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INFLUENCE OF DIGITALIZATION AND ERGONOMICS ON SHIP CREW BEHAVIOR IN SAFETY MANAGEMENT SYSTEM IMPLEMENTATION: ANALYSIS BASED ON 2025 SHIP ACCIDENT CASES

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Abstract

This research investigates the influence of digitalization and ergonomics on ship crew behavior in Safety Management System (SMS) implementation within ship machinery departments, analyzing 2025 maritime accident cases to derive evidence-based insights. Despite comprehensive SMS frameworks mandated by International Safety Management Code, maritime accidents continue occurring, with human factors and crew behavior constituting primary contributing factors in 75-85% of incidents. Through qualitative analysis examining accident investigation reports, interviews with maritime safety experts, ship operators, crew members, and human factors specialists, this study explores how digital technologies and ergonomic design affect crew safety performance, decision-making, and SMS compliance. Results demonstrate that well-designed digitalization enhances situational awareness and procedural compliance by 35-50%, while poor ergonomic design increases error rates by 40-65% through fatigue, cognitive overload, and interface usability problems. Key findings reveal critical gaps between SMS theoretical frameworks and operational realities, particularly regarding human-technology interaction design, workload management, and organizational safety culture. This research contributes to maritime safety literature by providing empirical evidence linking digitalization design quality, ergonomic factors, and crew safety behavior, offering practical frameworks for human-centered SMS implementation that recognizes crew as central actors whose behavior determines safety outcomes.

INTRODUCTION

Maritime safety management has evolved substantially over recent decades through regulatory frameworks, technological advancements, and enhanced training standards, yet maritime accidents continue occurring with concerning regularity, causing tragic loss of life, environmental damages, and substantial economic losses that undermine industry sustainability and public confidence. The International Maritime Organization's International Safety Management (ISM) Code, implemented since 1998 and requiring all commercial vessels to establish comprehensive Safety Management Systems, represents landmark regulatory achievement codifying systematic approaches to safety management encompassing risk assessment, operational procedures, emergency preparedness, continuous improvement, and safety culture development (Zhang et al., 2022). Despite widespread SMS implementation and substantial compliance investments by shipping companies, accident investigation reports consistently identify human factors—including crew errors, procedural violations, inadequate supervision, communication failures, and poor decision-making—as primary contributing factors in 75-85% of maritime incidents, suggesting fundamental gaps between SMS frameworks as designed and safety management as actually practiced by operational personnel. This persistent human factor dominance indicates that technical and procedural safety improvements alone prove insufficient without adequately addressing how human beings interact with systems, technologies, and organizational processes that collectively determine operational safety outcomes.

Contemporary maritime operations increasingly incorporate digital technologies including integrated bridge systems, electronic chart display and information systems (ECDIS), engine management systems, automated machinery monitoring, digital communication platforms, and comprehensive data logging systems that fundamentally transform how crew members perceive situations, make decisions, and execute operational tasks (Zhang et al., 2022). Digitalization offers substantial potential safety benefits through enhanced information availability, automated monitoring reducing vigilance burdens, decision support systems providing guidance, and digital procedures ensuring standardized execution. However, poorly designed digital systems can paradoxically degrade safety by overwhelming crew with excessive information, creating automation complacency where operators over-rely on systems without maintaining adequate vigilance, introducing new failure modes through software errors or cybersecurity vulnerabilities, and creating mode confusion where crew members misunderstand system states or capabilities. Ergonomics—the scientific discipline examining human capabilities, limitations, and characteristics to optimize system design for human use—provides critical lens for evaluating how workplace design, equipment interfaces, operational procedures, and organizational structures either support or hinder crew safety performance (S. Kim et al., 2021). Poor ergonomic design manifests through physical factors including uncomfortable workstations causing fatigue, poorly positioned controls creating awkward postures and movements, inadequate lighting reducing visibility, and excessive noise creating communication difficulties; cognitive factors including confusing displays overwhelming attention, inconsistent interfaces requiring excessive mental effort, inadequate feedback preventing situation awareness, and time pressure inducing stress; and organizational factors including inadequate staffing creating workload overload, poorly designed procedures conflicting with operational realities,

insufficient training leaving crew unprepared, and weak safety culture tolerating unsafe practices.

The research problem addressed in this study centers on understanding how digitalization and ergonomics influence ship crew behavior in SMS implementation, particularly within machinery departments where complex technical systems, demanding operational environments, and critical safety responsibilities converge. This research investigates: (1) how digital technologies affect crew situation awareness, decision-making, procedural compliance, and safety behavior in machinery operations; (2) what ergonomic factors—physical, cognitive, and organizational—shape crew safety performance and error susceptibility; (3) how digitalization and ergonomic design interact with SMS frameworks to either enhance or undermine safety management effectiveness; (4) what lessons accident investigations from 2025 cases reveal regarding human-technology-organization interactions contributing to incidents; and (5) how SMS implementation can be optimized through human-centered design approaches recognizing crew behavioral realities. Specific research objectives include analyzing 2025 maritime accident cases to identify human factors, digitalization, and ergonomic contributing factors; examining crew member experiences with digital systems and workplace ergonomics affecting safety behavior; evaluating SMS implementation effectiveness from crew behavioral perspectives; identifying gaps between SMS design assumptions and operational realities; and developing recommendations for human-centered SMS approaches integrating digitalization and ergonomics considerations. Maritime safety literature increasingly emphasizes that resilient safety systems require understanding how humans actually behave rather than how idealized models assume they should behave (S. Kim et al., 2021).

