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Human Factors Challenges in Future Remote Operations for Electrified Short-Sea Ro-Ro Ferries

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ABSTRACT

Maritime operations are undergoing significant transformation driven by increasing levels of autonomy, electrification, digitalization, and artificial intelligence. These trends, combined with crew shortages are accelerating interest in Remote Operation Centers (ROCs) for shore-based fleet supervision. This is particularly relevant for short-sea Ro-Ro ferry operations, where repetitive, constrained, and time-critical electrified routes make ROC operations a promising approach for improving safety, performance, and energy efficiency. However, ROC implementation is not merely a technical change — performance, safety, and scalability will depend heavily on how human factors challenges are understood and addressed. Existing research has identified key issues such as insufficient situational awareness, vigilance decline, workload dynamics, trust, and communication challenges. Yet prior work has largely focused on navigation-oriented supervision, with limited attention to engineering tasks, and much of the literature remains conceptual or simulation-based. Current research therefore provides only a partial view of human factors challenges within the broader sociotechnical reconfiguration of roles and human-technology interaction across ship and shore. This paper addresses this gap through an exploratory qualitative study combining field visits, observations, and interviews across onboard and real-world ROC environments for Nordic short-sea ferry operations. Data from more than 40 participants including master mariners, ship engineers, and maritime experts were analyzed using thematic analysis supported by MAXQDA and affinity diagramming. The findings reveal interconnected human factors challenges spanning cognitive, organizational, physical, and technical-system domains. Key challenges include loss of embodied navigational and engineering cues, high switching demands in multi-vessel supervision, cognitive fatigue from multi-screen monitoring, role ambiguity, and intensive cross-organizational communication. These are compounded by fragmented interfaces, alarm floods, and unreliable connectivity, increasing operator burden in time-critical operations. The findings extend prior research by providing an empirically grounded view across both navigational and engineering domains, with implications for system design, operator competencies, organizational arrangements, and human-centered ROC development.

Keywords: Remote operation, Human factors, Short-Sea shipping, Electrified ferries, Cognition, Situation awareness, Sociotechnical systems, Interaction design

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INTRODUCTION

Maritime operations are undergoing a broader transition driven by increasing levels of automation, electrification, digitalization, artificial intelligence, and expanded connectivity (Lützhoft & Earthy, 2024). At the same time, the industry faces structural pressures such as crew shortages, rising operational costs, and the need for more resilient and sustainable service models (Caesar, 2024). These developments are accelerating interest in more distributed forms of ship-shore collaboration, including emerging Remote Operation Center (ROC) concepts.

ROCs are increasingly envisioned as shore-based hubs for fleet-level oversight, coordination, and technical support. ROC operation appears particularly promising for short-sea Ro-Ro ferry services, where routes are geographically constrained and repetitive, turnaround times are tight, and operations are increasingly shaped by hybrid and battery-electric propulsion. In such contexts, shore-based supervision offers potential value through more proactive monitoring, improved energy management, and the ability to consolidate expertise across several vessels.

However, ROC implementation will involve a substantial reconfiguration of work, roles, and responsibilities (Man et al., 2018). Increasing attention to "Maritime 5.0" perspectives also underscores the need for a more human-centric paradigm that emphasizes effective collaboration between humans and intelligent systems (Autsadee et al., 2025). Remote operators must maintain awareness, coordinate across multiple actors, interpret complex technical and energy-related systems, and remain intervention-ready during abnormal situations. How human factors (HF) challenges are understood and addressed will therefore be central to ROC viability (Veitch et al., 2024).

Existing research on remote autonomous maritime operations has highlighted concerns around situational awareness, workload, vigilance, trust, and communication (Kari and Steinert, 2021; Fan et al., 2020). However, much of the existing work remains conceptual or simulation-based, focusing primarily on navigational supervision while leaving Engine Control Room (ECR)-related operations underexplored (Kooij et al., 2018), offering limited insight into challenges around the specific characteristics of electrified short-sea ferry operations. As a result, limited attention has been given to the human factors implications for this emerging ROC-dominant context.

