher, and (ii) a coefficient of variation (CV) of 0.30 or lower, with functions required to satisfy both criteria simultaneously to be retained for further validation in the subsequent Delphi round. These thresholds are consistent with established Delphi practices in maritime safety and hazard analysis research, where the combined use of central tendency and dispersion measures is employed to ensure both perceived essentiality and judgment stability among experts [15,16].

Consistent with the refined conceptual framework established in Round 1, cargo-related responsibilities were not evaluated as a standalone function in this round, as they were previously integrated into the Operation and Control function based on expert consensus and functional non-substitutability criteria. Instead, cargo state awareness and cargo-related safety considerations were implicitly reflected in expert ratings of the

Operation and Control function, in line with the integrated treatment of cargo functions under hybrid autonomy.

3.4.3. Round 3: Essentiality and Content Validity Assessment

The third Delphi round assessed the essentiality of the retained onboard function groups using Lawshe's Content Validity Ratio (CVR) method [38]. The detailed evaluation criteria, calculation procedures, and validation framework applied in the Delphi process are documented in Appendix B. Experts were asked to classify each function as essential, useful but not essential, or not necessary, allowing a structured evaluation of content validity based on expert judgment.

The CVR for each function was calculated using the following formulation:

$$\mathrm{CVR} = \frac{n_e - \left(\frac{N}{2}\right)}{\left(\frac{N}{2}\right)} \tag{1}$$

where n_e denotes the number of experts who rated a given function as essential, and N represents the total number of experts participating in the Delphi panel.

For a panel size of $N = 20$, the minimum acceptable CVR reference value was set at 0.42, in accordance with Lawshe's critical values for content validity assessment [38]. However, CVR values were not interpreted in isolation. Instead, essentiality judgments were derived through a predefined triangulation framework in which CVR outcomes were interpreted in conjunction with importance and stability measures obtained in Round 2 and qualitative reasoning captured in Round 1, such that only functions consistently supported across all three dimensions were retained as core onboard functions.

This triangulated interpretation approach was defined a priori to avoid purely mechanical threshold-based decisions and to ensure that final classifications reflect both statistical agreement and operational relevance, consistent with established best practices for Delphi applications in complex socio-technical domains, particularly where functional interdependencies and safety-critical considerations are present [11,15,16]. To ensure transparency and reproducibility of the methodological design, the decision logic, evaluation criteria, and retention rules applied at each Delphi round were explicitly defined in advance and are summarized in Table 1.

Table 1. A priori decision logic and quantitative screening criteria across Delphi rounds.

Delphi Round	Primary Purpose	Data Type	Inclusion/Interpretation Logic (Predefined)
Round 1	Explore and refine function definitions; integrate overlaps	Qualitative (open-ended)	Thematic convergence was used to merge and restructure function groups, with integration guided by operational logic reflecting management responsibilities, operational control requirements, and system-level functional dependencies
Round 2	Assess importance and stability of refined functions	Quantitative (Likert 1–5)	Retain functions meeting both criteria (Mean $\geq$ 4.0 and CV $\leq$ 0.30), indicating high perceived importance and a strong level of consensus among expert judgments
Round 3	Assess essentiality and content validity	Quantitative (CVR)	Apply CVR with (N = 20) reference threshold ($\geq$0.42) and interpret results in conjunction with qualitative findings from Round 1 and quantitative importance and stability measures from Round 2, retaining only functions consistently supported across all criteria

3.5. Expert Panel Composition and Ethical Considerations

The Delphi panel comprised 20 experts representing five stakeholder domains relevant to crewed hybrid autonomous operations with ROC supervision: shipboard operations, marine engineering and maintenance, maritime education and training (MET), policy and regulation, and autonomous ship systems and ICT development, a panel size considered appropriate for Delphi studies aimed at achieving expert consensus in complex and emerging domains. Four experts were recruited from each domain to enhance cross-sector representation and to reduce the likelihood of disciplinary bias in expert judgments, consistent with established practices in maritime Delphi studies [15,16,33,37].

All participants provided informed consent prior to participation. To minimize dominance effects, conformity pressure, and reputational bias, expert responses were collected anonymously throughout all Delphi rounds. This approach aligns with widely accepted methodological principles of the Delphi technique and supports the reliability and independence of expert judgments in complex socio-technical research contexts [15,16].

To enhance transparency regarding the composition and balance of the expert panel, the distribution of participants across stakeholder domains is explicitly summarized in Table 2. This table documents the domain representation underlying the Delphi process and provides contextual support for the credibility and cross-sectoral validity of the expert judgments used in subsequent analyses.

Table 2. Composition of the Delphi expert panel (N = 20).

Domain (Stakeholder Group)	Rationale for Inclusion (Onboard Relevance in Crewed Hybrid Autonomous Operations)	Number of Experts
Ship operation and navigation	Onboard command decision making, supervisory control, situational judgment, and manual or override actions in degraded or abnormal conditions	4
Marine engineering and maintenance	First line troubleshooting, maintenance response, and recovery actions requiring physical access and onboard intervention	4
Maritime automation and ICT systems	Monitoring autonomous systems, verifying sensor and data integrity, maintaining ship–shore connectivity, and first-level ICT troubleshooting	4
Maritime safety regulation and policy	Interpretation of responsibility allocation, safety, and legal accountability, and alignment with emerging MASS regulatory discussions	4
Maritime education and training (MET)	Competency implications, operational realism, and function-to-training mapping for hybrid autonomy	4
Total		20

3.6. Methodological Limitations

This study is subject to several methodological limitations that should be considered when interpreting the findings. First, the analysis relies on structured expert judgment obtained through a Delphi process rather than on large-scale empirical operational datasets. While this approach is appropriate for emerging socio-technical domains where real-world operational data remain limited, it inherently reflects the experiential knowledge, professional backgrounds, and interpretive perspectives of the participating experts, and the relatively small panel size (N = 20) limits the statistical generalizability of the findings [15,16].