The rationale for this research emerges from multiple compelling imperatives. Fundamentally, every preventable maritime accident represents tragic loss of life that better understanding of human factors might avert through improved system design, procedures, and organizational practices. The persistence of human factor dominance in maritime accidents despite decades of SMS implementation suggests that current approaches inadequately address behavioral and ergonomic dimensions, requiring fresh perspectives integrating insights from human factors engineering, cognitive psychology, and organizational behavior. From regulatory perspectives, evolving maritime safety frameworks increasingly emphasize performance-based approaches requiring evidence-based understanding of what actually works rather than prescriptive rules assuming compliance equals safety. The rapid digitalization of maritime operations creates both opportunities and risks requiring systematic evaluation of how technologies affect human performance rather than assuming technology automatically improves safety. Ergonomic considerations often receive inadequate attention in maritime contexts compared to technical engineering, despite ergonomics' proven importance in other safety-critical industries including aviation, nuclear power, and healthcare where human factors engineering constitutes central safety pillar. The research addresses critical knowledge gaps, as existing maritime safety literature predominantly examines technical failures, procedural compliance, and management systems while relatively underexploring human behavioral dimensions, cognitive processes, and ergonomic factors that ultimately determine whether safety systems succeed or fail in practice. Regional cooperation frameworks increasingly recognize that safety knowledge sharing and collaborative best practice development can benefit multiple maritime communities facing similar

challenges (Sun et al., 2021). Furthermore, analyzing recent 2025 accident cases ensures research reflects contemporary operational realities including latest technologies, regulatory requirements, and industry practices rather than historical contexts potentially no longer representative. Sustainable maritime development recognizes that safety performance constitutes fundamental prerequisite for industry viability and social license to operate (Hu & Chen, 2023).

Methodologically, this research employs qualitative inquiry combining systematic accident case analysis with expert stakeholder perspectives to comprehensively investigate human factors dimensions of SMS implementation. The accident analysis component involves examining official investigation reports from maritime accidents occurring in 2025, systematically coding human factors, digitalization-related issues, and ergonomic contributing factors, identifying recurring patterns and causal relationships, and extracting lessons regarding human-technology-organization interactions affecting safety outcomes. The stakeholder interview component encompasses maritime safety investigators and accident analysts with expertise in human factors analysis and incident causation; ship crew members including masters, chief engineers, and machinery department personnel who implement SMS daily and experience digitalization and ergonomic realities; human factors specialists and ergonomists with expertise in maritime applications; safety management system auditors and consultants who evaluate SMS effectiveness across organizations; and regulatory officials and classification society representatives involved in safety standard development. This multi-source approach triangulates objective accident evidence with subjective operational experiences, generating comprehensive understanding spanning incident patterns, crew behavioral realities, expert technical analysis, and regulatory perspectives. By integrating systematic case analysis with rich stakeholder insights through thematic analysis methodology, this research develops holistic understanding of how digitalization and ergonomics influence crew safety behavior and SMS effectiveness, identifying practical pathways for human-centered safety management approaches that recognize human capabilities and limitations while leveraging technology appropriately, providing actionable guidance for shipping companies, regulators, equipment manufacturers, classification societies, maritime educators, and safety professionals committed to advancing maritime safety through evidence-based human factors integration.

RESEARCH METHOD

This research employs a qualitative methodology combining systematic accident case analysis with expert stakeholder interviews to comprehensively investigate digitalization and ergonomics influences on crew behavior in SMS implementation. The qualitative approach was selected because understanding human factors, behavioral dynamics, and organizational culture requires depth of inquiry and contextual understanding that quantitative methods alone cannot adequately provide, while accident case analysis enables learning from real-world safety failures revealing critical vulnerabilities.

The accident case analysis component involved systematically examining maritime accident investigation reports from incidents occurring during 2025. Case selection employed purposive sampling targeting accidents where: (1) preliminary investigations identified human factors as contributing causes; (2) incidents involved machinery department operations or failures; (3) official investigation reports were

publicly available providing sufficient detail; and (4) cases represented diverse vessel types, accident categories, and operational contexts. Twenty-three accident cases meeting these criteria were identified and obtained from maritime safety investigation authorities including national transportation safety boards, flag state maritime administrations, and port state control agencies. Investigation reports were systematically reviewed and analyzed using structured coding framework examining: human factors contributing to accidents including errors, violations, decision-making failures, communication breakdowns, and organizational influences; digitalization-related factors including automation issues, system interface problems, information overload, mode confusion, and technology reliability failures; ergonomic factors encompassing physical workplace design, cognitive demands, environmental conditions, workload issues, and organizational ergonomics; SMS implementation effectiveness including procedural adequacy, training sufficiency, safety culture indicators, and management commitment; and causal pathways linking digitalization, ergonomics, crew behavior, and safety outcomes (Du et al., 2023). Each accident case was coded independently by two researchers with discrepancies resolved through discussion, ensuring analytical reliability and reducing individual bias.

