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A Socio-Technical Systems Model of Remote Maritime Operations: Total Interpretive Structural Modelling of Human Capability, Situation Awareness and Navigation Safety

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Highlights

Please indicate how your work links to systems science via your contributions to systems practice, theory, and/or methodology.

- Develops an eight-element socio-technical model that distinguishes navigator capability from the interface, information, workload, trust, and automation conditions of the remote-operation work system.
- Documents all 28 TISM pairwise judgements and examines alternative relationships through structural sensitivity analysis, making the model's assumptions and their implications transparent.

What are the main findings and/or the implications of the main findings?

- Operator Capability, HMI and Information/Data Conditions, Trust and Transparency, and Level of Automation have direct modelled links to Decision-Making Quality alongside indirect pathways through Situation Awareness.
- The Situation Awareness → Decision-Making Quality → Navigation Safety ordering remains unchanged across tested contextual alternatives, but explicit decision-making-to-SA feedback makes the two elements mutually reachable, highlighting the temporal boundary of the model.

Abstract

The shift to Maritime Autonomous Surface Ship (MASS) operations redistributes safety-critical functions among Remote Operation Centre (ROC) navigators, automation and digital systems. Yet, relationships among Operator Capability, cognition, work-system conditions and Navigation Safety remain insufficiently integrated. This study develops a literature-grounded socio-technical model using a 48-study systematic literature review, thematic synthesis, Total Interpretive Structural Modelling (TISM), MICMAC analysis, structural sensitivity analysis and preliminary expert review. Retrospective eligibility re-assessment and author-confirmed source verification finalised the 48-study evidence base; historical screening and coding provenance was partially reconstructed. Eight elements were retained: Operator Capability, Situation Awareness (SA), Decision-Making Quality, Navigation Safety, Human–Machine Interface and Information/Data Conditions, Workload, Trust and Transparency, and Level of Automation. The six-level hierarchy places automation upstream of interface/information conditions; Operator Capability, workload and trust/transparency; SA; decision making; and Navigation Safety. SA is a cognitive state supporting decision making, with selected human and system conditions also modelled

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as direct influences. Downstream ordering persisted across contextual alternatives but changed when decision-making-to-SA feedback merged SA and decision making. The model represents structural reachability, not empirically established causality, mediation or predictive validity. Preliminary expert review informed refinement, not empirical validation. The model supports Goal-Directed Task Analysis, competency mapping and simulator-based ROC assessment.

Keywords: socio-technical systems; remote maritime operations; maritime autonomous surface ships; situation awareness; human–system interaction; total interpretive structural modelling; remote operation centre; navigational safety

1. Introduction

1.1. Background and Motivation

Maritime Autonomous Surface Ships (MASSs) are increasingly promoted to enhance safety and reduce human error in waterborne transport [1]. However, despite rapid technological progress, the safety of navigation remains one of the primary challenges to large-scale deployment of autonomous shipping [2], particularly in complex and congested operational environments. Maritime casualty investigations continue to demonstrate the importance of the human element: European Maritime Safety Agency (EMSA) data for 2014–2020 indicated that 89.5% of the reported safety investigations included human-action accident events or contributing factors catalogued as human behaviour [3]. This figure indicates the substantial involvement of the human element in investigated occurrences but does not mean that human action was the sole cause of 89.5% of maritime accidents. Shore-based maritime research likewise identifies human factors as important to the safe performance of Vessel Traffic Service operators [4]. In addition, regulatory initiatives such as the IMO Regulatory Scoping Exercise (RSE) have repeatedly highlighted unresolved challenges related to collision avoidance, COLREG compliance, and the interpretation of "good seamanship" in autonomous and remotely operated contexts [5]. These challenges indicate that Navigation Safety cannot be addressed solely through technological reliability but should be understood as a socio-technical outcome emerging from interactions among humans, automation, and operational context [6].

From a socio-technical systems perspective, ROC operation represents a safety-critical work system in which performance emerges from interactions among Operator Capability, task demands, automation behaviour, interface support, information quality, workload, fatigue, trust, transparency, and organisational conditions. Recent MASS and human–automation research shows that increasing automation reconfigures rather than removes the human role, altering monitoring, control, coordination, and recovery responsibilities [7–9]. This transition is important because remote operators must maintain Situation Awareness (SA) through mediated information rather than direct onboard perception while also managing automation uncertainty, workload, trust calibration, and decision transparency [10–12].

Recent maritime safety research increasingly treats autonomous and remotely controlled navigation as a socio-technical safety problem in which operator performance depends on interactions among human capabilities, automation, interface design, workload, information quality, and supervisory control. A systematic review of human–AI interaction in autonomous ship systems found that human operators remain active contributors to safety and that increasing interaction with autonomous systems can introduce new risks, requiring careful consideration of human control, interaction design, and function allocation [13]. Shore-based maritime traffic research similarly demonstrates that human factors remain important to safe

performance in complex monitoring and supervisory environments [4]. More recent experimental research in remote-control environments has further shown that operator mental workload varies with navigational task demands and represents an important consideration for remote maritime performance assessment [10]. Together, these findings support treating ROC/MASS safety as an emergent property of the wider human–automation work system rather than as a consequence of technical reliability or operator competence in isolation.

Complementary evidence from shore-based Vessel Traffic Services (VTS) research further supports the socio-technical framing of remote maritime operations. Relling et al. (2019) [14] examined future VTS development from a socio-technical systems perspective, while Relling et al. (2022) [15] considered how VTS functions and traffic organisation may evolve to support coexistence between automated and conventional vessels. Research involving VTS operators has also highlighted fatigue and cognitive workload as relevant human-performance conditions in shore-based maritime monitoring and coordination [16,17]. Although VTS operators and ROC navigators have different operational responsibilities, these studies provide complementary evidence for considering human capabilities, task demands, organisational arrangements, and technological conditions within the wider maritime socio-technical system.

More specifically, human-factors and human–automation research shows that cognitive performance in highly automated systems is shaped by the interaction among automation reliability, workload, interface design, transparency, and operator state. Supervisory-control research indicates that automation can alter attention allocation, workload, trust, and intervention behaviour, particularly when operators must detect abnormal system behaviour or recover SA after periods of monitoring [12,18]. Recent SA research across complex domains likewise confirms that SA remains central to performance in dynamic systems, while maritime studies highlight the value of transparency and decision support in helping operators understand automation behaviour and make timely decisions [11,19]. These developments strengthen the need for a systems-based structural model that explains how human capability, contextual conditions, SA, decision making, and navigational safety are connected.

Against this background, a growing body of MASS research identifies SA and decision making as central human factors governing safe navigation. Autonomous ship safety studies consistently show that failures in perception, comprehension, or projection of navigational situations can escalate rapidly into unsafe outcomes, particularly when automation operates under uncertainty or abnormal conditions [20,21]. Recent reviews further confirm that even highly automated systems remain dependent on human supervisory roles, especially for collision avoidance, emergency intervention, and autonomy handover [7].

1.2. Research Gap

Although numerous studies address skills, competencies, Situation Awareness (SA), and decision making in MASS operations, the literature remains fragmented. Existing studies often examine these constructs separately or present them as lists of requirements, without sufficiently explaining how Operator Capability, cognitive processes, and ROC work-system conditions are structurally related to navigational safety. SA is frequently recognised as important in remote and autonomous maritime operations, but its position within the broader interaction among Operator Capability, decision making, automation, interface and information conditions, workload, and human–automation interaction remains insufficiently integrated. The casualty-investigation percentage cited in Section 1.1 is contextual evidence of human involvement in maritime safety events, not an estimate of how frequently competency, Situation Awareness, workload or trust-related problems occur in ROC/MASS operations. Because the available studies differ in operational settings,

research designs and outcome definitions, the present qualitative synthesis does not provide a comparable statistical distribution of these problem areas.

A further methodological gap concerns how ROC/MASS competencies have been studied. Existing research commonly relies on systematic reviews, expert interviews, surveys, questionnaires, Delphi techniques, or multi-criteria decision-making approaches to identify, classify, or prioritise possible ROC/MASS skills and competencies [1,8,22–24]. These approaches are valuable for identifying competencies that may be required in future remote-operation roles. However, they provide less explanation of how existing STCW navigational competencies can be evaluated when enacted within the different information, automation, interface, and supervisory conditions of the ROC workplace.

This gap is important because ROC/MASS operation requires navigators to perform safety-critical functions through remote supervision, mediated sensor information, HMI displays, automation status information, data connectivity, workload management, trust calibration, and distributed coordination. The relevant question is, therefore, not only which additional competencies may be required but also whether existing navigational capability enables operators to acquire and use the SA required for the task, reach appropriate navigational decisions, and support safe performance under remote-operation conditions. Existing competencies may ultimately be retained, reinterpreted, refined, supplemented, or replaced depending on the requirements identified for the ROC context; these possibilities require systematic evaluation rather than assumption.

From a socio-technical perspective, remote maritime operations should be understood as work systems in which safety is associated with interactions among human capability, system design, automation behaviour, organisational conditions, and operational context rather than with any single factor alone [4,6,25]. Within such systems, SA is not simply another competency label; it is a cognitive state involving perception, comprehension, and projection that supports subsequent decision making [26,27]. However, this does not require all effects of operator or work-system conditions on decision making to operate exclusively through SA. Interface and information conditions, automation characteristics, Trust and Transparency, Operator Capability, and other task conditions may also influence decision processes through conceptually distinct pathways [7,10–12,19,26].

Accordingly, a method is needed to structure the relationships among Operator Capability, ROC work-system conditions, SA, Decision-Making Quality, and Navigation Safety without assuming a predetermined exclusive pathway. This study addresses that need by using Total Interpretive Structural Modelling (TISM) to develop a literature-grounded, theory-building representation of these relationships. The purpose is not to produce another static list of ROC competencies or to establish causal effects but to provide a structured theoretical basis for subsequent Goal-Directed Task Analysis (GDTA), STCW competency mapping, and simulator/ROC-based evaluation of whether existing navigational competencies remain appropriate under remote and automation-supported operating conditions.

1.3. Aim of This Study

This study addresses the identified conceptual and methodological gap by conducting a thematic synthesis of the MASS and ROC literature and subsequently structuring the resulting socio-technical factors using Total Interpretive Structural Modelling (TISM). TISM is used as a theory-building method to organise literature-derived constructs into an interpretable hierarchy and to examine the directional structural relationships among Operator Capability, ROC work-system conditions, Situation Awareness (SA), Decision-Making Quality, and Navigation Safety [28,29].

The purpose of the model is not to provide an empirically validated or predictive assessment tool. Rather, it provides a structured theoretical foundation for examining

how Operator Capability and ROC work-system conditions may relate to SA, decision making, and navigational safety, and for subsequently evaluating whether existing STCW navigational competencies remain appropriate when enacted in remote and automation-supported operations. The model was informed by preliminary expert review and can be further examined through the GDTA, STCW competency mapping, and simulator/ROC-based assessment.

The operational scope of the present model is an individual remote navigator undertaking direct remote navigation of a MASS vessel from a Remote Operation Centre. Within this boundary, the operator is responsible for monitoring the navigational situation, making or supporting safety-critical navigational decisions, and intervening through the remote-control system when required. The model represents one remotely operated vessel within a bounded operational decision episode; simultaneous multi-vessel supervision, multi-operator coordination, and broader handover processes are outside the present model boundary and require separate consideration.

Accordingly, this study represents a theory-building phase within a broader multi-phase research programme. In that programme, ROC-specific conditions, such as mediated sensor information, HMI and information/data conditions, automation level, workload, fatigue, trust, transparency, and distributed coordination, are treated as characteristics of the remote-operation work system within which Operator Capability is enacted. Subsequent evaluation can, therefore, examine whether operators acquire and use the SA required for the task, reach appropriate decisions, execute selected actions correctly, and achieve acceptable navigational outcomes while also considering whether observed limitations arise from competency, training, interface, information, automation, workload, procedural, or other system-related factors.

1.4. Contribution of This Study

This study makes three contributions to the MASS and maritime safety literature:

a. **Theoretical contribution:** This study provides a socio-technical representation of remote maritime navigation that integrates Operator Capability, Situation Awareness (SA), Decision-Making Quality, Navigation Safety, and relevant ROC work-system conditions within a single structural model. Rather than treating SA as an exclusive mediator, the model positions SA as an important cognitive pathway while allowing conceptually distinct direct influences from selected human and system conditions to Decision-Making Quality. The resulting structure, therefore, represents navigational safety as a downstream outcome of interacting human, cognitive, technological, and contextual conditions rather than as a direct consequence of operator competence or automation alone.

b. **Methodological contribution**: By combining a systematic literature review, thematic synthesis, TISM, MICMAC analysis, preliminary expert review, and structural sensitivity analysis, this study provides a transparent theory-building procedure for translating literature-derived constructs into explicit pairwise relationships and hierarchical structural positions. The approach distinguishes direct relationships from indirect pathways and uses sensitivity analysis to examine which structural conclusions are retained when plausible alternative relationships are introduced. TISM and MICMAC are, therefore, used to organise and interpret relationships within the defined model boundary rather than to establish causal effect magnitude, statistical mediation, or predictive validity. The distinct contribution is, therefore, not the competence–SA–decision–performance sequence alone but the explicit separation of Operator Capability from ROC work-system conditions, the documentation of direct and indirect structural pathways, and

the use of sensitivity analysis to support later diagnostic interpretation of observed performance limitations.

c. **Practical contribution**: The resulting model provides a structured foundation for subsequent evaluation of existing navigational competencies in ROC/MASS operations. It supports future GDTA, STCW competency mapping, and simulator/ROC-based assessment by distinguishing Operator Capability from the interface, information, workload, trust/transparency, and automation conditions under which that capability is enacted. This distinction can support later assessment of whether existing navigational competencies should be retained, reinterpreted, refined, supplemented, or replaced for remote and automation-supported operations, while avoiding the assumption that every observed SA or performance limitation necessarily represents a competency deficiency.

2. Methodology

2.1. Review Design and Methodology

The systematic review design adopted in this study is consistent with prior maritime safety research combining qualitative evidence synthesis with structural modelling to examine complex human-factor domains [30]. This design was used to investigate the relationships among Operator Capability, including relevant skills and competencies, SA, Decision-Making Quality, Navigation Safety, and ROC work-system conditions in MASS operations. The research design integrates a systematic literature review (SLR) with thematic synthesis, followed by Total Interpretive Structural Modelling (TISM), to move from evidence synthesis towards an explicit theory-building representation of structural relationships among the retained constructs.

The systematic literature review was conducted to identify peer-reviewed studies addressing human factors, SA, decision making, skills and competencies, and safety in autonomous or remotely operated maritime systems. The review followed established SLR principles to support transparency, replicability, and reduced selection bias [31,32].