To address these gaps, this paper presents an exploratory qualitative study based on field visits, observations, and interviews with maritime professionals across onboard bridge and ECR settings, as well as emerging shore-based operational contexts in Nordic short-sea ferry operations. The aim is to identify and synthesize overarching human factors challenges associated with future ROC operations for electrified Ro-Ro ferry services, contributing a sociotechnical perspective on the evolving nature of operator work and high-level considerations for human-centered ROC system design.

RELATED WORK

The transition from onboard operations to distributed shore-based ROC fundamentally reshapes maritime work, shifting operators from direct control roles toward supervisory forms of human-automation interaction (Man et al., 2018; Lynch et al., 2024; Veitch & Alsos, 2024). Prior research has identified several core constructs critical to this transition, including situational awareness (SA), cognitive workload, trust in automation (Man et al., 2015; Man et al., 2018; Kari & Steinert, 2021; Fan et al., 2020). ROC operators may be required to supervise multiple vessels simultaneously, increasing the risk of information overload and "carryover effects," in which information associated with one vessel is mistakenly attributed to another (Fan et al., 2020). Furthermore, the lack of ship sense or direct physical connection to the vessel results in the loss of vital kinetic cues, such as vibrations and heaving, traditionally used by seafarers to achieve "harmony" with the ship's response to the environment (Prison et al., 2013; Man et al., 2018). This detachment can lead to "out-of-the-loop" syndrome, where operators struggle to intervene effectively after long periods of passive monitoring characterized by boredom and vigilance decrement (Man et al., 2018; Porathe, 2023).

Despite these insights, much of the existing literature remains conceptual or simulation-based (Gernez et al., 2025), relies on expert judgment in the absence of real accident data (Li & Yuen, 2024), and has predominantly focused on navigational supervision and collision-avoidance scenarios (Tao et al., 2024), leaving ECR-related operations and broader sociotechnical issues under-explored (Wróbel et al., 2020). While some human factors research has examined conventional onboard ECR work and environments (Mallam & Lundh, 2013; Mallam & Lundh, 2016), limited attention has been given to how such engineering-related work may evolve in future shore-based ROC operations.

These gaps become especially evident in the context of electrified short-sea and Ro-Ro ferry operations. Future ROC concepts will likely involve continuous supervision of propulsion systems, battery status, diagnostics, charging coordination, schedule optimization, and other functions. Such operations may involve tightly coupled interdependencies and could shape HF challenges differently from more generalized autonomy scenarios. However, there remains limited research examining the distinctive operational rhythms and constraints of electrified, battery-powered, or hybrid vessels operating in short-sea contexts (Kooij et al., 2018; Lützhoft & Earthy, 2024).

These gaps motivate the need for empirical, field-grounded research across onboard and shore-based operational settings, which the present study addresses.

METHOD

This study adopted an exploratory qualitative approach to investigate human factors challenges associated with future ROC operations in short-sea electrified and hybrid Ro-Ro ferry services. Data were collected through field studies combining site visits, observations, and semi-structured interviews across onboard bridge and ECR environments, as well as emerging shore-based operational settings relevant to future ROC work. Fieldwork was conducted primarily within Nordic short-sea ferry operations and included electrified and hybrid Ro-Ro ferries, ROC facilities, a pilotage operator, a maritime training academy, and a shore-based operation center. Sites were selected to capture perspectives from onboard operations, emerging ROC environments, and adjacent domains with relevant remote supervisory experience. In total, 44 maritime professionals participated, including 27 participants with navigational backgrounds (e.g., master mariners) and 17 participants with engineering-oriented or technical expert roles.

The empirical material was analyzed using iterative thematic analysis (Braun & Clarke, 2006). Interview transcripts and field notes were systematically coded to identify recurring patterns related to human factors challenges in future ROC operations using MAXQDA (VERBI Software, 2021), while affinity diagramming (Beyer & Holtzblatt, 1998) was used to further cluster insights and synthesize higher-level sociotechnical themes across coded contents.

FINDINGS

The thematic analysis yielded four overarching categories of interconnected human factors challenges relevant to future ROC operations in the context of electrified short-sea Ro-Ro ferry services: cognitive, organizational, physical, and technical system design challenges.