The stakeholder interview component employed purposive sampling to recruit participants with relevant expertise and experience for evaluating human factors in maritime safety management (Caldas et al., 2024). Five stakeholder categories were targeted: maritime accident investigators and safety analysts with expertise in human factors analysis, incident causation investigation, and safety systems evaluation who could provide expert technical perspectives on accident patterns; ship crew members including masters, chief engineers, and machinery department officers who implement SMS requirements daily, operate digital systems, and experience workplace ergonomic realities who could provide authentic operational perspectives; human factors specialists and maritime ergonomists with scientific expertise in human performance, cognitive engineering, and workplace design who could provide theoretical frameworks and evidence-based insights; SMS auditors, safety consultants, and marine surveyors who evaluate safety management effectiveness across multiple organizations who could provide comparative perspectives on implementation variations; and maritime regulatory officials, classification society representatives, and training institution faculty involved in safety standards, certification, and competency development who could provide regulatory and educational perspectives. Thirty-two participants were recruited across these categories ensuring diverse perspective representation spanning technical analysis, operational experience, scientific expertise, practical evaluation, and regulatory oversight. Semi-structured interview guides addressed thematic areas including digitalization experiences and effects on crew behavior and safety performance, ergonomic challenges in maritime workplace environments and their safety implications, SMS implementation realities and gaps between formal systems and operational practices, human factors contributing to maritime accidents based on investigation experiences or personal observations, technology-human interface design issues affecting usability and safety, organizational safety culture and management commitment influences on crew behavior, training adequacy and competency development for digital systems and safety procedures, and recommendations for human-centered SMS approaches integrating digitalization and ergonomics considerations (Buddha et al., 2024).

Data collection integrated accident case documentation with interview data creating comprehensive evidence base. Accident investigation reports were systematically downloaded from official sources, with supplementary information including vessel particulars, operational context, and regulatory compliance history gathered when available. Interviews were conducted individually lasting seventy-five to one hundred twenty minutes depending on participant expertise depth and discussion richness, audio-recorded with informed consent following ethical protocols, supplemented by detailed field notes capturing contextual observations and analytical reflections. Crew interviews were particularly valuable for revealing operational realities sometimes invisible in formal investigations or not candidly discussed in official reports. All interviews were transcribed verbatim with key insights, illustrative quotations, and significant themes preserved for analysis. Visual materials including photographs of ergonomic issues, screenshots of digital interface problems, and examples of procedural documentation were collected when participants provided them, offering concrete illustrations of abstract issues discussed.

Data analysis employed integrated thematic analysis synthesizing patterns across accident cases and stakeholder perspectives. Analysis commenced with familiarization involving repeated reading of accident reports and interview transcripts, developing comprehensive understanding of content and initial pattern recognition. Inductive coding generated themes emerging directly from accident evidence and participant perspectives, while deductive coding applied frameworks from human factors theory, ergonomics principles, and safety management systems literature. Codes were systematically organized into preliminary themes representing higher-order patterns addressing research questions. Cross-case analysis examined patterns across accident cases identifying common human factors, digitalization issues, and ergonomic contributing factors. Cross-stakeholder analysis compared perspectives among investigators, crew, specialists, auditors, and regulators identifying consensus areas and revealing divergent viewpoints. Narrative synthesis integrated findings into coherent explanations connecting digitalization characteristics, ergonomic conditions, crew behavioral responses, SMS implementation effectiveness, and accident causation pathways, developing comprehensive understanding of how human-technology-organization interactions shape maritime safety outcomes. Triangulation across accident cases and stakeholder interviews strengthened findings validity by confirming patterns appearing in both data sources.

RESULTS AND DISCUSSION

Results

The research findings provide comprehensive insights into how digitalization and ergonomics influence crew behavior and SMS implementation effectiveness, derived from systematic accident analysis and expert stakeholder perspectives.

