Mikko Lehtimäki

Supporting the high-speed workboat cockpit work operations with the mastery of human factors

How to ensure the system performance and safety?

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Tiivistelmä

Inhimillisten tekijöiden merkitys on tunnistettu nopeiden työveneiden merenkulussa, mutta niiden kokonaisvaltainen hyödyntäminen on kuitenkin puutteellista. Tässä väitöskirjassa tarkastellaan inhimillisten tekijöiden hallintaa systeemisenä ilmiönä sekä tutkitaan niiden roolia suorituskyvyn ja turvallisuuden muodostumisessa. Tutkimus perustuu useisiin aineistoihin, joita analysoidaan laadullisin ja määrällisin menetelmin.

Nopeita työveneitä käytetään maanpuolustuksessa, pelastus- ja poliisitoiminnassa sekä merenkulun infrastruktuurin ja energiateollisuuden tehtävissä. Veneiden kasvaneet nopeudet sekä toimintaympäristön piirteet kuormittavat miehistöjä erityisesti kognitiivisesti. Ohjaamotyöskentelyssä miehistöihin kohdistuvat vaatimukset eivät aina ole tasapainossa sosioteknisten resurssien kanssa. Vaikka operaatiot pääosin onnistuvat, vaaratapahtumia ei aina tunnisteta sosioteknisen järjestelmän ilmentyminä, eikä niistä kerry systemaattista oppimista tukevaa tietoa. Lisäksi suorituskyvyn, tehokkuuden ja turvallisuuden tulkinnat voivat olla ristiriitaisia.

Väitöskirjan osatutkimukset tarkastelevat inhimillisten tekijöiden hallintaa toisiaan täydentävistä näkökulmista. Ensimmäinen osatutkimus osoittaa, että vaaratilanne- ja onnettomuusanalyysit painottuvat yksilöihin sekä sivuuttavat miehistöyhteistyön ja resurssienhallinnan merkityksen. Toinen jäsentää miehistön suorituskykyä tunnistamalla keskeiset kompetenssit ja niitä kuvaavat käyttäytymismallit, luoden perustan toiminnan arvioinnille ja kehittämiselle. Kolmas analysoi miehistöjen mentaalista työkuormaa, sen vaihtelua ja hallintaa sekä osoittaa kompetenssien, teknologian ja ohjaamoratkaisujen keskeisen roolin työkuorman säätelyssä. Neljäs laajentaa tarkastelun organisatoriselle tasolle ja korostaa tarvetta siirtyä yksilökeskeisyydestä kohti kehittyneempää miehistöresurssien hallintaa, yhtenäisiä toimintatapoja ja ennakoivaa toimintakulttuuria. Yhdessä osatutkimukset tuottavat kokonaisvaltaisen näkemyksen inhimillisten tekijöiden systeemisestä hallinnasta kohdealalla sekä jäsentävät sen keskeiset osa-alueet ja kehittämissuunnat.

Tutkimus osoittaa, että sosioteknisen järjestelmän rakenteisiin voidaan vaikuttaa, kun kehityskohteet tunnistetaan systemaattisesti. Tämä edellyttää yhteisen ymmärryksen vahvistamista sekä tutkimustietoon perustuvaa päätöksentekoa. Näin voidaan tukea vuorovaikutusta järjestelmän eri tasojen välillä sekä parantaa suorituskykyä ja turvallisuutta vaativissa merenkulun tehtävissä.

Asiasanat: HF Tool, inhimilliset tekijät, käyttäytymismallit, kompetenssit, mentaalinen työkuorma, merenkulun turvallisuus, miehistöresurssien hallinta, nopea työvene, ohjaamotyöskentely, onnettomuustutkinta, resilienssi

Abstract

The importance of mastery of human factors (HF) has been recognised in high-speed workboat (HSW) operations, however, the comprehensive utilisation of HF remains incomplete. This dissertation examines mastery of HF as a systemic phenomenon and its role in shaping performance and safety. The study is based on multiple datasets analysed using both qualitative and quantitative methods.

HSWs are used in defence, rescue, law enforcement, and maritime infrastructure and energy sectors. As vessel speeds increase and operating environments become more challenging, crews face greater cognitive demands. However, the demands of cockpit work are not always aligned with available socio-technical resources. Although operations are typically successful, incidents are not always recognised as manifestations of the socio-technical system and, therefore, do not consistently drive organisational learning. Moreover, interpretations of performance, efficiency, and safety may be inconsistent.

The sub-studies of this dissertation examine the mastery of HF from complementary perspectives. The first sub-study shows that incident and accident analyses tend to focus on individual performance while overlooking crew cooperation and resource management. The second models crew performance by identifying key competencies and their associated behavioural markers, providing a basis for evaluation and development. The third analyses mental workload, its variability, and its management, highlighting the roles of competencies, technology, and cockpit design. The fourth extends the analysis to the organisational level, emphasising the need to move from an individual-oriented approach towards more advanced crew resource management, standardised procedures, and a proactive safety culture. Together, the sub-studies provide a comprehensive view of systemic mastery of HF in HSW operations and outline its key dimensions and development pathways.

The study shows that the structures of socio-technical systems in HSW operations can be influenced through the systematic identification of development needs. This requires strengthening shared understanding, supporting evidence-based decision-making, enhancing interaction across system levels and improving performance and safety in demanding maritime operations.

Keywords: accident investigation, behavioural markers, cockpit work, crew competencies, crew resource management, HF Tool, high-speed workboat, human factors, maritime safety, mental workload, resilience engineering

ESIPUHE

Väitöskirjani liittyy rajalliseksi osaksi merenkulun vuosituhantisia perinteitä. Suhtaudun nöyrästi tähän historialliseen jatkumoon ja ymmärrän uuden tiedon vain täydentävän aiempaa. Uskon silti, että tieteellisen tutkimustiedon ympärille syntyy merkityksellistä liikehdintää, jolla maailmaa muutetaan.

Väitöskirjani juuret ulottuvat 1800-luvun loppupuolelle Itämeren karikkoisille ja Pohjanmeren ankarille vesille. Isoäitini isoisä, merikapteeni Juho Penttilä (1849–1921), aloitti merenkulkijana vuonna 1866, seilasi purjelaivoilla ja päätti uransa höyrylaivoja kipparoiden. Hänen jäämistöönsä kuuluva käsinkirjoitettu teos Merikulun tiedettä (1872) näyttää, että pyrkimyksillä “merikulun” kehittämiseksi on suvussa pitkät perinteet. Kiitos tästä työstä ja merestä geeneissäni.

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Päädyin kontra-amiraali (evp) Heimo Iivosen (1935–2024) avittamana varusmiespalvelukseen Merivoimiin vuonna 1993. ÖTA Hallilla koettiin Ojarannan myrkkytynnyreiden nosto, SS Park Victoryn ympäristönsuojeluoperaation alku ja MS Sally Albatrossin onnettomuus. MV Estonia upposi heti kotiutumiseni jälkeen ja monet tutut lähtivät Utön raskaisiin olosuhteisiin. Vältyin siltä, mutta elin tapahtumat heidän mukanaan. Meripelastamisen eetos juurtui osaksi elämääni. Kiitos Merivoimat pohjatyöstänne.

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Vaasassa huhtikuussa 2026

Mikko Lehtimäki

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Figures

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Abbreviations

HF Human Factors

HSW High Speed Workboat

Original publications

The summary part of the dissertation is based on the following publications, which are referred to in the text with Roman numerals I–IV.

[I] Lehtimäki, M., & Teperi, A. M. (2025). Human factor analysis of cockpit work incidents in high-speed workboats: the mystery hidden between the lines. *International Journal of Occupational Safety and Ergonomics, 1-13*. https://doi.org/10.1080/10803548.2024.2445979. © 2025 Central Institute for Labour Protection – National Research Institute (CIOP-PIB).

[II] Lehtimäki, M., & Teperi, A. M. (2025). Developing behavioural markers of high-speed workboat crews' competencies. *International Journal of Occupational Safety and Ergonomics, 1-14*. https://doi.org/10.1080/10803548.2025.2499338 Copyright © 2025, The Authors. Published by Informa UK Limited, trading as Taylor & Francis Group. CC BY 4.0.

[III] Lehtimäki, M., & Teperi, A. M. Workload in cockpit work on high-speed workboats: How to improve crew performance [under review from 19 Nov 2024], PREPRINT (Version 1) available at Research Square. https://doi.org/10.21203/rs.3.rs-5438272/v1 CC BY 4.0.

[IV] Lehtimäki, M., & Teperi A. M. (2025). Supporting high-speed workboat crew performance with blunt-end human factors. *International Journal of Human Factors and Ergonomics*, 12(3):242–272. https://doi.org/10.1504/IJHFE.2025.151130 Copyright © 2025, The Authors. Published by Inderscience Online.

The use of articles I-IV as interim publications of the dissertation has been authorised by the publishers.

The first author in all papers (I-IV) is Mikko Lehtimäki. The second author is Research Professor Anna-Maria Teperi from the Finnish Institute of Occupational Health (also docent, University of Vaasa, Finland). The authors' contributions are acknowledged as follows (Table 1) (Contributor Role Taxonomy, 2025):

Table 1. Author's contributions.

Paper	First author	Second author
Paper I	Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing	Conceptualization, Methodology, Supervision, Validation, Review & Editing
Paper II		Supervision, Validation, Review & Editing
Paper III		Supervision, Validation, Review & Editing
Paper IV		Methodology, Supervision, Validation, Review & Editing

1 INTRODUCTION

1.1 Background and purpose

This dissertation aims to explore the mastery of human factors (HF) in safety-critical high-speed maritime operations, especially in the cockpit work of high-speed workboats (HSWs). HSWs are utilised in rescue, defence, and police operations, as well as in other maritime environments critical to the security of supply and the energy sector.

In this dissertation, mastery of HF is defined as a continuous, human-oriented development and learning process occurring within an organisation or system, in contrast to the notion of HF management as a conventional top-down process. This definition is consistent with previous HF research (Teperi, 2012) and aligns with the grammatical notion of mastery as “possessing great skill, technique, or knowledge” (Merriam-Webster, n.d.). The term management is used in the study, for example, to describe processes that systematically manage operational safety. The dissertation comprises four sub-studies (Studies I–IV) and a synthesis of their results.

HSW operations take place in a sociotechnical environment consisting of technical, psychological, and social elements (Vicente, 1999), as well as activities and external factors (Wilson, 2024). In this environment, crew performance emerges through interaction and is continuously challenged physically, psychologically, and biomechanically (Dobbins et al., 2010; Stevens & Parsons, 2002; Ullman et al., 2024). Increased vessel speeds and a faster-paced operating environment have intensified cognitive demands on operators, highlighting the need for systemic approaches that align human capabilities with operational requirements (Turan et al., 2016). Supporting HSW crews is a holistic process that can be understood as a continuous, practice-based activity across all organisational levels to align resources and human capacity with situational demands (Hollnagel, 2014; Blandford et al., 2014).

Despite its recognised importance in safety management (Dekker, 2014; Dekker, 2002; Reason, 1990, 2017), proactive mastery of HF (CIEHF, 2021) remains insufficiently developed in the maritime context (Schröder-Hinrichs et al., 2012; Teperi et al., 2019). Although HF principles have been incorporated into merchant shipping regulation (IMO, 2011) and further developed (EMSA, 2022), they have not been comprehensively applied to HSW operations. As operational demands increase, there remains a need to better understand how system performance and safety are constituted and supported in practice.

However, there is limited empirical understanding of how mastery of HF is developed and enacted as a systemic, practice-based process in HSW operations. This gap is reflected in how responsibility for safety has often been disproportionately placed on frontline crews at the "sharp end" (Flin et al., 2013), while the practical mastery of sociotechnical resources has received limited attention. This study adopts the concepts of ”sharp end” and ”blunt end” (Dekker, 2014), referring respectively to cockpit operations and the broader organisational context supporting them.

The premise of this dissertation is that unsafe conditions in HSW operations may develop gradually through interacting contributing conditions (Dekker, 2014; Reason, 1990). Approaches focusing narrowly on individual factors risk sub-optimization and are insufficient for understanding safety in complex systems (O'Neil & Kriz, 2013; Cook, 2013; Perrow, 1999). Accordingly, enhancing safety and performance requires systemic development of HF as an interconnected whole (IAEA, 2019; IEA, 2021; Wilson, 2014).

The dissertation aims to enhance understanding of the factors shaping human and system performance and their proactive development in HSW maritime operations. The knowledge produced is intended to support improvements in system performance (IATA, 2024), operational efficiency (Stowers et al., 2017), and operational safety (Hollnagel, 2014; IAEA, 2020; Weick, 1987), while also contributing to the broader development of resilience in the high-speed maritime sector (Hollnagel, 2014b; Hollnagel et al., 2006; Hollnagel & Nemeth, 2022).

The theoretical starting point of the study is conceptual theorising, which links agency and structure through practice and enables new perspectives for professional operators in the HSW field (Llewelyn, 2003). The value of this approach lies not in producing comprehensive or generalisable concepts, but in offering "new ways of seeing" (Giddens, 1987). The theoretical perspectives underpinning the study are elaborated in Chapter 3.

1.2 Aims of the study

The current doctoral thesis aims to develop prerequisites for systemic mastery of HF in HSW cockpit work. The research problem was as follows: How can system performance and operational safety in HSW operations be supported through the mastery of HF?

The aims of the four separate studies (sub-studies I–IV) were:

I. To evaluate the HF analyses of incidents and accidents in HSW cockpit work in Finland from 2009 to 2021, and to obtain information for improving HSW operations.

II. To evaluate the behavioural markers of critical HSW crew competencies in cockpit work by modelling crew performance.

III. To evaluate the measurement and management of crews' mental workload in cockpit work on board HSWs.

IV. To evaluate the development of blunt-end HF required to support crew performance in the cockpit work of HSWs.

The specific research questions (Table 2), presented next, were:

Table 2. Research questions in sub-studies I–IV.

Sub-study	Paper title	Research questions
I	Human factor analysis of cockpit-work incidents in high-speed workboats: The mystery hidden between the lines	RQ1. Which factors contributed to the incidents, according to the incident and accident reports? Which types of HF were highlighted in the recommendations issued in the reports? RQ2. How were the incidents investigated, and what methods were used?
II	Developing behavioural markers of high-speed workboat crews' competencies	RQ1. What are the critical crew competencies and behavioural markers in HSW cockpit work? RQ2. How does the behavioural marker taxonomy prototype structure the activities of the crew?
III	Workload in cockpit work on high-speed workboats: How could crew performance be improved?	RQ1. How can subjective measures be applied when measuring mental workload in cockpit work on board HSWs (Likert scale, based on estimates of reserve capacity and unweighted NASA TLX)? RQ2. What kind of mental workload does cockpit work on board HSWs cause for crews?

Sub-study	Paper title	Research questions
		RQ3. What factors affect mental workload, and how can management of this phenomenon be improved, according to the crews?
IV	Supporting high-speed workboat crew performance with blunt-end human factors	RQ1. Which critical HF need to be enhanced to improve the practical blunt-end support of crew performance in HSW cockpit work?

1.3 Dissertation structure

This dissertation is structured in five chapters. The Introduction chapter (I) presents the background, the need for information, and the social justification of the research, as well as the objectives of the dissertation, the research problem, and the research questions of the sub-studies I–IV.

In the Context chapter (II), the background of maritime safety factors is outlined. Next, the context of the research topic is introduced, including a description of the activity and the operating environment. Finally, the objectives of working in the cockpit of HSWs are described.

The chapter titled Theoretical background (III) describes the disciplinary and philosophical discussion, as well as the ontological foundations of the dissertation. This chapter continues with an introductory chapter describing the factors behind operational resilience and the literature pivotal to the research topic. The third and fourth parts of the main chapter utilise literature to outline the fundamentals of mastering HF in a more structured manner across various levels of sociotechnical systems.

The chapter titled Methodology (IV) describes the research strategy and the data and methods used in the sub-studies (I–IV) in more detail. This main chapter concludes with a description of the ethical factors of research.

In the fifth main chapter, general discussion (V), the results of the sub-studies (I–IV) of the dissertation are considered in relation to each other and to previous research in the field, and recommendations are presented based on the results. The results are synthesized to summarize the research project's goals. Chapter V also describes the practical and scientific contribution of the dissertation, as well as the limitations and topics for further research. This chapter ends in the chapter Conclusion, which summarizes the key results of the study.