Thematic analysis was then used to synthesise the qualitative evidence across the reviewed studies. The analysis followed the six-phase process proposed by Braun and Clarke [33]: familiarisation with the data, initial code generation, searching for themes, reviewing themes, defining and naming themes, and producing the synthesis. The thematic synthesis followed a hybrid deductive–inductive approach. Navigation Safety, Situation Awareness, and Decision-Making Quality were established as three preliminary themes before detailed coding. These themes provided an initial analytical structure but were not treated as fixed or exhaustive categories. During full-text reading and coding, the preliminary themes were refined, and additional patterns were identified inductively, including Operator Capability as the fourth theme. This process is described in further detail in Section 2.6.

2.2. Review Protocol and Transparency

The review protocol was registered on the Open Science Framework (OSF) on 6 November 2025, following completion of the database searches and supplementary reference-list screening (OSF registration: 42w9z; DOI: 10.17605/OSF.IO/42W9Z). The archived Rayyan records contain inclusion-status events dated 15–16 October 2025. The available records do not establish whether these events represented preliminary record organisation or formal eligibility screening. Therefore, the registration is reported with this chronological qualification rather than being presented as preceding all screening activity.

The registered protocol specified independent screening by two reviewers, with disagreements resolved by a third reviewer. During implementation, this procedure was adapted to a collaborative three-author screening process, in which uncertain or potentially

excluded records were reviewed jointly before a final decision was made. No separate pilot double-screening exercise or formal inter-rater reliability statistic was undertaken. Other deviations from the registered procedure are reported in the relevant methodological sections where applicable.

The registered protocol also proposed a formal methodological quality appraisal and associated sensitivity analysis. These procedures were not implemented as originally specified; instead, the methodological basis and evidential role of each included study are differentiated in the revised synthesis and Supplementary File S2, as described in Section 2.6.

2.3. Eligibility Criteria

The review targeted studies addressing the human element in MASS contexts, particularly studies that analysed or proposed skills and competencies for ROC operations, remote operators, or seafarers transitioning to remote-operation roles. To ensure relevance and comparability, the formal review included English-language peer-reviewed journal articles published between 1 January 2010 and 31 October 2025, consistent with the eligibility period specified in the registered OSF protocol. Studies from irrelevant subject areas, such as chemistry, medicine, marine freshwater biology, and mining/mineral processing, were excluded. These eligibility criteria defined the formal evidence base for the qualitative synthesis. Books, book chapters, regulatory documents and other theoretical, methodological or contextual sources could be cited to explain the framework or interpret findings but were not counted among the formally included journal articles.

2.4. Search Strategy and Information Sources

The primary search was conducted across three databases: Web of Science, Scopus, and TRID. Web of Science and Scopus were selected to capture peer-reviewed studies in maritime, human factors, safety, and automation research, while TRID was used to broaden coverage of the transportation and remote-operation literature that may not be indexed in the other databases. A secondary search was conducted to capture studies linking operator skills, SA, decision making, and MASS safety outcomes.

Keyword development was guided by the PICo framework [34], with Population defined as MASS operators, Interest as skills and competencies, and Context as ROC operations. The search strategy was organised around three keyword themes: autonomous ships, the human dimension, and skills/SA. These themes were combined using Boolean operators and truncation, such as competenc*, to capture relevant variations, as shown in Tables 1 and 2.

The database searches were executed on 13 October 2025. Supplementary backward reference-list screening was subsequently completed on 31 October 2025 to identify additional eligible studies published within the predefined eligibility period. The reference-list screening was a supplementary identification procedure rather than an updated database search. Accordingly, 13 October 2025 represents the formal database search cut-off, whereas 31 October 2025 represents the completion date of supplementary searching. Additional recent and relevant human factors, systems, and maritime automation studies were consulted to strengthen the contextual framing and interpretation. These supplementary sources were used to support interpretation and positioning of the study but were not treated as additional records in the formal SLR dataset unless they met the original search and screening criteria.

Table 1. Search keywords and Boolean operators for the primary search.

Theme (1)		Theme (2)		Theme (3)
Autonomous Ships		**Human Dimension**		**Skills and Competencies**
"Maritime Autonomous Surface Ship*" OR "Autonomous Ship*" OR "Autonomous Vessel*" OR "Unmanned Ship*" OR "Remote Ship*" OR "Smart Ship*" OR "Autonomous Shipping" OR "Remotely Operated Ship" OR "Autonomous Merchant Ship*" OR "Remote Operation Centre*" OR "Remote Control Centre*" OR "Shore Control Centre" OR "Shipping 4.0" OR "Shipping 5.0"	AND	"Human Element*" OR "Human Factor*" OR "Seafarer*" OR "E-farer" OR "Non-Seafarer*" OR "Crew" OR "Operator*" OR "Remote Operator*" OR "Master*" OR "Navigator*" OR "Trust in Autonomy" OR "Onboard Personnel" OR "Ship Personnel" OR "Human Oversight" OR "Human Intervention" OR "Human-Machine Interaction" OR "Dynamic Human-Machine System" OR "Human-Machine Teaming" OR "Human-Machine Cooperation"	AND	"Competenc*" OR "Skill*" OR "Conceptual Framework*" OR "Framework Develop*" OR "Qualification*" OR "Proficienc*" OR "Barrier*" OR "Challenge*" OR "Obstacle*" OR "Training" OR "Education" OR "Responsibilities" OR "Barriers" OR "Challenges" OR "Workload" OR "Cognitive Load" OR "Situation Awareness" OR "Decision Making" OR "Curriculum Development" OR "Training Programs" OR "Guidelines" OR "standards" OR "Regulatory" OR "IMO" OR "Policy" OR "STCW"

Table 2. Search keywords and Boolean operators for the secondary search.

Theme (1)		Theme (2)		Theme (3)
Autonomous Ships		**Human Dimension**		**Situation Awareness**
"Maritime Autonomous Surface Ship*" OR "Autonomous Ship*" OR "Autonomous vessel*" OR "Unmanned Ship*" OR "Remote Ship*" OR "smart ship*" OR "Autonomous shipping" OR "Remotely Operated Ship" OR "Autonomous merchant ship*" OR "Remote Operation Centre*" OR "Remote control Centre*" OR "shore control centre" OR "Remote Operating Centre"	AND	"Human Element*" OR "Human Factor*" OR "Seafarer*" OR "E-farer" OR "Non-Seafarer*" OR "Crew" OR "Operator*" OR "Remote Operator*" OR "Master*" OR "Navigator*" OR "Trust in Autonomy" OR "Onboard Personnel" OR "Ship Personnel"	AND	"Situation awareness" OR "Decision Making" OR "Workload" OR "Cognitive Load" OR "Trust*"

Tables 1 and 2 present the conceptual keyword groups used to construct the primary and secondary searches. To improve search transparency, Supplementary File S3 documents the researcher-confirmed Boolean keyword expressions, database roles, eligibility criteria, execution dates, retrieval counts, and reconciliation with the PRISMA flow diagram. Where historical database-specific search fields, filter settings, or processing stages could not be recovered from the archived records, these limitations are identified explicitly. The primary search used all three databases. TRID was not repeated in the secondary search because that search was designed as a narrower supplementary search targeting Situation Awareness, decision making, workload, cognitive load, and trust within the MASS/ROC literature; Web of Science and Scopus were used for this focused multidisciplinary maritime and human-factors search.

The primary search was designed to capture studies addressing MASS, the human element, and skills or competencies, while the secondary search focused more specifically on studies linking operator skills, SA, decision making, workload, cognitive load, trust, and MASS safety outcomes.

2.5. Study Selection, De-Duplication, and Screening (PRISMA)

Study identification and selection followed the PRISMA 2020 reporting framework [35,36]. The original search report recorded 544 records from the primary database searches: Web of Science ($n = 204$), Scopus ($n = 173$), and TRID ($n = 167$). A further 172 records were reported from the secondary searches: Web of Science ($n = 89$) and Scopus ($n = 83$). Supplementary

backward-reference screening, completed on 31 October 2025, was reported to have identified 43 references, bringing the historical aggregate identification total to 759 records. As part of the methodological reconciliation undertaken during manuscript revision in 2026, the archived EndNote library was examined and found to contain two groups labelled "Snowball (37)" and "Snowball (6)". Of the 40 preserved membership identifiers, 35 bibliographic titles were recovered, 31 of which matched records in the archived Rayyan library. Consequently, the surviving records do not independently establish that all 43 references were distinct additional records or that each underwent full-text assessment. Ten supplementary selected studies were documented separately, although their individual screening histories could not be completely reconstructed. The recovered records, identification-route overlaps, and remaining limitations are documented in Supplementary File S3.

The original study selection report recorded 381 duplicate removals, leaving 378 records for screening. Of these, 177 were reported as excluded during initial screening, 201 reports were sought for retrieval, and 1 report was unavailable, leaving 200 reports for full-text eligibility assessment. These figures represent the historical screening aggregates, as the individual records could not be fully reconciled with all reported screening stages. The archived Rayyan dataset contains 201 records, including 48 labelled as included and 153 as excluded. A separate supplementary-selection register identifies 10 additional selected studies, giving 58 historically selected publications. During the 2026 eligibility reassessment, eight publications were initially reclassified as contextual literature. Two further publications were subsequently excluded from the formal synthesis: an autonomous underwater vehicle risk-modelling study and an article published in *Sea Technology* for which peer-reviewed journal status could not be established. Accordingly, 48 studies were retained in the revised formal evidence base. The reclassified publications remain available for contextual or theoretical discussion but are not counted among the formal SLR studies. Figure 1 and Supplementary Files S2 and S3 distinguish the historical screening figures from the documented retrospective eligibility decisions.

The historical PRISMA flow diagram reported 200 full-text assessments and 150 exclusions, yielding a remainder of 50. These figures were retained as originally reported screening aggregates; however, the available archival records did not permit complete reconstruction of the corresponding individual screening decisions. Separately, the recovered Rayyan inclusion records ($n = 48$) and supplementary-selection register ($n = 10$) identified 58 historically selected publications. These records could not be matched individually to the historical remainder of 50 and, therefore, represent a separate documentary account. During the 2026 eligibility reassessment, 10 of the 58 publications were reclassified as contextual literature, resulting in the revised formal evidence base of 48 studies documented and author-confirmed in Supplementary File S2. Accordingly, the difference of 152 between the historical 200 full-text assessments and the revised 48 studies is an arithmetic residual, not a verified revised exclusion count. Figure 1 and Supplementary File S3 distinguish these historical screening aggregates from the retrospective eligibility reassessment.

2.6. Data Extraction and Synthesis Approach

Data extraction and thematic synthesis were supported by NVivo using a hybrid deductive–inductive approach. Three preliminary themes—Navigation Safety, Situation Awareness, and Decision-Making Quality—were established before detailed coding to provide an initial analytical structure. These themes guided the examination of the literature but were not treated as fixed or exhaustive categories. During full-text reading and coding, the preliminary themes were examined and refined, while additional codes and patterns were identified inductively. This process led to the identification of Operator Capability as a fourth theme, resulting in the four-theme structure presented in Section 3.

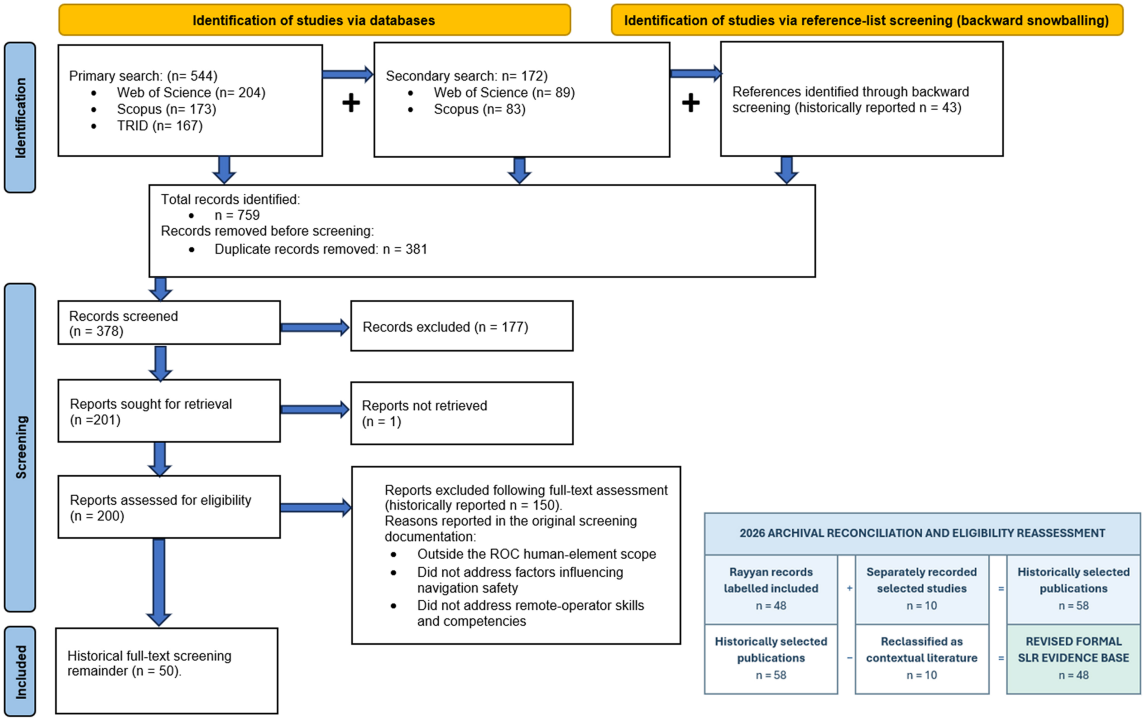


Figure 1. Historical PRISMA screening aggregates and 2026 archival reconciliation of the formal SLR evidence base. Note: The original PRISMA diagram reported 200 full-text assessments and 150 exclusions, producing a historical remainder of 50. These figures are retained as historical screening aggregates. The separate 2026 archival reconciliation identified 58 historically selected publications (48 Rayyan-labelled inclusions and ten supplementary selections). Following eligibility reassessment, ten publications were reclassified as contextual literature, leaving 48 studies in the revised formal SLR, as documented in Supplementary File S2. The historical remainder of 50 and the 58 selected publications could not be reconciled at the individual-record level. Accordingly, the two components illustrate distinct documentary stages rather than a single fully reconstructed screening pathway. The colours provide visual differentiation between the historical PRISMA stages and the separate 2026 archival reconciliation. The pale-blue panel identifies the retrospective reconciliation, while the green-shaded box highlights the final revised 48-study formal SLR evidence base. Further details are provided in Supplementary File S3.

The primary qualitative extraction and coding were conducted by the corresponding author. Extracted material included study characteristics and findings relevant to Operator Capability, cognition, human–automation interaction, ROC work-system conditions, and navigational safety. Codes were compared and consolidated iteratively into higher-order categories. This process resulted in four higher-order themes, Operator Capability, Situation Awareness, Decision-Making Quality, and Navigation Safety, together with recurring sub-themes, including HMI and information/data conditions, workload and fatigue, Trust and Transparency, and Level of Automation. These higher-order themes and sub-themes subsequently informed the eight TISM elements.