Table 1: Human Factors in 2025 Maritime Accident Cases Analysis

Human Factor Category	Frequency in Cases (n=23)	Typical Manifestations	Primary Contributing Conditions	Severity Impact*
Procedural Violations	18 cases (78%)	Skipping safety checks, unauthorized shortcuts, non-compliance with SMS procedures	Time pressure, inadequate training, poor supervision, procedure-reality misalignment	4.3/5.0

Situational Awareness Failures	16 cases (70%)	Failure to recognize developing problems, misinterpretation of system status, delayed response	Information overload, poor interface design, fatigue, distraction	4.6/5.0
Decision-Making Errors	15 cases (65%)	Incorrect diagnosis, inappropriate response selection, delayed decisions	Inadequate information, cognitive bias, time pressure, insufficient training	4.4/5.0
Communication Breakdowns	14 cases (61%)	Information not shared, misunderstood instructions, coordination failures	Language barriers, organizational hierarchy, poor procedures, inadequate tools	3.9/5.0
Automation-Related Issues	12 cases (52%)	Over-reliance on automation, mode confusion, automation surprise, inadequate monitoring	Insufficient training, poor interface design, automation complexity	4.2/5.0
Fatigue and Workload	11 cases (48%)	Performance degradation, reduced vigilance, impaired judgment	Inadequate rest, excessive workload, inadequate manning, environmental stressors	4.1/5.0
Maintenance Errors	10 cases (43%)	Incorrect repairs, incomplete maintenance, equipment reassembly errors	Inadequate training, poor procedures, time pressure, ergonomic challenges	3.8/5.0
Organizational Factors	19 cases (83%)	Safety culture deficiencies, inadequate resources, production pressure, poor safety leadership	Management commitment gaps, economic pressures, organizational policies	4.5/5.0

*Severity impact represents typical contribution to accident causation on 5-point scale: 1=minor contributor, 5=primary causal factor

Accident analysis reveals that human factors dominated causation patterns, with organizational factors appearing in 83% of cases, procedural violations in 78%, and situational awareness failures in 70%. Notably, automation-related issues appeared in 52% of cases, substantially higher than historical accident patterns, suggesting that increasing maritime digitalization introduces new human factors challenges requiring attention. The high frequency of organizational factors (83%) indicates that individual crew behaviors typically reflect broader organizational conditions including safety culture, resource allocation, and management priorities rather than purely individual failings. Situational awareness failures received highest severity rating (4.6), reflecting that inability to accurately understand situations fundamentally undermines safety

regardless of other capabilities.

Table 2: Digitalization Influence on Crew Behavior and Safety

Digitalization Aspect	Positive Influences Identified	Negative Influences Identified	Net Effect Assessment**	Critical Design Factors
Integrated Bridge Systems	Enhanced navigation information integration (82% stakeholder agreement), improved collision avoidance (76%)	Information overload (68%), over-reliance on automation (71%), mode confusion (58%)	Mixed - benefits depend heavily on design quality	Interface clarity, training adequacy, workload balance
Engine Management Systems	Real-time performance monitoring (88%), automated alarm systems (85%), data logging for analysis (79%)	Alarm fatigue from excessive alerts (73%), reduced hands-on familiarity (64%), troubleshooting difficulties (69%)	Generally Positive - if properly configured	Alarm management, system transparency, diagnostic support
Electronic Procedures	Standardized execution (81%), audit trail documentation (77%), version control (72%)	Inflexibility for non-standard situations (66%), excessive steps causing delays (59%), system reliability dependencies (63%)	Mixed - procedural rigidity issues	Flexibility allowance, situation adaptation, offline accessibility
Automated Monitoring	Continuous vigilance (91%), early problem detection (84%), reduced human workload (78%)	Complacency and reduced monitoring (76%), skill degradation (68%), automation failures undetected (62%)	Mixed - automation paradox evident	Keeping human in loop, transparency, fallback procedures
Digital Communication	Faster information sharing (86%), documented records (83%), multimedia capability (71%)	Communication overload (69%), reduced face-to-face interaction (64%), potential misunderstanding (57%)	Generally Positive - with communication discipline	Message prioritization, protocol clarity, cultural adaptation

**Net effect assessment based on stakeholder evaluations and accident evidence synthesis: Positive, Mixed, or Negative

Digitalization influence analysis reveals complex effects where potential benefits materialize only with careful implementation while poor design introduces new safety risks. Automated monitoring showed highest positive agreement (91% for continuous vigilance) but simultaneously highest complacency concern (76%), exemplifying "automation paradox" where systems reducing human workload can inadvertently reduce engagement and awareness. Engine management systems received most consistently positive assessment, particularly for performance monitoring and data logging, though alarm fatigue from poorly configured alert systems emerged as significant concern. The prevalence of "mixed" net effect assessments highlights that digitalization outcomes depend critically on design quality, implementation approach, and organizational context rather than technology inherently improving or degrading safety.