Cognitive Challenges

Loss of embodied situational awareness. A defining characteristic of ROC operations is the removal of operators from the physical vessel environment. Onboard crews currently rely on a rich palette of embodied, multisensory cues – engine vibrations, machinery sounds, smell of burning insulation, the vessel's motion in swells – to build and maintain situational awareness. Engineers described relying on abnormal sounds and smells to detect developing faults before alarm thresholds were reached. In a ROC context, this embodied layer is entirely absent, forcing operators to reconstruct situational understanding through mediated data streams and sensor-derived indicators, raising concerns about delayed anomaly detection and reduced contextual understanding of vessel state.

Alarm fragmentation and information overload. Alarm management emerged as a critical challenge across multiple field sites. On one visited hybrid ferry, engineers estimated that nearly half of all alarms were false positives, primarily caused by battery sensor failures, while alarm handling was distributed across multiple display panels. At another hybrid ferry, engineers described blackout scenarios generating hundreds of simultaneous alarms. One visited ROC facility operated up to 13 screens per workstation across heterogeneous subsystems. Participants expressed concerns that, without intelligent alarm aggregation and prioritization, such information environments could become difficult to manage during concurrent fleet events.

Multi-vessel context switching and attention management. The defining operational model of future ROCs, namely the simultaneous supervision of multiple vessels, introduces substantial demands on attention management and working memory. One operator envisioned two navigational operators and one engineer supervising four to six vessels simultaneously. Another visited ROC facility reported that when an operator becomes occupied with a critical event on one vessel, fleet wide monitoring temporarily shifts to a backup operator, a configuration participants considered potentially fragile at larger operational scales. Participants also described extensive multi-screen monitoring environments requiring continuous scanning across heterogeneous subsystems, contributing to cognitive fatigue during prolonged supervisory work. Expert interviewees and experienced mariners consistently identified the "carryover effect" as a latent operational risk, referring to the inadvertent transfer of assumptions or contextual understanding from one vessel to another (Fan et al., 2020). Frequent switching between vessels with different routes, battery states, traffic situations, and alarm conditions was perceived as cognitively demanding and may increase the risk of confusion, delayed responses, and misattribution of vessel state.

Vigilance decline and boredom in passive monitoring. The fixed and repetitive nature of short sea ferry routes, often involving 10 to 30 minute crossings along constrained and highly predictable corridors, creates extended periods of low stimulus monitoring between episodic active interventions. This creates a "boredom vigilance paradox," where operators must maintain high readiness precisely during periods in which routine operational stability suppresses arousal and encourages disengagement (Veitch & Alsos, 2024). Field participants and expert interviewees frequently identified vigilance decline, mind wandering, and "out of the loop" syndrome as risks associated with prolonged passive ROC monitoring. Some navigator noted that skill degradation may increase as automation reduces intervention frequency, while intervention readiness must still be preserved for safety critical situations.

Trust calibration and automation bias. Trust in automation emerged as a complex challenge involving both under trust and over trust. Under trust was reflected in navigators' skepticism toward ROC viability due to reliability concerns surrounding automated charging infrastructure and alarm system limitations. Over trust was illustrated through incidents in which automated mode switches occurred without warning alarms during critical approach maneuvers, leaving crew to respond reactively. Multiple participants identified limited transparency in automated behavior as a key contributor to misaligned trust, particularly when operators could not clearly determine what the system was doing, why it was acting, or what it would do next. Transparency and explainability were therefore viewed as critical for maintaining appropriate operator trust.

Organizational Challenges

Role and authority ambiguity. The transition from ship based to shore-based command introduces ambiguity regarding authority, accountability, and operational decision boundaries. Across field sites, participants described a growing grey zone between onboard crew decisions and ROC operator involvement, particularly as onboard manning decreases. One operator outlined a phased transition roadmap in which captains initially retain authority while ROC responsibilities gradually expand, yet protocols governing control transfer across these phases remained largely undefined. Diverging perspectives also emerged regarding future authority structures. Some navigators argued that onboard personnel should retain maneuvering authority in the near term, while some ROC fleet engineer proposed that the ROC should function as the primary controller from the outset, with authority transferred onboard only when necessary. Participants expressed concern that unresolved authority boundaries may lead to hesitation, conflicting actions, or accountability gaps during abnormal situations.