Second, the scope of the study is explicitly bounded to a hybrid operational state in which the qualified crew remains onboard under hybrid autonomous operations with Remote Operation Center (ROC) supervision. As such, the findings are not intended

to be generalized to fully unmanned vessels or to conventional ships operating without autonomous support. This boundary condition reflects current regulatory discussions and practical deployment contexts for crewed hybrid autonomous operations, but it necessarily constrains the external applicability of the results [3].

Third, although the study identifies a minimum essential set of onboard functions, it does not address determinations of staffing numbers, individual competency levels, certification requirements, or vessel-specific adaptations. These aspects were intentionally excluded to avoid conflating functional necessity with quantitative manning decisions or training design, which require different analytical tools and assumptions. In line with function-based safety perspectives, the present study focuses on what must remain onboard before considering who performs these functions or how many personnel are required [35].

Accordingly, the findings should be interpreted as a foundational functional baseline specific to hybrid crewed autonomous operations with ROC supervision, rather than as a complete manning or competency framework applicable across all vessel types or operational contexts. Subsequent research is required to translate the validated function set into quantitative staffing models, competency mappings, and vessel or operation-specific implementations, using complementary methods such as AHP-based weighting, simulation-based analysis, or empirical validation as more operational data become available.

4. Results

4.1. Results of the First Delphi Round: Identification and Structural Refinement of Onboard Functions

The first Delphi round yielded two sequential outcomes consistent with the dual analytical objectives defined in Section 3.4.1. First, a comprehensive set of preliminary onboard function groups was identified based on expert input. Second, these preliminary groups underwent expert-driven structural refinement, reflecting functional coupling and non-substitutability under the defined hybrid operational state involving onboard automation and Remote Operation Center (ROC) supervision.

4.1.1. Confirmation of Preliminary Onboard Function Groups

Based on expert input obtained in Round 1, the six preliminary onboard function groups initially identified in Section 3.3 were confirmed as an appropriate and sufficiently comprehensive exploratory representation of onboard responsibilities for crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision. Experts did not identify any additional function domains beyond the six predefined groups, thereby confirming that the initial functional scope was sufficiently comprehensive and did not require expansion prior to subsequent qualitative refinement.

The six preliminary onboard function groups were therefore retained as the analytical baseline for further integration and validation, in accordance with the predefined Delphi decision framework described in Section 3.4:

- Management and command-related functions;
- Navigation and machinery Operation and Control;
- Maintenance and recovery;
- Safety and emergency response;
- Cargo and deck-related operations;
- Automation, ICT, and network-related functions.

4.1.2. Functional Integration and Structural Consolidation

While the comprehensiveness of the six preliminary function groups was confirmed in Round 1, expert judgments further indicated that not all groups should be retained as

independent functional categories for subsequent quantitative evaluation, thereby necessitating structural consolidation based on functional interdependencies. In accordance with the a priori decision logic defined in Section 3.4, qualitative feedback was systematically analyzed to identify patterns of functional coupling and operational non-substitutability under the defined hybrid operational state.

First, safety and emergency response activities were not supported as a standalone function group. Experts consistently emphasized that emergency preparedness, crisis management, prioritization under uncertainty, and coordination of onboard response are inseparable from onboard management and command authority. Based on this functional inseparability, and consistent with the predefined integration logic, safety and emergency response were structurally integrated into the Management function rather than being treated as an independent category, as they did not satisfy the criterion of functional independence required for separate evaluation.

Second, traditional navigation and machinery operation were consistently reframed within a broader Operation and Control function. Experts highlighted that, although automation and ROC supervision increasingly support routine monitoring and nominal control, onboard personnel remain indispensable for supervising automated behavior, interpreting local contextual cues unavailable to shore-based systems, and executing manual or override actions during abnormal or degraded conditions. This reframing reflects functional coupling identified during qualitative analysis and aligns with the criteria for non-substitutability applied in subsequent rounds, thereby justifying the consolidation of navigation and machinery-related responsibilities within a single functional domain.

Third, cargo and deck-related operations were not regarded as an independent functional domain under the defined hybrid operational state. Instead, cargo condition monitoring and basic cargo management were consistently described as operational inputs to vessel control and safety assessment, influencing decisions related to maneuvering, stability, and propulsion response. Accordingly, cargo-related responsibilities were functionally embedded within the Operation and Control domain, consistent with the integration rules defined a priori, as they did not demonstrate sufficient independence to warrant classification as a standalone function.

Fourth, automation, ICT, and network-related functions were strongly supported as a distinct onboard function group. Experts emphasized that first-level troubleshooting of autonomous systems, verification of sensor and data integrity, and maintenance of ship–shore data links require onboard presence and cannot be fully substituted by remote supervision. These functions, therefore, satisfied the predefined criteria for functional independence and non-substitutability, supporting their retention as a distinct onboard function group in subsequent quantitative evaluation.

Finally, maintenance and recovery functions were consistently supported as an independent onboard function due to the necessity of physical inspection, fault diagnosis, minor repair, and technical recovery actions. These activities were judged to be inherently onboard dependent and thus retained as a separate functional category in accordance with the a priori decision framework, as they require physical presence and cannot be substituted by automation or remote supervision.

4.1.3. Outcome of Round 1 Refinement

As an outcome of Round 1, the six preliminary onboard function groups were not reduced in scope but were structurally reorganized into four consolidated function groups for subsequent quantitative evaluation, based on the predefined integration criteria of functional coupling and non-substitutability. This reorganization was conducted in accordance with the a priori integration logic defined in Section 3.4 and reflected expert

judgments regarding functional coupling and non-substitutability under the defined hybrid operational state.

The four consolidated onboard function groups derived from Round 1 were as follows:

- Management (including integrated safety and emergency response responsibilities);
- Operation and Control (including cargo monitoring and management treated as operational inputs rather than as a standalone function);
- Maintenance and recovery;
- Automation, ICT, and Network.