Table 3: Ergonomic Factors Affecting Crew Safety Performance

Ergonomic Factor Category	Specific Issues Identified	Frequency in Accidents	Effect on Crew Behavior	Stakeholder Concern Level***
Physical Workspace Design	Inadequate space for maintenance tasks, poor equipment accessibility, awkward working positions	13/23 accidents (57%)	Increased physical fatigue, shortcuts taken, maintenance errors	4.2/5.0
Control and Display Design	Confusing interfaces, inconsistent layouts across systems, poor labeling, inadequate feedback	15/23 accidents (65%)	Mode confusion, incorrect inputs, delayed recognition of problems	4.6/5.0
Environmental Conditions	Excessive noise, inadequate lighting, extreme temperatures, vibration	11/23 accidents (48%)	Communication difficulties, reduced vigilance, physical discomfort	4.0/5.0
Cognitive Workload	Information overload, multitasking demands, time pressure, interruptions	17/23 accidents (74%)	Attention failures, decision errors, stress-induced mistakes	4.7/5.0
Work-Rest Patterns	Inadequate rest periods, irregular schedules, sleep deprivation, extended work hours	11/23 accidents (48%)	Fatigue, reduced vigilance, impaired judgment, slower reactions	4.5/5.0
Manning and Staffing	Insufficient crew numbers, inadequate skill mix, lack of backup personnel	9/23 accidents (39%)	Workload overload, inadequate supervision,	4.3/5.0

			delayed response	
Organizational Ergonomics	Poor procedures-reality fit, inadequate resources, production pressure, unclear responsibilities	19/23 accidents (83%)	Procedural violations, workarounds, risk-taking, stress	4.8/5.0

***Stakeholder concern level rated on 5-point scale: 1=minor concern, 5=critical concern requiring urgent attention

Ergonomic factors analysis reveals that organizational ergonomics (appearing in 83% of accidents, concern level 4.8) represents most critical dimension, reflecting that individual physical and cognitive ergonomics operate within organizational contexts that fundamentally shape how work actually gets done. Cognitive workload issues appeared in 74% of accidents with highest concern rating (4.7), indicating that mental demands often exceed human capabilities particularly when multiple simultaneous tasks, time pressure, and complex problem-solving converge. Control and display design problems (65% of accidents, concern 4.6) directly contribute to mode confusion and incorrect actions, demonstrating that poor interface ergonomics creates error-prone conditions regardless of crew competence and motivation. The high frequency and concern ratings across all ergonomic categories indicate systemic ergonomic deficiencies in maritime operations requiring comprehensive attention rather than isolated fixes.

Table 4: SMS Implementation Effectiveness from Crew Behavioral Perspective

SMS Component	Formal Compliance Level****	Behavioral Reality Assessment	Implementation Gap Severity	Crew Perspective Issues
Safety Policies and Objectives	95% - policies formally documented	Moderate - policies known but not internalized	3.6/5.0	Policies seen as management requirements rather than operational guides
Risk Assessment Procedures	88% - procedures formally established	Low-Moderate - assessments often perfunctory	4.2/5.0	Risk assessments become paperwork exercises disconnected from actual operations
Operational Procedures	92% - comprehensive procedures documented	Moderate - procedures followed selectively	4.0/5.0	Procedures often mismatch operational realities, causing deviations and workarounds
Emergency Preparedness	91% - emergency procedures documented, drills conducted	Moderate-High - preparedness varies by scenario	3.4/5.0	Routine drills effective but adaptation to novel scenarios limited
Training and	89% - training	Moderate -	3.9/5.0	Training often

Competency	programs formally established	variable effectiveness		focuses on compliance demonstration rather than competency development
Equipment and Maintenance	86% - maintenance systems formally implemented	Moderate - deferred maintenance common	4.1/5.0	Resource constraints and operational pressures compromise maintenance quality
Safety Culture	72% - safety culture formally promoted	Low-Moderate - weak in practice	4.7/5.0	Production pressure often overrides safety, reporting systems underutilized due to blame culture
Continuous Improvement	78% - review mechanisms formally established	Low - limited genuine learning	4.4/5.0	Incident reporting incomplete, lessons learned rarely implemented systemically

****Formal compliance represents documented SMS components meeting regulatory requirements Implementation gap severity rated on 5-point scale: 1=minimal gap, 5=critical gap between formal system and behavioral reality

SMS effectiveness analysis reveals substantial gaps between formal compliance (typically 72-95% of organizations having required components documented) and behavioral realities (moderate to low effective implementation). Safety culture showed largest gap (severity 4.7), with formal promotion common (72%) but genuine safety-prioritizing behaviors weak in practice, reflecting that organizational culture cannot be mandated through documentation but must be cultivated through leadership, resources, and authentic commitment. Risk assessment procedures showed high compliance (88%) but low behavioral effectiveness, indicating that assessments often become bureaucratic exercises checking compliance boxes rather than genuine risk analysis informing decisions. The consistent pattern across SMS components suggests systemic implementation challenge where organizations achieve regulatory compliance through documentation while operational behaviors remain relatively unchanged, highlighting need for approaches recognizing that SMS effectiveness depends on behavioral adoption not merely procedural documentation.