The analytical process did not treat frequency of occurrence alone as evidence of importance. Findings were interpreted according to their relevance to the review questions, operational context, methodological basis, and the extent to which they provided direct evidence for a construct or relationship. Where findings were inconsistent, context-dependent, or did not support a clearly distinguishable relationship, the disagreement was retained rather than resolved by simple majority. Such uncertainty was considered during the subsequent pairwise TISM assessment and, where appropriate, through structural sensitivity analysis. No statistical meta-analysis or pooled estimation of human-factor

prevalence or effect magnitude was undertaken. Numerical findings cited from previous studies are interpreted only within their reported populations, denominators, outcome definitions and operational contexts; they are not treated as interchangeable or directly transferable to ROC/MASS operations. The numerical results generated in the present study comprise descriptive review-flow counts and model-dependent binary reachability and driving/dependence calculations, rather than inferential tests or independently measured causal effects. Their interpretation remains conditional on the specified construct definitions, model boundary and pairwise assessments.

To improve analytical traceability, Supplementary File S2 provides a retrospectively assembled, source-linked evidence register for the 48 studies retained in the revised formal synthesis following the eligibility reassessment described in Section 2.5. The corresponding author reviewed and confirmed the recorded study information, source locations, evidence summaries, thematic associations, and interpretation limitations against the available source publications. Publications excluded from the formal synthesis but relevant to the theoretical or operational context were retained as contextual references and distinguished from the included studies. The register documents source-located evidence summaries, study characteristics, thematic associations, and revision-stage mappings to the retained TISM elements and pairwise relationships. This evidence mapping was assembled during manuscript revision and is distinguished from the original NVivo coding records, which were unavailable for reconstruction. The thematic findings are presented in Section 3, while their traceability to the retained TISM elements is detailed in Section 4.3.

A formal study-level methodological quality score or risk-of-bias appraisal was not applied to the heterogeneous evidence base. This represents a deviation from the originally registered protocol, which proposed a formal quality-appraisal step. Because the review was intended to identify and structurally organise constructs and reported relationships rather than estimate a pooled intervention effect, the revised analysis instead distinguishes the methodological basis and evidential role of each included study. Empirical studies, conceptual contributions, and secondary reviews are, therefore, identified separately in Supplementary File S2. These categories of evidence are not assumed to provide equivalent forms of evidence. This limitation is acknowledged when interpreting the thematic synthesis and the subsequent TISM relationships.

2.7. Linking Thematic Synthesis to TISM

Thematic synthesis is effective for identifying recurring constructs, patterns, and reported relationships across a body of literature, but it does not by itself establish a hierarchical structural ordering or distinguish whether particular influences should be represented as direct or indirect within a specified model. To address this limitation, the findings of the thematic synthesis were subsequently translated into a Total Interpretive Structural Modelling (TISM) framework.

TISM extends conventional Interpretive Structural Modelling (ISM) by requiring explicit interpretive justification for the relationships represented among retained elements [28,29]. In this study, the higher-order themes and recurring sub-themes identified through the literature synthesis provided the initial conceptual basis for the eight TISM elements. Pairwise relationships were then assessed to determine whether the reviewed evidence or established theory supported a conceptually distinguishable direct influence within the defined ROC/MASS model boundary. This procedure allowed direct and indirect pathways to coexist and enabled the literature-derived constructs to be organised into an interpretable hierarchy. The resulting model should, therefore, be understood as a theory-building structural representation rather than as evidence of causal effect magnitude, statistical mediation, or predictive validity. This use of qualitative synthesis followed

by structural modelling is consistent with approaches proposed for organising complex socio-technical relationships into explicit conceptual structures [37–39].

Within the broader research programme, the TISM developed in this study provides a theoretical foundation for subsequent task-level and competency evaluation. GDTA can be used to identify navigational goals, cognitive judgement requirements, and the Level 1–3 SA information requirements needed to resolve those judgements in ROC operations. These requirements can then be mapped against relevant STCW navigational competencies, followed by simulator/ROC-based assessment of whether operators acquire and use the required SA, reach appropriate decisions, execute selected actions correctly, and achieve acceptable navigational outcomes under representative remote-operation conditions.

The purpose of this progression is not to assume that observed performance limitations necessarily reflect inadequate competency. Subsequent evaluation should also consider interface and information conditions, automation characteristics, workload, Trust and Transparency, procedures, training, communication, sensor limitations, latency, and other relevant work-system factors when interpreting performance. The present TISM, therefore, serves as a structural starting point for later diagnostic evaluation rather than as a final competency-assessment model.

To strengthen the credibility of this theory-building phase, a structured preliminary expert review was also conducted to assess the clarity, relevance, completeness, and theoretical plausibility of the proposed elements and selected relationships. The review was developmental rather than confirmatory and was used to inform construct definitions and model interpretation. It should not be interpreted as empirical validation or as expert endorsement of every relationship in the subsequently revised TISM structure.

3. Results: Thematic Analysis

The thematic synthesis identified four interrelated themes relevant to navigation performance in MASS operations: Navigation Safety, Situation Awareness, Decision-Making Quality, and Operator Capability. The first three themes provided the initial deductive structure, while Operator Capability was identified inductively during full-text reading and coding, as described in Section 2.6. Following the eligibility reconciliation described in Section 2.5, 48 studies were retained in the revised formal synthesis. Additional contextual publications informed the theoretical discussion but were not counted as included studies. Supplementary File S2 provides the supporting study-level evidence register linking the included literature to the thematic findings and subsequent TISM elements.

Theme 1: Navigation Safety as an Emergent Socio-Technical Outcome

Navigation Safety emerged as a central operational outcome in the literature on MASS operations. The IMO regulatory scoping exercise highlights challenges associated with applying existing maritime regulatory instruments, including the COLREGs, to autonomous shipping [5]. From a system-theoretic perspective, Navigation Safety depends on interactions among technical, operational, organisational, and human factors [20]. Research on collision-avoidance navigation systems further identifies collision prevention as an important technical and operational challenge for MASSs [21]. These findings support treating Navigation Safety as a key outcome in the subsequent TISM analysis.

Navigation Safety was interpreted as an operational outcome influenced by cognitive, technical, and organisational factors rather than as an isolated construct. Research on human–MASS interactions highlights the relevance of situation awareness, decision making, and human–automation interaction to safe navigation, particularly in mixed-traffic environments [7]. Broader human–technology research in shipping also supports examining safety through interconnected psychological, social, and operational perspectives [40]. Together, these sources provide a conceptual basis for examining Navigation Safety in

relation to the other identified constructs. Accordingly, Navigation Safety was retained as the principal operational outcome in the subsequent TISM analysis, while the direction and form of its relationships with the other elements were examined through the structural modelling process.

Theme 2: Situation Awareness as a Cognitive Basis for Decision Making

Situation Awareness (SA) provides an important cognitive basis for navigational judgement and decision making in MASS operations. According to Endsley's three-level model, SA involves the perception of relevant environmental elements (Level 1), comprehension of their meaning (Level 2), and projection of their future status (Level 3) [26,41]. These processes provide a conceptual basis for understanding how navigators interpret operational information and anticipate developing situations. Research examining human factors in Vessel Traffic Services also provides relevant shore-based maritime context [4], although its findings should not be assumed to apply directly to ROC navigators.

Historical maritime accident research provides contextual evidence of the importance of SA in navigational safety. Grech et al. [42] analysed 177 maritime accident reports using Leximancer and manually coded a subset of 26 reports. Within the manually coded subset, 71% of the identified human errors were classified as SA-related problems. This finding highlights the relevance of SA to maritime safety but should not be interpreted as the proportion of all maritime accidents attributable to SA failures or assumed to apply directly to ROC/MASS operations.

In ROC operations, the fundamental processes of SA remain relevant, although the means by which navigators acquire and interpret operational information differ from those available onboard. Remote operators depend on sensor-derived and communicated information, making data availability, reliability, integration, and presentation important considerations for maintaining SA [7,43]. In mixed-traffic MASS operations, situational information may also need to be coordinated among remote operators, automated ship systems, conventional vessels, and Vessel Traffic Services. Research on distributed SA highlights the importance of information exchange and consistent situation interpretation across these actors [7,44].

The reviewed literature suggests that operator knowledge, skills, training, and experience are important considerations for human performance in autonomous shipping. These capabilities may support the acquisition and interpretation of operational information, helping navigators perceive relevant elements, comprehend their significance, and project future developments. Consistent with Endsley's three-level model [26,27], SA provides a cognitive basis for navigational judgement and decision making while remaining conceptually distinct from the decisions and actions themselves. Accordingly, the thematic synthesis supports retaining SA as a distinct cognitive construct related to Operator Capability and Decision-Making Quality. The direction and form of these relationships are examined subsequently through TISM rather than assumed to have been empirically established.

Theme 3: Decision Making in Relation to SA and Automation Interaction

Decision making in MASS operations involves evaluating the navigational situation and selecting an appropriate response using SA, relevant knowledge, experience, operational rules, and available system support. Simulation-based research has examined how remote operators perceive and comprehend operational information during emergency situations [45]. Related research has developed a model for assessing bridge operators' collision-risk SA [46] and compared remote operators' collision-avoidance decisions with those generated by an automated collision-avoidance system [47]. Together, these studies highlight the relevance of SA and navigational judgement to operator performance while supporting their treatment as related but conceptually distinct constructs in the subsequent TISM analysis.

Research on the human element in autonomous shipping identifies trust, awareness and understanding, control, and training and work organisation as important considerations for future maritime operations [48]. Complementary research on human–autonomous system interaction highlights how changes in automation level can alter task allocation and interdependencies between remote operators and automated ship systems [49]. These findings suggest that decision making should be examined in relation to automation configuration, human–system coordination, and the operator's understanding of system behaviour.

Automation introduces additional demands for navigational decision making because operators must judge when to rely on automated functions and when intervention is necessary. Research involving simulated supervisory control of MASSs found that an automation malfunction reduced operators' trust in the system and altered their monitoring behaviour [12]. Research examining decision transparency in autonomous collision avoidance also reported varying effects across SA levels and intervention measures, indicating that providing additional system information does not necessarily improve operator performance [11]. Together, these findings suggest that trust calibration, transparency, and information presentation are relevant considerations for navigational judgement and response selection. This interpretation is consistent with situation awareness theory, which distinguishes SA from subsequent decision making and action [41].

Theme 4: Skills and Competencies as Enablers of SA and Decision Making

Research on MASS operator competencies identifies a combination of traditional navigational knowledge and skills with emerging technical, digital, cognitive, and interpersonal capabilities [8,24]. Studies examining the transition from shipboard navigation to remote operations further highlight the relevance of seafaring experience, adaptability to emerging technologies, and additional training for future ROC operators [50]. Related research identifies decision-making demands associated with autonomous-system interaction [22] and cybersecurity risks affecting navigation-support systems [51]. Together, these findings support treating Operator Capability as a multidimensional construct encompassing established maritime expertise and capabilities relevant to remote and automation-supported navigation.

Operator skills and competencies are relevant not only to the execution of navigational tasks but also to the cognitive and technological demands of remote operations. Research on technostress among seafarers highlights challenges associated with adapting to digital technologies and the importance of managing technology-related demands [52]. Research examining explainability and trust in autonomous systems further suggests that understanding automation behaviour may support appropriately calibrated reliance, although the effects of explanations on trust vary across studies [53]. Together, these findings suggest that technological adaptability and informed interaction with automation are relevant considerations when characterising Operator Capability for ROC operations. Their specific contributions to SA and decision-making performance require further investigation.

Although the present model focuses on an individual ROC navigator, remote navigation occurs within a wider socio-technical system. Research on human–MASS interactions and distributed SA highlights the potential importance of information exchange and coordination among remote operators, automated ship systems, conventional vessels, and maritime traffic services [7,44]. Changes in the type and Level of Automation may also redistribute information-processing, decision-making, and action-related functions between operators and automated systems [54]. Maritime simulation research has examined communication and workload during routine and emergency operations [55], while remote-ship studies have investigated operator workload and stress under different operational demands [56]. These findings support considering coordination, automation configuration, and workload when interpreting operator performance. In the present TISM, workload is retained as a distinct element, whereas

wider coordination and distributed SA are treated as contextual considerations rather than separately modelled constructs within the individual-navigator boundary.

Integrated Thematic Interpretation

The integrated thematic synthesis identified four recurring domains relevant to remote-navigation performance: Operator Capability, Situation Awareness, Decision-Making Quality, and Navigation Safety. The literature also repeatedly identified ROC work-system conditions—including HMI and information/data conditions, workload and fatigue, Trust and Transparency, Level of Automation, and distributed coordination—as relevant to how these human and cognitive constructs are enacted in remote and automation-supported operations.

Across the reviewed studies, Operator Capability was associated with the knowledge, skills, competencies, and experience required to perform remote navigational functions; SA was associated with perception, comprehension, and projection of operational conditions [26,27]; Decision-Making Quality concerned the timeliness and appropriateness of navigational judgements and response selection; and Navigation Safety represented the downstream operational concern, including collision avoidance, grounding avoidance, safe intervention, and prevention of unsafe navigational states. These domains were repeatedly discussed as related, but the thematic synthesis alone did not establish a definitive hierarchy, exclusive pathway, or causal ordering among them.

The synthesis also indicated that ROC-specific work-system conditions may be relevant to more than one stage of operator performance. Interface design and information availability can affect access to operational information; workload and fatigue may constrain attention and information processing; Trust and Transparency can shape understanding and reliance on automation; and Level of Automation can alter monitoring, supervisory-control, and intervention requirements. These conditions were, therefore, retained as distinct contextual and system-related constructs rather than being treated solely as background variables.

Figure 2 summarises this literature-derived thematic framework. It is intentionally non-hierarchical: it identifies the principal constructs and work-system conditions emerging from the thematic synthesis without prescribing their final directional relationships. The subsequent TISM analysis examines which relationships should be represented as direct or indirect and how the retained elements are structurally ordered within the defined ROC/MASS model boundary.

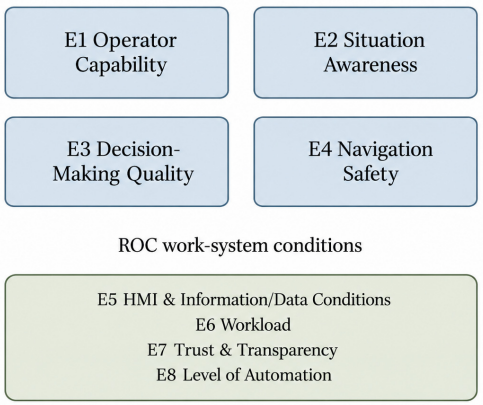


Figure 2. Literature-derived thematic framework for ROC/MASS navigation performance. Note: The figure identifies the principal constructs and work-system conditions derived from the thematic synthesis. It does not represent a final directional or causal structure; pairwise directionality and hierarchical ordering are examined subsequently through TISM. The blue boxes represent the four principal thematic constructs (E1–E4), while the green box groups the four ROC work-system conditions (E5–E8).