Communication and coordination complexity. The shift toward remote operations fundamentally reconfigures the communication environment. Information previously conveyed through shared physical context, gestures, or brief verbal exchanges in a co-located operational environment must instead be communicated explicitly, often under time pressure. At one visited operation center, engineers described spending substantial time reconstructing operational context with onboard crew. Battery mode switching coordination between bridge and ECR personnel on hybrid ferries was described as particularly communication intensive and potentially more complex in distributed ROC settings. Participants also highlighted that ROC operators may need to coordinate with vendors, port authorities, and emergency services, responsibilities that currently rely heavily on the onboard captain's direct involvement.

Competence profiles, training, and cultural resistance. Participants described ROC operations as requiring substantially different competence profiles from traditional seafaring, including electrical and digital system literacy, remote diagnostic capabilities, multi vessel attention management, and cross role coordination skills. Some interviewees characterized this transition as a shift from "dirty hands" mechanical work toward digitally mediated shore-based operations. Expert participants further identified the absence of ROC specific training standards and certification pathways as a major barrier to adoption. Cultural resistance also emerged among experienced mariners, particularly regarding highly digitalized and screen-based monitoring environments. Several participants expressed preference for hands on physical interaction with vessel systems, highlighting potential trust and identity related barriers to ROC adoption.

Regulatory gaps and financial viability. Participants consistently highlighted regulatory uncertainty as a major barrier to ROC implementation. Existing regulatory frameworks remain largely oriented toward traditionally crewed vessels, leaving issues such as multi vessel supervisory watchkeeping, shore-based certification, and accountability for automated decisions insufficiently defined. Commercial viability was also questioned. One ROC operator described a business model largely dependent on reducing onboard crew costs, estimated to account for 50 to 60 percent of operational costs on short routes. However, current regulatory requirements to retain onboard crew were perceived as undermining the primary economic rationale for ROC operations.

Physical and Ergonomic Challenges

ROC operations involve prolonged sedentary and screen-based monitoring work. Participants and observations from field sites highlighted ergonomic concerns related to extended static posture, continuous visual monitoring, and reduced physical movement during long supervisory shifts. Tablet-based ship manoeuvring interfaces also raised potential ergonomic and interaction concerns related to limited precision and lack of tactile feedback during ship handling tasks.

Technical and System Design Challenges

Charging infrastructure reliability and battery system complexity. For electrified short sea ferries, charging infrastructure reliability emerged as a major operational challenge with direct implications for ROC operations. Visited ferry operators reported recurring reliability issues in automated charging infrastructure, including sensor alignment problems and failures during charging connection and disconnection procedures. Participants described battery management as operationally demanding, requiring continuous coordination of charging, energy usage, and propulsion mode switching during tight turnaround cycles, adding further monitoring and coordination demands for future ROC operations.

System fragmentation and legacy integration. Current Bridge, ECR and ROC environments were characterized by fragmented system landscapes combining legacy platforms with newer battery and automation systems. We have observed inconsistent alarm displays, heterogeneous HMI styles, and multiple disconnected subsystems within the same workstation environment. One visited ROC facility integrated navigation, power management, alarm systems, CCTV, and communication tools across multiple displays with differing interaction logics. This fragmentation can increase cognitive load, complicating training, and making critical information more difficult to identify under time pressure.

Connectivity, bandwidth, and data quality limitations. Reliable connectivity was consistently described as foundational yet technically fragile for ROC operations. Connection loss was directly observed during one ROC site visit. Remote pilotage specialists additionally identified communication latency as a major constraint, suggesting that delays beyond approximately one second may become unacceptable during time critical maneuvering operations. Short sea coastal operations were also perceived as vulnerable to geographic variability in satellite and cellular coverage. Participants further identified cybersecurity risks associated with increased digital connectivity as an additional operational concern.

Passive sensory blindspots and collision avoidance automation limitations. Participants emphasized that remote operations lack many of the passive sensory cues available onboard, including machinery sounds, vessel motion, visual angle judgment, and informal interactions with nearby vessels. Navigators argued that collision avoidance automation currently lacks the contextual seamanship judgment used by experienced mariners to interpret traffic behavior and ambiguous operational situations.