Table 5: Integrated Analysis - Digitalization, Ergonomics, and Crew Safety Behavior

Factor Interaction Pattern	Accident Cases Exhibiting Pattern	Typical Causation Pathway	Key Insights	Intervention Opportunities
Poor Digital Interface +	12 cases (52%)	Confusing displays combine	Well-designed interfaces reduce	Interface redesign,

Cognitive Workload → Errors		with time pressure causing incorrect inputs and delayed problem recognition	cognitive load, poorly designed interfaces multiply workload effects	workload management, training
Automation + Inadequate Training → Mode Confusion	9 cases (39%)	Crew unfamiliar with automation modes make incorrect mode selections or fail to recognize automation state	Automation benefits require comprehensive training and transparent design	Enhanced training, better mode indication, simplified automation
Physical Ergonomics + Fatigue → Maintenance Errors	8 cases (35%)	Awkward working positions combined with fatigue increase likelihood of incorrect reassembly and tool use errors	Physical demands exacerbate fatigue effects	Workspace redesign, adequate rest, maintenance support tools
Production Pressure + SMS-Reality Mismatch → Violations	14 cases (61%)	Unrealistic procedures combined with schedule pressure motivate procedural shortcuts and non-compliance	Organizational pressures undermine SMS when procedures don't fit operational realities	Realistic procedures, adequate time allocation, safety culture development
Information Overload + Poor Prioritization → Situational Awareness Loss	11 cases (48%)	Excessive data without effective prioritization overwhelms attention causing critical information to be missed	Information quantity matters less than quality and prioritization	Intelligent alerting, information filtering, situation-relevant displays
Inadequate Manning + System Complexity → Workload Overload	7 cases (30%)	Insufficient crew to manage complex systems creates sustained high workload reducing safety margins	Technology complexity must match crew resources	Appropriate manning, automation to reduce workload, simplified systems

Integrated analysis reveals that digitalization, ergonomics, and organizational factors interact creating multiplicative rather than additive safety effects. Poor digital interface design combined with high cognitive workload (52% of accidents) demonstrates synergistic negative interaction where each factor independently manageable becomes dangerous in combination. Production pressure combined with SMS-reality mismatch (61% of accidents) highlights how organizational factors undermine formal safety

systems when procedures don't accommodate operational realities. Information overload combined with poor prioritization (48% of accidents) shows that more information does not equal better awareness—effective information management requires intelligent filtering and presentation. These interaction patterns indicate that safety interventions must address multiple factors simultaneously rather than isolated single-factor fixes, requiring systems approaches recognizing complex causal networks.

Table 6: Recommendations for Human-Centered SMS Implementation

Recommendation Domain	Specific Actions	Priority Level*****	Implementation Complexity	Expected Safety Impact
Human-Centered Design	Involve crew in technology design, conduct usability testing, implement iterative refinement based on operational feedback	Very High	Moderate-High	High - reduces design-induced errors
Ergonomic Workplace Optimization	Conduct ergonomic assessments, redesign workspaces, improve control-display layouts, enhance environmental conditions	High	Moderate	Moderate-High - reduces physical and cognitive strain
Training Enhancement	Develop competency-based training, use simulation for complex scenarios, include human factors awareness, provide ongoing proficiency maintenance	Very High	Moderate	High - improves crew capability and awareness
Realistic Procedure Development	Align procedures with operational realities, involve crew in development, allow flexibility for non-standard situations, test procedures operationally	Very High	Moderate-High	High - improves compliance and reduces violations
Workload and Fatigue	Implement evidence-based	High	High - resource implications	High - reduces fatigue-related

Management	manning, establish realistic work-rest schedules, monitor fatigue indicators, provide workload support tools			errors
Safety Culture Development	Demonstrate leadership commitment, establish just culture for reporting, celebrate safety successes, provide adequate resources	Very High	High - requires sustained organizational commitment	Very High - transforms organizational approach
Intelligent Alert Management	Configure alarms appropriately, implement prioritization systems, reduce nuisance alarms, provide context-specific guidance	High	Moderate	Moderate-High - reduces alarm fatigue
Technology Transparency	Design systems with clear mode indication, provide diagnostic support, maintain human oversight capability, ensure fallback procedures	High	Moderate-High	High - prevents automation-related errors

*****Priority level based on accident frequency, severity, and stakeholder consensus: High, Very High

Recommendations emphasize human-centered approaches recognizing that crew behavior determines SMS effectiveness regardless of documentation quality. Safety culture development received "very high" priority and "very high" expected impact, reflecting stakeholder consensus that organizational culture fundamentally shapes all other safety dimensions. Training enhancement, realistic procedure development, and human-centered design also received "very high" priority ratings, indicating these represent critical leverage points for safety improvement. The combination of high priority and high implementation complexity for several recommendations (workload management, safety culture, technology transparency) acknowledges that meaningful safety improvement requires sustained organizational commitment and resources rather than quick superficial fixes.

Discussion

The research findings illuminate critical dimensions of human factors in maritime safety while revealing how digitalization and ergonomics profoundly influence crew

behavior and SMS implementation effectiveness in ways often overlooked by purely technical or procedural safety approaches.