The complete Papers (I–IV) are presented at the end of the publication as separate appendices.

2 CONTEXT

2.1 Safety in maritime

Safety can be described as a shared competence formed by those involved at all levels of activity (Gherardi, 2018) or as a dynamic state in which nothing undesirable usually happens or has happened for the benefit of different parties, including the environment (IAEA, 2020; Weick, 1987). The higher the safety level, the fewer accidents occur at work, the less environmental damage and work-related illnesses are caused, and the less production is disrupted (ETPIS, 2021). Safety is maintained at an acceptable level by managing the related processes and continuously observing the threats posed by operations. When people are involved in the activities, absolute safety cannot be expected (ICAO, 2013). Nevertheless, activities being considered safe reflects the number of events that could be harmful to workers, the public, or the environment being at an acceptably low level due to the characteristics of the system (Hollnagel, 2014b). Safety II -paradigm considers instead, safety as "a condition, where the number of successful outcomes is as high as possible" and as "an ability to succeed under varying conditions" (Hollnagel, 2014b). From the point of view of optimization of resilience, both perspectives support each other.

The maritime sector is a safety-critical one (Schröder-Hinrichs et al., 2012), where individual hazards and deviations should not cause catastrophic consequences for people or the environment (Singh & Rajput, 2016; Wears, 2012). Safety management is a key requirement and a common goal of personnel in safety-critical organisations; the aim is to protect human health and the environment in general and to minimize the danger to life and property (IAEA, 2006; IMO, 2011; Wilson, 2014). Although the maritime sector is valued as a safe system, it is considered one of the most dangerous industries and significantly riskier than, for example, civil aviation (Berg, 2013; Hetherington et al., 2006; Langard et al., 2015) and other safe macro technical systems such as the nuclear industry, civil aviation and European rail transport (Amalberti, 2001). In connection with these fields, the term high-reliability organisation is used, where activities involve constant dangers. However, the number of errors that occur is small overall, but their consequences are often significant (Baker et al., 2006).

The use of proactive and systematic safety management has been mandatory in the maritime sector for many years (IMO, 2003; IMO, 2011). Efforts have been made to improve maritime safety, primarily through statutory international agreements (IMO, 2018; SOLAS, 1974), taking into account the impact of HF on accidents (IMO, 2011) and the need for proactive safety management (IMO, 2003). These measures have been partially successful (Kongsvik et al., 2014), but not to a sufficient extent, as there is a risk of superficial implementation of standards without a tight link to the actual activities of crews and shipowners (Schröder-Hinrichs et al., 2012; Teperi et al., 2019a). In the maritime speciality area of HSWs, the authorities' regulations are fragmented, and the unique requirements of the operations have not been sufficiently considered. This phenomenon may have led to different interpretations of safety issues by organisations (SIAF, 2018) and conflicts between safety-related potential and realization (Turan et al., 2016).

Despite the significant improvements in the maritime sector, accidents do happen. The safety of the maritime industry is, compared to defined high-reliability organisations, undermined by the perception of safety as a separate factor from real work, the commercial value of which, unlike civil aviation, is more difficult to identify (Turan et al., 2016), even though the losses caused by a single maritime accident can be enormous (Lee & Wong, 2021). On an HSW, instead of massive economic losses, the catastrophic events may cause human casualties, loss of hulls, and failure in critical maritime operations.

With equipment failures and external factors becoming the cause of accidents less frequently, attention is now increasingly being directed to examining the HF that contributed to accidents (Amalberti, 2001; EMSA, 2020; Hetherington et al., 2006) despite the challenging nature of analysing them comprehensively (Fjeld et al., 2018; Wróbel, 2021). A human element (IMO, 2003) contributed to casualties and incidents in 80.1 % of the investigated cases from 2014 to 2023, considering both human action and human behaviour in events. Regarding the number of accidents and incidents involving passenger and service ships, a growing trend has been observed since 2020. The statistics encompass "ships flying the flag of one of the EU Member States or [incidents that] occurred within EU Member States' territorial sea or internal waters, or involved substantial interests of EU Member States", as reported by Member States in the EU database for maritime incidents EMCIP (European Marine Casualty Information Platform) (EMSA, 2024). In most of these accidents (70%), the background factors were identifiable from HF on board ships (EMSA, 2024), but also at the shipping company level, whose operating culture always affects safety at the sharp end (Chauvin et al., 2013; Turan et al., 2016). Although the quantification of factors contributing to accidents is often irrelevant (Wróbel, 2021), the role of HF in incidents is significant and undeniable (Hetherington et al., 2006).

Although it is challenging to compare the level of safety in different industries (Amalberti, 2001; ETPIS, 2021; Hollnagel, 2014; Weick, 1987), the underlying assumption of this study is that the HSW organisations still have a long way to go to become fully-fledged organisations with consistently strong reliability records. A high-reliability organisation would be distinguished by everyone involved in the operations having a shared understanding of how results depend on a system in which all parts work in a closely intertwined manner (Weick & Roberts, 1993) and proactively seek to avoid accidents (Hollnagel, 2014). In addition to the likely consequences, the activities should also aim to prepare for unlikely events (Christianson et al., 2011). Maintaining and developing safe operations and safety-related resilience requires a well-developed understanding of and support for human diversity (Hollnagel, 2016). In the next chapter, the context of the HSW maritime speciality is discussed in more detail.

2.2 Case "Cockpit work in high-speed workboats"

HSWs are used in the rescue sector, national defence, police operations, as well as in operations related to the maintenance of maritime infrastructure and the energy industry, which are crucial for the security of supply.

In this study, cockpit work in HSW operations is defined as a bounded sociotechnical setting that can be analysed and understood as a coherent case (Eisenhardt, 1989). Although the activity varies across contexts, it represents a conceptually delimited form of sociotechnical practice through which the phenomena under study can be interpreted. This framing is consistent with the interpretive and hermeneutic approach adopted in the study, where the aim is to develop a contextually grounded understanding rather than to assume uniformity across settings. As is typical in case study research, cockpit work was analysed as a contextually embedded phenomenon using multiple datasets and in real operating environments (Piekkari et al., 2009).

In this study, an HSW refers to a professional boat measuring 5.5 to 24 metres in length (Eurofins, 2021), with a top speed exceeding 20 knots. A knot is a maritime unit of speed measurement. A vessel travelling at a speed of one knot travels through the water for a distance of one nautical mile (1852 m) in one hour. An HSW can have a sliding or semi-sliding hull and operates without using the ground effect or getting out of the water (IMO, 2000). An HSW can be used for professional, trade, or non-recreational purposes and can also be used to respond to an oil spill or as a fire or police boat (Act on the Technical Safety and Safe Use of Ships 2009/1686). The International Maritime Organisation (IMO) also uses the term high-speed craft to describe the operational profile of an HSW. Warships and troop carriers are included in the scope of this dissertation, although they are not included in the definition of the IMO's high-speed craft vessels (IMO, 2000), as these often operate faster than other traffic, and their speed is occasionally used as a tool to avoid a collision. Active measures that violate water transport regulations are sometimes also required to avoid a collision (Hoppe, 2005).

Cockpit work in an HSW is characterized as a dynamically implemented and safe management of the boat in ever-changing conditions (de Waard, 1996), accordingly to civil aviation, primarily “aviating, navigating and communicating” (FAA, 2018) to follow a predetermined route plan (Maritime Act 1994/674, Chapter 6., 1994) and reacting to factors encountered during the sea voyage, such as other waterborne traffic (Water Traffic Act 782/2019, Chapter 2). Cockpit work in HSWs is part of the work carried out in the diverse sociotechnical system of seafaring, which includes but is not limited to, ship manoeuvring, navigation, communication, management, (Harris, 2011), crew cooperation, cargo management (Grech et al., 2008), and decision-making (Cahill et al., 2014).

2.2.1 Factors challenging the operations

This study was implemented in Finland, where HSWs are used in geographically fragmented and difficult-to-navigate inland and sea areas, and the number of official and unofficial fairways is enormous. There are about 11,000 nautical miles of fairways marked on nautical charts alone and more than 35,000 maritime safety devices (FTIA, 2024). HSWs operate in changing external conditions, which are affected by wind, waves, currents, temperature, light, visibility, ice, thunderstorms, and weather changes in addition to other water traffic (Ministry of the Environment, 2006). Crews are exposed to constant mechanical stress, such as shocks and vibrations, on the unstable surface of HSWs (Myers et al., 2011; Ullman et al., 2024), which challenges physical and cognitive performance (Dobbins et al., 2008). Tasks are also very often carried out outside of fairway areas, as is usual in littoral waters globally. For the above reasons, Finnish waters are an ideal laboratory for the development of cognitively demanding cockpit work for HSWs and high-speed vessels.

The rapid development of HSWs and the increasing complexity of the operating environment challenge the functionality of the HSW operating system, as in many other safety-critical operating environments (EASA, 2016) (Figure 1). Modern HSW hulls can reach speeds of up to 60 knots, a capability that has more than doubled in the last 20 years. Human decision-making comes under tremendous pressure in these circumstances (Porathe, 2018), where the direction of the route is constantly changing (Cummings et al., 2010) and the consequences of decisions are often only noticeable with a delay (Olsson & Jansson, 2006). Instead of the seaworthiness of the HSWs, the goals of the operations are challenged more by an incomplete support for human performance (Taunton et al., 2011).

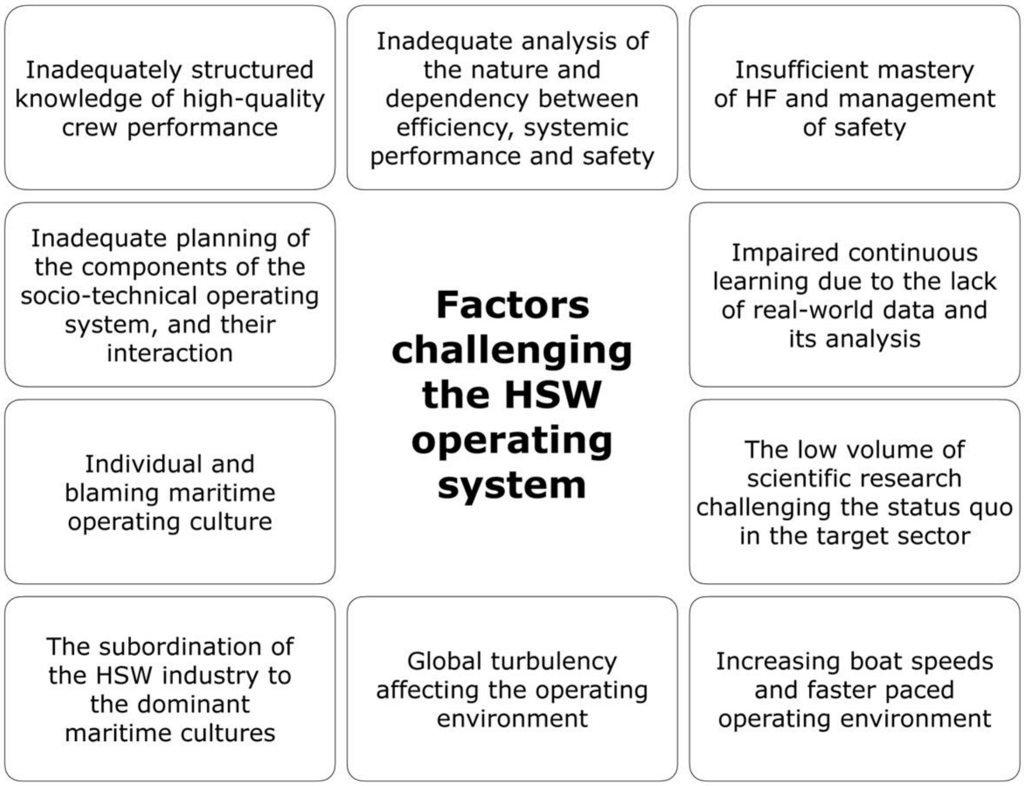

Figure 1. Factors challenging the HSW operating system as the premises behind the research gap in the dissertation.

The cockpit work in HSWs involves encountering complexity, diversity, dynamism, problems in information processing, and constant disruptive factors, paraphrasing Vicente (1999). In dynamic conditions, and especially in poorly planned operations, crew members are forced to make interpretations based on incomplete information and independent clues from the operating environment, which increases complexity and may make it difficult to identify equivocal causal relationships or "causal couplings" (Tolman & Brunswik, 1935). Decisions must too often be made by assessing the likelihood of their consequences, which is also part of the reality (Norros, 2014). In times of global uncertainty, the available global navigation satellite system information and the understanding of the situation are even more incomplete. When the alternatives are difficult to distinguish from each other, the cognition of the crews is challenged (Lipshitz & Strauss, 1997). The ability of crew members to understand the problems that have arisen, utilise information, and make the right decisions is compromised, especially without practical crew cooperation (Weick, 1987) and effective interaction between the crew and the sociotechnical operating environment (Hutchins, 1995).

HSWs and their crews form a complex system comprising countless components (Wilson, 2014), which is a permanent part of other overlapping systems, or at least communicates continuously with them. Examples include alarm and command centres, military branches, and operational targets (Maier, 1998), all of which challenge crew decision-making in multi-actor joint operations, an issue identified as essential in research on safety-critical complex systems (Norros, 2004). Operational tasks are increasingly being performed in the target domain, and the content of the work as a whole has also become more diverse and fast-paced. Operations are often carried out in haste, which can lead to harmful multitasking and an operating culture where an artificial sense of urgency predisposes individuals to deviate from pre-planned, safe working methods (Rajapakse & Emad, 2021).

Incidents and accidents occur in the HSW sector, but no adequate solutions have been found to prevent them. Accidents involving increasingly fast HSWs carry a high risk of catastrophic consequences. However, ground contact incidents and groundings, for example, have too often been seen as Wears (2012) has also described a compromising phenomenon, a part of normal operations rather than a signal of a poor safety situation or a complex chain of causes and consequences. Routine successes and the prevailing operating culture may have led to a perception that the safety situation is good enough and there is little need for rapid development (Hollnagel, 2014). Information on incidents and the factors affecting them has been poorly utilised, which has slowed the learning of organisations.

The development of safety and crew performance has been hindered by the maritime operating culture, where focusing on individual errors, reactivity, individualism, and firm trust in the technical skills of crew members and prevailing norms are part of the nature of operations (Hollnagel, 2014; Teperi et al., 2018, 2019). The culture and practices of seafaring have been shaped over millennia in a working environment far from the mainland and beyond help (Mack, 2011). That has led to an overemphasis on the role and responsibility of the individual, which is typical of safety-critical sectors (Brommels, 2000), even though there have been attempts to question hero myths (Helmreich & Foushee, 2010; Turan et al., 2016).

The achievement of goals is also hampered by the subordination of the specialism of HSWs to the dominant maritime cultures, such as ship-class seafaring and recreational boating. Compared to the enormous economic value and global shipping traditions, encompassing 248,000 ships (Kuittinen et al., 2021; Langard et al., 2015) and tens of millions of pleasure boats, HSWs represent a relatively small segment. For instance, the number of workboats and vessels in Finland accounts for less than 1% (Mäkelä et al., 2010) of the approximately 875,700 motorised boats (Traficom, 2024). Tangible and non-material solutions from mainstream maritime cultures are helpful, and often vital, in the HSW sector. Nevertheless, the real development of crew safety and system performance depends on regulation, as well as safety and solution planning, based on the current starting points of the target sector (Schröder-Hinrichs et al., 2013).

Therefore, there is tremendous pressure to develop the HSW operating system, which provides the premise for this dissertation. In a complex operating environment, every effort must be made to ensure safe operation and to prevent negative consequences (Hollnagel, 2014b; Weick, 1987). Efforts must also be made to strengthen the resilience of organisations' functioning, especially in circumstances where the root causes of adverse events cannot be solidly established (Hollnagel, 2014b; Qiao et al., 2021). In many future solutions in the HSW sector, lessons can also be learned from multidisciplinary research, and more successfully, even from outside the maritime field, such as civil aviation (Haavik et al., 2017; Teperi, 2012).

To enable the development, the objectives of the activities must be defined aligning Norros (2004), and the system's development targets must be identified in relation to them. In the next chapter, the objectives of HSW cockpit work are discussed.