DISCUSSION

This study provides an empirically grounded account of human factors challenges associated with future ROC operations for electrified short sea Ro-Ro ferry services. The findings confirm several concerns identified in prior ROC and autonomous shipping literature, including vigilance decline, loss of situational awareness, alarm overload, and trust calibration challenges (Man et al., 2015; Man et al., 2018; Kari and Steinert, 2021; Veitch & Alsos, 2024; Porathe et al., 2014). However, the study extends prior work by grounding these challenges within the operational realities of electrified short sea ferry services and by giving greater visibility to engineering and ECR related work that has received comparatively limited attention in ROC research.

The findings suggest that electrification introduces additional operational complexity beyond conventional remote navigation scenarios developed primarily around traditionally propelled vessels. Continuous supervision of charging systems, battery condition, propulsion mode transitions, and fragmented multi system environments creates substantial coordination and monitoring demands for future ROC operators. These demands become particularly significant in repetitive high frequency ferry operations characterized by tight turnaround cycles and limited recovery margins. The findings therefore indicate that future ROC work cannot be understood solely through navigational supervision models, but must also account for engineering related operational complexity and distributed technical coordination.

The organizational findings further highlight that ROC development represents not only a technological transition, but a broader redistribution of work between ship and shore. Tasks are not simply transferred; they are reconfigured through increased data mediation, distributed troubleshooting, remote coordination, and evolving authority relationships. Consequently, challenges related to authority, communication, competence development, and regulation should not be understood as isolated organizational issues, but as interconnected sociotechnical tensions emerging from distributed operations. Unclear authority structures may amplify communication failures during abnormal situations, undefined competence profiles complicate training and certification, and unresolved regulatory frameworks constrain the testing and operationalization of new ROC configurations. Future ROC viability therefore depends not only on technological capability, but also on the deliberate co-design of organizational structures, governance models, communication practices, and operational responsibilities.

Implications for Design and Operation

The findings carry several high-level implications for future ROC development. First, future ROC systems require stronger support for alarm aggregation, prioritization, and cross vessel information management to reduce cognitive fragmentation and monitoring overload. Second, electrified vessel operations introduce new monitoring and coordination demands that require integrated support for battery systems, charging infrastructure, and distributed engineering workflows. Third, ROC operations require competence profiles that extend beyond traditional seafaring, including digital system literacy, multi vessel supervisory skills, and cross role coordination capabilities. Finally, the findings suggest the need for clearer authority structures, communication protocols, and organizational arrangements governing interaction between ROC operators, onboard crew, and external stakeholders.

Limitations and Future Research

This study is exploratory and qualitative, aiming to synthesize emerging ROC challenges rather than produce statistically generalizable results. The findings are grounded primarily in Nordic short sea electrified ferry contexts and emerging ROC environments, which may limit transferability to other operational domains. Because many ROC concepts remain under development, some findings reflect anticipated rather than stabilized practices. Future research should investigate mature ROC operations, engineering related workflows in electrified vessel contexts, and organizational arrangements for distributed coordination.

CONCLUSION

This paper presented an exploratory qualitative study of human factors challenges associated with future ROC operations for electrified short sea Ro-Ro ferry services. Drawing on field visits, observations, and interviews with 44 maritime professionals across bridge, ECR, and emerging ROC environments, the study identified interconnected cognitive, organizational, physical, and technical system design challenges shaping future ROC work.

The findings extend prior ROC literature by providing an empirically grounded view of how human factors challenges manifest across both navigational and engineering domains within the operational realities of electrified short sea ferry operations. In particular, the study highlights challenges related to multi vessel supervision, alarm overload, charging infrastructure reliability, fragmented system environments, evolving authority structures, and distributed coordination.

The findings further suggest that ROC feasibility is not solely a technical challenge, but a broader sociotechnical one. Safe, effective, and scalable ROC operations will depend not only on advances in automation and remote control technologies, but also on how future systems support human cognition, coordination, competence development, communication, and organizational governance. Human factors considerations are therefore not peripheral to ROC development, but foundational to its long-term viability.

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