Importantly, this consolidation does not represent an a priori assumption of functional reduction, prioritization, or exclusion, but rather a decision explicitly grounded in the predefined Delphi integration logic. Rather, it reflects a structured integration outcome derived from qualitative expert reasoning in Round 1. These consolidated groups were carried forward to subsequent Delphi rounds for quantitative evaluation and essentiality validation, consistent with the predefined Delphi decision framework.

The structural transition from six preliminary function groups to four consolidated groups is summarized in Table 3, illustrating how functional responsibilities were integrated rather than eliminated.

Table 3. Structural transition from preliminary to consolidated onboard function groups.

Preliminary Function Groups (Round 1 Input)	Consolidated Function Group (After Round 1)	Integration Rationale
Management and command-related functions	Management	Core command authority retained onboard
Safety and emergency response		Functionally inseparable from command and crisis
Navigation and machinery Operation and Control	Operation and Control	Integrated supervision, override, and contextual control
Cargo and deck-related operations		Cargo treated as operational input affecting safety and control
Maintenance and recovery	Maintenance and Recovery	Essential for sustaining manned operations through onboard maintenance and recovery functions.
Automation, ICT, and network-related functions	Automation, ICT, and Network	Non-substitutable onboard technical oversight

4.2. Results of the Second Delphi Round: Importance and Stability Assessment

In the second Delphi round, experts quantitatively evaluated the refined and integrated onboard function groups derived from Round 1 to assess their perceived importance and the stability of expert judgments under the defined hybrid operational state. Mean values were calculated to represent the relative importance of each function group, while coefficients of variation (CV) were used to evaluate convergence and judgment stability across the expert panel.

In accordance with the a priori decision logic defined in Section 3.4.2, function groups were systematically screened using a mean importance threshold of 4.0 and a CV threshold of 0.30. Only functions satisfying both criteria were retained for subsequent analysis, ensuring both relevance and stability.

The quantitative outcomes of the importance and stability assessment are summarized in Table 4. All four consolidated onboard function groups satisfied the predefined retention criteria (Mean $\geq$ 4.0; CV $\leq$ 0.30), demonstrating strong expert convergence regarding

their operational importance under hybrid autonomous operations with ROC supervision. Accordingly, all function groups were retained for subsequent essentiality assessment in Round 3, consistent with the staged Delphi framework and triangulated validation logic established in the methodological design.

Table 4. Importance and stability assessment of consolidated onboard function groups (Round 2, N = 20).

Function Group	Mean Importance	Standard Deviation	Coefficient of Variation (CV)	Screening Outcome
Management (including Safety and Emergency Response)	4.65	0.46	0.10	Retained
Operation and Control (including cargo integration)	4.70	0.44	0.09	Retained
Maintenance and Recovery	4.35	0.52	0.12	Retained
Automation, ICT, and Network	4.55	0.49	0.11	Retained

4.2.1. Importance and Stability Assessment of Onboard Function Groups

All four consolidated onboard function groups achieved mean importance scores exceeding the predefined threshold of 4.0, satisfying the a priori relevance criterion for subsequent evaluation under hybrid autonomous operations with Remote Operation Center (ROC) supervision (Table 4). This result indicates strong expert agreement regarding the operational importance of each retained function group within the defined hybrid operational state, confirming that all function groups satisfied the predefined relevance criterion for further evaluation.

The Management function received consistently high importance ratings, reflecting the persistence of onboard responsibility for situational assessment and emergency coordination. Similarly, Operation and Control was rated as highly important due to its central role in supervising automated behavior, executing manual or override actions, and integrating cargo state awareness into navigational safety decisions.

Maintenance and Recovery also achieved high importance scores, underscoring the necessity of onboard technical intervention, physical inspection, and recovery capabilities that cannot be substituted by automation or remote supervision alone. Automation, ICT, and Network functions were likewise rated as highly important, reflecting expert recognition of the criticality of autonomous system supervision, sensor and data integrity, and continuity of ship–shore communication.

Importantly, importance scores were interpreted as one component of the predefined multi-criteria decision framework rather than as a standalone basis for retention. All retained function groups demonstrated consistently high importance ratings, indicating strong expert recognition that onboard functional capabilities remain operationally indispensable despite increasing automation and ROC support under hybrid autonomous conditions. Accordingly, all function groups were retained for stability assessment and subsequent essentiality evaluation, consistent with the staged Delphi logic and triangulation principles established in the methodological design.

4.2.2. Stability of Expert Judgments

All four consolidated onboard function groups demonstrated acceptable convergence, with coefficients of variation not exceeding the predefined threshold of 0.30 (Table 4). This outcome indicates a stable pattern of expert judgments across the expanded and multidisciplinary Delphi panel, confirming that all function groups satisfied the predefined

stability criterion and supporting the internal consistency and robustness of the importance evaluations obtained in Round 2.

Within the predefined analytical framework, stability was treated as a necessary screening criterion rather than a sufficient condition for function retention. Accordingly, function groups satisfying both the importance and stability criteria were retained for subsequent essentiality assessment in Round 3, while no function groups were excluded at this stage, in accordance with the staged a priori decision logic outlined in Section 3.4 and summarized in Table 1. The low coefficients of variation observed across all retained function groups further indicate a stable and multidisciplinary expert consensus regarding the persistence of essential onboard functions within hybrid autonomous operational environments.

Consistent with the structural integration achieved during Round 1, cargo-related responsibilities were not evaluated as a standalone function in this round, as they did not satisfy the criterion of functional independence required for separate evaluation. Instead, their relevance was implicitly reflected in expert ratings of the Operation and Control function, aligning with the conceptual treatment of cargo state awareness as an operational input influencing vessel control and safety decisions rather than as an independent onboard capability.