4. Rationale and Significance of TISM

While the thematic analysis identifies the key constructs linking operator skills and competencies, SA, decision making, and Navigation Safety in MASS operations, it does not explain their hierarchy, directionality, or relative driving power. In particular, the thematic findings show that safety is influenced by human cognitive processes and ROC-specific contextual conditions, but they do not clarify which factors act as upstream drivers and which function as dependent outcomes. To address this limitation, this study employs TISM to move beyond descriptive synthesis toward an interpretable systems-level model [28,29].

TISM is well suited to this study because, unlike conventional ISM, it requires an explicit explanation for why each relationship exists. This is important in human factors and safety research, where understanding the logic behind a relationship is as important as identifying the relationship itself. Therefore, TISM was selected to:

1. Establish a hierarchical structure among skills and competencies, SA, decision making, and safety outcomes.
2. Identify driving and dependent factors influencing Navigation Safety in MASS operations.
3. Provide an interpretable model that can inform later GDTA, STCW competency mapping, and simulator/ROC-based performance assessment.

4.1. TISM Procedures

The TISM procedure followed established steps: developing the Structural Self-Interaction Matrix (SSIM), converting the SSIM into the Initial Reachability Matrix (IRM), incorporating transitivity to derive the Final Reachability Matrix (FRM), conducting level partitioning, and performing MICMAC analysis to calculate driving and dependence power [28,29].

To make the quantitative processing of the TISM structure explicit, the eight retained elements were represented by an 8 × 8 binary reachability matrix, $A = [a_{ij}]$, derived from the SSIM. Each entry a_{ij} was assigned 1 when a direct influence from element i to element j was retained, and 0 otherwise. Diagonal entries were assigned 1 to represent self-reachability. The Final Reachability Matrix (FRM) was obtained by applying Boolean transitive closure, as expressed in Equation (1). The MICMAC driving power (D_i) and dependence power (P_i) of each element were then calculated as the corresponding FRM row and column sums, respectively, as shown in Equation (2). These quantities describe structural reachability within the specified TISM model and do not represent statistical effect sizes, causal coefficients or inferential estimates. The input matrices, transitive-closure calculations and resulting structural measures are documented in Supplementary File S1.

$$\begin{gathered} r_{ij}^{(0)} = a_{ij} \\ r_{ij}^{(k)} = r_{ij}^{(k-1)} \vee \left(r_{ik}^{(k-1)} \wedge r_{kj}^{(k-1)} \right), \quad k = 1, \ldots, 8 \end{gathered} \tag{1}$$

Here, $\vee$ denotes logical OR, $\wedge$ denotes logical AND, and the final reachability matrix is $R = [r_{ij}^{(8)}]$.

$$D_i = \sum_{j=1}^{8} r_{ij}, \quad P_i = \sum_{j=1}^{8} r_{ji} \tag{2}$$

Here, D_i and P_i represent the driving and dependence powers of element i, respectively, while r_{ij} denotes the corresponding binary entry in the Final Reachability Matrix. The indices i and j range from 1 to 8, and self-reachability ($r_{ii} = 1$) is included in both calculations.

The eight retained elements generated 28 unique unordered pairs requiring interpretive assessment. The pairwise judgement, not an individual study or a statistical effect estimate, was the unit of structural specification; the resulting decisions were then transformed into reachability matrices and hierarchical levels.

4.2. Structural Self-Interaction Matrix (SSIM)

Eight elements (E1–E8) were identified from the thematic synthesis. A single contextual question guided the pairwise judgements: "Does element i directly influence element j within the defined ROC/MASS model boundary, based on the reviewed evidence or established theory?" Relationships were encoded using the standard SSIM symbols V, A, X, and O. For reporting clarity, the SSIM is presented in upper-triangular form, with each pairwise relationship assessed once. The SSIM records directional qualitative judgements rather than numerical effect sizes: V and A designate a direct relationship in one direction or the other, X denotes direct relationships in both directions, and O denotes no direct relationship retained within the defined modelling boundary.

4.3. Identification of Elements

To strengthen traceability between the thematic synthesis and the TISM model, the eight elements were not selected arbitrarily. They were derived from recurring themes and sub-themes identified across the reviewed literature and retained because they represented the main outcome, cognitive, capability, contextual, and system-driver dimensions relevant to ROC/MASS Navigation Safety. Table 3 summarises how each TISM element was derived from the thematic synthesis, including its conceptual role, key sub-dimensions, and supporting references.

Table 3. Traceability between thematic synthesis findings and retained TISM elements.

Thematic Synthesis Finding	TISM Element Retained	Conceptual Role in the Model	Key Sub-Dimensions	Supporting Studies from the Formal SLR
Navigation Safety is the final operational concern in MASS/ROC operations. Although collision avoidance remains central, safe navigation also includes grounding avoidance, maintenance of safe track and clearance, preservation of navigational control, and prevention or recovery from unsafe navigational states.	**E4 Navigation Safety**	Terminal operational outcome	Collision avoidance; grounding avoidance; maintenance of safe track and clearance; preservation of navigational control; prevention or recovery from unsafe navigational states	[43,50,57]
Safe performance is associated with the correctness, timeliness, and appropriateness of navigational judgements, option evaluation, response selection, and decisions about whether intervention is required under normal, time-critical, and degraded operating conditions.	**E3 Decision-Making Quality**	Decision-process element	Decision timeliness; decision appropriateness; option evaluation; response selection; intervention judgement; selection of collision-avoidance or other navigational responses	[43,48,50,58]
Situation Awareness is repeatedly identified as an important cognitive requirement in remote and automated navigation, involving perception of task-relevant operational information, comprehension of its current meaning and relationships, and projection of likely future states. In ROC contexts, this SA must be developed from mediated rather than direct onboard information.	**E2 Situation Awareness**	Cognitive State Supporting decision making	Level 1: perception of task-relevant operational information; Level 2: comprehension of its operational meaning and relationships; Level 3: projection of likely future states	[43,45,46]

Table 3. *Cont.*

Thematic Synthesis Finding	TISM Element Retained	Conceptual Role in the Model	Key Sub-Dimensions	Supporting Studies from the Formal SLR
Operator Capability is repeatedly discussed through traditional navigation, digital/automation-related, cognitive, and non-technical competencies required for remote and automation-supported maritime operations.	**E1 Operator Capability**	Human capability condition	Traditional navigation knowledge and skills; COLREG/collision-avoidance reasoning; digital and automation-related skills; sensor and data interpretation; supervisory-control competence; cognitive and problem-solving skills; communication and coordination; adaptive capacity	[1,24,50,58,59]
Remote operation depends on mediated information and interface conditions, including display design, sensor integration, information availability, data quality, reliability, alarm presentation, and connectivity. The literature indicates that these conditions can affect operators' information acquisition and interpretation, workload, and decision support.	**E5 HMI and Information/Data Conditions**	Interface and information condition	Interface design; presentation and integration of sensor information; information availability; data quality and reliability; connectivity and latency; alarm presentation; presentation of automation status	[9,49,60]
Remote supervision introduces workload, fatigue, vigilance, monitoring, and attentional demands that may constrain the cognitive resources required to develop and maintain SA and may affect broader operator performance.	**E6 Workload**	Operator-state and task-demand condition	Mental workload; fatigue; vigilance; monitoring demand; attentional demand; shift-based monitoring demands	[10,55,56]
Automation use introduces trust- and transparency-related human–automation interaction conditions that can influence operators' reliance on automated functions and their willingness to accept, question, or override automation during supervisory control.	**E7 Trust and Transparency**	Human–automation interaction condition	Trust in automation; trust calibration; automation transparency; explainability of automation behaviour; calibrated reliance on automated functions	[11–13,53]
The Level of Automation configures how navigational functions, control authority, and supervisory responsibilities are distributed between the operator and automated systems. Changes in this configuration can alter interface requirements, workload, trust and reliance, intervention demands, and the competencies required for remote operation.	**E8 Level of Automation**	System-configuration condition	Degree of automation; human–function allocation; allocation of control and decision authority; supervisory-control configuration; functions retained under human control; functions delegated to automation	[7,13,49]

Note: The studies listed in the final column are representative studies drawn from the formal SLR evidence base rather than an exhaustive listing of all 48 included studies. Supplementary theoretical, methodological, regulatory, and contextual sources used elsewhere in the manuscript are not included in this column. Bold text in the second column identifies the eight retained TISM elements (E1–E8).

Based on this traceability process, eight core elements were retained for TISM analysis:

1. E1 Operator Capability;
2. E2 Situation Awareness;
3. E3 Decision-Making Quality;
4. E4 Navigation Safety;
5. E5 HMI and Information/Data Conditions;
6. E6 Workload;
7. E7 Trust and Transparency;

8. E8 Level of Automation.

These elements represent human capability, cognitive, decision-process, operational-outcome, interface/information, contextual, human–automation, and system-configuration dimensions identified as relevant to ROC/MASS navigation performance. At this stage, the thematic synthesis establishes their relevance but does not prescribe a final hierarchy or exclusive influence pathway. The direction and form of the relationships among the eight retained elements are examined subsequently through the pairwise TISM assessment.

The preliminary expert review supported the relevance and retention of the eight-element structure while informing refinements to element definitions and sub-dimensions, particularly Operator Capability, Navigation Safety, Trust and Transparency, Workload, and human–function allocation. The subsequent pairwise reassessment determined how relationships among these retained elements were represented in the revised TISM.

4.4. Pairwise Comparison and SSIM Construction

Each of the 28 unique unordered pairs among the eight TISM elements was reassessed to determine whether a direct directional relationship should be represented within the defined ROC/MASS model boundary. Pairwise judgements were grounded in the findings of the reviewed literature, supplemented where necessary by established Situation Awareness and human–automation theory. The purpose of this assessment was not to preserve a predetermined competence–SA–decision-making–safety sequence but to determine whether the available evidence supported a conceptually distinguishable direct influence between the two elements being considered. The interpretive basis for the pairwise judgements is documented in Table 4.

Table 4. Pairwise decision record used in TISM construction.

Left Element (A)	Right Element (B)	TISM Decision	Revised Theoretical Justification	Key Evidence/ Interpretive Basis
E1 Operator Capability	E2 Situation Awareness	YES: E1 → E2	Operator knowledge, experience and task capability support the perception, comprehension and projection processes required to develop and maintain SA.	[26,41]
E1 Operator Capability	E3 Decision-Making Quality	YES: E1 → E3	Operator capability may influence decision making directly through experience, procedural and rule-based knowledge, learned response strategies and problem-solving capability, while also influencing decision making indirectly through SA.	[22,26,41]
E1 Operator Capability	E4 Navigation Safety	NO direct relationship	No separate direct relationship is represented in the operator-centred base model. Capability contributes to safety through cognitive, decision and subsequent action processes rather than being treated as an independent direct determinant of the safety outcome.	Modelling boundary of this study
E1 Operator Capability	E5 HMI and Information/ Data Conditions	NO direct relationship	Operator capability does not determine the interface and information-delivery conditions provided by the ROC system within the bounded operational episode.	Modelling boundary of this study

Table 4. *Cont.*

Left Element (A)	Right Element (B)	TISM Decision	Revised Theoretical Justification	Key Evidence/ Interpretive Basis
E1 Operator Capability	E6 Workload	NO direct relationship	Experience and capability may affect experienced workload, but E6 includes both task-demand and operator-state characteristics and the reviewed evidence did not support a sufficiently stable direct direction for the base model. This relationship was therefore examined in sensitivity analysis.	[10,41]
E1 Operator Capability	E7 Trust and Transparency	NO direct relationship	The evidence identifies Trust and Transparency primarily as human–automation interaction conditions but does not provide sufficient evidence for a conceptually distinct directional relationship from overall Operator Capability to the combined Trust and Transparency construct. No direct relationship was therefore retained in the base model.	[53]
E1 Operator Capability	E8 Level of Automation	NO direct relationship	Automation level can change the competencies required by an operational role, but E1 is defined here as capability already possessed or enacted by the operator. Required competence and possessed capability are therefore kept conceptually separate.	[13,50]
E2 Situation Awareness	E3 Decision-Making Quality	YES: E2 → E3	SA provides the perceptual, comprehension and projection basis from which operators evaluate the situation and select timely and appropriate responses.	[26,27,41]
E2 Situation Awareness	E4 Navigation Safety	NO direct relationship	SA is not equated with action or navigational outcome. Within the model, its contribution to safety is represented through decision making and subsequent operational action rather than as an independent direct safety pathway.	[26,41]
E2 Situation Awareness	E5 HMI and Information/ Data Conditions	YES: E5 → E2	Interface design and information/data conditions determine how remote operators obtain, integrate and interpret information needed to maintain SA. Poor presentation, unavailable information or degraded data can therefore constrain SA.	[26,41,60]
E2 Situation Awareness	E6 Workload	YES: E6 → E2	Elevated workload can constrain attentional and information-processing resources needed to perceive, comprehend and project relevant system states.	[10,41,56]
E2 Situation Awareness	E7 Trust and Transparency	YES: E7 → E2	Transparency, explainability and appropriately calibrated trust can support understanding of automation behaviour, mode/status awareness and interpretation of automated information, thereby contributing to SA.	[11,12,53]

Table 4. *Cont.*

Left Element (A)	Right Element (B)	TISM Decision	Revised Theoretical Justification	Key Evidence/ Interpretive Basis
E2 Situation Awareness	E8 Level of Automation	YES: E8 → E2	Automation level and human–function allocation can change monitoring demands, operator involvement, mode complexity and out-of-the-loop exposure, thereby influencing SA.	[13,41]
E3 Decision-Making Quality	E4 Navigation Safety	YES: E3 → E4	The appropriateness and timeliness of navigational decisions and interventions contribute directly to whether safe navigational states are maintained or recovered. The relationship represents influence rather than deterministic causation.	[7,57]
E3 Decision-Making Quality	E5 HMI and Information/ Data Conditions	YES: E5 → E3	HMI and information-presentation conditions can affect decision support, option presentation, intervention selection and decision bias directly, while also influencing decision making indirectly through SA.	[22,41]
E3 Decision-Making Quality	E6 Workload	NO direct relationship	The reviewed evidence supports relationships between workload, SA and broader operator performance, but a distinct direct effect specifically on the defined E3 decision-quality construct could not be separated sufficiently from indirect cognitive pathways.	[10,56]
E3 Decision-Making Quality	E7 Trust and Transparency	YES: E7 → E3	Trust and transparency can influence reliance on automation, acceptance or rejection of automated recommendations, intervention behaviour and willingness to override automated functions. This direct pathway may coexist with an indirect pathway through SA.	[11,22,53]
E3 Decision-Making Quality	E8 Level of Automation	YES: E8 → E3	Automation and human–function allocation can alter decision authority, available decision support, option generation and the extent to which action selection is performed by the human or automated system.	[13,41,54]
E4 Navigation Safety	E5 HMI and Information/ Data Conditions	NO direct relationship	Direct technical failure-to-safety pathways may exist in the wider socio-technical system, but they are outside the operator-centred cognitive/decision pathway represented by the present TISM. E5 effects are represented through E2 and E3.	Modelling boundary of this study
E4 Navigation Safety	E6 Workload	NO direct relationship	Workload is not represented as an independent direct determinant of Navigation Safety. Its human-performance effects are represented through SA and related cognitive/decision processes.	[10] & modelling boundary of this study
E4 Navigation Safety	E7 Trust and Transparency	NO direct relationship	Trust/transparency effects are represented through SA and decision behaviour rather than as a separate direct link to the navigational outcome.	[11,53]