2.2.2 Objectives of cockpit work

When working in the cockpit of an HSW, the primary goal is to achieve high-level system performance, safety, and operational efficiency. The first two objectives are not separate but are different sides of the same coin. For example, a task is to be carried out successfully and safely during high-performance operations (Stowers et al., 2017).

The starting point of this study is that in the cockpit work of HSWs, operational efficiency is subordinated to the primary goals, that is, system performance and safety, which are primarily built from the same elements. In complex adaptive organisations, safety is formulated as an emergent phenomenon (Reiman et al., 2015), requiring a more concretely developable system performance. A prerequisite for development is that the components of the system are known in sufficient detail and as a whole. The visible result of the cockpit work of HSWs is, aligning Chauvigné (2018), affected by all available resources according to the requirements of the situation and the task. When the goal is to save a human life, succeed in a military operation, or secure critical infrastructure, the system requires operational reliability that is difficult to measure, which must be pursued by constantly influencing the system's components (Weick, 1987). Evaluating the success of a task or the effectiveness of operations is a complex solution based on the organisation's core values (Quinn & Rohrbaugh, 1983). In efficient operations, the task is completed within the target time (Stowers et al., 2017), and threats to operations are detected in order to respond to them (IATA, 2024). In addition to the primary objectives of cockpit work, such as adherence to the route plan, the ability of crews to recover from adverse situations to restore normal operations is one of the key objectives and essential to ensure safety (Gucciardi et al., 2018).

The performance of the system is built on a complex set of HFs at different levels of the sociotechnical operating system of maritime, on land, and at sea (Dekker, 2015; Grech et al., 2008; IMO, 2003; Teperi, 2012; Wilson, 2014). Crew performance, on the other hand, comprises a combination of human capacity and constraints that is significant for the safety and efficiency of operations, according to professionally guiding bodies and authorities (IATA, 2013). Human capacity can be increased by recognizing and supporting the knowledge, skills, and attitude needed by the crew in managing the work situation and preparing for changing and unforeseen situations (EASA, 2023; IATA, 2013; ICAO, 2013).

The aim of the managing system design must be to support a sense of control among the crews. If operations are not managed proactively, they often drift into a reactive state with harmful consequences (Olsson & Jansson, 2006). Porathe (2018) has used Hollnagel's cyclical and four-step COCOM (Contextual Control Model) as a background theory for maritime work and system design, in which human situation management is described as a mutually reinforcing circle of the operating environment, past feedback, and expectations for the future, in which people and technical systems interact with each other (Hollnagel, 2002). The four steps are: (1) In the Strategic control of COCOM, analytical focus is aimed at long-term goals without time pressure. (2) In Tactical control, a person acts according to a ready-made protocol or rules, while the perception of the future is limited to the current moment and is shorter than in the strategic mode. In step (3), Opportunistic control, the conditions determine the measures. Planning and anticipation are limited due to the operating environment and time pressure, which are difficult to perceive. The professional skills of those participating in the activities may be inadequate in certain circumstances, and not all factors affecting the activities are fully understood. In a state of (4) Unclear control, a person does not reflect on cognitive activity but is driven to act through trial and error. The state of unclear control describes human action in extreme circumstances or where control over events has been lost. (Hollnagel, 2002; Porathe, 2018).

The underlying assumption of this study is that supporting the sharp end of the operating system (Flin et al., 2013) in a dynamic and complex maritime environment requires systematic development efforts. These efforts should promote strategic planning, which is currently achieved to varying degrees in the target sector. At the same time, crew members are often exposed to weak situational control, as well as challenges related to shared situational awareness and decision-making during voyages. This combination can result in safety being seriously compromised.

3 THEORETICAL BACKGROUND

3.1 Disciplinary and philosophical discussion

This dissertation is presented under the auspices of the doctoral programme of the University of Vaasa, within the discipline of Administrative Science in Public Management. The dissertation consists of four interlinked sub-studies (I–IV), belonging to the multidisciplinary field of HF and ergonomics (IEA, 2021), from which, as stated in Chapter 3.3, the term HF is used, including the ergonomics perspective, and considered to include all human activities at sea and on land (IMO, 2003).

This study combines the HF discipline (Arenius et al., 2010; IEA, 2021; Teperi, 2012; Teperi et al., 2018), social science theories, and multidisciplinary cognitive science to address the research problem (Saariluoma, 2001). A multidisciplinary approach is favoured both in the discipline of HF and in administrative science research (Salminen, 2011). In complex sociotechnical systems, multidisciplinary collaboration and cooperation between safety-critical domains are needed to enrich the system design (Carayon, 2006; Aven & Ylönen, 2018). Administrative science, in contrast, holds that information produced from different perspectives and the combination of this information are needed to perceive the different aspects and dimensions of the phenomena of management and leadership and the entities they form (Paananen et al., 2022).

Administrative science is interested in leadership development (Salminen, 2011) in chaotic and unstable operating environments, where cause-and-effect relationships are difficult to perceive and reductionism is unable to explain or predict complex phenomena (Vartiainen & Raisio, 2011). The discipline develops "activities related to leadership that promote choices made in the name of or for the benefit of the organisation" (Hyyryläinen, 2012). The discipline of HF aims to proactively support and facilitate human work, especially in dynamic, complex, and uncertain operating conditions (CIEHF, 2021; Lipshitz & Strauss, 1997; Norros, 2004; Tolman & Brunswick, 1935; Vicente, 1999). The similarities between disciplines are obvious, and they also extend to the concept of safety. While the purpose of the HF is to develop safety in its various forms, the goals are the same in several fields of social sciences and, for example, in security management science, which is separate from administrative science (Lumijärvi & Virta, 2011), even though perspectives on safety are very discipline-specific.

Philosophical or methodological solutions determine which knowledge is seen as valid and how conclusions about the validity of knowledge are derived (Johnson et al., 2000). The theoretical framework of this dissertation aligns with the research field of administrative science when it utilises sociotechnical systems theory (Trist & Bamforth, 1951), which refers to "the development of methods, tools and techniques to assess HF and ergonomics workplace requirements" (Waterson et al., 2015) or "to enhance the performance of work systems by recognizing how the behaviours of human actors affect the operation of technology" (Pasmore et al., 2019). In this study, the sociotechnical perspective is inextricably linked to the HF discipline's viewpoints and efforts to comprehensively understand the components of the HSW operating system, their interaction, and the factors affecting its functioning.

Sociotechnical systems theory has been applied in various fields to promote the proactive development of safety (Carayon, 2006), investigate accidents (Leveson & Moses, 2012; Rasmussen, 1997), and supplement more traditional risk assessment and management approaches (Aven & Ylönen, 2018). In sociotechnical systems, subjective human perspectives interact with structures to form an integrated whole. Structures can be defined as "rules and resources, recursively implicated in the reproduction of social systems" (Giddens, 1984). Human actors have possibilities to affect structures. Maritime traditions and the pressures of maritime subcultures, instead, often steer operations towards outcomes considered inevitable. Alternative bifurcations are, however, always possible. With the help of HF perspectives, system performance and safety in the HSW maritime sector can be developed by explicitly demonstrating the factors affecting the visible outcome of operations and by legitimizing the actors in the field to influence the structures. The sociotechnical theme is discussed in more detail in Chapter 3.4.

Ontologically, the study adopts a primarily subjectivist position, where the phenomena under investigation are understood as shaped through human cognition and meaning-making. At the same time, the study acknowledges that the operating environment includes material and organisational elements that are not solely dependent on human interpretation. Therefore, the study takes a socio-technical view in which human activity and system performance emerge from the interaction between subjective experience and structural conditions (Johnson et al., 2000; Puusa et al., 2020).

Epistemologically, the dissertation adopts an interpretive–pragmatic stance, where knowledge is understood as contextually constructed through meaning-making processes (Welch et al., 2011). In addition, knowledge is evaluated based on its practical consequences and usefulness (Legg, 2009). From this perspective, human activity is not treated as objectively observable in isolation from its context and interpretation (Johnson et al., 2000; Norros, 2004).

Knowledge production is therefore seen as a process that generates insights, develops theoretical understanding, and supports practice within a socio-technical context (Welch et al., 2011; Puusa et al., 2020). The approach is further informed by hermeneutic understanding and a systemic HF framework, positioning the study as contributing both interpretive–theoretical and constructive–practical knowledge. Within this framework, the study integrates exploratory, analytical, and applied orientations: it reveals under-researched phenomena, develops interpretive and theory-elaborative understanding, and produces knowledge applicable to practice. These dimensions are unified within a socio-technical and Safety II-informed perspective that emphasises adaptability and resilience (Hollnagel, 2014).

In this study, these perspectives are combined pragmatically: interpretive approaches are used to understand human activity, while system-level perspectives are applied to support practical improvements. This case study examines people's subjective experiences and interprets them in relation to background theory (Puusa et al., 2020). In this way, the study contributes both to interpretive understanding and to the development of practically applicable knowledge within the HSW socio-technical context.

3.2 Resilience of the operations and evolving safety thinking

This study aims to create new knowledge to support system performance, resilience, and safety in HSW cockpit operations. An organisation that anticipates the future and has resilient characteristics adapts to unexpected situations and recovers from failures more efficiently (Woods & Hollnagel, 2006). Resilience describes the crew's ability to recover from exposure to adversity to restore normal functionality (Gucciardi et al., 2018) or the flexibility shown by the whole system "prior to, during or following changes or disturbances" (Turan et al., 2016). Clear signs of organisational resilience include analytical questioning of safety analyses and decisions affecting safety, as well as continuous learning, with the help of information obtained from outside one's frame of reference (Dekker & Pitzer, 2016).

The resilience of systems and the safety of operations have been pursued in different eras of safety science within various research traditions (Le Coze et al., 2014). As operational environments have become more complex, retrospectively tracing the linear chain of events – the root causes (Dekker, 2014; Leveson, 2004, 2011; NASA, 2020; Rasmussen, 1997), systemic errors and individual causal links – has become less critical (Dekker et al., 2011; Leveson, 2004). Technical-inductive reasoning (Heinrich, 1931) has lost much of its relevance. The pioneering "Swiss cheese" method, which describes the vulnerabilities of systems and the protections developed for them (Reason, 1990, 2013) has been, despite its valid content (Larouzee & Le Coze, 2020), supplemented by a broader understanding of human behaviour and social significance (Rasmussen, 1990), as well as systemic phenomena, in particular, the interaction between system components (Branford, 2011; Leveson, 2011; Peters, 2014). Different scientific schools have developed concepts to support learning, foresight, and safety. Among these, Resilience Engineering (Woods & Hollnagel, 2006) has been particularly influential, shaping HF thinking from multiple perspectives (Le Coze, 2019).

Resilience engineering encompasses researching and developing safety management to support people in coping with complexity and pressure (Hollnagel et al., 2006; Hollnagel & Nemeth, 2022). The scope of the domain also includes seeking to balance productivity with safety and ensure the resilience of operations as a whole (Patriarca et al., 2018). The aim is to balance proactive, concurrent, and reactive ways of working (Hollnagel et al., 2010). Woods (2015) defined Resilience as "reducing risks of sudden failure in complex systems by ability to rebound from trauma, robustness as a synonym for resilience, graceful extensibility instead of brittleness, and architectures for sustained adaptability, when adapting to future surprises". The four cornerstones of resilience engineering are "about what a system can do — including its capacity (Woods, 2018) to anticipate, synchronise, be ready to respond and learn proactively" (Hollnagel et al., 2006). In the operating system of HSWs, the resilience-engineering perspective legitimately highlights the need to develop anticipation, interaction among sociotechnical system components and the levels of maritime organisations, as well as continuous learning. The HF area related to crew competencies facilitating resilient action is approached in this dissertation in Sub-study II from the perspective of competency-based learning pedagogy, which is based on thinking that promotes the continuous development and competencies of individuals, supporting visible and measurable activities related to human behaviour, and individuals taking responsibility for their learning (Henri et al., 2017).

The viewpoints of the HF discipline are presented more specifically in Chapter 3.3. (Mastery of human factors). Moreover, the crew competence perspective is discussed in Chapter 3.4. (The sociotechnical perspective in HF).

3.2.1 Safety I and Safety II

The content of this dissertation has been influenced by several new paradigms of safety science, in which HF feature, and people adapting their actions to circumstances is seen as a success factor (Borys et al., 2009). Adaptive safety thinking (Borys et al., 2009) is primarily applied to HSW operations, utilising the systemic HF

Tool framework (Teperi, 2012), following the Safety II paradigm, but also recognizing the complementary effect of the Safety I perspective (Hollnagel, 2014b).

The Safety I paradigm is characterized by centralized control of safety management and the achievement of goals, whereas the Safety II paradigm encourages guided adaptability in emergent situations and conditions (Provan et al., 2020). In the Safety I paradigm of safety research, people are seen as the main culprits for errors, which are prevented primarily by controlling individual actions, isolating normal activities from non-normal ones, and eliminating individual causes that predispose them to unwanted results in the operations. In contrast, the Safety II addresses HF extensively, and people are seen as a success factor in operations (Hollnagel, 2014b). The diversity of human performance is accepted in Safety II as part of the activity, and the underlying factors of sharp-end work are understood as a critical explanatory factor in success and failure (Dekker, 2015). In Safety II, the ability and tendency of people to adapt their actions dynamically to circumstances are seen as a prerequisite for safety rather than failure or guilt (Hollnagel, 2014b). The aim is to "help safe variations to happen and help variations to be safe" (Provan et al., 2020).

The Safety I and II paradigms support each other, and neither is applicable on its own as a background philosophy for the operating system in safety-critical operations (Hollnagel, 2014b). While practices aligned with the Safety I perspective are essential for the success of sharp-end risk management, Safety II supports the resilient characteristics of organisations, more strategic management of the safety of the operating system (Hollnagel, 2014), the utilisation of best practices, and the development of a high-level safety culture (Qiao et al., 2021). Maritime safety management practices are still primarily based on the traditional concept of safety, and the effects of the recent paradigm shift are still barely visible (Teperi et al., 2019). In Finland, the maritime sector seems to still rely on the Safety I approach. The perspective is technical, regulation is widely trusted, the development of safety is implemented in organisations from top to bottom, and human performance is mainly seen as a factor that causes errors (Teperi et al., 2018). The prevailing situational complexity in the HSW maritime sector instead requires a more adaptive Safety II approach to support the resilience of operations (Wahl et al., 2020). Due to challenges in transitioning from conceptual Safety II thinking to evidence-based actionable insights (Verhagen et al., 2022), there is a significant need for further research on integrating Safety I/II in the maritime sector.

3.3 Mastery of human factors

In this study, the systemic and multidisciplinary thinking of HF and ergonomics (IEA, 2021) was utilised to create new information to support diverse human activities in the HSW system, and to develop the prerequisites for system performance and safety (IEA, 2021).

The HF concept deals with the interaction between people and objects, systems, and the environment, and is what develops the operating system to meet the demands of human activity (CIEHF, 2021; IEA, 2021). The HF discipline studies physical and cognitive ergonomics as well as organisational factors (IEA, 2021). When studying physical ergonomics, the focus is on the physical dimensions of people and working conditions and their interdependence. Cognitive ergonomics, on the other hand, treats humans as processors of information as part of a larger system (Harris, 2011). Thirdly, systemic ergonomics specializes in developing the functioning of complete systems and human interaction with systems, as opposed to focusing on individual parts of the system (Wilson, 2014).

HF research considers the operational context holistically, encompassing interactions, complexity, recognition of emergence, and embedding of the professional effort involved within the organisational system (Wilson, 2014). The HF concept thus considers human dynamic interaction (Hollnagel, 2014; Reason, 1990; Wears, 2012) with the systems (Wilson, 2014) and between the HF components as a whole (IEA, 2021). This kind of systemic thinking views the complex parts of a system as working in an organized way to achieve a common goal as part of a specific whole, as the interaction of the parts of the system is shaped by the properties of the system (Buchanan, 2019).

Positioning the HF discipline with traditional philosophical perspectives is complex. HF research is needed to structure complex phenomena as a prerequisite for finding practical solutions (Norros, 2014), noting that there are contradictions between practical applications and scientific epistemology (Kant, 2018; Norros, 2014). A systemic perspective justifies the philosophical background of HF, design thinking, and an attempt to develop human well-being and performance (Dul et al., 2012). Compared to the inductive or deductive paradigm, the holistic HF perspective is close to modern design thinking, where the justifications are more abductive, promoting opportunities for development in situations where conclusions and predictions have to be made based on the combined effect of countless variables. Imperfection is seen in design thinking as an opportunity for development (Dunne et al., 2022), as it is in Safety II (Hollnagel, 2014b), which serves as a background framework in this study.