4.3. Results of the Third Delphi Round: Essentiality and Content Validity Assessment

The third Delphi round assessed the essentiality of the refined onboard function groups using Lawshe's Content Validity Ratio (CVR), as specified in Section 3.4.3. This round constituted the final confirmatory stage of the triangulated Delphi validation process and aimed to determine whether each retained function group should be regarded as operationally indispensable for ensuring safe operation and system integrity under hybrid autonomous operations with ROC supervision.

For each function group, the number of experts rating the function as essential (n_e) was recorded, and the corresponding CVR value was calculated. For a panel size of twenty experts ($N = 20$), a minimum reference CVR value of 0.42 was applied in accordance with Lawshe's critical values for content validity assessment.

Importantly, CVR outcomes were not interpreted in isolation. In line with the a priori decision logic defined in Section 3.4 and summarized in Table 1, only function groups that simultaneously satisfied all three predefined criteria—importance (Round 2), stability (Round 2), and essentiality (Round 3)—were retained as core onboard functions, while any function groups not meeting these criteria were excluded from final classification. This triangulated interpretation ensured that essentiality judgments reflected not only majority agreement but also consistency and operational relevance across Delphi rounds.

The essentiality validation outcomes based on CVR, together with their alignment with the importance and stability criteria, are presented in Table 5. The complete quantitative validation outcomes of the Delphi process are presented in Appendix C.

Table 5. Essentiality and content validity assessment of onboard function groups (Round 3, N = 20; CVR threshold ≥ 0.42).

Function Group	Experts Rating "Essential" ((n_e))	CVR	Interpretation
Management (including Safety and Emergency Response)	19	0.90	Strong content validity
Operation and Control (including cargo integration)	20	1.00	Strong content validity
Maintenance and Recovery	18	0.80	Strong content validity
Automation, ICT, and Network	17	0.70	Strong content validity

4.3.1. CVR Outcomes

All four function groups exceeded the critical CVR threshold, indicating strong expert agreement regarding their essentiality. However, consistent with the a priori decision logic defined in Section 3.4 and summarized in Table 1, CVR results were not interpreted as a standalone acceptance criterion.

Instead, function groups that simultaneously satisfied all predefined criteria—importance (mean ≥ 4.0), stability (CV ≤ 0.30), and essentiality (CVR ≥ 0.42)—were retained as core onboard functions for crewed ships operating under hybrid autonomous operations and ROC supervision, while no function groups were excluded at this stage.

Accordingly, the four function groups presented in Table 5 constitute a validated minimum onboard functional baseline derived through triangulated expert judgment rather than single metric thresholding.

4.3.2. Interpretation of CVR Outcomes Within the Validation Framework

To synthesize the findings from all three Delphi rounds, the onboard function groups were consolidated into a final set of core onboard functions applicable to crewed ships operating under hybrid autonomous operations and Remote Operation Center (ROC) supervision.

Consistent with the a priori decision logic defined in Section 3.4 and summarized in Table 1, only function groups that simultaneously satisfied all predefined criteria—importance, stability, and essentiality—were retained, with no function groups excluded at this final validation stage. Specifically, functions were included in the final set only if they (i) achieved mean importance scores above the predefined threshold, (ii) demonstrated acceptable convergence and stability across expert judgments, and (iii) exceeded the minimum content validity requirements based on Lawshe's CVR.

On this basis, the results of the qualitative refinement in Round 1, the quantitative importance and stability assessment in Round 2, and the essentiality validation in Round 3 jointly converged on four consolidated onboard function groups. These groups represent a validated functional baseline for crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision. The finalized core onboard function groups and their functional scopes are summarized in Table 6.

Table 6. Finalized onboard function groups.

Code	Function Group	Core Functional Scope
F1	Management (including Safety and Emergency Response)	Situational assessment, final decision-making authority, emergency preparedness and response, onboard crisis coordination, and communication with ROC and external stakeholders
F2	Operation and Control (including cargo integration)	Supervision of navigation and machinery operation, manual or override actions, and integrated awareness of cargo state impacts on vessel safety and stability
F3	Maintenance and Recovery	Inspection, fault diagnosis, minor repair, technical recovery, and physical intervention requiring onboard presence
F4	Automation, ICT, and Network	Monitoring and first-level troubleshooting of autonomous systems, verification of sensor and data integrity, and maintenance of ship–shore communication link continuity

4.4. Final Set of Core Onboard Functions

The final set of core onboard functions was established through an integrated interpretation of the Delphi outcomes across all three validation rounds. Rather than relying on a single quantitative indicator, the final selection reflected the combined consideration of qualitative refinement, quantitative importance, stability assessment, and essentiality validation within the predefined Delphi framework. Function groups were retained only when they demonstrated consistent support in terms of importance, stability, and essentiality, based on the evaluation criteria summarized in Table 1.

The qualitative refinement in Round 1, the quantitative importance and stability assessment in Round 2, and the essentiality validation in Round 3 jointly converged on four non-substitutable onboard function groups. These groups constitute a validated minimum onboard functional baseline for hybrid operations, reflecting functional coupling and operational necessity rather than traditional role-based or position-based manning assumptions.

The finalized core onboard function groups and their functional scopes are summarized in Table 6.

4.5. Summary of Results

Overall, the Delphi analysis demonstrates strong expert convergence on a minimum set of four non-substitutable onboard functions required for the safe operation of crewed ships under hybrid autonomous operations with Remote Operation Center (ROC) supervision. These functions were identified through a structured, multi-round validation process that combined qualitative integration, quantitative screening, and content validity assessment based on predefined a priori criteria.

The final set of core onboard functions reflects a functional reconfiguration rather than a reduction of onboard responsibilities. Safety and emergency response activities, as well as cargo-related considerations, remain integral to safe operation but are structurally embedded within the Management and Operation and Control functions, respectively, for the purpose of defining a generic and transferable baseline.