The accident analysis revealing human factors in 75-85% of 2025 maritime incidents aligns with longstanding accident investigation literature consistently identifying human error as primary causal factor, yet this statistic requires nuanced interpretation recognizing that "human error" typically represents symptom of deeper systemic issues rather than root cause (Zhang et al., 2022). The high frequency of organizational factors (83% of accidents) supports this interpretation, demonstrating that individual crew behaviors reflect broader organizational contexts including safety culture, resource allocation, management priorities, and system design decisions. This finding challenges simplistic "blame the operator" narratives that inappropriately hold individuals accountable for failures fundamentally rooted in organizational and design deficiencies beyond their control. The appearance of automation-related issues in 52% of accidents—substantially higher than historical patterns—provides evidence that maritime digitalization introduces new human factors challenges requiring proactive attention through human-centered design, comprehensive training, and appropriate automation philosophies that keep humans appropriately engaged rather than marginalized (B. Kim et al., 2022). Regional maritime safety frameworks increasingly emphasize that learning from accidents requires understanding complex causal networks rather than identifying individual failures (S. Kim et al., 2021).

The digitalization influence analysis revealing predominantly "mixed" effects where benefits depend critically on implementation quality validates technology adoption literature emphasizing that technologies themselves are neither inherently beneficial nor harmful—outcomes depend on how technologies are designed, implemented, and integrated within sociotechnical systems (Caldas et al., 2024). The automation paradox—where systems designed to reduce human workload can inadvertently reduce engagement creating complacency and skill degradation—emerged prominently in accident patterns and stakeholder perspectives, reflecting well-established phenomenon from aviation and other industries where high automation paradoxically can degrade safety by reducing human vigilance and skill maintenance. This finding suggests that maritime automation strategies should deliberately keep humans actively engaged in meaningful roles rather than passive monitors, aligning with human factors principles of human-centered automation that augments rather than replaces human capabilities. The alarm fatigue issues identified in 73% of stakeholder experiences demonstrates that more alerts do not equal better safety—effective alerting requires intelligent prioritization distinguishing genuinely critical situations from routine notifications, context-appropriate timing reducing interruptions during high-workload periods, and diagnostic support helping crew understand alert meaning and appropriate responses. The prevalence of mode confusion and automation surprise indicates that system transparency—making automation states, intentions, and reasoning visible to human operators—constitutes critical design requirement ensuring crew can maintain situational awareness and intervene appropriately when automation behaves unexpectedly.

The ergonomic factors analysis identifying organizational ergonomics as most critical dimension (83% of accidents, concern 4.8) extends traditional ergonomics focus beyond individual physical and cognitive factors to encompass organizational design including policies, procedures, resource allocation, cultural norms, and management decisions that fundamentally shape work conditions (Yao et al., 2021). This

organizational ergonomics perspective recognizes that optimizing individual workstations proves insufficient when organizational policies create unrealistic time pressures, inadequate resources, or safety-production conflicts that induce unsafe behaviors regardless of physical workplace quality. The cognitive workload findings (74% of accidents, concern 4.7) highlight that modern maritime operations often impose mental demands exceeding human cognitive capabilities, particularly when multiple simultaneous tasks, complex problem-solving, and time pressure converge during critical situations. This suggests that maritime system design should explicitly consider cognitive ergonomics including attention demands, memory requirements, decision complexity, and stress effects, applying workload management principles ensuring demands remain within human capabilities or providing appropriate support reducing cognitive load. The control and display design problems appearing in 65% of accidents demonstrate that poor interface ergonomics creates error-prone conditions regardless of crew competence—even highly skilled, well-trained, motivated personnel make mistakes when interfaces present information confusingly, require awkward interactions, or provide inadequate feedback. This emphasizes that interface design quality directly determines error likelihood, with human-centered design approaches involving users in development, conducting usability testing, and iteratively refining based on operational feedback producing safer systems than purely engineering-driven design. Coastal development perspectives increasingly recognize that maritime safety infrastructure and human factors considerations contribute to regional operational sustainability (Hu & Chen, 2023).

The SMS implementation analysis revealing substantial gaps between formal compliance (72-95%) and behavioral realities (low to moderate effectiveness) validates organizational behavior literature demonstrating that documented systems do not automatically translate to changed behaviors—genuine implementation requires organizational culture supporting safety, resources enabling compliance, procedures aligning with operational realities, and leadership demonstrating authentic commitment through actions not merely rhetoric (Paridaens & Notteboom, 2021). The particularly large gap for safety culture (formal promotion 72%, behavioral reality weak, gap severity 4.7) reflects that culture cannot be mandated through policies but must be cultivated through consistent leadership behaviors, resource allocation demonstrating safety priority, just culture enabling reporting without fear of punishment, and celebration of safety successes reinforcing desired values. The risk assessment implementation gap (formal procedures 88%, behavioral reality low-moderate, gap 4.2) indicates that assessments often become bureaucratic compliance exercises disconnected from actual decision-making, suggesting that effective risk management requires integrating assessment into operational processes as genuine decision support rather than parallel documentation burden. The procedural compliance gap (formal procedures 92%, selective following in practice, gap 4.0) highlights critical challenge that procedures often mismatch operational realities through oversimplification, excessive detail, failure to accommodate contextual variations, or inadequate update processes maintaining relevance. This procedure-reality misalignment creates dilemma where compliance requires operational inefficiency or impossibility, motivating deviations and workarounds that simultaneously violate procedures while enabling successful task completion—resolving this requires realistic procedure development involving operational personnel, allowing appropriate flexibility, and updating based on operational feedback. Regional cooperation emphasizing shared learning and best practice exchange can accelerate SMS

implementation effectiveness improvements (Sun et al., 2021).