On the practical level, a professional specializing in HF seeks to combine theory, principles, knowledge, and working methods to optimize human well-being and also remain aware of the performance of the system as a whole (Teperi, 2012). Utilising HF engineering, operating environments are designed in such a way that the factors influencing operations promote human performance and operational safety, considering and effectively promoting dynamic relationships between human, technological, and organisational factors (IAEA, 2019).

The HF discipline has also been criticised for the weaknesses in its research methods, the use of invalid concepts, and problems related to impact. Part of this criticism involves analysing human activity with too narrow a perspective, such as measuring different phenomena for their own sake without considering their broader significance (de Winter & Eisma, 2024). Criticism has also been directed at the fact that the necessary and safety-critical variation of human activity is not sufficiently understood, leading to illusions of reality, paradoxically contrary to the goals of the HF discipline (Hollnagel & Dekker, 2025). Considering the critique, which has also been argued for example by Waterson (2015), the HF discipline still collates critical information from accidents (Sandhåland et al., 2015). It also offers numerous opportunities to enhance system performance and operational safety, including in the context of HSWs. The discipline is ultimately based on pragmatic concerns and produces tangible information and solutions for real phenomena affecting the systems, and often without competing benchmarks (Dekker et al., 2010). The design of work, the usability of systems, and the related design and development processes have a key impact on operating systems and their safety (Cook & Nemeth, 2010; Gordon et al., 2007; Hale & Hovden, 1998; ICAO, 2013).

The ultimate purpose of this study is to advance the development of the HSW operating system by strengthening the systemic mastery of HF in cockpit work, following the fundamental goals of the HF discipline (Wilson, 2000). In, for example, civil aviation, these HF aims have been described as identifying human capacity and its limitations and combine them with knowledge of tools, systems, equipment, work content, working environment and methods, as well as training, team selection and personnel management, to improve human performance, safety and job satisfaction (FAA, 1993). Sub-studies (I–IV) included in the dissertation include segments directing attention to the levels of the operating system and its different components, following the broad HF perspective, rather than analysing human activity in an insignificant and detrimental way.

3.4 The sociotechnical perspective

The maritime industry is a safety-critical system (Schröder-Hinrichs et al., 2012) based on the interaction of technical and social components (Paxion et al., 2014), designed, managed, maintained, and operated by humans (Wróbel, 2021) with its flaws and vulnerabilities. A system is "a set of interrelated or coupled activities or entities (hardware, software, buildings, spaces, communities and people), with a joint purpose, links between the entities which may be of state, form, function and causation, and which changes and modifies its state and the interactions within it given circumstances and events, and which is conceptualized as existing within a boundary; it has inputs and outputs which may connect in many–to–many mappings; and with a bow to the Gestalt, the whole is usually greater (more useful, powerful, functional, etc.) than the sum of the parts" (Wilson, 2014).

The sociotechnical system can be understood as the interplay of technical, psychological, and social elements (Vicente, 1999) together with the activity itself and the external conditions that shape it (Wilson, 2014). In maritime contexts, these systems are often examined through the SEPTIGON model, which extends the SHEL framework (Edwards, 1972; Hawkins, 1984, 2016). While SHEL emphasizes the interaction of software, hardware, environment, and liveware (Hawkins, 2016), SEPTIGON incorporates broader social, economic, political, and cultural dimensions, making it particularly relevant for maritime operations (Koester, 2007). Thus, the maritime socio-technical system includes not only the crew, organisation, and technology, but also the cultural practices, norms, and environmental conditions that shape operations. These models from the HF discipline describing the sociotechnical system share the basic idea of the human being as a unifier of different resources, and the central importance of teamwork for the safety of activities and resilience to error (Hawkins, 2016).

Reductionist investigation of the sociotechnical system through the use of individual factors (Dekker, 2014; Vicente, 2004), such as only through details related to cognition (Kaidesoja & Paavola, 2017) or the crew's individual and disconnected competencies, as Mansikka et al. mentioned (2019), is not particularly useful, even though humans like to look for simple solutions or individual causes for complex problems (Hollnagel, 2014). In modern work environments, however, understanding human mental functioning requires a broader perspective (Ward et al., 2017). In this study, the research problem is approached from the systemic perspective of HF instead of reductionism (IEA, 2021). The approach provides a holistic theoretical perspective that takes dynamic interaction of system components into account (Hollnagel, 2014; Reason, 1990; Wears, 2012; Wilson, 2014). It considers the key HF related to individual, working group, and organisational levels as well as work activities in the maritime context (Teperi et al., 2015, 2016), whose significance for safety is widely accepted in the HSW sector. However, those activities have not yet been utilised for the development of practical operations.

3.4.1 HF Tool describing different levels of operations

The HF Tool (Teperi, 2012; Teperi et al., 2018) served as the central theoretical framework of this study, providing a multilevel perspective on HF. As a holistic approach, it conceptualises the sociotechnical system as an integrated whole (Wilson, 2014) and enables the analysis of human activity within the HSW maritime context. The HF Tool is a research-based and empirically validated pedagogical method for enhancing safety (Juvonen et al., 2025), and this study further contributes to its validation by demonstrating its capacity to link systemic thinking with the Safety II paradigm in safety research.

Initially, the HF Tool was developed to implement the HF approach in the safety-critical work of air traffic management. It was intended for use by air traffic controllers and their supervisors operating at the sharp end to understand the background of incidents (Teperi, 2012). The HF Tool model has been utilised, particularly in safety-critical fields, to enhance the mastery of HF and ultimately to foster organisational development and renewal of safety thinking and practices (Teperi et al., 2015, 2017, 2023). In addition, the HF Tool has been modified and expanded to different contexts, such as, for example, in the nuclear industry (Hamer et al., 2023), the railway sector (Teperi et al., 2023), the maritime industry (Teperi et al., 2016, 2018; Teperi et al., 2019a), aviation maintenance (Teperi et al., 2019b), and the construction industry (Nykänen et al., 2020).

The HF Tool is based on a systemic, holistic, and sociotechnical understanding of the HF that influence the mastery of complex systems through work and the development of organisations. In the HF Tool framework, the levels of individuals, work groups, organisations, and work activities, which are central in the maritime context, are aligned (Teperi et al., 2015, 2016), as a prerequisite of system safety (Rasmussen, 1997) (Table 3). In systemic thinking, the diverse parts of a system are seen to work in an organized manner to achieve a common goal as part of a given whole, as the interaction between the parts of the system changes based on the properties of the system (Buchanan, 2019).

The HF Tool concept aims for a participatory orientation at all these levels, as in HF thinking overall (Wilson, 2014). The model leans on, e.g., the doctrines of positive, i.e., solution–oriented psychology, refocusing scientific energy to understand and create factors that assess individuals and organisations in their work (Teperi et al., 2023).

HF Tool thus aligns with Hollnagel's (2014b) and Dekker’s (2015) perspectives on recognising that things are often going well thanks to people’s positive capacity (Dekker, 2015). The HF Tool does not primarily describe the complex cross-connections of system components (Hollnagel, 2012; Hollnagel & Nemeth, 2022) but instead consists of a practical structure designed for use by experts (Hamer et al., 2023).

Next, the four levels of the sociotechnical operating system are described, according to the HF Tool, starting from the individual level, where individuals are considered both assets and bottlenecks in the operational system HF (Table 3). Secondly, the especially pivotal level of team performance is presented. Thirdly, the work activities, meaning factors related to which constantly affect practical activities, such as employees, tools, and general operating conditions (Hollnagel, 2014), and ultimately system performance, safety, and efficiency (EMSA, 2022), are described. Finally, the organisational factors are discussed. Organisation-level solutions for the operation of sociotechnical systems are emphasized especially in Human and Organisational Factors thinking, which specializes in the discipline of HF (Schöbel et al., 2022).

Table 3. HF Tool adapted to the maritime industry (in Teperi et al., 2016; paraphrasing Teperi et al., 2015).

Individual's actions and characteristics	Work actions, characteristics of work
1. Competence, mastery of work	13. Quality and content of work; work demands
2. Situation awareness (perception, memory, decision-making, response/execution)	14. Quantity of work; time pressure, having to rush
3. Working along instructions and agreed procedures	15. Work organisation, work distribution, job descriptions; clarity
4. Understanding the bigger picture/overall situation	16. Usability and functionality of devices, software, and technology
5. Proacting, preconceptions, and assuring assumptions	17. Procedures and instructions; functionality, clarity and being up-to-date
6. Workload (overload/underload) and means for managing it	18. Opportunities to influence one's work and working conditions
7. Vigilance, alertness, fatigue symptoms	19. Feedback on work, professional appreciation
8. Life situation, anxiety, level of (long-term) stress	20. Opportunity/ability to evaluate and develop one's work processes
9. Age; quality and quantity of work experience	21. Assuring competence (training, exercises, other ways of learning)
10. Health, work ability	22. Work hygiene factors, physical work environment, working conditions, occupational hygiene factors (noise, ventilation, lighting, temperature, layout)
11. Motivation, attitudes	
12. Emotional state and reactions, mood	

Group-level factors	Organisation-level factors
23. Shared understanding of the situation among all group members	30. Management and leadership; structure, styles
24. Knowledge of all group members is used	31. Organisation/safety culture
25. Communication within group (e.g. are misunderstandings, misinterpretations, and misheard utterances corrected)	32. Cooperation between different organisation levels and units (e.g. office, ship, technology, quality and safety, manning)
26. Structure and cohesion of the group, group dynamics (social relations, atmosphere, mutual support)	33. Understanding ship safety as a whole throughout the shipping company's management
27. Communication between different groups (deck, engine room, VTS, pilot, tugboats, icebreakers, harbour, other ships); model maritime glossary; language skills	34. Decisions made (incl. resources; personnel, equipment)
28. Information flow, communication practices, incl. change of watch, change of shift	35. Change management (personnel, systems)
29. Decision-making in the group (e.g. role of the watch officer)	36. Cooperation with partners, e.g. shipping companies, authorities
	37. The company's support for ship operations (SMS/DPA)

Notes: SMS/DPA = safety management system/designated person ashore, VTS = vessel traffic services

3.4.1.1 Individuals as assets and bottlenecks

All work-related system design must consider human strengths, but limits to human resources must also be considered to avoid human and organisational errors. HF system design must take into account proactively the physical and cognitive capacity of crew members, as well as human characteristics such as culture, education, experience, needs, resources, and limitations (IEA, 2021). The high level of professionalism of individual crew members is a prerequisite for operations (Belev et al., 2018) but does not guarantee safe operations following traditional maritime thinking.

Human information processing

Despite the enormous human capability to process information, the vulnerability of human activity in complex activities is based on the limited thinking capacity to understand the surrounding system. Important information can be easily overlooked, assessments of the situation are incomplete, measures are short–sighted, and the wrong factors are overemphasized (Weick, 1987). Humans receive information with their multiple senses (Battich et al., 2020) and process information with different resources of memory (Atkinson & Shiffrin, 1968; Baddeley, 2000; Baddeley & Hitch, 2010; Miller, 1994), which are always limited to some extent (Baddeley, 2000; Miller, 1956; Norman & Bobrow, 1975; Reason, 1990; Sweller et al., 1998) and very individual (Lysaght et al., 1989; Saariluoma, 2001). When there is more information to process than the individual has the capacity for, the result is cognitive overload and increased stress (Hahn et al., 1992; Phillips-Wren & Adya, 2020), and finally, the deterioration of the quality of decisions (Hall et al., 2007). Sea voyages in HSWs also include monotonous work phases in which low mental workload may cause consequences similar to those of a detrimentally high mental workload (Casner & Gore, 2010; Rajapakse & Emad, 2021).

A person has an incredibly good, but also limited, ability to multitask, for example (Reason, 1990). Weaknesses in cognitive performance are particularly pronounced in tasks that simultaneously require the same spatial or verbal cognitive resources (Cowan et al., 1997; Reason, 1990; Wickens, 1981) instead of dividing resources between different tasks (Norman & Bobrow, 1975). In a critical phase of work, even a single radio message can make work more difficult (Cherry, 1953; Conway et al., 2001) when it causes a new and previous interruptive process of information processing (Maglić et al., 2020) that is needed for situational analysis, necessary choices and measures (Norman & Shallice, 1980).

Individual traits

Seafarers always behave as themselves at work, which is influenced by countless individual traits. Human activity in seafaring is often affected by fatigue, which impairs the quality of work (Matthews & Desmond, 2002) and performance, especially in secondary tasks (IMO, 1993; Hockey et al., 1998). Fatigue tends to manifest itself primarily in monotonous work phases (Carskadon & Dement, 1987; Williamson et al., 2011) and significantly increases the risk of accidents (Akhtar & Utne, 2014; Williamson et al., 2011).

In HSWs, the dynamicity, complexity, and uncertainty expose crew members to stress and a degraded quality of work. Problems related to work tasks, methods, and equipment cause frustration for maritime crews, which can be a threat to safe operations. Such emotional states can be caused, for example, by the behaviour of other actors in the operating environment or challenges in private life (Rajapakse & Emad, 2021). Frustrations can cause anger, which negatively affects attentiveness and decision-making, as well as delays in corrective actions needed in different situations (Dingus et al., 2016; Stephens et al., 2013). Good mental and physical condition improves stress tolerance, especially in group work (Ćorović & Djurovic, 2013), where problems related to the mood and emotional reactions of crew members can adversely affect (Rajapakse & Emad, 2021) attentiveness (Bruya & Tang, 2018; Colflesh & Conway, 2007; Kahneman, 1973; Norman & Shallice, 1980; Olsson & Jansson, 2006) and the ability to make successful decisions is vital in the operating environment of HSWs (Dingus et al., 2016; Stephens et al., 2013).

Individuals' success in complex situations can be developed by increasing teamwork (Weick, 1987) and by decentralizing cognitive activity to the operating environment and making efficient use of all human and technical resources (Andreasson et al., 2019). Although individual crew members have traditionally been seen as the backbone of operations, the thinking should be changed so that effective resource management and crew cooperation form the basis for safe operations. To succeed in this, the individual HF must be thoroughly understood in the operating systems of HSWs.

3.4.1.2 Team performance of the crews

Managing cockpit work in an HSW usually involves organizing crew members into alternating (Klein et al., 2006) maneuvering groups, in which individuals perform tasks simultaneously or in sequence (Marks et al., 2001) and work towards shared goals (Mathieu et al., 2017). A group is composed of two or more individuals who interactively, interdependently, and dynamically combine their roles to pursue common goals (Driskell & Salas, 1992; Dyer, 1985) more effectively than a group of individuals (Kozlowski & Ilgen, 2006).

Imminently, crew structure planning has a significant impact on achieving goals (Helmreich & Foushee, 2010; Klein et al., 2006) and ensuring performance independent of the continuous crew changes typical of the target sector (Hancock & Chignell, 1988). In an optimal situation, in addition to the requirements related to the tasks, the composition of crews should consider very individual factors (Causse et al., 2019), such as the personalities of crew members (Driskell & Salas, 1992) to achieve common goals and facilitate the construction of a common identity (Ford et al., 2013). HSW maritime organisations define and regulate a minimum crew structure and the qualifications of crew members, but the management is not as structured as, for example, in civil aviation. Particular pressure is placed on the fact that those involved in the activities have adequate knowledge and understanding of the impact of individual traits on work in safety-critical HSW operations, to adapt operations proactively to the characteristics of each crew.

The success of teamwork is affected by cognitive, motivational, and behavioural factors (Kozlowski & Ilgen, 2006). Manoeuvring groups have traditionally operated as command–control teams (Lehner et al., 1997). However, in modern crew cooperation, the dynamic relationship between the members of the control group should be based on interaction, interdependence, and complementarity of each other's human capacity (Burke et al., 2006; Salas et al., 1992). To succeed in this, a high level of understanding of the factors affecting group-level activity and crew performance is required, along with the design of systems that leverage this information.

Crew performance

In the cockpit work of HSWs, system performance is formed by a circular mechanism, in which regulation and HF at different levels of the operating system continuously affect the activity of the crews, which is reflected in the attitudes, motivation, and morale prevailing in the organisation (Helmreich & Foushee, 2010). In a sociotechnical operating environment, the performance of sharp-end crews can never be analysed as such but always concerning the machine subsystem and the visible results of the activity, which are further rolled into an input to the human system (Mansikka et al., 2019).