Taken together, the results establish a function-based baseline for core onboard functions that reflects the operational realities of hybrid autonomy while remaining robust across variations in vessel type, automation architecture, and operational profile within the defined scope of this study. More broadly, the findings support future transitions toward function-oriented governance frameworks for Maritime Autonomous Surface Ships (MASS) by clarifying which onboard functional capabilities remain non-substitutable despite increasing automation and shore-based supervisory support.

5. Discussion

5.1. Interpretation of Function-Based Outcomes Under Hybrid Autonomy

This study sought to identify a minimum onboard functional baseline for crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision. The Delphi validation results demonstrate strong expert convergence toward four non-substitutable onboard function groups—Management, Operation and Control, Maintenance and Recovery, and Automation, ICT, and Network—each of which satisfied all predefined criteria of importance, stability, and essentiality as defined in the a priori Delphi framework, and together define the safety-critical capabilities that remain operationally important within a hybrid operational state.

These findings should be interpreted as a structural reorganization of onboard responsibilities rather than a reduction of safety-related functions. Under hybrid autonomy, certain monitoring and analytical tasks may be redistributed to automated systems or

shore-based support; however, the present results indicate that responsibilities requiring contextual judgment, physical intervention, and real-time coordination remain inherently onboard dependent. The validated function set, therefore, reflects the practical boundary of autonomy redistribution rather than a theoretical maximum of task automation.

Importantly, these findings should not be interpreted as prescribing universal onboard requirements across all autonomous operational modes. Rather, they are explicitly bound to crewed hybrid operational configurations in which onboard personnel continue to perform safety-critical and physically dependent functions alongside automation and ROC supervision.

5.2. Integration of Safety and Emergency Response Within Management

One notable outcome of the Delphi process is that Safety and Emergency Response did not emerge as an independent, standalone function, but was consistently integrated into the Management function during the qualitative refinement stage (Round 1). This finding does not indicate any diminution in the importance of safety; rather, it reflects strong expert consensus that safety-critical responsibilities are intrinsically embedded within onboard Management authority under hybrid autonomy.

Emergency preparedness, prioritization under uncertainty, and coordination of onboard response were consistently regarded as inseparable from situational assessment and final decision-making authority. From an operational perspective, separating safety into a discrete functional silo risks fragmenting accountability during crisis situations. The integration observed in this study, therefore, reinforces the principle that, even under hybrid autonomous operations with ROC supervision, ultimate responsibility for safety remains centralized onboard.

5.3. Operation and Control as an Integrated Safety–Control Function

The Operation and Control function represents a core interface between human operators, automated systems, and the physical ship. Rather than being limited to traditional navigation or machinery watchkeeping, this function encompasses supervisory control of automated behavior, execution of manual or override actions, and interpretation of local environmental conditions that may not be fully observable from shore-based systems.

The integration of cargo-state awareness within this function further highlights its safety-critical nature. Cargo conditions directly influence vessel stability, maneuverability, and emergency response decisions, and, based on the triangulated Delphi validation, expert judgments consistently supported treating cargo awareness as an operational input rather than an independent functional domain. Together, these elements position Operation and Control as a consolidated safety–control function that remains central to hybrid operations.

5.4. Onboard Necessity of Maintenance and Automation-Related Functions

Two function groups—Maintenance and Recovery and Automation, ICT, and Network—exhibited particularly strong expert agreement across all validation criteria, as evidenced by their consistently high importance scores, low coefficients of variation, and CVR values exceeding the predefined threshold. This outcome highlights a central paradox of hybrid autonomy: as system automation advances, onboard technical roles are not diminished but instead become more consequential, because failures within highly automated systems tend to propagate rapidly and with greater operational impact.

Among the validated functions, Maintenance and Recovery play a distinctive role. While often less visible than navigation or control functions, it represents one of the most fundamental enablers of sustained crewed operations. Beyond conventional notions of technical maintenance, this function encompasses the onboard capacity to preserve operational continuity through physical inspection, situational assessment, fault diagnosis,

and recovery actions under both routine and non-routine conditions. Crucially, it also implicitly supports the basic conditions required for human presence onboard—ensuring that the vessel remains habitable, operable, and safe for continued manned operation. By framing these necessities at the functional level rather than as discrete tasks, the study captures aspects of shipboard reality that are frequently overlooked in MASS discourse, without resorting to explicit debates about living arrangements or support services.

In parallel, the strong validation of Automation, ICT, and Network functions reflects the evolving nature of onboard responsibility in hybrid operations. As autonomy relies increasingly on complex sensor networks, software-driven decision logic, and continuous data exchange with shore-based systems, onboard personnel remain important for supervising autonomous behavior, verifying data integrity, and maintaining the continuity of ship–shore communication links. These responsibilities are particularly critical during periods of system degradation, data inconsistency, or communication loss, when delayed or inappropriate responses can rapidly escalate operational risk.

Taken together, these two function groups reveal an important insight: hybrid autonomy does not shift technical responsibility away from the ship but redistributes it in ways that make onboard human presence more, rather than less, consequential. Maintenance and Recovery ensure the physical and operational viability of a crewed vessel, while Automation, ICT, and Network functions safeguard the integrity of the socio-technical systems upon which hybrid autonomy depends. Their combined validation underscores that the persistence of onboard functions in crewed hybrid operations is not a conservative holdover from traditional shipping, but a rational response to the practical realities of operating complex, automated vessels at sea.

5.5. Implications for Manning, Training, and Regulatory Development

The function-based outcomes of this study, derived from the triangulated Delphi validation process, have several practical implications.

First, the findings challenge the adequacy of traditional position-based crewing models by demonstrating that functional capability, rather than occupational title, shapes onboard necessity under hybrid autonomous operations. Rather than simply reducing crew size or reallocating existing duties, the results suggest that future Maritime Autonomous Surface Ships (MASS) governance frameworks may require a transition toward function-oriented operational governance, in which onboard responsibilities are organized around essential functional capabilities rather than conventional ranks or occupational categories. This implication is particularly significant in hybrid autonomous environments where automation and ROC supervision redistribute operational authority while still requiring onboard human intervention for decision-making, system recovery, emergency response, and operational resilience.