Table 4. *Cont.*

Left Element (A)	Right Element (B)	TISM Decision	Revised Theoretical Justification	Key Evidence/ Interpretive Basis
E4 Navigation Safety	E8 Level of Automation	NO direct relationship	Automation level is treated as a system configuration condition that restructures upstream human and work-system processes; it is not interpreted as an independent direct empirical determinant of Navigation Safety.	[13] & modelling boundary of this study
E5 HMI and Information/Data Conditions	E6 Workload	YES: E5 → E6	Interface and information-presentation conditions can increase information-search and mental-processing demands, thereby increasing operator workload. This relationship is conceptually distinct from E5 → E2 because workload is treated as a separate operator-state/task-demand construct rather than as part of SA.	[41]
E5 HMI and Information/Data Conditions	E7 Trust and Transparency	NO direct relationship	HMI characteristics and transparency may interact, but transparency is already represented within E7. A separate E5→E7 pathway was not included because it would risk overlap between the retained constructs at this level of abstraction.	[53] & modelling boundary of this study
E5 HMI and Information/Data Conditions	E8 Level of Automation	YES: E8 → E5	Changes in automation and function allocation alter interface requirements, system-state information, integration requirements and the information needed for monitoring, supervision and intervention.	[13,41,61]
E6 Workload	E7 Trust and Transparency	NO direct relationship in base model	Workload and trust/transparency may interact during supervisory control, but the available evidence did not support a stable directional relationship for the base structure. Alternative one-way and reciprocal relationships were therefore examined through sensitivity analysis.	Modelling boundary and sensitivity analysis of this study
E6 Workload	E8 Level of Automation	YES: E8 → E6	Automation and human–function allocation change monitoring, supervisory and intervention demands and can consequently alter the operator workload profile.	[41,56]
E7 Trust and Transparency	E8 Level of Automation	YES: E8 → E7	Automation level changes the operator's supervisory relationship with the system, the opacity of automated behaviour, and the need for transparency, explainability and calibrated reliance.	[11,53,54]

A direct relationship was represented where the reviewed evidence or established theory supported an influence of one element on another that was conceptually distinguishable from an indirect pathway through another retained TISM element. Direct and indirect pathways were, therefore, permitted to coexist. For example, an element could influence Decision-Making Quality both directly and indirectly through Situation Awareness where the evidence supported both pathways. Conversely, where the available evidence indicated a possible association but did not allow a distinct direct influence to be differentiated sufficiently from an indirect pathway, the direct relationship was not represented in the base SSIM.

The pairwise assessment was bounded as a static, forward-influence representation of a single operational decision episode. Accordingly, the model represents Operator Capability and ROC work-system conditions as antecedent influences on SA and decision making, followed by Navigation Safety outcomes. This boundary does not imply that feedback processes are absent in practice. Decisions may subsequently alter information-seeking behaviour, monitoring priorities, or later SA, and contextual conditions may interact dynamically over time. Such feedback processes were excluded from the base SSIM to maintain a defined temporal boundary and were examined separately through structural sensitivity analysis. This distinction is consistent with situation awareness theory, which treats SA and decision making as distinct constructs while recognising that they may interact dynamically across continuing task cycles [41].

The complete pairwise reassessment shows that SA remains an important cognitive pathway within the proposed structure but is not assumed to be the exclusive pathway through which upstream influences affect decision making. In particular, Operator Capability, HMI and Information/Data Conditions, Trust and Transparency, and Level of Automation were judged capable of influencing Decision-Making Quality directly where the literature or established theory supported a conceptually distinct pathway. These direct relationships coexist with indirect pathways through SA. By contrast, Workload → Decision-Making Quality was not represented as a separate direct relationship because the reviewed evidence did not allow its effect on the defined decision-quality construct to be distinguished sufficiently from effects operating through SA and related cognitive processes.

Together, Tables 3 and 4 provide traceability from thematic synthesis to TISM construction. Table 3 identifies the literature-derived elements and their conceptual roles, while Table 4 records the decision and interpretive basis for all 28 unique element pairs. The subsequent SSIM, IRM and FRM are structural transformations of these documented pairwise judgements. The complete pairwise record, calculation workflow, level-partition iterations and structural sensitivity analysis are also provided in the supplementary workbook to support reproducibility.

Relationships were coded using four standard SSIM symbols:

- V: element i directly influences element j within the defined model boundary.
- A: element j directly influences element i within the defined model boundary.
- X: direct relationships are represented in both directions within the defined model boundary.
- O: no direct relationship is represented within the defined model boundary and available evidence.

An O designation should, therefore, not be interpreted as evidence that no relationship or interaction can occur in practice; it indicates only that a distinct direct relationship was not included in the specified base model.

The SSIM was constructed in upper-triangular form, with each element pair evaluated once to avoid redundancy. Lower-triangular cells were intentionally left blank, as reciprocal relationships are logically inferred during reachability matrix development, as shown in Table 5. This approach is consistent with established ISM and TISM methodologies [28,29].

Because several plausible relationships were deliberately excluded from the parsimonious base structure, structural sensitivity analysis was subsequently undertaken to examine the extent to which the model hierarchy and reachability results depended on these modelling decisions. The analysis tested selected alternative direct relationships among Operator Capability and contextual conditions, together with a decision-making-to-SA feedback pathway. Comparisons considered changes in direct relationship structure, final reachability, hierarchical levels, and driving/dependence powers. The purpose of this

analysis was not to identify a statistically optimal structure but to distinguish structural conclusions that remained stable across plausible alternatives from those that depended on the specified modelling boundary.

Table 5. Structural Self-Interaction Matrix.

From\To	E1	E2	E3	E4	E5	E6	E7	E8
E1 Operator Capability	—	V	V	O	O	O	O	O
E2 Situation Awareness		—	V	O	A	A	A	A
E3 Decision-Making Quality			—	V	A	O	A	A
E4 Navigation Safety				—	O	O	O	O
E5 HMI and Information/Data Conditions					—	V	O	A
E6 Workload						—	O	A
E7 Trust and Transparency							—	A
E8 Level of Automation								—

4.5. Interpretive Grounding of Pairwise Relationships

TISM requires explicit interpretive justification for the relationships represented among the retained elements [28]. In this study, pairwise judgements were grounded in the synthesised literature and, where necessary, established situation awareness and human–automation theory. The assessment considered whether the available evidence supported a direct directional influence that was conceptually distinguishable from an indirect pathway through another retained element. The interpretive basis for each of the 28 unique element pairs is documented in Table 4.

Situation Awareness was treated as an important cognitive state supporting Decision-Making Quality, but it was not assumed to be the exclusive pathway through which upstream human or work-system conditions influence decision making. Where the literature or established theory supported a conceptually distinct relationship, Operator Capability, HMI and Information/Data Conditions, Trust and Transparency, and Level of Automation were also permitted to influence Decision-Making Quality directly. Direct and indirect pathways could, therefore, coexist within the model.

The retained contextual and system elements were also differentiated according to their conceptual roles. HMI and Information/Data Conditions represent the interface and information environment through which remote operators access and interpret operational information; Workload represents an operator-state and task-demand condition; Trust and Transparency represent human–automation interaction conditions; and Level of Automation represents a system-configuration condition affecting human–function allocation and supervisory-control requirements. These constructs may influence SA, Decision-Making Quality, or other retained work-system conditions rather than functioning solely as modifiers of SA.

The SSIM should, therefore, be interpreted as a theory-building representation of specified structural relationships rather than as a causal model. A represented direct relationship indicates that the reviewed evidence or established theory supported a conceptually distinguishable influence within the defined model boundary. Conversely, an omitted direct relationship indicates only that such a relationship was not represented in the base model; it does not establish that the two constructs cannot interact in practice. The model was further bounded as a static, forward-influence representation of a single operational decision episode, with alternative contextual relationships and Decision-Making Quality → SA feedback examined separately through structural sensitivity analysis.

Because this study represents a literature-grounded theory-building phase, the resulting SSIM is not treated as an empirically validated or predictive structure. Transparency was strengthened by tracing the retained elements to the thematic synthesis, documenting the interpretive basis for all pairwise judgements, reporting the SSIM-to-reachability

transformation, and examining plausible alternative specifications through sensitivity analysis. The preliminary expert review served as a developmental assessment of construct relevance, clarity, completeness, and theoretical plausibility; it should not be interpreted as empirical validation or as expert endorsement of every relationship in the subsequently revised pairwise structure.

4.6. Preliminary Expert Review of TISM Elements and Pairwise Relationships

A structured preliminary expert review was conducted with three experts to assess the clarity, relevance, completeness, and theoretical plausibility of the developing TISM model. The experts represented relevant experience in maritime navigation, MASS/ROC operations, human factors, simulator assessment, STCW/competency, Navigation Safety, and unmanned surface vessel operations. The structured review instrument comprised five substantive components: assessment of the eight proposed TISM elements for clarity, relevance, and definition adequacy; assessment of the preliminary competence → SA → decision-making → safety pathway; plausibility assessment of 12 selected pairwise relationships; assessment of the model scope and its suitability as a foundation for subsequent GDTA and simulator/ROC-based assessment; and overall judgement with opportunities for free-text recommendations. Five-point rating scales were used for the element, pathway, and selected pairwise assessments, supplemented by qualitative comments.

Experts were purposively recruited on the basis of relevant subject-matter expertise in maritime navigation, maritime human factors and safety, maritime education and training, STCW/competency assessment, MASS/ROC operations, simulator assessment, and/or maritime technology. The review was conducted individually using the same structured instrument. Experts were provided with the developing eight-element model, the 12 selected preliminary pairwise relationships, their interpretive rationale, and the proposed preliminary hierarchy before providing their assessments. Accordingly, the exercise was designed as a structured developmental review of an already-developed preliminary model rather than as independent elicitation or independent construction of the TISM hierarchy.

The expert review was developmental rather than confirmatory. Overall, the feedback provided preliminary support for the relevance and theoretical plausibility of the proposed elements and for using the model as a basis for subsequent methodological development. The experts also identified areas requiring refinement, including the definitions and scope of Operator Capability, Navigation Safety, Trust and Transparency, human–function allocation, and ROC-specific contextual conditions. These comments informed refinement of the construct definitions and explanatory framing while retaining the eight-element structure.

Importantly, the expert review assessed 12 selected preliminary pairwise relationships rather than the complete set of 28 unique element pairs. It was conducted before the subsequent comprehensive pairwise reassessment reported in Table 4. During that later stage, all 28 unique pairs were reassessed using the synthesised literature, established theory, the clarified construct definitions, and the specified modelling boundary. Consequently, some relationships included in the preliminary expert-review instrument were modified or not retained in the final base structure. The final SSIM, therefore, reflects the comprehensive literature- and theory-based reassessment rather than direct aggregation of the experts' ratings. The preliminary expert review should not be interpreted as expert endorsement of every relationship in the final revised structure, nor as empirical validation or statistical consensus.

An anonymised summary of the three expert profiles, the 12 relationships reviewed, individual ratings and qualitative comments, and a response-to-feedback audit showing how substantive comments informed subsequent model refinement are provided in Supplementary File S4.

4.7. TISM Results

4.7.1. Reachability Matrix and Transitivity Analysis

Following SSIM construction, the qualitative pairwise relationships were converted into a binary Initial Reachability Matrix (IRM) using standard transformation rules: V → 1,0; A → 0,1; X → 1,1; and O → 0,0. Diagonal entries were assigned a value of 1 to indicate self-reachability. The resulting IRM represents the direct relationships among the eight elements, as shown in Table 6.

Transitivity was then applied systematically to the IRM to derive the Final Reachability Matrix (FRM). Under the transitivity rule, if element i reaches element j and element j reaches element k, element i is also considered to reach element k indirectly. In Table 7, direct relationships and self-reachability are denoted by 1, transitive-only relationships introduced through the closure procedure are denoted by 1*, and 0 indicates no reachability within the specified model. The FRM, therefore, represents the complete reachability structure generated from the documented SSIM and IRM rather than additional discretionary pairwise judgements.

Table 6. Initial Reachability Matrix (IRM).

Elements	E1	E2	E3	E4	E5	E6	E7	E8
E1 Operator Capability	1	1	1	0	0	0	0	0
E2 Situation Awareness	0	1	1	0	0	0	0	0
E3 Decision-Making Quality	0	0	1	1	0	0	0	0
E4 Navigation Safety	0	0	0	1	0	0	0	0
E5 HMI and Information/Data Conditions	0	1	1	0	1	1	0	0
E6 Workload	0	1	0	0	0	1	0	0
E7 Trust and Transparency	0	1	1	0	0	0	1	0
E8 Level of Automation	0	1	1	0	1	1	1	1

Table 7. Final Reachability Matrix (FRM) After Transitivity.

Elements	E1	E2	E3	E4	E5	E6	E7	E8
E1 Operator Capability	1	1	1	1*	0	0	0	0
E2 Situation Awareness	0	1	1	1*	0	0	0	0
E3 Decision-Making Quality	0	0	1	1	0	0	0	0
E4 Navigation Safety	0	0	0	1	0	0	0	0
E5 HMI and Information/Data Conditions	0	1	1	1*	1	1	0	0
E6 Workload	0	1	1*	1*	0	1	0	0
E7 Trust and Transparency	0	1	1	1*	0	0	1	0
E8 Level of Automation	0	1	1	1*	1	1	1	1

4.7.2. Level Partitioning and Model Construction

Level partitioning was conducted using the reachability, antecedent, and intersection sets derived from the FRM. Elements whose reachability set equalled the intersection set were assigned to the top level and removed from the next iteration. This process was repeated until all elements were assigned to hierarchical levels, as shown in Table 8. The complete iteration-by-iteration reachability, antecedent, and intersection sets used in the level-partitioning procedure are provided in the supplementary workbook to support reproducibility.

The level-partitioning procedure produced a six-level hierarchy. Navigation Safety occupies Level 1 as the terminal operational outcome within the specified structure. Decision-Making Quality occupies Level 2 as the immediate decision-process element upstream of Navigation Safety, while Situation Awareness occupies Level 3 as the cognitive state supporting decision making.

Table 8. Level partitioning results (Level 1 = terminal operational outcome).

Level (1 = Top)	Element
1	E4 Navigation Safety
2	E3 Decision-Making Quality
3	E2 Situation Awareness
4	E1 Operator Capability
4	E6 Workload
4	E7 Trust and Transparency
5	E5 HMI and Information/Data Conditions
6	E8 Level of Automation

Level 4 comprises Operator Capability, Workload, and Trust and Transparency. Although these elements occupy the same structural level, their conceptual roles differ. Operator Capability represents the human capability available to perform remote navigational functions, whereas Workload and Trust and Transparency represent work-system and human–automation conditions that may influence SA and, where supported by the pairwise assessment, decision making.