This dissertation extensively utilises information on mastery of crew competencies in civil aviation. The method is justified by the fact that the numerous solutions used in cockpit work in civil aviation are also suitable for the maritime operations of HSWs, despite the apparent differences in operating environments. Crew performance in civil aviation is structured by areas of competence, which describe the skills, attitudes, and knowledge required by the crew to master situations and prepare for changing and unpredictable situations (EASA, 2023). In this study, the criteria for civil aviation competency assessment are applied to the structuring of HSW crew performance (EASA, 2023) (Table 4).

Table 4. Crew competencies in civil aviation (EASA, 2023).

Abbreviation	Competency	
KNO	Application of knowledge	Demonstrates knowledge and understanding of relevant information, operating instructions, aircraft systems, and the operating environment.
PRO	Application of procedures and compliance with regulations	Identifies and applies appropriate procedures in accordance with published operating instructions and applicable regulations.
COM	Communication	Communicates through appropriate means in the operational environment, in both normal and non-normal situations.
FPA	Aeroplane flight path management — automation	Controls the flight path through automation.
FPM	Aeroplane flight path management — manual control	Controls the flight path through manual control.
LTW	Leadership and teamwork	Influences others to contribute to a shared purpose. Collaborates to accomplish the goals of the team.
PSD	Problem-solving and decision-making	Identifies precursors, mitigates problems, and makes decisions.
SAW	Situation awareness and management of information	Perceives, comprehends, and manages information and anticipates its effect on the operation.
WLM	Workload management	Maintains available workload capacity by prioritizing and distributing tasks using appropriate resources.

Some of the mentioned competence areas focus on more technical work phases, while others describe the activity and behaviour shown in non-technical work phases. However, it is even impossible to separate them from each other (Van Avermaete, 1998), and it is no longer considered necessary for the management of competencies

(EASA, 2023). All of the mentioned competencies affect crew performance. However, some are emphasized from the point of view of crew collaboration due to their social (LTW, COM) or cognitive emphasis (PSD, SAW, WLM) (Mansikka et al., 2019). Competencies cannot be assessed as such and always require more detailed structuring into concrete behavioural markers (Chauvigné, 2018), defined in detail in civil aviation (EASA, 2023) and for the HSW operations in the Sub-study II of this dissertation. Next, the competencies of the crew are briefly described, which have a particular impact on the success of teamwork.

Pivotal team working competencies

(LTW) The crew's ability to work in a team is often more important than optimizing the actions of individual and humanly imperfect crew members (Foushee, 1984; Ginnet, 2010). However, influencing the complex phenomena of activities in a working group is challenging (Helmreich, 1975), which is why organisations have often focused on the development of individual competence (Foushee, 1984). Good teamwork distributes the workload and creates the conditions for ensuring solutions made by others (Degani & Wiener, 1991; Mathieu et al., 2000). Leadership, on the other hand, indicates the goal of the crew (Zaccaro & Marks, 1999) and ensures efficient and safe operations by supporting the crew and pooling resources (Hackman & Wageman, 2005).

(COM) Crew communication is the key factor in ensuring shared situational awareness and coordination between the team (Wright & Endsley, 2008). Neglect, ambiguity, or even partial absence of communication weakens the cohesion and performance of the working group and exposes it to mistakes (Gillespie et al., 2013). The different situational mental models held by crew members make it difficult for them to communicate effectively and often lead to misinterpretations (Mathieu et al., 2000). Problems with communication and interaction have caused accidents in maritime (Fjeld et al., 2018), which is why the hierarchy that is harmful to communication should be reduced (White, 2012) and the operating culture should be developed to be more interactive (Daly & Mort, 2014). Communication and leadership competencies are interrelated, as a culture of communication is created primarily by leading by example (Lateef, 2018).

(PSD) In the maritime industry of HSWs, an intuitive decision-making approach has often been used even in the face of necessity (Steigenberger et al., 2017), which is a prerequisite for managing dynamic situations, but also exposes them to harmful assumptions (Soll et al., 2016) and makes crew cooperation more difficult (Salas et al., 1995). Decision-making has also been emphatically the responsibility of the individual. In safety-critical activities, this can have serious consequences, as the decision-making process is prone to errors (Hagen, 2018; Reason, 1990) and rigidities, especially in changing and demanding situations (Orasanu, 2010; Sundstrom et al., 1990). Group decision-making practices can increase compliance with regulations and procedures, verification procedures, shared situational awareness, and good decisions (Behrend & Dehais, 2020; Porter et al., 2003; Salas et al., 1995), especially in complex situations where it is challenging to identify causal relationships (Orasanu, 2010) or to make a single correct decision (Steigenberger et al., 2017). By considering the perspectives of several crew members, more information is available, unnecessary errors can be prevented, and the workload is distributed more evenly (Orasanu, 2015), which further emphasizes the intertwining of competencies.

(SAW) Situational awareness, i.e. "identifying the surrounding factors and understanding their impact in the near future in the available time and space", has a profound impact on the achievement of goals and is related not only to individuals, but especially to the common perception of various factors by crew members in HSW maritime (Endsley, 1995). Shared situational awareness is formed by verbally sharing mental models and utilising common technical sources of information (Endsley, 1995; Mathieu et al., 2000). The concept of situational awareness encompasses not only spatial, system, and task–related levels (Wickens, 2002), but also elusive changes (Fletcher et al., 2003) related to human functional capacity (Teperi, 2012). The phenomenon of situational awareness is closely intertwined with other competencies. Without effective communication, it is not possible to ensure a shared situational awareness, and the workload of individuals may become overwhelming, causing corrective measures to be taken and increasing cognitive load (Kanki, 2010). Situational awareness is also the basis for effective decision-making (Haerkens et al., 2012).

(WLM) The impact of the limited human resources on the mental workload must be considered in the design of HF processes (IEA, 20215) to ensure safe work (Olsson & Jansson, 2006). Harmful mental workload, even experienced by an individual crew member, can seriously hamper the management of crew resources (EMSA, 2022). An imbalance between situational demands and personal resources or capacity (de Waard, 1996) can lead to negative consequences, such as impairing cognitive performance (Lysaght et al., 1989; Norman & Bobrow, 1975; Porathe, 2018) and stress, which on the one hand can promote performance (Driskell et al., 1986) by moderately stimulating a person’s state of alertness (Easterbrook, 1959; Kahneman, 1973; Yerkes & Dodson, 1908). Sea voyages also involve monotonous work phases in which a decrease in concentration and apathy threatens the achievement of goals (Rajapakse & Emad, 2021). A low mental workload can be a sign of low demands in relation to resources and a good operational strategy (Casner & Gore, 2010) or, on the other hand, the failure to do the necessary work (Matthews & Reinerman-Jones, 2017). The mental workload is concretely managed in sharp-end work by placing the right work at the right time, staggering work performances, managing time effectively (e.g., slowing down speed), prioritizing work performance, and generally optimizing the use of all available resources (FMA, 2009).

3.4.2 Developing work, tools, and support for the competencies

The functionality of work processes, system usability, and design processes is a priority to ensure smooth and safe cockpit work (Cook & Nemeth, 2010; Gordon et al., 2007; Hale & Hovden, 1998; ICAO, 2013). However, crews often have to adapt to poorly synchronized components of the operating system, which causes frustration, ambiguity and adaptation of working methods to the conditions of the situation (Hollnagel, 2012).

To develop the synchronization of strategic goals and tactical–level solutions, a better understanding of the reality of work is needed in terms of processes and details (Wilson, 2012). Information for HF planning can be obtained, for example, by observing work-related activities in real working conditions, by monitoring the effectiveness of the measures taken, and by continuously developing the system, paying special attention to situations that involve uncertainty and stress factors (IEA, 2021). Strategic, process–specific, and detailed information can be used to ensure the timeliness of work phases, identify harmful overlaps, avoid synchronization conflicts, and optimize work methods and instructions to correspond to reality in real time (DuVernet et al., 2015; Sackett et al., 2012; Wilson, 2012). Effective work practices must ultimately be documented to ensure safe operations (Qiao et al., 2021), from the perspective of how seafaring work is actually done (Berg, 2013; Hollnagel, 2014a; Rajapakse & Emad, 2021).

In the cockpit work of HSWs, the uncertainty related to the working environment is, as usual, tied up human resources (Hollnagel, 2014b), and therefore, to make work more efficient (Degani et al., 1999), standardized working methods must be designed and commitment to them must be ensured (Rajapakse & Emad, 2021). However, the methods must also consider the possibility of switching to non–linear practices as complexity increases (Cahill et al., 2013), because more strategic control (Morgan et al., 2015) can, for example, reduce the mental workload experienced by crews in complex conditions more effectively than linear practices (Schmidt et al., 2021). In the maritime sector, deviations from standardized working methods are one key factor behind incidents. Although the work of seafarers is strictly regulated, the regulations or the operating instructions of shipping companies are not always followed (Rajapakse & Emad, 2021). Maritime quality systems are very different from those of civil aviation, for example, and in the absence of binding regulation, there is a risk of conflicts between safety-related potential and realization (Turan et al., 2016). There may also be practical reasons for deviations. If the linear practices described in the guidelines are not suitable for the reality of dynamic work, deviations from the guidelines will occur, also with dangerous consequences (Rajapakse & Emad, 2021).

From separate technical components to holistic design

The technical systems used in cockpit work should facilitate the efficient and safe work of the crew, ensure the availability of information, and help to detect and minimize errors (Trafi, 2012). In a safety-critical work environment, the characteristics of a well-functioning technical system relate to the user's sense of control and meaningfulness, positive emotions, and general well-being. Accordingly, goals, challenges, needs, and methods of use of the operating environment must be known thoroughly (Karvonen, 2019). In particular, the design of the system must address the interaction between humans and technology to efficiently and safely achieve the system's usage objectives (Hollnagel, 2011). That has not always been achieved in the HSW field. As a result of poor optimization of the interaction between human labour and technology (Shackel, 1992) problems arise in decision-making, teamwork coordination, and other complex cognitive processes (Militello et al., 2015), and ultimately in safety (Berg, 2013; Blandford et al., 2014).

The strain on crews can be reduced by designing the physical structures and ergonomics of the cockpits to achieve operational objectives efficiently, safely, and to the satisfaction of the operators (FAA, 2016). The development of technology and crew interaction must incorporate the known solutions of traditional ergonomics (Dobbins et al., 2008b), as well as the ease of use of equipment and systems, and suitability for their operating environment (Holzinger, 2005). Strain is reduced by improving usability and by considering factors related to the HSW's movements, internal and external visibility, soundscape and communication, environmental protection, health and safety, interaction of different components, maintenance and monitoring of the design work (Abd Samad et al., 2021; Dobbins et al., 2008a; Dobbins et al., 2008b; Ullman et al., 2024). To reduce the complexity of the work and the mental workload, particular efforts must be made to improve the availability of sufficient, timely, and straightforward information (Porathe, 2018).

When designing solutions, designers must consult their users extensively (Abras et al., 2004). They must also be aware of the working methods used in the cockpits, to ensure mental models of the crew members are shared (Olsson & Jansson, 2006). Instead of focusing on the usability of individual devices, the emphasis should be on developing larger entities and addressing specific problem areas. To develop in this way, a more holistic perspective must be utilised in the development of systems, such as design thinking, which is based on taking user needs into account, informal cooperation in the development of solutions, facing failures as opportunities, and constantly seeking solutions for the future (Dunne et al., 2022).

Ensuring crew competencies

Practical training of crews, sufficient qualification requirements, and ensuring sufficient experience are prerequisites for the success of humane work (Berg, 2013). High-quality crew training and orientation are prerequisites for safe operations (Tvedt et al., 2018), which is why the quality of training (Venkadasalam, 2015), effectiveness (EASA, 2016; Ernstsen & Nazir, 2020), and current scientific justifications must be ensured at different levels of activity (Salas et al., 2012). The requirements of HSW maritime speciality must be considered in the organisation of training, as well as sufficient training hours to produce (SIAF, 2021) experience that is necessary to ensure the safety of operations (Hetherington et al., 2006). In the HSWs, the competencies of the crews must be ensured, using diversely general education, apprentice–methods and on–the–job learning, simulators (Salas et al., 2012; Sellberg et al., 2022) and use of new technologies (Mallam et al., 2019), to ensure balance between formal qualifications and practical skills (Emad & Roth, 2008).

In this study, the Competency-based learning pedagogy is utilised to encompass the area of crew competence (Henri et al., 2017). This pedagogical perspective has also been utilised in maritime (IMO, 2011). As an operationalization of Competency-based learning thinking, this study utilises information from civil aviation, where human activity is supported and evaluated systemically with the help of the Evidence-based training model, which is based on supporting crew competencies (EASA, 2023). Evidence-based training is based on considering the individual development needs of the crew members and the evidence of human activity in the organisation of training (Dapica et al., 2022). In the Evidence-based training model, the educational objectives are described with competencies (EASA, 2023), that describe the knowledge, skills and attitude needed by the crew in managing the work situation and preparing for changing and unforeseen situations (EASA, 2016; IATA, 2013; ICAO, 2013), and that precede the high-level performance of the crew, considering the human action and behaviour necessary for the performance of the task (Mansikka et al., 2019).

3.4.2.1 Organisational foundations

Maritime organisations have a great responsibility with the resources available to ensure operational performance and operational safety. The core task of organisations is to promote the utilisation of efficient working methods and practices proactively, the utilisation of information in background work and on the sharp end, continuous development and learning, as well as interaction between organisational levels and the building of a high-quality safety culture (Qiao et al., 2021). From the point of view of Safety II, organisation-level HF is essential for the development of sociotechnical systems (Schöbel et al., 2022).

Understanding the factors that affect maritime safety is reflected in the everyday practices that form the organisational culture (Bolcaș & Ionescu, 2019), and these factors further influence the development of the culture. Although according to organisational culture theories, people are influenced by leading the development of cultures (Schein & Schein, 2016), the measures intended to develop the operating culture, such as management hierarchies and practices that affect other organisation-level HF (March & Olsen, 1983), must be practical.

The level of safety culture directly determines an organisation's safety-related performance (ICAO, 2021). A well-functioning maritime safety culture is a complex combination of the skills, attitudes, motivation, and commitment to shared values and convictions of those working at different levels of the organisation. All of these are maintained by developing a blame-free and inclusive atmosphere that encourages taking responsibility (IMO, 2010). Factors affecting safety must be known at all levels of the organisation (IAEA, 2019), and core values and activities must be jointly committed to ensure a high-quality safety culture (WANO, 2013). According to maritime operators, a good safety culture consists of openness and well–organized, smooth, and safe work. Developing a safety culture requires a systems perspective, the participation of operational personnel, and open access to safety-related information (Teperi et al., 2018).

Obtaining and using high-quality and up-to-date information at different levels of the operating system is a prerequisite for a functional organisation and continuous safety development. The operating system must promote systematic problem-solving, experimental activities, learning from personal experience and that of others, and the transfer of knowledge and competence (Garvin, 1994; Helms & Nixon, 2010). Information can be produced and shared by utilising safety reporting systems that consider situational factors and hazards at various levels of operations. Compared to other safety-critical industries, the information obtained from safety observations is not utilised in the maritime sector at a high level, which exposes to repeatedly encountering the same adverse effects (Amalberti, 2001; Berg, 2013). Safety reporting systems in the maritime field are fragmented, and the collection and utilisation of information affecting safety is often inefficient (Turan et al., 2016).