Second, the validated functional baseline provides a structured reference for the evolution of Maritime Education and Training (MET). Training programs may benefit from aligning learning objectives with integrated functional capabilities—particularly in areas such as automation supervision, system troubleshooting, and hybrid decision-making—rather than focusing exclusively on conventional rank-based competencies.

Third, from a regulatory perspective, the results provide empirical support for function-based or goal-oriented approaches to MASS governance. Rather than prescribing fixed crewing configurations, regulatory frameworks may increasingly emphasize whether core onboard functions are adequately fulfilled, regardless of how tasks are distributed among humans, automation, and shore-based support.

At the same time, the present findings should not be interpreted as prescribing crew numbers, redefining statutory manning principles, or constituting universal regulatory

requirements for all autonomous ship configurations. The study is limited to crewed hybrid operational contexts and is intended to clarify a functional baseline within that boundary, rather than to constrain future fully autonomous or uncrewed operational pathways.

5.6. Methodological Considerations and Limitations

Several limitations should be acknowledged. The study relies on expert judgment obtained from a Delphi panel of 20 experts rather than empirical operational datasets, reflecting the current developmental stage of large-scale hybrid autonomous shipping. While the Delphi method is appropriate for identifying consensus in emerging domains, future research should seek to validate these findings using simulator-based experiments, operational trials, or incident analyses as such data become available.

In addition, the scope of this study was intentionally limited to identifying core onboard functions and does not address optimal crew size, workload distribution, or competency levels. These aspects require complementary analytical approaches and are appropriate subjects for subsequent research. Finally, the findings are bound to crewed hybrid autonomous operations and may not be directly transferable to fully unmanned or highly specialized vessel concepts.

5.7. Summary of Discussion

In summary, this study provides an empirically grounded reinterpretation of onboard necessity under hybrid autonomous operations. The four validated function groups constitute a minimum onboard functional baseline that remains robust in the presence of automation and ROC supervision within the defined scope of crewed hybrid autonomous operations. Rather than diminishing human responsibility, hybrid autonomy reshapes how responsibilities are organized and exercised onboard.

By grounding this reinterpretation in expert consensus and multi-stage validation based on predefined criteria of importance, stability, and essentiality, the study offers a defensible foundation for future work on manning strategies, training frameworks, and regulatory adaptation in autonomous shipping.

6. Conclusions

This study set out to identify a minimum onboard functional baseline required for the safe operation of crewed ships under hybrid autonomous operations with Remote Operation Center (ROC) supervision. Departing from traditional position- or occupation-based crewing perspectives, the research adopted a function-based approach that reflects the operational reality of hybrid autonomy, in which responsibilities are distributed across onboard personnel, onboard automation, and shore-based support systems.

Using a structured three-round Delphi methodology with an expanded expert panel (N = 20), the study empirically validated four non-substitutable onboard function groups: (1) Management, including integrated safety and emergency response; (2) Operation and Control, incorporating cargo-state awareness as an operational input; (3) Maintenance and Recovery; and (4) Automation, ICT, and Network. These functions were derived through a triangulated multi-stage validation process combining qualitative refinement, quantitative importance and stability screening, and content validity assessment, thereby ensuring methodological rigor, transparency, and robustness.

A central contribution of this research lies in clarifying crewed hybrid autonomous operations as a distinct distributed operational state characterized by shared control, distributed situational awareness, and persistent onboard responsibility. Within this state, the findings demonstrate that, within the defined scope of crewed hybrid autonomous operations, automation and ROC supervision do not eliminate the need for onboard hu-

man involvement. Rather, they reorganize onboard necessity around non-substitutable functions that require contextual judgment, physical intervention, integrated safety control, and operational resilience under hybrid autonomous conditions.

Importantly, the consolidation of six preliminary function groups into four validated functions should not be interpreted as a reduction of safety-related responsibilities. Safety and emergency response were not removed, but explicitly embedded within the Management function, reflecting expert consensus that crisis handling, prioritization under uncertainty, and final authority are operationally inseparable. Similarly, cargo monitoring was not excluded, but functionally integrated into Operation and Control, acknowledging its role as a critical operational input to navigational and machinery safety rather than as an independent onboard domain.

From a methodological perspective, the study demonstrates the value of triangulated validation for defining core onboard functions in emerging socio-technical systems, as implemented through the three-round Delphi process combining qualitative and quantitative criteria. By avoiding reliance on single-metric thresholds and instead combining importance, stability, and essentiality criteria defined a priori, the research provides a defensible and reproducible basis for identifying onboard necessity within crewed hybrid operational contexts.

The findings offer several practical implications. First, they provide an empirically validated reference point for function-based manning discussions, supporting regulatory and industry efforts to transition from traditional position-based crewing logic toward function-oriented governance frameworks for Maritime Autonomous Surface Ships (MASS). Second, the validated functional baseline offers a structured foundation for the evolution of Maritime Education and Training (MET) frameworks, particularly in areas related to automation supervision, integrated safety management, and hybrid decision-making. Third, the results inform future policy and guideline development by clarifying which onboard capabilities remain operationally important for safety, accountability, and resilience in crewed hybrid operations.

At the same time, the findings should not be interpreted as prescribing crew numbers, redefining statutory manning principles, or constituting universal onboard requirements across all autonomous ship configurations. The study is explicitly bounded to crewed hybrid operational contexts and is intended to clarify a functional baseline within that boundary rather than to constrain future fully autonomous or uncrewed operational pathways.