HMI and Information/Data Conditions occupy Level 5. This position reflects the direct relationships from E5 to Situation Awareness, Decision-Making Quality, and Workload. In particular, the inclusion of E5 → E6 places interface and information conditions structurally upstream of workload in the base model. This does not imply that HMI/information conditions are empirically stronger than the Level 4 elements; the level reflects reachability and direction within the specified TISM structure.

Level of Automation occupies Level 6 as the deepest upstream system condition. Within the model, automation level directly influences HMI and Information/Data Conditions, Workload, Trust and Transparency, Situation Awareness, and Decision-Making Quality. It does not directly determine Operator Capability or Navigation Safety. Its Level 6 position, therefore, reflects its broad structural reach across the remote-operation work system rather than an empirically quantified causal effect [62].

4.7.3. TISM Hierarchical Model

The TISM hierarchy derived from the Final Reachability Matrix comprises six structural levels, representing differentiated positions of system configuration, interface/information conditions, human and contextual conditions, Situation Awareness, decision making, and Navigation Safety outcome, as shown in Figure 3. The hierarchy should be interpreted as a structural ordering based on the specified pairwise relationships and transitive reachability, rather than as a ranking of empirical causal strength.

4.7.4. MICMAC Analysis

MICMAC analysis was conducted using the FRM to describe the structural driving and dependence characteristics of the eight elements. Driving power was calculated as the row sum of the FRM, representing the number of elements reachable from a given element, including itself, while dependence power was calculated as the column sum, representing the number of elements from which that element is reachable. These measures indicate structural reachability within the specified TISM model; they should not be interpreted as empirical effect sizes, causal strength, or statistical importance. The recalculated values are presented in Table 9.

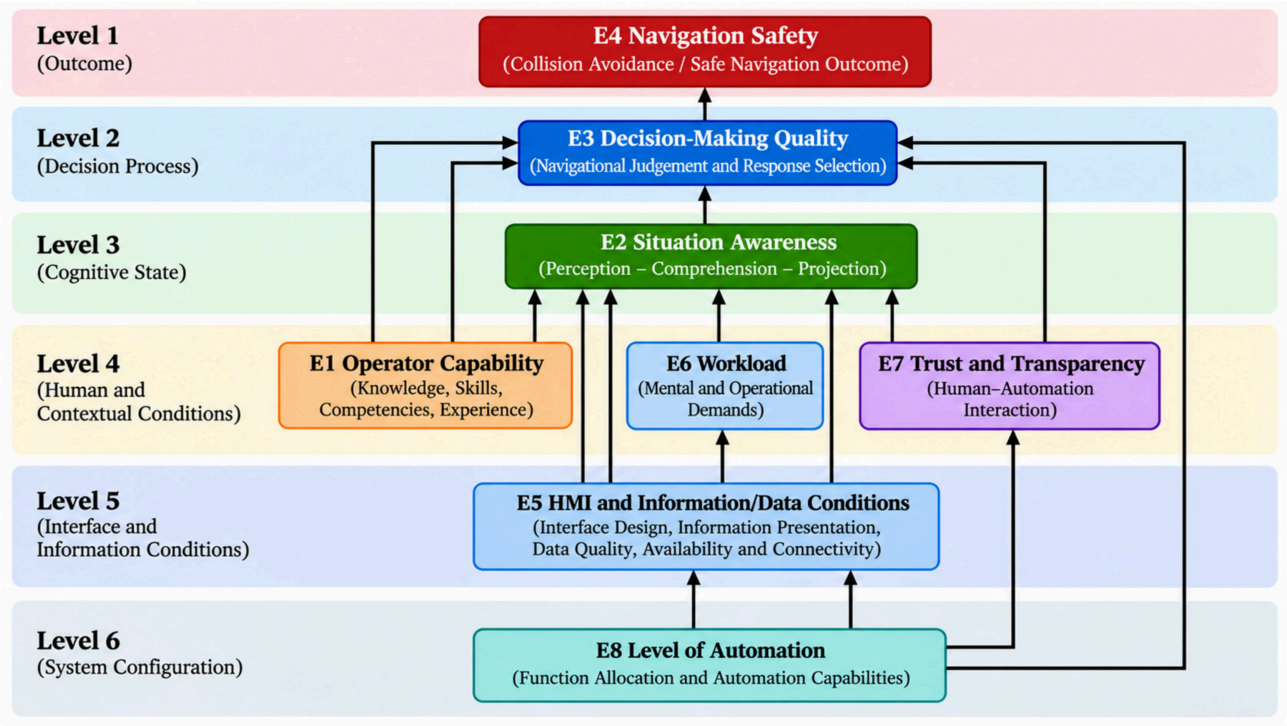


Figure 3. TISM hierarchical structure for ROC/MASS operations. Note: All arrows represent direct relationships retained in the final SSIM/IRM. The hierarchical levels are derived from the Final Reachability Matrix (FRM) and indicate structural position within the bounded TISM model; they do not represent causal strength, empirical importance, or effect magnitude. Only direct relationships are shown in the figure for clarity; transitive reachability relationships identified in the FRM are not displayed. The model represents a bounded forward-influence structure for a single operational decision episode and does not imply that feedback or other interactions cannot occur in continuing operational cycles.

Table 9. MICMAC driving and dependence power (based on FRM).

Element	Driving Power	Dependence Power
E1 Operator Capability	4	1
E2 Situation Awareness	3	6
E3 Decision-Making Quality	2	7
E4 Navigation Safety	1	8
E5 HMI and Information/Data Conditions	5	2
E6 Workload	4	3
E7 Trust and Transparency	4	2
E8 Level of Automation	7	1

The MICMAC results are consistent with the hierarchical structure while providing a complementary description of structural reachability. Level of Automation has the highest driving power (7) and low dependence (1), indicating that it reaches a relatively large proportion of the retained model while receiving no represented influence from other elements apart from self-reachability. HMI and Information/Data Conditions also show comparatively high driving power (5) with low dependence (2), reflecting their direct and indirect reach to workload, SA, decision making, and Navigation Safety.

Operator Capability, Workload, and Trust and Transparency each have driving powers of 4, although their dependence powers differ. Operator Capability has dependence power 1 because no other retained element directly or transitively reaches it within the specified model. Workload has dependence power 3 because it is structurally reachable from both

Level of Automation and HMI and Information/Data Conditions, in addition to itself. Trust and Transparency has dependence power 2 because it is reachable from Level of Automation and itself.

Situation Awareness, Decision-Making Quality, and Navigation Safety show progressively greater dependence and lower driving power as the structure approaches the terminal operational outcome. SA has driving/dependence powers of 3/6, Decision-Making Quality 2/7, and Navigation Safety 1/8. These values describe their downstream structural positions; they do not establish that upstream elements exert stronger empirical effects than downstream elements.

No formal four-quadrant MICMAC classification was applied in this study. Table 10, therefore, uses descriptive structural-role labels rather than the conventional autonomous, dependent, linkage, and driver categories. These labels are interpreted from the FRM-derived driving and dependence powers together with each element's hierarchical position and conceptual role in the bounded TISM structure; no numerical quadrant thresholds are implied.

Table 10. Descriptive structural roles indicated by the TISM–MICMAC analysis.

Structural Role	Elements	Interpretation
Deepest upstream system condition	E8 Level of Automation	Broad structural reach across the retained work-system elements, with low dependence within the specified model
Upstream interface/information condition	E5 HMI and Information/Data Conditions	Structurally upstream of workload, SA and decision making, with indirect reach to Navigation Safety
Human and contextual conditions	E1 Operator Capability; E6 Workload; E7 Trust and Transparency	Distinct human/work-system conditions influencing SA and/or decision making through the direct relationships specified in the SSIM
Cognitive state	E2 Situation Awareness	Downstream of several human/system conditions and upstream of decision making
Decision-process element	E3 Decision-Making Quality	Receives multiple upstream influences and directly precedes Navigation Safety
Terminal operational outcome	E4 Navigation Safety	Most dependent element and terminal outcome within the bounded model

Taken together, the MICMAC results should be interpreted as a structural description of the revised model rather than as evidence of causal magnitude or predictive importance. The analysis shows which elements occupy relatively upstream or downstream positions under the specified pairwise relationships and transitivity rules. The sensitivity of these structural positions to plausible alternative relationships is examined separately through structural sensitivity analysis.

4.7.5. Structural Sensitivity Analysis

Structural sensitivity analysis was conducted to examine whether the principal hierarchy depended on selected alternative pairwise specifications. The six-level model was used as the base case. Alternative specifications examined removal of the E5 → E6 relationship; addition of E1 → E6; addition of the direct E6 → E3 relationship; alternative directional relationships between E6 Workload and E7 Trust and Transparency; reciprocal E6 ↔ E7 interaction; and reciprocal feedback from E3 Decision-Making Quality to E2 Situation Awareness. Combined contextual alternatives were also examined. Table 11 summarises the resulting level structures.

Table 11. Structural sensitivity analysis of alternative relationship specifications.

Scenario	Relationship Change	No. of Levels	Resulting Hierarchy	Main Interpretation
Revised base model	None	6	L1 E4; L2 E3; L3 E2; L4 E1/E6/E7; L5 E5; L6 E8	Reference structure
Add E6 → E3	+ E6 → E3	6	L1 E4; L2 E3; L3 E2; L4 E1/E6/E7; L5 E5; L6 E8	Direct workload-to-decision pathway added; transitive closure, MICMAC powers and hierarchy unchanged.
Remove E5 → E6	− E5 → E6	5	L1 E4; L2 E3; L3 E2; L4 E1/E5/E6/E7; L5 E8	E5 position depends on its direct workload relationship
Add E1 → E6	+ E1 → E6	6	L1 E4; L2 E3; L3 E2; L4 E6/E7; L5 E1/E5; L6 E8	E1 moves further upstream
Add E6 → E7	+ E6 → E7	7	L1 E4; L2 E3; L3 E2; L4 E1/E7; L5 E6; L6 E5; L7 E8	Contextual ordering changes
Add E7 → E6	+ E7 → E6	6	L1 E4; L2 E3; L3 E2; L4 E1/E6; L5 E5/E7; L6 E8	Contextual ordering changes
Add E6 ↔ E7	Reciprocal E6–E7	6	L1 E4; L2 E3; L3 E2; L4 E1/E6/E7; L5 E5; L6 E8	E6/E7 form a mutually reachable block
Add E3 → E2 feedback	+ E3 → E2	5	L1 E4; L2 E2/E3; L3 E1/E6/E7; L4 E5; L5 E8	SA and DM merge structurally
Combined contextual alternatives	+ E1→E6; + E6↔E7	6	L1 E4; L2 E3; L3 E2; L4 E6/E7; L5 E1/E5; L6 E8	Downstream ordering retained
Combined contextual + feedback	Contextual alternatives + E3→E2	5	L1 E4; L2 E2/E3; L3 E6/E7; L4 E1/E5; L5 E8	Feedback collapses SA/DM ordering

The disputed direct relationships from Operator Capability, HMI and Information/Data Conditions, Trust and Transparency, and Level of Automation to Decision-Making Quality were incorporated into the revised base model following the comprehensive pairwise reassessment and, therefore, were not treated as alternative sensitivity specifications. The sensitivity analysis instead focused on the remaining uncertain contextual and feedback relationships. Because no formal four-quadrant MICMAC classification was applied in this study, comparisons focused on changes in direct relationship structure, reachability-derived driving and dependence powers, and hierarchical levels rather than transitions between conventional MICMAC categories.

The analysis showed that the relative positioning of several upstream and contextual elements was sensitive to plausible alternative relationship specifications. Removing E5 → E6 returned E5 to the same level as E1, E6 and E7, producing the earlier five-level hierarchy. Adding E1 → E6 moved Operator Capability further upstream, while alternative relationships between Workload and Trust and Transparency changed the relative positioning of these contextual elements. These changes indicate that the internal ordering of the upstream work-system conditions should not be interpreted as fixed or empirically established.

In contrast, the downstream structure was retained across the tested contextual alternatives. Navigation Safety remained the terminal Level 1 outcome, Decision-Making Quality remained immediately upstream at Level 2, and Situation Awareness remained at Level 3 whenever the model retained the forward-influence boundary. Level of Automation also remained the deepest upstream element across the tested specifications, although the total number of hierarchical levels varied.

The main exception occurred when an explicit E3 → E2 feedback relationship was introduced. Under this specification, Situation Awareness and Decision-Making Quality formed a mutually reachable block and, therefore, occupied the same hierarchical level. This result reinforces the importance of the temporal boundary adopted for the base TISM: the ordered E2 → E3 relationship represents a bounded decision episode rather than a claim that decision making can never influence subsequent SA in continuing operational cycles.

Overall, the sensitivity analysis indicates that the downstream E2 → E3 → E4 ordering was retained across the tested contextual alternatives but changed when explicit within-model feedback from Decision-Making Quality to SA was introduced. By contrast, the detailed ordering among Operator Capability, HMI and Information/Data Conditions, Workload,

and Trust and Transparency is more sensitive to alternative relationship assumptions. These findings support cautious interpretation of the model as a bounded structural representation rather than a definitive causal ordering of the complete ROC socio-technical system.

An additional sensitivity scenario introduced a direct E6 Workload → E3 Decision-Making Quality relationship alongside the existing indirect E6 → E2 → E3 pathway. The number of direct model relationships increased from 15 to 16. However, E6 already reached E3 through E2 in the base model, so the added direct link did not change the transitive closure, driving and dependence powers, or six-level hierarchy. This result indicates structural invariance under the tested alternative, not evidence that Workload lacks a direct influence on decision making in actual ROC operations.

5. Discussion

5.1. From Thematic Synthesis to TISM

The thematic synthesis identified the principal constructs associated with ROC/MASS Navigation Safety, including Operator Capability, Situation Awareness (SA), Decision-Making Quality, Navigation Safety, and ROC-specific work-system conditions. However, thematic synthesis alone does not establish the hierarchical position or structural direction of relationships among these constructs. TISM was, therefore, used to organise the literature-derived relationships into an interpretable structural model, supported by explicit pairwise judgements, transitive reachability, and MICMAC analysis.

The TISM extends the thematic framework by showing that Navigation Safety is associated with a layered socio-technical structure rather than with a single linear pathway. Operator Capability, HMI and Information/Data Conditions, Workload, Trust and Transparency, and Level of Automation occupy different upstream positions and may influence SA and/or Decision-Making Quality through the direct relationships retained in the SSIM. SA remains an important cognitive pathway because perception, comprehension, and projection support operators in interpreting dynamic operational conditions and informing subsequent decisions [26,27,63]. However, the revised model does not assume that every upstream influence on Decision-Making Quality operates exclusively through SA. Human–automation and maritime decision-making research also indicates that Operator Capability, interface and information conditions, automation characteristics, and Trust/Transparency can influence decision processes through pathways that are not reducible to SA alone [11,20,22,53,64].