Cooperation at organisational levels

The management of maritime organisations requires an in-depth understanding of the phenomena of sharp-end operations as well as the organisation's mission, the level of interaction between organisational levels, and the management culture (Leveson, 2004; Puisa et al., 2018). Management's core task is to demonstrate a common goal and ensure the resources and prerequisites for operations align with the demand for the end product in the face of continuous imperfection. To succeed, attention must be constantly focused on ensuring synchronization between organisational levels and reducing work-as-imagined and work-as-done conflicts. In reality, however, the sharp end often has to adapt to solutions at other levels of the organisation, which have a detrimental effect on personnel, technical systems, tools, and working conditions. Differing perceptions of reality in the workplace can weaken system performance and seriously jeopardize operational safety (Hollnagel, 2014b; Schein & Schein, 2016). Problems with the interaction between organisational levels, such as owners, senior management, safety management, technical staff, and other specialised personnel at the blunt end and crews operating HSWs at the sharp end, have generally challenged performance and safety goals in maritime (Puisa et al., 2018). Failures in interaction, management, and feedback mechanisms can result in wrong decisions related to finances, technical resources, and personnel, as well as disadvantages that are difficult to resolve, mainly due to poor communication at the organisational levels (Puisa et al., 2018; Teperi, 2012; Teperi et al., 2018). Interaction problems can, for example, lead to the modification of working methods in a harmful direction in terms of technology (Blandford et al., 2014). The hierarchies of line organisations often hinder the necessary communication, interactivity, and cooperation (Sadler, 2003; Turan et al., 2016) and weaken the sense of responsibility experienced by individuals at different levels of action (Shapiro et al., 2008) in violation of the Safety II approach. These challenges are typical in safety-critical sectors and also in the maritime field (Cameron & Quinn, 2011; Grint, 2011).

3.5 Summary of the theory

In the maritime sector, there is a great need, and opportunities for development in the management of safety by utilising the proactive mastery of HF (Qiao et al., 2021; Teperi et al., 2019) and adapting the demands of the task, technical systems and environmental factors to human resources and their limitations, instead of having to adapt to the above (Grech et al., 2008). The safety–criticality of HSW maritime challenges the mastery of HF as system performance, as safety is ultimately ensured by the ability of systems to adapt to dynamic and complex conditions and learning about human performance traits for operational development. Work in modern safety-critical operational environments can only be successful by scaling resources to meet the requirements of real work at all levels of the organisation and operations (Hollnagel, 2014b; IEA, 2021; March & Olsen, 1983). The current paradigm shift in safety thinking (Safety I–II, Hollnagel, 2014), effectively combining these aspects (such as Safety I and II) (Teperi et al., 2019a) and encouraging adaptive perspectives of safety research, offers an opportunity for improving the mastery of HF and the management of the safety level (Borys et al., 2009; Qiao et al., 2021; Teperi et al., 2019b; Teperi et al., 2019a). However, the effects of a change of perspective still need to be visible (Teperi et al., 2019).

In this study, the mentioned gap is addressed by utilising the perspectives of the discipline of HF to develop prerequisites for the proactive mastery of the operating system in detail and as a whole (Rasmussen et al., 2000). In the end, the "common root cause" that affects the system performance in operations is a diverse combination of background factors that need to be understood at all levels of operations to ensure safe operations and to prevent negative consequences (Hollnagel, 2014b; Weick, 1987).

This dissertation joins the academic field of HF, and its implementation in the discipline of administrative science is a functional solution, as multidisciplinary perspectives of HF and administrative science provide the researcher with the necessary room for manoeuvre. Although there may be criticisms of the solution, multidisciplinary collaboration is a valid prerequisite for encouraging a holistic understanding (Carayon, 2006; Aven & Ylönen, 2018), coping with chaotic and unstable operating environments (Vartiainen & Raisio, 2011), and ensuring operational safety. The theoretical and philosophical foundations of this dissertation are summarized in Figure 2.

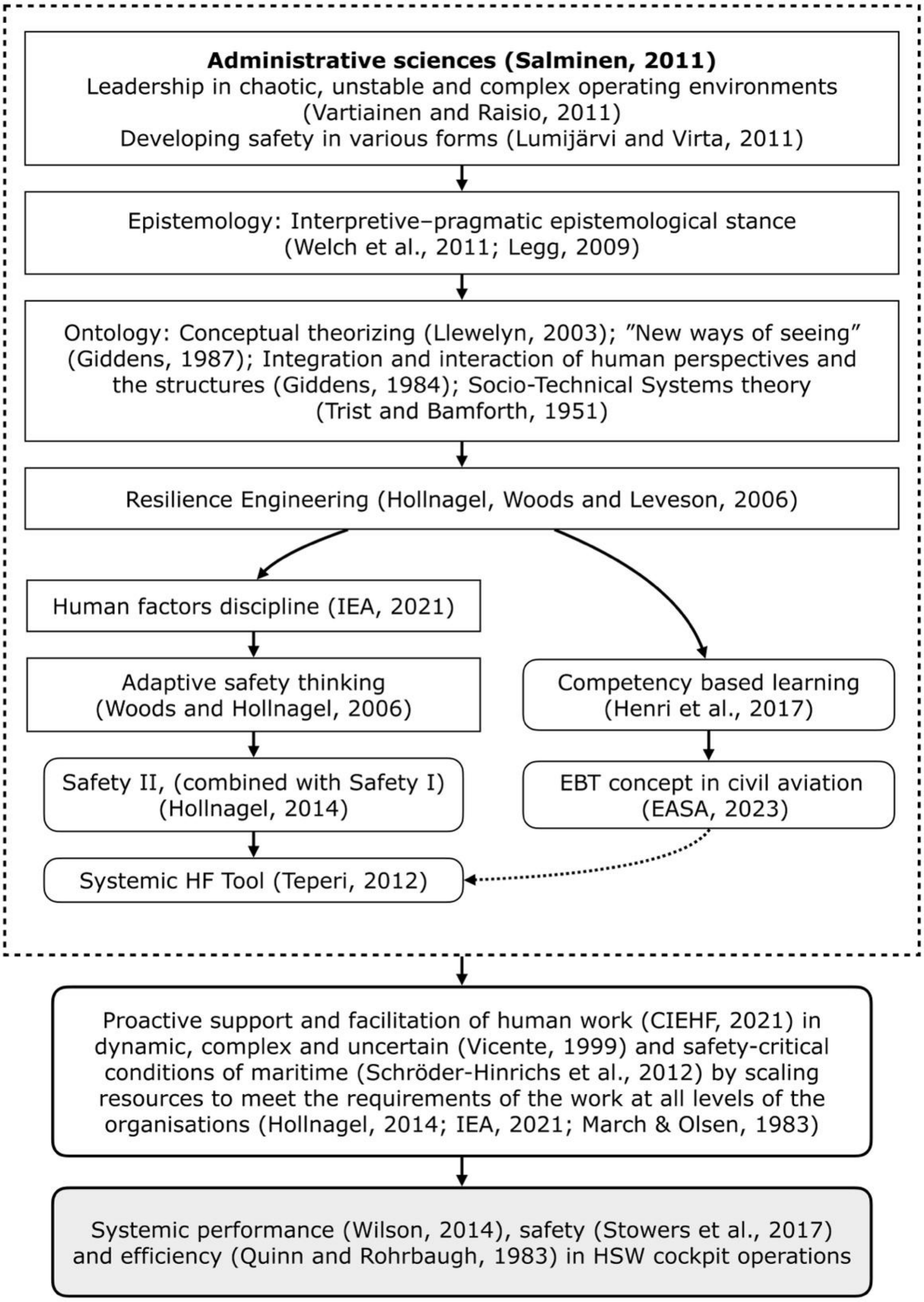

Figure 2. Theoretical and philosophical foundations in the dissertation.

This study bridges the concepts of the mastery of HF, safety management (Qiao et al., 2021; Teperi, 2012), and leadership development (Salminen, 2011) in cockpits and upper organisational levels. The aim is to support all actors in the target sector under the disciplinary umbrella of HF (CIEHF 2021). As stated previously, the theoretical perspective of sociotechnical systems theory (Trist & Bamforth, 1951) encompasses the disciplines of administrative science and HF, covering both human and technical levels of operations to enhance the performance of work systems (Pasmore et al., 2019) in the HSWs. The scientific, but "enough practical for mariners" HF Tool concept (Teperi et al., 2018) structures the sociotechnical levels of operations in the study. This theoretical viewpoint integrates "the subjective human perspectives to interact with the structures" (Giddens, 1984) and legitimates the participation of individuals in the structures. A summary of these structures, which belong to the sociotechnical system of HSWs, was briefly introduced in previous chapters concerning the HF Tool concept.

The theoretical starting point of this study is to "link agency and structure" (Llewelyn, 2003) and enable new perspectives for the operators of the HSW field (Giddens, 1987). There is a valid demand for new ways of thinking in the target maritime sector, because proactive mastery of HF remains rare and "the business of few" (sic), as is usual in the maritime sector (Turan et al., 2016). The degraded interaction of the system's components (CIEHF, 2021) and the non–holistic view of levels of operations (Teperi et al., 2015, 2016) still affects inefficiency, imbalance, failure of risk management, and an increase in risk factors (IEA, 2021). This dissertation responds to the need to develop the resilience of the HSW operating system (Woods & Hollnagel, 2006) by creating new information balancing these perspectives: the proactive, concurrent, and reactive ways of working (Hollnagel et al., 2010) and ensuring more sophisticated foresight, learning, and safety of operations.

At the HSW maritime organisations that are the subject of the current research, it is the responsibility to promote the well-being, health, and safety of employees and to produce sustainable solutions. These goals cannot be achieved without proactive HF planning (IEA & ILO, 2021). Combining the complementary Safety I and II perspectives of safety thinking is essential to achieve the goals (Hollnagel, 2014b; Qiao et al., 2021; Teperi, 2012) and moving towards holistic viewpoints instead of age-old sub-optimization of the maritime sector. The centralized control (Safety I) of safety management needs urgently "guided adaptability" (Safety II) to cope with emergent situations and conditions (Hollnagel, 2014b; Provan et al., 2020) of HSWs, where the demands in operations have been accelerated during the past years because of the increased speeds of HSW hulls, diversified operations, and unstable global situation. In these conditions, the ultimate goal is to ensure system performance by utilising systemic measures in response to necessity.

4 METHODOLOGY

4.1 Research strategy

The study was conducted as an empirical case study to understand the phenomena affecting activity in HSW environment and to supplement incomplete knowledge, drawing on case study research practices (Eisenhardt, 1989). Theory and empirical materials were reflected in a circular manner (Eisenhardt, 1989), utilising a hermeneutic perspective. Hermeneutic research was based on understanding and interpretation and did not proceed from individual cases towards statistical generalisations (Laine, 2001); rather, the researcher deepened own pre-understanding of the phenomenon through iterative engagement with the material. This circular process aims at developing a more refined and critically reflected understanding that moves beyond the researcher's initial assumptions (Vilkka, 2021; Laine, 2001).

Within interpretive–pragmatic framework, the study integrated exploratory, analytical, and applied orientations: the exploratory parts aimed to develop new theoretical perspectives and provide a more detailed interpretive understanding of the phenomenon (Piekkari et al., 2009). The parts with theory elaboration, utilised existing concepts and models to develop new theoretical perspectives and structure empirical observations in relation to prior knowledge (Fisher & Aguinis, 2017). The theoretical perspective of the study drew on interpretive sensemaking and employed a subjectivist approach to understand meanings within a specific operating environment (Welch et al., 2011).

Sub-study I explained how HF were understood in the target sector and set the context for the research problem. Sub-study II identified the main competencies underlying effective crew performance and highlighted the required human abilities for operations. Sub-study III examined how mental workload in cockpit work was measured and managed, addressing performance from both cognitive and operational perspectives. Sub-study IV shifted to the organisational level, identifying broad measures and conditions that supported and sustained crew performance. Together, these four sub-studies offered different but complementary perspectives on the main research problem (Figure 3).

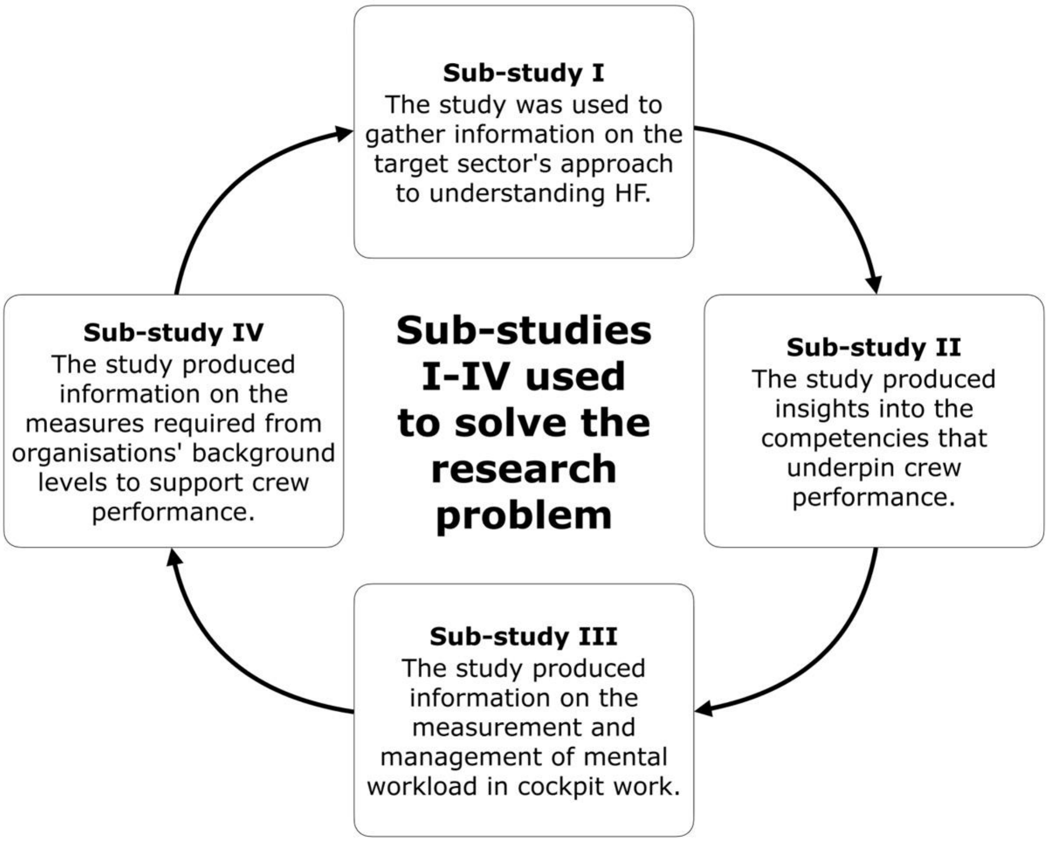

Figure 3. Sub-studies I–IV addressing the research problem.

4.2 Participants, data, and methods

The dissertation utilised a qualitative and quantitative analysis approach (Table 5) in four sub-studies (I–IV). To validate the conclusions in the dissertation, the study utilised multiple methods, including data and methods triangulation (Molina-Azorin & Fetters, 2017). Several different datasets, along with the integration of analysis results, developed the researcher's understanding of the topic (Seppänen-Järvelä et al., 2019). Solutions for acquiring and utilising different kinds of data were made opportunistically but systematically during the study (Eisenhardt, 1989). HF Tool was used extensively to structure HF in every phase of the dissertation, as emphasized in Sub-studies I and IV.

Table 5. Aims, case selection, data collection, data analysis, and process approach in the sub-studies I–IV.

Sub-study	I	II	III	IV
Aims	Evaluation of the HF' analysis of CW incidents	Forming and testing of a BM taxonomy for HSW crew performance	Evaluation of the realization, measurement, and management of MWL in HSW CW	Evaluation of the work and organizational factors required to support crew performance in CW
Case selection	Investigation and incident reports data available in Finland from 2009 to 2021	Information from civil aviation, the multidisciplinary HF field, and maritime, for forming the taxonomy, a comprehensive observation sample from the HSW field for testing	Comprehensive observation sample from the HSW field	The personnel in pivotal HSW maritime organisations in Finland
Data collection	Investigation and incident reports (SIAF n=7/ORG n=69) from ORGs (n=11) and the SIAF	Documents, p.BM taxonomies (n=2), HF models (n=3), ORG documents (n=28), incident analysis data (Sub-study I), HSW CW regulation in Finland, STCW agreement. Observation data from ORG (n=5)	Questionnaires (2), crew interviews, and observation in ORGs (n=5). Actual voyages (n=5), Crews (n=5), Crew members (n=10). MWL measurements (n=210) during observations and retrospectively	Questionnaire for operators (n=281) at four levels of ORGs (n=5)
Data analysis	Document analysis on a quantitative basis, utilising the HF Tool	Document analysis, analysis of the observational data, and prototype model testing on a quantitative basis	Quantitative and qualitative analysis for questionnaires and crew interviews, utilising the behavioural marker taxonomy (I) and the HF Tool. Statistical analysis for MWL measurements	Statistical analysis for answers from the questionnaire respondents, based on the HF Tool
Process approach	Theory elaboration	Theory elaboration, testing	Theory elaboration, testing	Theory elaboration
Notes: BM = behavioural marker, CW = cockpit work, HF = human factors, HSW = high-speed workboat, MWL = mental workload, ORG = Finnish maritime organisations, SIAF = Safety Investigation Authority of Finland				

4.2.1 Sub-study I

Document analysis was the primary method used in Sub-study I. The research approach enabled HF theory elaboration for the HSW cockpit work context, using incident and accident data available from HSW maritime organisations and the Safety Investigation Authority of Finland, in Finland between 2009 and 2021. In the study, the data from the documents were summarized, classified, and operationalized for quantitative analysis into statistical variables. The analysis employed a descriptive statistical method rather than statistical reasoning. The study was carried out using qualitative methods but combined with quantitative analysis at the data interpretation stage, which is typical for mixed–methods research (Archibald et al., 2015)

The data collection, which ended at the beginning of August 2022, was not without slowdowns and reflected, from one perspective, the immaturity of safety reporting systems in the HSW target field. The request for research permits was addressed to 26 organisations that investigated incidents as part of their operations. From these, 22 maritime organisations granted the research permit. Seven organisations reported that suitable data were not available. Two organisations did not respond or provide any material despite the granting of the research permit. In total, 13 organisations submitted data (133 documents) for the study.