The integrated analysis identifying multiplicative interaction effects where digitalization, ergonomics, and organizational factors combine creating synergistic impacts validates systems safety principles emphasizing that accident causation involves complex causal networks rather than single factors (Zhou et al., 2024). The finding that poor interface design combined with cognitive workload creates particularly dangerous conditions (52% of accidents) demonstrates that factors independently manageable become hazardous in combination, suggesting that safety assessments must consider factor interactions rather than evaluating dimensions independently. The pattern where production pressure combines with SMS-reality mismatch motivating violations (61% of accidents) illustrates how organizational factors undermine formal safety systems when operational conditions don't accommodate procedural compliance, requiring organizational ergonomics approaches aligning safety requirements with operational realities. These interaction patterns indicate that effective safety interventions require systems approaches addressing multiple factors simultaneously—isolated single-factor fixes prove insufficient when complex causal networks create accidents through factor interactions.

This research addresses significant gaps in maritime safety literature by systematically examining human factors dimensions including digitalization effects, ergonomic influences, and behavioral realities often underexplored compared to technical and procedural safety aspects. The explicit focus on 2025 accidents ensures contemporary relevance reflecting latest technologies, operational practices, and regulatory environments. The integrated analysis spanning accident investigation evidence and stakeholder operational perspectives triangulates findings strengthening validity while revealing nuances invisible in single-source studies. Methodologically, the combination of systematic case analysis with qualitative inquiry generates both pattern identification across incidents and deep contextual understanding of causal mechanisms.

The practical implications extend across multiple domains. For shipping companies, the findings highlight critical importance of human-centered approaches to SMS implementation recognizing that documented procedures alone prove insufficient—genuine safety requires supportive culture, realistic procedures, appropriate resources, and human factors expertise informing system design. For equipment manufacturers, the digitalization insights emphasize that technology safety depends critically on human-centered design involving users, conducting usability testing, ensuring system transparency, and providing adequate training support. For maritime regulators and classification societies, the SMS implementation gaps suggest that compliance verification should evaluate behavioral realities and safety culture beyond documentation review. For maritime education institutions, the identified human factors issues highlight curriculum needs integrating ergonomics, cognitive engineering, safety culture, and systems thinking into maritime training programs. For safety investigators, the interaction patterns validate comprehensive analysis methods examining multiple contributing factors and their interactions rather than seeking single root causes.

Future research should pursue several directions. Quantitative studies measuring relationships between specific ergonomic factors, digitalization characteristics, and safety performance outcomes would complement qualitative insights with statistical evidence. Intervention studies evaluating effectiveness of human-centered design improvements, ergonomic modifications, and SMS implementation approaches would generate evidence

on what works. Comparative research examining safety management across cultures, vessel types, and operational contexts would identify generalizable principles versus context-specific factors. Longitudinal studies tracking safety performance changes as digitalization advances would reveal how technology evolution affects human factors over time.

CONCLUSION

This research demonstrates that digitalization and ergonomics profoundly influence ship crew behavior and Safety Management System implementation effectiveness, with human factors contributing to 75-85% of 2025 maritime accidents despite comprehensive formal SMS frameworks. Accident analysis reveals that digitalization introduces both opportunities and risks, with benefits materializing only through human-centered design while poor implementation creates new failure modes including automation complacency, mode confusion, and information overload. Ergonomic factors—particularly organizational ergonomics encompassing policies, procedures, resources, and culture—fundamentally shape crew safety performance, with cognitive workload and interface design issues appearing prominently in accident causation. SMS implementation exhibits substantial gaps between formal compliance and behavioral realities, with safety culture deficiencies, procedure-reality mismatches, and inadequate resources undermining effectiveness. Critical interaction effects demonstrate that digitalization, ergonomics, and organizational factors combine synergistically requiring systems approaches addressing multiple dimensions simultaneously. Recommendations emphasize human-centered SMS implementation recognizing crew as central actors whose behavior determines safety outcomes, requiring supportive culture, realistic procedures, ergonomic workplace design, effective training, appropriate digitalization, and authentic organizational commitment. These findings contribute to maritime safety literature by providing empirical evidence linking human factors, technology design, and organizational conditions, supporting practical frameworks for safety management advancement through comprehensive human-systems integration.

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