Within the downstream part of the structure, SA influences Decision-Making Quality, which in turn influences Navigation Safety. This ordering is consistent with classical SA theory and with maritime research linking SA and navigational decision making to safe performance in remote and autonomous operations [20,26,27,64,65]. The E2 → E3 → E4 ordering was retained across the tested contextual sensitivity specifications. However, when an explicit Decision-Making Quality → SA feedback relationship was introduced, SA and Decision-Making Quality became mutually reachable and occupied the same hierarchical level. Accordingly, the base ordering should be interpreted as a bounded representation of a single operational decision episode rather than as evidence that decision making cannot influence subsequent SA during continuing operational cycles.

The TISM, therefore, provides a theory-building representation of structural relationships within the defined ROC/MASS model boundary. It does not establish causal effect magnitude, statistical mediation, or predictive validity. These questions require subsequent empirical investigation under representative remote-operation conditions.

5.2. Interpretation of the TISM Hierarchical Structure

The revised TISM produces a six-level hierarchy that differentiates system configuration, interface and information conditions, human and contextual conditions, cognitive

state, decision process, and navigational outcome, as illustrated in Figure 3. These levels represent structural reachability within the specified model and should not be interpreted as rankings of empirical importance or causal strength.

Navigation Safety occupies Level 1 as the terminal operational outcome. Its position indicates that all other retained elements can reach it directly or indirectly within the revised FRM. This interpretation is consistent with socio-technical safety perspectives, which treat safety as an emergent property of interactions among human, technological, organisational, and operational components rather than as the result of a single factor [4,25].

Decision-Making Quality occupies Level 2 and directly influences Navigation Safety. This positioning is consistent with studies showing that the correctness, timeliness, and appropriateness of navigational decisions and interventions are important to maintaining or recovering safe vessel states in remote and autonomous maritime operations [7,20,57,65].

Situation Awareness occupies Level 3 and directly influences Decision-Making Quality. SA, therefore, remains an important cognitive component of the model because perception, comprehension, and projection provide the informational basis for understanding current conditions and anticipating future system states before navigational decisions are made [26,27,63]. Its Level 3 position, however, should not be interpreted as evidence of exclusive statistical mediation. The revised pairwise assessment also retains direct pathways from Operator Capability, HMI and Information/Data Conditions, Trust and Transparency, and Level of Automation to Decision-Making Quality where the literature or established theory supported conceptually distinguishable influences [11,22,53].

Level 4 comprises Operator Capability, Workload, and Trust and Transparency. These elements occupy the same structural level but represent different types of influence. Operator Capability refers to the knowledge, skills, competencies, and experience available to the operator and directly influences both SA and Decision-Making Quality. Workload is represented as a work-system and operator-state condition influencing SA, whereas Trust and Transparency represent human–automation interaction conditions influencing both SA and Decision-Making Quality. This distinction is consistent with research emphasising the continuing importance of traditional and emerging navigational competencies, workload management, automation supervision, and calibrated human–automation interaction in MASS operations [20,22,53,57,59,64,66].

HMI and Information/Data Conditions occupy Level 5. Their upstream position reflects direct relationships with SA, Decision-Making Quality, and Workload. This distinction is particularly important in ROC operations because operators obtain operational information through remote interfaces, sensors, data-processing systems, communication links, and automation displays rather than through the same direct perceptual access available onboard. Interface design and information availability can, therefore, affect the acquisition and interpretation of information required for SA, while information presentation and processing demands may also affect workload and decision performance [11,41,66].

Level of Automation occupies Level 6 as the deepest upstream element in the revised structure. It directly influences HMI and Information/Data Conditions, Workload, Trust and Transparency, SA, and Decision-Making Quality. This position reflects the structural consequences of automation level and human–function allocation for monitoring, information presentation, supervisory control, Workload, reliance, and intervention requirements [13,54]. It does not indicate that automation has the largest empirical effect on Navigation Safety, nor does the revised model represent automation as directly determining Operator Capability or Navigation Safety.

For competency evaluation, the revised hierarchy, therefore, supports a more cautious interpretation than a simple competence → SA → decision-making → safety chain. Existing navigational competencies should be examined in terms of whether operators can use their

available capability to acquire and use the SA required for appropriate decision making under the interface, information, Workload, trust, and automation conditions of ROC work. At the same time, poor SA or poor decision performance should not automatically be interpreted as evidence of a competency deficiency, because interface constraints, information quality, system design, Workload, automation behaviour, procedures, and other contextual conditions may also contribute to observed performance limitations. This interpretation remains consistent with research emphasising digital literacy, automation supervision, information integration, communication, trust calibration, and Situation Awareness in MASS and remote-operation contexts [20,53,57,59,64,66].

5.3. Role and Positioning of Contextual and System Conditions

The TISM differentiates Operator Capability from the contextual and system conditions under which remote navigation is performed. Operator Capability represents the knowledge, skills, competencies, and experience available to the operator, whereas HMI and Information/Data Conditions, Workload, Trust and Transparency, and Level of Automation represent distinct characteristics of the ROC work system and human–automation environment. These constructs should, therefore, not be interpreted as interchangeable determinants of performance, even where they occupy adjacent or equivalent hierarchical levels.

HMI and Information/Data Conditions occupy Level 5, structurally upstream of Operator Capability, Workload, and Trust and Transparency at Level 4. This position reflects the retained direct relationships from HMI and Information/Data Conditions to Situation Awareness, Decision-Making Quality, and Workload. In remote maritime operations, interface design, sensor integration, information availability, data quality, connectivity, alarm presentation, and automation-status displays can influence what information operators can perceive and integrate and the cognitive effort required to obtain and interpret that information [11,12,41,43,67].

Workload and Trust and Transparency occupy Level 4 but represent different mechanisms. Workload is represented as an operator-state and task-demand condition that can constrain attentional and information-processing resources required for SA, particularly during monitoring, degraded-mode, or time-critical operations [10,56]. Trust and Transparency represent human–automation interaction conditions that can influence both SA and decision making by shaping how operators understand automation behaviour, calibrate reliance, interpret system recommendations, and decide whether intervention or override is required [11,12,53]. Their shared hierarchical position, therefore, reflects structural reachability rather than equivalent functional roles.

Level of Automation occupies Level 6 as the deepest upstream condition in the revised hierarchy. Changes in automation and human–function allocation can alter interface requirements, information needs, monitoring responsibilities, Workload profiles, Trust and Transparency requirements, supervisory-control demands, and decision authority [13,54]. The model, therefore, treats automation level as a system-configuration condition with broad structural reach rather than as a direct empirical determinant of Navigation Safety.

These distinctions are important for competency evaluation. Poor performance in ROC/MASS operations cannot automatically be attributed to inadequate operator competence. A navigator with appropriate knowledge and experience may still experience degraded SA or decision performance if information is unavailable or delayed, interfaces are poorly designed, Workload is excessive, automation behaviour is unclear, or trust is poorly calibrated. Conversely, supportive system conditions may facilitate the effective use of existing navigational capability in remote operations [11,41,43,53].

Accordingly, the proposed model does not treat contextual conditions merely as modifiers of a single competence → SA → decision-making pathway. Some contextual and

system elements influence SA, some influence Decision-Making Quality directly, and some influence both. Their role in subsequent competency evaluation is, therefore, diagnostic: observed limitations should be interpreted by considering Operator Capability together with information availability, interface design, Workload, automation characteristics, Trust and Transparency, procedures, and other relevant work-system conditions before a competency gap is inferred.

Illustrative Application to Competency Evaluation

To illustrate how the present model can inform later competency evaluation without implying that the full STCW mapping has already been completed, consider a collision-risk situation in which a remote navigator must assess an approaching vessel while radar or other sensor information is partially degraded or delayed. An illustrative existing competence from STCW Table A-II/1 is "Use of radar and ARPA to maintain safety of navigation", which requires the navigator to interpret and analyse available radar information while considering equipment limitations and prevailing circumstances. In the present framework, the relevant cognitive judgement might be as follows: is collision risk developing, and is the available information sufficiently reliable to support a navigational response? Resolving this judgement would require Level 1 SA of own-ship and target-vessel position, course, speed, relative movement, sensor status and information currency; Level 2 SA of the developing traffic relationship, collision-risk significance and reliability of the available information; and Level 3 SA of the projected encounter and likely consequences of maintaining or altering course and speed. These SA requirements would then support selection of an appropriate navigational response, followed by physical execution through the remote-control system. Illustrative navigation-performance indicators could include the correctness and timing of collision-risk identification, appropriateness and timing of the selected manoeuvre, compliance with applicable collision-avoidance requirements, resulting CPA/TCPA or other encounter-safety measures, and whether a safe navigational state is maintained or recovered. This example is illustrative only; formal STCW KUP mapping and specification of scenario-specific performance thresholds belong to the subsequent empirical phases of the wider research programme.

This sequence also illustrates the diagnostic purpose of separating Operator Capability from ROC work-system conditions. If the information required for the judgement is available, timely and sufficiently reliable, but the operator repeatedly fails to interpret the developing collision risk or select an appropriate response, the evidence may indicate a competency or training limitation. Conversely, if the operator's SA is degraded because essential information is unavailable, delayed, inconsistent, poorly integrated or inadequately presented, the same performance failure should not automatically be attributed to competency. Interface design, connectivity, sensor limitations, Workload, procedures, automation behaviour and other contextual conditions would also need to be examined. Accordingly, the model provides a diagnostic structure for later GDTA, STCW mapping and simulator assessment rather than itself determining whether a particular STCW competency is adequate.

Beyond the illustrative radar/ARPA encounter, later assessment could examine watchkeeping and COLREG application in mixed traffic, route and position integrity where grounding risk develops, and remote ship handling in confined waters. These are prospective scenario applications for identifying task-specific judgements, Level 1–3 SA requirements, decisions, physical execution, and navigational outcomes; they do not represent completed competency mapping, evaluated scenarios, or changes to mandatory STCW provisions.

5.4. MICMAC Interpretation of Structural Driving and Dependence

The MICMAC analysis complements the TISM hierarchy by describing the structural driving and dependence characteristics of the retained elements. These values are derived from reachability in the FRM and, therefore, indicate how extensively an element can reach, or be reached by, other elements within the specified structure. They should not be interpreted as empirical effect sizes, statistical importance, or causal strength.

Level of Automation has the highest driving power in the revised model, with a driving/dependence profile of 7/1. This reflects its broad structural reach to HMI and Information/Data Conditions, Workload, Trust and Transparency, Situation Awareness, Decision-Making Quality, and, indirectly, Navigation Safety. HMI and Information/Data Conditions also occupy a comparatively upstream position, with a driving/dependence profile of 5/2, reflecting their direct relationships with Workload, SA, and Decision-Making Quality. These structural positions are consistent with human–automation research showing that automation level, function allocation, interface design, and information presentation can substantially reconfigure the operator's monitoring, supervisory, and decision environment [13,54].

Operator Capability, Workload, and Trust and Transparency each have a driving power of 4, although their dependence powers differ. Operator Capability has low dependence because no other retained element reaches it within the specified model boundary. Workload has greater dependence because it is structurally reachable from both Level of Automation and HMI and Information/Data Conditions, whereas Trust and Transparency is reachable from Level of Automation. These differences reinforce the distinction between Operator Capability and contextual or human–automation conditions rather than treating all Level 4 elements as equivalent.

Situation Awareness, Decision-Making Quality, and Navigation Safety show progressively greater dependence and lower driving power as the model approaches the terminal operational outcome. SA has a driving/dependence profile of 3/6, Decision-Making Quality 2/7, and Navigation Safety 1/8. These values are consistent with their downstream structural positions but do not demonstrate statistical mediation or causal magnitude. SA remains an important cognitive state supporting decision making, while Decision-Making Quality directly precedes Navigation Safety in the bounded forward-influence structure [26,27,57].

Importantly, the revised MICMAC configuration no longer supports interpreting all upstream influences as operating only through SA. Operator Capability, HMI and Information/Data Conditions, Trust and Transparency, and Level of Automation also have direct relationships with Decision-Making Quality, where supported by the pairwise assessment. MICMAC, therefore, describes the reachability consequences of these relationships rather than establishing that one cognitive pathway exclusively explains Navigation Safety.

The structural sensitivity analysis further qualifies this interpretation. The downstream E2 → E3 → E4 ordering remained unchanged across the tested contextual alternatives, whereas the relative positions of several upstream elements varied when plausible additional relationships were introduced. When reciprocal E3 → E2 feedback was introduced, SA and Decision-Making Quality became mutually reachable and occupied the same level. Consequently, the MICMAC and hierarchical results should be interpreted within the bounded static decision-episode assumption adopted for the base model rather than as evidence of a universally stable ROC system structure.

5.5. Implications for SA-Based Simulator Evaluation

The model provides a structured basis for subsequent simulator- or ROC-based evaluation of remote-navigation performance. Operator Capability represents the knowledge, skills, competencies, and experience available to the operator, while Situation Awareness

represents the operator's perception, comprehension, and projection of the operational situation [26,27]. Decision-Making Quality should be assessed separately as the appropriateness and timeliness of the judgement or action selection that follows from the operator's understanding of the situation. Navigation Safety then represents the downstream operational outcome. These constructs should, therefore, be measured as related but conceptually distinct components of performance rather than treated as interchangeable indicators.

This distinction is particularly important for evaluating the transferability of traditional navigational competencies to ROC/MASS operations. A simulator assessment should first examine whether the operator acquires and maintains the SA required for the navigational task, then whether that information is used to reach an appropriate decision, and subsequently whether the selected action is executed correctly and produces an acceptable navigational outcome. This sequence is consistent with the conceptual distinction in SA theory between Situation Awareness, decision making, and performance of actions [26,41].

Accordingly, future evaluation may combine objective and subjective measures of SA with indicators of decision quality, action execution, and navigational performance. Simulator studies in remote and maritime navigation have demonstrated the value of examining SA and operator performance under collision-risk, emergency, and remote-control conditions, although the specific measurement approach should be matched to the scenario and research question [45–47].

The ROC work-system conditions represented in the TISM—particularly automation level, HMI and information/data conditions, Workload, and Trust/Transparency—should, therefore, be controlled, varied, or documented during simulator scenarios where relevant. Their purpose is not simply to create difficulty but to reproduce the conditions under which Operator Capability must be enacted. These factors may influence SA, decision making, or both and should consequently be considered when interpreting observed performance [11,41,53,56].

Importantly, a failure to maintain SA, make an appropriate decision, execute the selected action correctly, or achieve a safe outcome should not by itself be interpreted as evidence of a competency gap. The observed limitation may instead, or additionally, reflect inadequate information availability, interface design, sensor limitations, communication or data latency, Workload, automation behaviour, procedures, training, organisational arrangements, or action-execution problems. Simulator-based competency evaluation should, therefore, adopt a diagnostic interpretation in which competency implications are inferred only after plausible system, task, and contextual explanations have been considered.