We analysed all the investigation methods as well as factors that prevented, slowed down, or strengthened cockpit work, adhering to the recommendations to improve the operations. Fifty-seven incident reports were omitted because they addressed minor groundings during landing or approaching landing. Seventy–six incident reports were selected from 11 organisations for the final dataset. The safety investigation reports from Safety Investigation Authority Finland were publicly available for research purposes and seven reports were analysed. The content of the material was summarized, classified, and operationalized for quantitative analysis. The HF Tool concept was used for HF analysis (Teperi, 2012). Despite the challenges in gathering the data, the analysis method revealed the phenomena regarding the HF perspectives in the HSW target field.

4.2.2 Sub-study II

The methodological research approach in Sub-study II was based on data and method triangulation in various ways (Molina-Azorin & Fetters, 2017). The purpose of this triangulation was to enhance the validity of the study results and ensure that the dissertation contributed to the existing body of knowledge in safety-critical HSW maritime sector (Fusch et al., 2018). Content analysis was utilised to form a taxonomy prototype of the behavioural markers of critical HSW crews' competencies (Klampfer et al., 2001). The work phase utilised literature, research data in the target field, safety examinations, work instructions, operating methods, and manuals, as well as observation related to ethnographic methods (Klein et al., 2010). The document analysis began with evaluating the cockpit-work content of the datasets and their relationships. The data was then broken down, simplified, and grouped using axis coding. The competency criteria from civil aviation were used throughout as a basis for the work and compared to other data (EASA, 2023).

The operationalization of the behavioural marker taxonomy into HSW maritime was first conducted by ensuring that the model was suitable for preventing common HSW cockpit-work incidents (using the data from Sub-study I). STCW Code Table A–II/3 was used to consider critical technical skills in cockpit work, and ultimately, regulatory compliance was ensured with regulations in Finland regarding the cockpit work of HSWs.

Technically recorded observation data from actual cockpit work were gathered to test and develop the behavioural marker taxonomy. Observation is considered a critically important part of the development of safety-critical systems (IEA, 2021) and the understanding of human activity in real–world operating conditions (Hutchins, 1995). As a research method, observation can be employed to facilitate theory elaboration (Klein et al., 2003). Observation is part of the naturalistic decision-making research tradition, in which empirical and experimental methods are used to analyse and optimize the relationships between human work, technology and the operating environment, and to identify HF that affect safety at different levels of activity, emphasizing the reality of human behaviour instead of theoretical models (IAEA, 2019; Kerle & Hoffman, 2013; Militello & Hoffman, 2008; Rosen et al., 2012). The naturalistic decision-making method was first used in the 1980s to study human decision-making in dynamic, complex, and uncertain conditions (Klein, 2008), where operations are challenged by drift, unclear goals, ineffective feedback mechanisms, time pressure, the necessity of success, the number of actors, and organisational factors that complicate the situation (Orasanu & Connolly, 1993). Observation is part of a qualitative research approach, and quantitative research phases preceded this study as well (Metsämuuronen, 2005). Ultimately, the analysis of the data did not differ significantly from the processing of qualitative data obtained through interviews, for example (Grönfors, 2007).

The observation data were technically recorded and analysed retrospectively. A data recorder was developed for the study, which recorded data on a timeline. The same recorder was also used in Sub-study III. The observations were carried out from an external researcher's perspective (Grönfors, 2007) in five Finnish maritime organisations. The observations were implemented across different crews, boat classes, technical designs, and working methods to ensure the validity of the data.

4.2.3 Sub-study III

The research approach in Sub-study III was twofold. Firstly, two different subjective mental workload measurement techniques were tested to measure the mental workload in the HSW operations. Mental workload data is crucial for identifying bottlenecks in sharp-end system performance, particularly during capacity-intensive and low-demand working phases (FAA, 2005). Secondly, HF, which affected crew mental workload in HSWs, were evaluated to support the field in developing the mental workload management.

The study utilised qualitative and quantitative methods, integrating them to support the validity of research (Hurmerinta & Nummela, 2020). The technical data-collecting system, also used in Sub-study II, was utilised to collect mental workload data from the crews (n=5), as well as cockpit recordings to be used in retrospective phases. A Likert scale measure was used for mental workload measurements (n=210) during actual voyages (n=5) in Finnish HSW organisations in the autumn of 2022. That measure was adapted from the modified Bedford pilot workload scale (Hart, 2006), based on an estimate of crew reserve capacity. The Likert scale measures were validated using unweighted NASA TLX measurements retrospectively.

Crew background variables were assessed prior to observations using an electronic questionnaire. Following the observed voyages, information about the working conditions in HSW cockpits was evaluated using a retrospective questionnaire, which considered, for example, the impact of the technical system's characteristics on mental workload (Pauzie, 2014). The crews were also interviewed in group interviews about the factors that affected mental workload during voyages and crew proposals for improving mental workload management. The mental workload data were analysed and compared using descriptive methods and statistical reasoning. Interview data were analysed by quantifying the data and assessing the distribution of HF. The behavioural marker prototype from Sub-study II and the HF Tool were used to classify the data.

4.2.4 Sub-study IV

The research approach in Sub-study IV was based on first synthesizing the phenomena (9) that challenged HSW crew performance (based on sub-studies I–III). Using semi-structured questionnaire data, information was manipulated to develop blunt-end operations to support sharp-end crew performance. The quantitative and qualitative data were triangulated to ensure the validity of results and conclusions (Hurmerinta & Nummela, 2020)

The questionnaire covered both blunt-end and sharp-end organisational levels and was conducted in Finnish HSW maritime organisations (n = 5) between May and October 2024. The blunt end was classified into four levels of organisations: Headquarters (for example, Managing Director, Command of the Maritime Staff, Director of Maritime, Safety Manager), Operational level (for example, Head of Training, Operations Manager), and Technical level (for example, Technical Manager, Technical Specialist, Procurement Specialist). The sharp-end level was defined as HSW crew members. The respondents (n = 281) answered in nine structured questions with 33 response options. Additionally, answers were provided to eight open-ended questions. The proportion of respondents to the population was estimated to be 20%, but this estimate excluded data from one organisation.

The questionnaire data were combined and analysed at the group level. The analysis used a descriptive statistical method and statistical reasoning. Open-ended responses complemented the responses obtained through structured questions. The HF Tool was utilised in the development of questionnaire design and data analysis.

4.3 Ethics

The University of Vaasa Human Science Ethics Committee confirmed, in its decision submitted on 30 August 2022, that no ethical review was required for the research (Annex 1).

4.3.1 Research permits and participants

The target organisations were required to receive a written research permit. The participants in the study were required to provide written consent, which they did in writing (FSD, 2022). Participation in the study was voluntary. The participants were provided with a research bulletin and a privacy notice. The results were analysed and reported at the group level, so it was not possible to identify individual participants or organisations. Personal data was pseudonymized by coding organisations and target persons, and by storing the code required for this purpose separately from the data.

4.3.2 Confidentiality

All data processed during the sub-studies accorded with the research permits granted and requirements set by the target organisations. All data generated during the study were considered confidential information. The obligation of maintaining confidentiality was binding on all persons participating in the study. Only researchers had/have access to the data during its life cycle. Those who assisted in the study confirmed their commitment to maintaining confidentiality with a non-disclosure agreement.

Processing of personal data

The study processed personal data (EU General Data Protection Regulation 2016/679, Article 4), other identifiable information (FSD, 2022), including audio and video material. The legal basis for collecting personal data was considered to be public interest (EU General Data Protection Regulation 2016/679, Article 6) and national data protection law (Data Protection Act 4 §, 2018). However, direct identifiers referring to the person in the target organisation, such as full name, personal identity code, email address based on the person's name, and biometric identifiers, were removed from the material to be handed over to the researcher (The General Data Protection Regulation 2016/679, Article 4). Personal data will be stored until the end of all validation stages of the study.

4.3.3 Data management

As a rule, the level of protection of material disclosed by maritime organisations was no more than ST IV (Government Decree on Security Classification of Documents 1101/2019), and the data management plan met the requirement. The research materials were stored carefully and systematically, ensuring the privacy of the research subjects was not compromised (FSD, 2022). The material was stored following good research ethics and document management guidelines. The material was not available in the information network but was stored in a locked, non-public space with separate recorders. No copies were made of the physical material.

Confidentiality requirements for documents were considered throughout their life cycle. The information collected during the study will be used solely for research purposes. Audio and video recordings, as well as personal data, were stored in accordance with the University of Vaasa's instructions until any checks on the research's reliability had been carried out. The destruction of research data is carried out after the research is completed, taking into account confidentiality requirements and, primarily, following the instructions of the organisation that sent the data. In the absence of such instructions, the instructions of the Office of the Data Protection Ombudsman and the University of Vaasa are applied.

4.3.4 Open science

Sub-studies I, II, and IV have been published in international scientific journals, and the research results were made available to readers in accordance with the publication's policies. Sub-study III was under peer review in April 2026, and it is attached as a preprint version. The objectives, progress, and results of the studies were communicated during the research project in several seminars and on electronic communication platforms.

4.3.5 The role of financiers and the researcher

The funders did not participate in the planning of the research; the collection, analysis, or interpretation of the data, the writing of the research report, nor in the selection of the publication to which to offer the research article.

The researcher has worked for decades in the field of HSWs, both as a volunteer and as an expert commissioned by various organisations. In this study, the researcher represented only the research project of the University of Vaasa, and other roles did not affect research ethics decisions.

5 GENERAL DISCUSSION

This dissertation builds on interdisciplinary HF research and addresses the following research problem: How can system performance and operational safety in HSW operations be supported through the mastery of HF?

5.1 Results and contribution

The knowledge produced in this dissertation (Sub-studies I–IV) contributes to maritime research and to the research tradition of systemic HF (CIEHF, 2021). Its primary scientific contribution lies in advancing the ongoing shift from the Safety I paradigm towards Safety II thinking in the maritime domain (Hollnagel, 2014b), while also demonstrating the value of combining these perspectives in line with contemporary safety science (Hollnagel, 2014b; Le Coze et al., 2014; Provan et al., 2020; Qiao et al., 2021; Teperi et al., 2019; Wahl et al., 2020). More specifically, this dissertation shows that resilient HSW operations depend not only on crew competencies but also on the extent to which all components of the sociotechnical system support and sustain human performance.

The study adopted a participatory and interdisciplinary approach grounded in HF research, integrating perspectives from multiple safety-critical domains. This approach emphasised collaboration between stakeholders across different levels of the HSW operating system and supported the identification of system-level development needs (Giddens, 1984; 1987). From a sociotechnical perspective, the inclusion of multiple actors and viewpoints is essential for interpreting system performance and enabling effective development of system components and their interaction (Trist & Bamforth, 1951; Hollnagel, 2014b; Llewelyn, 2003). The analysis was structured using the HF Tool (Teperi, 2012; Teperi et al., 2018), which provides a systemic framework for examining HF. In this study, it facilitated a balanced interpretation of human performance by addressing both successful and adaptive activity in addition to failures. These findings suggest that the HF Tool provides a feasible approach for structuring and analysing sociotechnical systems in practice, thereby contributing to its further validation in the maritime domain and supporting the multi-level synthesis of findings presented in the sub-studies.

This dissertation addressed the research problem through four interlinked sub-studies (I–IV), which together provide a comprehensive and multi-level understanding of HF in HSW operations. Rather than representing separate lines of research, the sub-studies form a coherent whole that examines system performance from complementary perspectives. Sub-study I identified critical gaps in the assessment of HF in the HSW sector, particularly highlighting the limitations of individual-centred interpretations and the underutilisation of safety reporting as a tool for learning. Building on this foundation, Sub-study II operationalised competency frameworks from civil aviation in the maritime context, providing a structured model of the competencies required for high-level crew performance. Sub-study III extended the analysis to the cognitive dimension of performance by examining mental workload in real operational settings, offering methodological and practical insights into its measurement and management in the HSW domain. Finally, Sub-study IV shifted the focus to the organisational level, identifying blunt-end factors that shape the conditions for crew performance and highlighting the need for systemic support for sharp-end operations. These findings suggest that crew performance in HSW operations cannot be understood in isolation but must be analysed across multiple, interacting levels of the sociotechnical system. Together, the sub-studies demonstrate that improving system performance requires the coordinated development of competencies, working conditions, organisational practices, and analytical approaches to HF.

This dissertation combined qualitative and quantitative data sources, enabling methodological triangulation and strengthening the robustness of the findings. More importantly, the use of multiple data sources made it possible to capture HF across different levels of the sociotechnical system, which would not have been achievable through a single methodological approach. The limitations identified in individual datasets further highlight this need. For example, incident and accident reports (Sub-study I) revealed restricted and often individual-centred interpretations of HF, demonstrating the limits of relying solely on retrospective safety data. In contrast, observational and measurement-based approaches (Sub-studies II and III) provided access to real-time human activity and cognitive processes, while organisational-level data (Sub-study IV) captured the broader conditions shaping operational performance. Rather than treating methodological diversity solely as a means of increasing validity, this study demonstrates its importance for revealing different dimensions of system performance. Taken together, the combined datasets enabled a more comprehensive and context-sensitive understanding of HF in HSW operations, highlighting the value of multi-method approaches in the analysis of complex sociotechnical systems.

The summary of results, as well as the scientific and practical contributions, are presented in Table 6.

Table 6. Summary of findings and contributions by the sub-study.