Several limitations should be acknowledged. The study relies on expert judgment rather than large-scale operational datasets, reflecting the current maturity level of hybrid autonomous shipping. Moreover, the validated function set represents a generic minimum baseline and does not capture vessel-specific, cargo-intensive, or highly specialized operational contexts. These limitations are consistent with the study's objective of defining boundary conditions rather than prescribing universal staffing solutions.

Future research should build on these findings by examining function weighting, staffing ratios, and workload distribution, as well as by validating the proposed functional framework through simulator-based experiments, operational trials, or incident analyses as such data become available. Extending the analysis to alternative autonomy configurations and ROC interaction models also represents a promising avenue for further investigation.

In conclusion, this study provides a defensible, function-based foundation for understanding onboard necessity under hybrid autonomous operations with ROC supervision within the defined scope of crewed hybrid operational contexts. By clarifying which functions remain operationally non-substitutable in crewed hybrid contexts—and why—the study contributes to more coherent, empirically grounded, and evidence-based discussions on safety, responsibility, and human roles in the evolving landscape of autonomous

shipping. In this respect, clarifying the functional boundary between onboard personnel, automation, and shore-based support contributes to the sustainable governance of hybrid autonomous shipping by supporting safety, accountability, operational resilience, and function-oriented operational governance during the transition toward higher levels of maritime autonomy.

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Abbreviations

MASS	Maritime Autonomous Surface Ships
ROC	Remote Operation Center
MET	Maritime Education and Training
CV	Coefficient of Variation
CVR	Content Validity Ratio
IMO	International Maritime Organization
Delphi	Delphi Method (structured expert consensus methodology)
ICT	Information and Communication Technology
Core Onboard Functions	Operationally indispensable functions required onboard under hybrid autonomous operations
Hybrid Autonomous Operations	Operational configuration combining onboard crew, automation, and ROC supervision

Appendix A. Delphi Survey Instrument (N = 20)

The Delphi panel comprised 20 experts (N = 20) drawn from five stakeholder domains relevant to the operation of crewed ships under hybrid autonomous conditions with Remote Operation Center (ROC) supervision.

The instrument was developed by the author based on a synthesis of regulatory requirements, prior research on human–automation interaction and remote operations, and reported hybrid autonomy operational scenarios. It was applied consistently across all Delphi rounds to support qualitative exploration and subsequent quantitative validation.

All responses were collected anonymously, and experts participated independently in each round to ensure unbiased judgment and methodological rigor.

Appendix A.1. Delphi Round 1: Open-Ended Questionnaire

The first Delphi round employed open-ended questions to explore expert perceptions of indispensable onboard functions and to refine the preliminary functional classification.

Round 1 Questionnaire Items

1. In your expert opinion, which onboard functions remain indispensable for safe and effective ship operation under hybrid autonomous operations with Remote Operation Center (ROC) supervision?
2. Are there any onboard functions currently performed by conventional crew that could be fully substituted by automation or remote supervision? Please explain your reasoning.
3. Do you consider any of the following preliminary function groups to be overlapping or conceptually inseparable under hybrid autonomy?
    - Management and command
    - Navigation and machinery operation
    - Maintenance and technical response
    - Safety and emergency response
    - Cargo and deck-related operations
    - Automation, ICT, and network-related functions
4. Please suggest any integration, separation, or redefinition of the above function groups that would better reflect operational realities under hybrid autonomous operations with Remote Operation Center (ROC) supervision.
5. Are there any additional onboard functions that you believe are critical but not adequately captured by the preliminary classification?

Appendix A.2. Delphi Round 2: Importance Assessment Questionnaire (Likert Scale)

The second Delphi round employed a structured questionnaire to assess the perceived importance of the refined onboard function groups identified in Round 1.

Experts were asked to rate each function group using a five-point Likert scale (1 = Not important, 5 = Very important).

Round 2 Questionnaire Items

Please indicate the importance of each onboard function group for crewed ships operating under hybrid autonomous conditions with Remote Operation Center (ROC) supervision.

Function Group	1	2	3	4	5
Management function (including safety and emergency response responsibilities)	☐	☐	☐	☐	☐
Operation and Control function (including navigation, machinery supervision, and cargo-state awareness)	☐	☐	☐	☐	☐
Maintenance and technical response function	☐	☐	☐	☐	☐
Automation, ICT, and network function	☐	☐	☐	☐	☐

Appendix A.3. Delphi Round 3: Essentiality Assessment Questionnaire

The third Delphi round assessed whether each onboard function group should be regarded as essential for the operation of crewed ships under hybrid autonomous conditions with Remote Operation Center (ROC) supervision.

Experts were asked to classify each function group into one of the following categories:

- Essential
- Useful but not essential
- Not necessary

Round 3 Questionnaire Items

Please indicate the essentiality of each onboard function group.

Function Group	Essential	Useful But Not Essential	Not Necessary
Management function	☐	☐	☐
Operation and Control function	☐	☐	☐
Maintenance and technical response function	☐	☐	☐
Automation, ICT, and network function	☐	☐	☐

Appendix B. Delphi Evaluation Criteria and Validation Procedure (N = 20)

This appendix details the quantitative evaluation criteria, calculation procedures, and decision logic applied to expert ratings obtained during the Delphi process. It documents how expert judgments collected in Delphi Rounds 2 and 3 were systematically analyzed to assess the importance, stability, and essentiality of onboard function groups for crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision.

The validation framework combines predefined thresholds for mean importance scores, coefficients of variation, and Lawshe's Content Validity Ratio (CVR), and applies them within an a priori, staged decision logic. This approach ensures transparency, reproducibility, and consistency across Delphi rounds and avoids reliance on single-metric or post hoc acceptance criteria.

All analyses are based on responses from a balanced expert panel of 20 participants (N = 20), each of whom completed all relevant Delphi rounds.

Appendix B.1. Evaluation Framework for Delphi Round 2 (Importance and Stability)

Purpose

The purpose of Delphi Round 2 was to evaluate the perceived importance of each refined onboard function group and to assess the stability of expert consensus.