5.6. Applicability to Dynamic, Time-Critical, and Degraded-Mode ROC Scenarios

Although TISM provides a static structural representation, the revised model can inform the design and interpretation of dynamic ROC/MASS scenarios. The six-level hierarchy identifies the principal human, cognitive, interface, information, Workload, trust, automation, decision, and safety constructs that should be considered when examining operator performance under normal, high-workload, time-critical, and degraded-mode conditions. The model should, therefore, be used as a structural guide for scenario design rather than as a simulation of real-time cognitive or system dynamics.

In simulator or ROC-based studies, scenario design should control, vary, or document conditions such as automation level, HMI and information/data quality, Workload, fatigue, Trust and Transparency, communication demands, sensor degradation, and data latency where these are relevant to the operational task. These conditions may influence SA, decision making, action execution, or more than one stage of performance and should, therefore, be incorporated into the interpretation of observed outcomes rather than treated only as background variables [11,41,53,56].

Dynamic scenarios are also important because relationships among SA, decision making, and system conditions may evolve across successive operational cycles. For example, a decision may alter subsequent information-seeking behaviour, monitoring priorities, Workload, or later SA. The base TISM intentionally does not represent these feedback processes within a single static episode, but the sensitivity analysis showed that introducing reciprocal Decision-Making Quality → SA feedback changes their hierarchical relationship. This supports treating the base model as a bounded analytical representation rather than as a complete temporal model of ROC performance.

For competency evaluation, scenario-based assessment should, therefore, examine not only whether an operator achieves a safe navigational outcome but also whether the operator acquires the required SA, reaches an appropriate decision, executes the selected action correctly, and does so under representative ROC work-system conditions. Where performance limitations are observed, interpretation should distinguish among possible contributions from Operator Capability, SA failure, decision-making difficulty, action-execution error, interface or information constraints, Workload, automation behaviour, procedures, communication, and broader scenario or system-design factors.

The purpose of future simulator/ROC evaluation is consequently not to confirm a predetermined structural pathway but to examine whether the relationships proposed in the theory-building model are supported, modified, or contradicted under representative operational conditions. This provides a more defensible basis for later competency, training, interface-design, and system-level implications.

5.7. Theoretical Contribution

The principal theoretical contribution of this study is the integration of established situation awareness theory with a socio-technical representation of remote maritime operations. Classical SA theory distinguishes Situation Awareness from subsequent decision making and action, while also recognising that individual, task, interface, Workload, automation, and system factors can shape cognitive performance [26,27]. The TISM extends this theoretical framing to the ROC/MASS context by representing SA as an important cognitive pathway within a broader set of human–system relationships rather than as the sole mechanism through which upstream conditions influence navigational decision making.

A further conceptual contribution is the distinction between Operator Capability and the conditions under which that capability is enacted. In the revised model, capability represents the knowledge, skills, competencies, and experience available to the operator, whereas automation, interface and information conditions, Workload, and trust/transparency represent characteristics of the work system and human–automation environment. This distinction is particularly relevant to ROC/MASS operations because equivalent Operator Capability may produce different observed performance under different information, interface, automation, Workload, or communication conditions [13,22,41].

The model also refines the role assigned to SA. SA remains structurally upstream of Decision-Making Quality and is, therefore, an important cognitive component of remote-navigation performance. However, the revised pairwise structure allows selected upstream elements to influence Decision-Making Quality directly as well as indirectly through SA. This avoids treating SA as an exclusive statistical mediator and is more consistent with the broader human-factors literature in which experience, automation, interface design, transparency, trust, and task conditions may influence decisions through multiple interacting mechanisms [11,22,26,53].

Methodologically, this study contributes a transparent theory-building procedure in which literature-derived constructs are translated into explicit pairwise structural judgements, converted through TISM into a hierarchical model, examined through MICMAC

reachability, and challenged through structural sensitivity analysis. The revised pairwise decision rule also distinguishes between evidence of a conceptually separable direct relationship and evidence that may instead be represented through an indirect pathway. Accordingly, an omitted direct edge should be interpreted as "no direct relationship represented within the defined model and evidence base", rather than as evidence that two constructs cannot interact in practice.

These contributions should nevertheless be interpreted within this study's exploratory and theory-building scope. The proposed structure does not establish statistical mediation, causal effect size, predictive validity, or universal applicability across ROC configurations. Its value lies in providing an explicit and auditable conceptual structure that can subsequently be examined empirically through representative simulator and ROC studies.

6. Limitations and Future Research

This study has several limitations. First, the proposed TISM is derived from systematic literature synthesis, theoretical interpretation, and structured pairwise assessment rather than from completed empirical testing. It should, therefore, be interpreted as a literature-grounded, theory-building structural model rather than as a validated or predictive assessment model. The hierarchical levels, driving powers, and dependence powers represent relationships and reachability within the specified TISM structure; they do not quantify causal effect size, statistical mediation, predictive accuracy, or the relative empirical importance of the retained elements.

A further methodological limitation concerns the reproducibility of the original literature synthesis. Although the revised 48-study evidence register was retrospectively assembled, source-linked, and checked by the corresponding author against the available publications, the original NVivo coding records and some individual screening decisions could not be recovered. Accordingly, Supplementary Files S2 and S3 provide a documented revision-stage reconstruction rather than a complete reproduction of the original 2025 screening and coding procedures. These materials improve the traceability of the thematic findings and their interpretation within the TISM model, but they do not fully resolve the limitations associated with the historical screening and coding records.

The author-confirmed, source-linked evidence register strengthens the traceability of the thematic synthesis, while the study-design and applicability information in Supplementary File S2 provides context for interpreting the included evidence rather than a formal methodological-quality or risk-of-bias assessment. Similarly, the structural sensitivity analysis examines how alternative pairwise relationship specifications affect the TISM structure, rather than evaluating the quality or potential selection bias of the underlying literature. Accordingly, the consistency observed across the tested structural alternatives is interpreted within the scope and limitations of the reviewed evidence base, rather than as evidence of robustness to potential methodological weaknesses or selection bias.

Second, the resulting structure depends on the study boundary, construct definitions, available evidence, and pairwise relationship judgements. The structural sensitivity analysis was introduced to examine this dependence rather than to provide a statistical robustness test. The analysis showed that the downstream SA → Decision-Making Quality → Navigation Safety ordering was retained across the tested contextual alternatives, whereas the relative positions of several upstream elements changed when plausible relationships were modified. In particular, removing the HMI and Information/Data Conditions → Workload relationship returned the structure to a five-level hierarchy, while introducing reciprocal Decision-Making Quality → SA feedback caused SA and Decision-Making Quality to occupy the same level. Adding a direct Workload → Decision-Making Quality relationship did not alter the transitive closure, MICMAC driving and dependence powers, or six-level hierarchy

because Decision-Making Quality was already reachable from Workload through Situation Awareness. This structural invariance should not be interpreted as evidence against a direct influence of Workload on decision making in actual ROC operations. These findings indicate that the detailed hierarchical ordering should be interpreted as conditional on the specified relationships and temporal boundary rather than as a universally fixed ROC system structure.

Third, although this study includes a structured preliminary expert review of the TISM elements and selected relationships, this review should not be interpreted as final empirical validation or statistical consensus. Its purpose was developmental, supporting assessment of the clarity, relevance, completeness, and theoretical plausibility of the proposed model. Future research should extend this work through broader expert assessment and empirical examination under representative ROC/MASS conditions. In the wider research programme, structured expert assessment, including a Delphi-based process, may be used to examine the clarity and relevance of GDTA-derived SA requirements, their mapping to STCW competencies, and the proposed evaluation criteria. Such expert consensus procedures would complement, rather than substitute for, empirical simulator/ROC assessment. Where formal consensus or inter-rater agreement is required, the corresponding procedures and statistics should be selected prospectively according to the design and type of judgement being evaluated.

Fourth, TISM provides a static structural representation and does not simulate the continuous temporal dynamics of remote navigation. ROC/MASS operations involve repeated cycles of perception, comprehension, projection, decision making, action, feedback, and reassessment. The base model, therefore, adopts a bounded forward-influence decision episode in which SA precedes Decision-Making Quality and Decision-Making Quality precedes Navigation Safety. This analytical boundary should not be interpreted as implying that decisions, actions, system responses, or resulting outcomes cannot alter subsequent SA during continuing operations. Future empirical work should examine these temporal and feedback processes explicitly. For example, an intervention following unexpected automation behaviour may change subsequent monitoring demands, perceived workload, and trust in automation; these changes could in turn affect later information gathering, Situation Awareness, and decision making. Such feedback processes remain outside the static base hierarchy and require task-level empirical examination.

Fifth, the contextual and system conditions represented in the model should not be interpreted as independent causes of poor SA or unsafe performance. Automation level, interface and information conditions, Workload, Trust and Transparency, communication, sensor limitations, latency, procedures, training, organisational arrangements, and other operational factors may interact and may influence different stages of performance. Consequently, an observed failure in SA, decision making, action execution, or navigational outcome cannot by itself establish a competency deficiency.

Future research should, therefore, examine the proposed relationships using representative simulator and, where practicable, ROC-based studies. Goal-Directed Task Analysis can first be used to identify navigational goals, cognitive judgement requirements, and the Level 1–3 SA information requirements needed to resolve those judgements. Subsequent scenarios can then examine whether operators acquire and use the required SA, reach appropriate decisions, execute selected actions correctly, and achieve acceptable navigational outcomes under specified work-system conditions. Objective and subjective SA measures, decision-making indicators, action-execution measures, and navigational performance outcomes should be interpreted together so that competency-related explanations can be distinguished, where possible, from interface, information, Workload, automation, procedural, training, or broader system-design explanations.

Finally, the present model focuses primarily on the individual remote navigator. Future work may extend the framework to shared and distributed SA, team coordination, shared mental models, communication, and distributed decision making in multi-operator ROC environments. Such extensions would require additional constructs and relationship specifications rather than assuming that the present individual-level structure transfers unchanged to team-level operations.

7. Conclusions

This study developed a literature-grounded socio-technical structural model of remote maritime navigation by integrating systematic literature review, thematic synthesis, Total Interpretive Structural Modelling (TISM), MICMAC analysis, structural sensitivity analysis, and preliminary expert review. The purpose was not to establish a causal or predictive model but to organise the relationships among Operator Capability, Situation Awareness (SA), Decision-Making Quality, Navigation Safety, and relevant ROC work-system conditions into an explicit theory-building structure that can support subsequent empirical evaluation.

The TISM produced a six-level hierarchy, positioning Navigation Safety as the terminal operational outcome and Level of Automation as the deepest upstream system condition, with cognitive, decision-making, human-capability, and contextual elements occupying intermediate levels. These hierarchical positions and the MICMAC driving and dependence powers represent structural reachability within the specified model rather than empirical causal strength, effect magnitude, or statistical importance.

A central implication of the revised model is that SA remains an important cognitive basis for Decision-Making Quality without being treated as an exclusive mediator of all upstream influences. Operator Capability, HMI and Information/Data Conditions, Trust and Transparency, and Level of Automation may also influence Decision-Making Quality directly where the literature or established theory supports a conceptually distinct pathway. The model, therefore, represents remote-navigation performance as a socio-technical process involving interacting human capability, cognitive state, interface and information conditions, Workload, human–automation interaction, automation configuration, and decision processes rather than as a single competence → SA → decision-making → safety chain.

The structural sensitivity analysis further qualifies interpretation of the hierarchy. The downstream SA → Decision-Making Quality → Navigation Safety ordering was retained across the tested contextual alternatives under the forward-influence boundary, while the relative positions of several upstream elements changed when plausible relationships were modified. When explicit Decision-Making Quality → SA feedback was introduced, SA and Decision-Making Quality became mutually reachable and occupied the same hierarchical level. The base hierarchy should, therefore, be interpreted as a bounded representation of a single operational decision episode rather than as a complete temporal model of continuing ROC performance.

From a competency-evaluation perspective, the model provides a structured foundation for examining whether existing navigational capability remains appropriate when enacted under remote and automation-supported operating conditions. Subsequent GDTA can identify navigational goals, cognitive judgement requirements, and the Level 1–3 SA information requirements needed to resolve those judgements. These requirements can then be mapped against relevant STCW navigational competencies and examined through simulator/ROC-based assessment of whether operators acquire and use the required SA, reach appropriate decisions, execute selected actions correctly, and achieve acceptable navigational outcomes. Importantly, observed limitations in SA, decision making, action execution, or navigational performance should not automatically be interpreted as competency deficiencies; interface design, information availability and quality, sensor limitations,

latency, Workload, automation behaviour, procedures, training, communication, and other work-system conditions should also be considered.

The preliminary expert review provided developmental input into the relevance, clarity, completeness, and theoretical plausibility of the proposed elements and selected relationships, but it does not constitute empirical validation or statistical consensus. Accordingly, the contribution of this study is a transparent, literature-grounded and auditable theory-building structure that can be challenged, refined, or modified through subsequent empirical work in representative ROC/MASS environments.

8. AI Use Disclosure

AI-assisted language tools were used during manuscript preparation solely to support language clarity and editorial refinement. All conceptual development, analysis, interpretation of findings, and final scholarly decisions were undertaken by the authors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/systems14111483/s1, Supplementary File S1: TISM calculation workbook, including the SSIM, IRM, FRM, level-partitioning iterations, MICMAC calculations, pairwise audit, and structural sensitivity analyses, together with the additional E6 → E3 sensitivity verification; Supplementary File S2: Author-confirmed evidence register for the 48 studies retained in the revised formal SLR, including bibliographic information, identification routes, source-located evidence summaries, thematic associations, TISM element mappings, pairwise relationship audit, study-design characteristics, and interpretation limitations; Supplementary File S3: Historical screening provenance and 2026 eligibility reconciliation, including the recovered Rayyan and EndNote records, supplementary selections, backward-reference overlaps, retrospective eligibility decisions, and documented screening limitations; and Supplementary File S4: Preliminary Expert Review Audit Trail, including anonymised expert profiles, review procedures, individual assessments, qualitative comments, and the response-to-feedback record documenting model refinements.

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Informed Consent Statement: Informed consent was obtained from all three experts who participated in the preliminary TISM expert-review activity reported in this study. Participants were informed about the purpose of the review, the voluntary nature of participation, the confidentiality arrangements, and the intended academic use of their responses.

Data Availability Statement: The TISM matrices, calculation procedures, level-partitioning records, MICMAC results, and structural sensitivity analyses are provided in Supplementary File S1. The author-confirmed, source-linked evidence register for the 48 studies retained in the revised formal synthesis is provided in Supplementary File S2. Historical screening documentation and the retrospec-

tive eligibility reconciliation are presented in Supplementary File S3, while anonymised preliminary expert-review materials are documented in Supplementary File S4. The reconstructed supplementary records do not reproduce the unavailable original NVivo project or all original screening logs. Identifiable participant-level data are not publicly available in accordance with the approved ethical and data-management arrangements.

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