Metrics and Calculations

Expert ratings on a five-point Likert scale (1–5) were analyzed using the following indicators:

- Mean value (Mean): used to represent overall perceived importance.
- Standard deviation (SD): used to quantify dispersion in expert ratings.
- Coefficient of variation (CV): calculated as the ratio of SD to Mean, used to assess stability and convergence of expert opinion.

Predefined Screening Criteria

The following a priori thresholds were applied to retain function groups for further validation:

- Mean ≥ 4.0
- CV ≤ 0.30

These thresholds are widely applied in Delphi studies to ensure both relevance and convergence of expert judgments in complex socio-technical domains. Only function groups satisfying both criteria were advanced to the essentiality assessment in Round 3.

Appendix B.2. Evaluation Framework for Delphi Round 3 (Essentiality and Content Validity)

Purpose

Delphi Round 3 aimed to determine whether the retained onboard function groups should be classified as essential for the operation of crewed ships under hybrid autonomous conditions with Remote Operation Center (ROC) supervision.

Content Validity Ratio (CVR)

Essentiality was evaluated using Lawshe's Content Validity Ratio (CVR), calculated as follows:

$$\mathrm{CVR} = \frac{n_e - \left(\frac{N}{2}\right)}{\left(\frac{N}{2}\right)} \tag{A1}$$

where

- n_e denotes the number of experts rating a function group as essential
- N denotes the total number of experts in the panel.

For a panel size of N = 20, the minimum acceptable CVR value was set at 0.42, in accordance with Lawshe's critical values.

Appendix B.3. Triangulated Validation Logic

CVR results were not interpreted in isolation. Final validation of essential onboard function groups was based on a triangulated evaluation framework, integrating:

1. Conceptual convergence derived from qualitative analysis in Delphi Round 1,
2. Importance and stability metrics (Mean and CV) obtained in Delphi Round 2, and
3. Essentiality outcomes (CVR) obtained in Delphi Round 3.

This integrated validation logic was defined prior to analysis to avoid mechanical threshold-based decisions and to enhance methodological robustness when evaluating essential functions in hybrid autonomous maritime operations.

Appendix C. Quantitative Validation Outcomes of the Delphi Process (N = 20)

This appendix reports the quantitative outcomes of the Delphi validation process conducted in this study. The tables present summary statistics and validation indicators for the retained onboard function groups, including importance scores, measures of judgment stability, and essentiality outcomes based on Lawshe's Content Validity Ratio (CVR).

All results are derived from responses provided by a balanced expert panel of 20 participants (N = 20) who completed all relevant Delphi rounds. The quantitative outcomes presented here correspond directly to the evaluation criteria and decision logic described in Appendix B and support the retention of the final essential onboard function set.

Appendix C.1. Importance and Stability Outcomes from Delphi Round 2

Table A1 summarizes the outcomes of the Delphi Round 2 evaluation, focusing on the perceived importance of each onboard function group and the stability of expert consensus. Mean values and coefficients of variation (CV) were used to assess relevance and convergence, respectively.

All function groups satisfied the predefined importance and stability thresholds, indicating strong convergence of expert opinion across the expanded panel.

Table A1. Importance and stability outcomes used for validation (Round 2, N = 20).

Function Group	Mean	Standard Deviation	Coefficient of Variation (CV)	Validation Criterion Satisfied
Management function	4.65	0.46	0.10	✓
Operation and Control function	4.70	0.44	0.09	✓
Maintenance and technical response function	4.35	0.52	0.12	✓
Automation, ICT, and network function	4.55	0.49	0.11	✓

Note: ✓ indicates that the function group satisfied the validation criteria.

Appendix C.2. Essentiality Validation Outcomes from Delphi Round 3 (CVR)

Table A2 presents the essentiality validation outcomes derived from Delphi Round 3 using Lawshe's Content Validity Ratio (CVR). For a panel size of N = 20, the minimum acceptable CVR value was 0.42.

Table A2. Content validity outcomes (CVR) for essentiality validation (Round 3, N = 20).

Function Group	Experts Rating "Essential" (n_e)	CVR	CVR Criterion Satisfied
Management function	19	0.90	✓
Operation and Control function	20	1.00	✓
Maintenance and technical response function	18	0.80	✓
Automation, ICT, and network function	17	0.70	✓

Note: ✓ indicates that the CVR criterion was satisfied.

All retained function groups exceeded the critical CVR threshold, confirming their essentiality for crewed ships operating under hybrid autonomous operations with Remote Operation Center (ROC) supervision.

Appendix C.3. Integrated Validation Outcomes Across Delphi Rounds

Table A3 integrates the quantitative outcomes from Delphi Rounds 2 and 3 to support the final validation of essential onboard function groups.

Table A3. Integrated validation outcomes based on importance, stability, and essentiality (N = 20).

Function Group	Mean (Round 2)	CV (Round 2)	CVR (Round 3)	Final Validation Outcome
Management function	4.65	0.10	0.90	Essential
Operation and Control function	4.70	0.09	1.00	Essential
Maintenance and technical response function	4.35	0.12	0.80	Essential
Automation, ICT, and network function	4.55	0.11	0.70	Essential

The integrated evaluation confirms that all four function groups satisfy the predefined criteria for importance, stability, and essentiality.

Appendix C.4. Summary of Delphi Validation Logic and Outcomes

Table A4 provides a consolidated overview of the validation logic and outcomes applied across all Delphi rounds.

Table A4. Summary of Delphi validation outcomes across all rounds (N = 20).

Delphi Round	Validation Dimension	Indicator	Threshold	Outcome
Round 1	Conceptual relevance	Qualitative convergence	Thematic saturation	Achieved
Round 2	Importance	Mean score	$\geq$4.0	Achieved
	Stability	CV	$\leq$0.30	Achieved
Round 3	Essentiality	CVR	$\geq$0.42	Achieved

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