Paper	Summary of findings	Scientific contribution	Practical contribution
I	The study identified that HF analysis in safety reporting and accident investigations needed to be improved in the HSW maritime sector. Teamwork and communication competencies were poorly acknowledged, and the emphasis was on the performance of individuals. Several HF, including crew competencies and working methods, were found to play a role in incidents.	Confirmation of the results of previous maritime research, regarding the Safety I perspectives highlighted in the maritime sector. HSW domain-specific knowledge of HF perspectives in the field, with a special focus on safety reporting practices and incident investigations in maritime HSWs. Knowledge of the pivotal factors affecting incidents in the HSW field.	Pointing out the strengths and gaps in HF thinking helps develop an understanding of the sociotechnical system. This, in turn, enables proactive measures in mastering HF, conducting incident investigations, fostering continuous learning, and promoting a fairer operational culture. Incentives are provided to enhance the amount of incident data from the HSW field.
II	The study defined eight competencies, structured as behavioural markers, required of the crew in cockpit work of HSWs. The taxonomy prototype, based on aviation standards and further informed by HF' models and maritime knowledge, was validated at the prototype level using observation data from actual cockpit work.	The study complemented previous research on maritime behavioural marker taxonomies, paying particular attention to the detailed presentation of behaviours as well as non-technical skills. New HSW domain-specific knowledge to enhance the resilience of HSW operations.	Enhanced understanding of crew performance and the development of sociotechnical system components in the HSWs. Practical knowledge of HSW crew competencies to support high-level performance in cockpit work. Knowledge for developing crew assessments, training and maritime safety, including improving incident investigations and standard operating procedures with the behavioural taxonomy.
III	The study tested an experimental subjective Likert scale that assessed cognitive reserve capacity to measure crew MWL in the cockpit work of HSWs. Measurements were compared retrospectively with	Applied methodological information to measure MWL in real-life cockpit work among HSWs, utilising subjective NASA TLX and experimental Likert	Examples of tested methods to practically measure MWL in HSWs, and pointing out work phases and sociotechnical components to be

Paper	Summary of findings	Scientific contribution	Practical contribution
	an unweighted NASA TLX scale. The MWL measures were sensitive to cognitive load variations and suitable for measuring MWL in the maritime field. The crews' MWL were repeatedly reported as low, but cognitive reserves were repeatedly low in other work phases. Crew competencies in particular were seen to improve MWL management, which was especially weakened by insufficient skills, the technology used, its usability, and the cockpit layouts. Several proposals were made to enhance MWL management.	scales. Enhanced knowledge about HF affecting the MWL in HSWs, along with the development of MWL management.	developed. Information for better understanding human performance and developing proactive MWL management; emphasis on crew competencies, technology used, its usability, and the cockpit layout.
IV	The study examined the HF at the blunt end of HSW organisations to be developed to support crew performance in cockpit work. It identified a need to shift the working paradigm. The analysis encourages a shift from individuality to effective crew resource management, utilising standard operating procedures and unified technical solutions. Additionally, it highlights the need for a proactive and fair operating culture, as well as improved management of crew competencies. Organisational levels held the same views on development needs.	Confirming that despite the current availability of knowledge on HF, a practical shift is still needed from Safety I perspectives to the proactive and effective use of crew resources, enhanced crew competencies, unified technical solutions and procedures, and a fairer operating culture in maritime HSWs.	The study's results contribute to improving the support for system performance, especially for sharp-end crew performance in the HSW sector. The prevailing coherence in the perspectives of different organisational levels expected clear management decisions to implement development measures.
Notes: HF = human factors, HSW = high-speed workboat, MWL = mental workload			

The practical contribution of this study lies in promoting a broader and more systemic understanding of the factors shaping HSW operations and the prerequisites for proactive mastery of HF. The findings show how HF are both understood and misinterpreted in the HSW field (Sub-study I), identify key factors influencing crew performance (Sub-study II), examine the alignment between crew capacity and operational demands (Sub-study III), and highlight the role of organisational conditions in supporting sharp-end performance (Sub-study IV).

Across these levels, the findings emphasise the importance of strengthening interaction, cooperation, and trust within the HSW operating system. These elements are not merely supportive but fundamental for enabling effective mastery of HF and improving system performance. The study provides a structured basis for developing HF at the organisational level, supporting improvements in occupational safety, employee well-being, and operational effectiveness. However, these benefits require the active integration of HF knowledge into everyday practices.

The findings further indicate that organisations must move beyond passive awareness of HF towards continuous and systematic development. This includes building a shared understanding of human work, recognising behavioural variability, and acknowledging the complexity of organisational functioning (IEA, 2021). In this context, the study supports the development of more transparent, fair, and learning-oriented organisational cultures (Dekker, 2017), enabling management to more effectively influence the sociotechnical conditions that shape performance.

At the same time, the findings provide practical means for crew members to better understand human performance, reflect on their own practices, and develop performance collectively as a team. By making the prerequisites of performance more explicit, the study supports more informed decision-making at both individual and group levels, while reinforcing the role of system performance in shaping operational outcomes and efficiency.

The practical implications of this alignment are presented in more detail in Figure 4.

Individual-level HF

1. Facilitate understanding of strengths and bottlenecks of human information processing, including the phenomenon mental workload.
2. Increase sense of responsibility, participation in risk management and working by the standard operating procedures.
3. Increase anticipation in all work phases, including dynamic and effective situational speed control.
4. Facilitate communication of physical and mental performance, as well as changes in it, between the crew.

Work activities HF

1. Develop working methods that reflect crew competencies, optimise the use of information and crew resources, and follow the premises of work-as-done and mental workload management.
2. Develop the practical and dynamic use of standard operating procedures.
3. Develop practical route planning skills.
4. Develop the technical resources in terms of HSW maritime speciality, considering physical and cognitive ergonomics, effective use of crew resources and mental workload management.
5. Implement the knowledge of the crew competencies in training systems.
6. Ensure proper training in simulations and real-life operations.

Crew-level HF

1. Address the knowledge of crew competencies.
2. Facilitate effective CRM.
3. Emphasize high-quality teamwork and crew communication.
4. Encourage analytical group decision-making strategies, supporting the intuitive approach.
5. Develop shared situation awareness in all work phases.

Organisation-level HF

1. Mitigate the overly individual, blaming and hierarchical operating culture.
2. Develop a unified operational culture and collaboration between organisational levels; facilitate a common understanding of crew competencies.
3. Emphasise unified sociotechnical solutions in the operating system.
4. Avoid considering minor incidents as part of normal operations.
5. Develop the safety reporting systems by increasing data and ensuring comprehensive analysis.
6. Ensure the practical use of information from the incidents.
7. Develop understanding of systemic performance, the functionality of sociotechnical systems and HF; integrate it permanently in operations by explicit decisions of management.
8. Ensure the integration of CRM perspective in all decisions; allocate resources for CRM training that is operationalised for the HSWs, and implement CRM training across all organisational levels.
9. Encourage a continuum of scientific research in maritime HSWs, emphasising a practical perspective.
10. Ensure the implementation of scientific knowledge.

Figure 4. Practical contribution and implications of the study structured over four levels of the HF Tool.

5.2 Understanding the concept of crew performance

The findings of this dissertation (Studies I–IV) indicate that crew and system performance in the HSW maritime sector must be conceptualised more comprehensively than has traditionally been the case. This need stems from the historically fragmented treatment of performance, safety, and efficiency as separate constructs, despite their inherently interconnected nature. In practice, performance in the HSW context has often been implicitly equated with time efficiency in task execution. However, such a reductionist interpretation overlooks the complexity of real-world operations, where performance emerges from the interaction of multiple human, technical, and organisational factors within a sociotechnical system (Wilson, 2014).

These findings suggest that crew performance cannot be adequately understood as a measure of task efficiency alone but must instead be viewed as a system-level phenomenon closely linked to operational safety and the capacity to respond to changing conditions. From a system performance perspective, effective operations depend on the ability to detect and respond to emerging threats, as described in civil aviation context (IATA, 2013). This capability cannot be developed through individual-level explanations alone but requires a more comprehensive understanding of the sociotechnical factors influencing crew performance.

The findings further indicate that incident analysis in the HSW sector has often relied on simplified, inductive interpretations that focus on individual actions rather than systemic conditions. In practice, this has manifested as a tendency to attribute incidents to human error or individual consequences in cockpit work (Sub-study I), instead of examining the broader set of contributing factors shaping performance. While complex group-level HFs are inherently difficult to influence (Helmreich, 1975), these findings suggest that overlooking them significantly limits the potential for meaningful system development.

The findings indicate that prioritising efficiency can promote a culture of haste, as identified in Sub-study III. While such an approach may appear effective under routine conditions, it can undermine the system's capacity to adapt and recover in adverse situations. As a result, operations that appear efficient may, in practice, lack the resilience required to manage unexpected events. This reduction in adaptive capacity can weaken the crew's ability to observe and respond to prevailing threats (IATA, 2013) and to operate in a resilient manner in relation to safety (Hollnagel, 2016). More broadly, this highlights a fundamental tension in HSW operations between efficiency-driven performance and resilience-oriented safety, which must be carefully managed in the design and evaluation of operational systems.

5.2.1 Crew competencies and performance

The findings of this study conceptualise crew performance as a function of human capacity, operational constraints, and situational demands (IATA, 2013). Performance emerges from the extent to which these elements are aligned in a given situation. Within this framework, crew competencies constitute a critical prerequisite for maintaining sufficient capacity, particularly under conditions characterised by variability and uncertainty (Studies I, III–IV). Rather than being static attributes, competencies determine how effectively crews can respond to changing operational demands.

Sub-study II defines the core competencies—knowledge, skills, and attitudes—required for managing dynamic and unforeseen situations, drawing on established competency frameworks in civil aviation (EASA, 2016, 2023; ICAO, 2013; IATA, 2013). These frameworks were operationalised and adapted to the context of HSW operations, enabling their application to maritime cockpit work. The findings demonstrate that competency-based approaches developed in aviation are transferable to HSW operations, despite domain-specific differences. This transferability is supported by the shared characteristics of safety-critical, high-tempo environments, where performance depends on coordinated human activity under conditions of uncertainty. This interpretation is consistent with previous maritime research that has utilised aviation-derived frameworks to conceptualise the interdependent competencies of seafarers (e.g. Fan & Yang, 2023), while extending their application through context-specific operationalisation in the HSW domain.

This research addresses the need for more detailed and operationally relevant descriptions of crew competencies in cockpit work, complementing existing behavioural taxonomies in the maritime sector (Fjeld et al., 2018), particularly in relation to non-technical skills (da Conceição et al., 2017; O'Connor & Max Long, 2011; Saeed et al., 2017; Wahl & Kongsvik, 2017). Rather than merely identifying this gap, the study contributes by developing a structured and empirically informed representation of the competencies required for high-level crew performance in cockpit work. A conceptual decision in this work was not to distinguish between technical and non-technical skills, reflecting their inherently integrated nature in real operational contexts (Van Avermaete, 1998).

A key contribution of this dissertation is the development of a detailed behavioural marker taxonomy that captures competencies related to resource management and crew cooperation (Sub-study II). Previous research in the HSW context has addressed these aspects only to a limited extent, which has constrained the systematic development of crew performance and the sociotechnical system as a whole (Sub-study I). These findings suggest that competencies supporting high-quality crew cooperation are central to achieving effective performance in cockpit work.

By structuring HSW crew competencies into a behavioural marker taxonomy, this dissertation provides a detailed and operationally applicable representation of the behavioural foundations of crew performance. In this context, crew resilience can be understood as an emergent property of team functioning under varying operational conditions (Gucciardi et al., 2018). The behavioural markers identified in this study can therefore also be interpreted as indicators of resilience, as they capture the ways in which crews maintain or recover performance in the face of changing demands. These findings suggest that such an approach enables more systematic assessment, training, and development of crew performance in HSW operations.

5.2.2 Mental workload indicating bottlenecks in system performance

Visible outcomes of cockpit work, such as adherence to the route plan, provide an important starting point for analysing system performance. However, reliance on observable outputs alone risks overlooking critical aspects of human and system functioning, as performance is shaped by complex organisational and operational factors (Quinn & Rohrbaugh, 1983). These findings suggest that crew performance in HSW operations must be understood as a multidimensional phenomenon that cannot be fully captured through external indicators alone.

The findings indicate that multitasking, time pressure, and a perceived sense of urgency can have a detrimental effect on cockpit work in HSW operations (Sub-studies I-IV). These factors increase cognitive demands and may compromise the crew's ability to maintain effective performance, particularly in dynamic situations. Despite their significance, the multidimensional nature of mental workload has remained insufficiently explored in this sector, and the analytical measurement and proactive management of mental workload have not become established practices in HSW operations (Sub-study I).

The study addressed this gap by incorporating subjective workload assessment methods into the research strategy, including the unweighted NASA TLX (Hart & Staveland, 1988) and a Likert-scale-based adaptation of the modified Bedford pilot workload scale (Roscoe, 1984) (Sub-study III). These methods enabled the identification of variations in cognitive demands during real cockpit work, providing insight into otherwise unobservable aspects of system performance. In this sense, workload assessment offers a practical means of linking human experience with system-level performance.

The findings further show that mental workload in HSW operations is inherently dynamic and context-dependent (Sub-study III). Both excessive workload and insufficient cognitive demand can impair performance. Periods of low workload may lead to monotony, while high workload phases, observed in the study, even under relatively benign conditions, can exceed available cognitive capacity. These findings emphasise the need to maintain an optimal level of cognitive demand to support performance (Yerkes & Dodson, 1908; Lysaght et al., 1989; Matthews & Reinerman-Jones, 2017).

Importantly, mental workload cannot be understood or managed solely at the individual level. Rather, it emerges from the interaction between system components, including cockpit design, working methods, organisational practices, and operational goals (Blandford et al., 2014; Hollnagel, 2014b). These findings show that workload is shaped not only by individual cognition. It is also a product of how the sociotechnical system is designed and managed, especially regarding competencies, technology, and cockpit design, as implicated in the Sub-study III.

5.3 Redesign of the working paradigm

Seafarers' professional identity has traditionally emphasised the aspiration to complete tasks and operate independently (Nævestad et al., 2018), reflecting the historical demands of working in remote and often isolated environments (Mack, 2011). While traditional seamanship and individual-level HF remain essential for safe navigation, an overemphasis on individual capability may constrain cooperation and hinder the development of the HSW sociotechnical system across operational levels. These findings suggest that crew performance must be understood as an emergent property of a broader system in which structures and environments actively support human performance following Buchanan (2019), Kongsvik et al. (2020) and Haavik et al. (2017).

The persistence of individual-centred thinking has weakened the analytical approaches used to understand and develop operational performance. Incident analysis has often focused on identifying a single cause or attributing responsibility to individuals, without adequately examining whether high-quality performance was achievable under the available human and technical conditions (Sub-study I). Hindsight bias has further reinforced this tendency, as is usual when following the Safety I perspective (Hollnagel, 2014b), limiting the development of proactive mastery of HF in the HSW context.

Empirical evidence from safety reporting and accident investigations in Finland supports this interpretation. HF were identified as contributing to almost all incidents related to HSW cockpit work between 2009 and 2021 (Sub-study I), yet the analysis of contributing factors remained narrow and predominantly individual-centred. These findings suggest that such approaches shift responsibility to individual seafarers while limiting opportunities for systemic development.

The findings further highlight the need to strengthen cooperation, interaction, and shared understanding across all levels of the HSW operating system. Hierarchical structures and ineffective feedback mechanisms have weakened resource utilisation, crew cooperation, and group decision-making (Sub-study IV), supporting earlier findings in the maritime sector (Puisa et al., 2018). Improving mastery of HF therefore requires coordinated efforts across system levels and the reduction of counterproductive individualism.

Standardisation is identified as a key mechanism for supporting cooperation and reducing cognitive demands in complex operations. However, its application remains limited in the maritime sector (Haavik et al., 2017) and in the HSW field (Sub-study IV). While progress has been made in harmonising technical systems in shipping (IMO, 2019), the adoption of standardised systems and working methods remains uneven in the HSW sector. These findings suggest that structured operating procedures require greater emphasis, particularly given concerns about the effectiveness of crew resource management without standard operating procedures (Eurocontrol, 2004). At the same time, standardisation must remain flexible and context-sensitive to support crew performance in dynamic operations, as also mentioned by Haavik et al. (2017) and Rajapakse & Emad (2021).

The findings also emphasise the importance of developing a positive and learningoriented safety culture, supported by transparent practices, shared decision-making, and active participation across organisational levels. These fundamentals were highlighted in the study results and follow the previous knowledge (Nævestad et al., 2018; Teperi et al., 2018). Ultimately, improving HSW operations requires a shift from partial optimisation towards system-wide cooperation, where organisational structures, crew practices, and shared understanding are aligned into a coherent sociotechnical system (Dekker, 2017; Sub-study IV).

5.3.1 Data-driven mastery of operations

The findings of this dissertation suggest that effective mastery of HF in HSW operations requires a more systematic, data-driven understanding of system performance. Despite international efforts to develop HF in the maritime sector (IMO, 2011), the utilisation of HF-related knowledge, data, and analytical approaches remains limited. The study demonstrates the value of integrating knowledge from other safety-critical sectors, particularly civil aviation, where approaches to supporting human performance have been more systematically developed (EASA, 2023; IATA, 2024; ICAO, 2013; Van Avermaete, 1998). In this context, crew resource management (Cooper et al., 1980; Wahl & Kongsvik, 2018) and the HF Tool (Teperi, 2012; Teperi et al., 2018) provide complementary frameworks for analysing and developing system performance.

A prerequisite for such development is a shared and transparent understanding of the sociotechnical system, including its structure, key components, and interactions across operational levels. Without a unified and data-informed view of system performance, HF development is likely to remain fragmented and reactive. These findings suggest that organisations must first strengthen their understanding of human performance in relation to system characteristics (Sub-study III), followed by the adoption of coherent analytical frameworks for identifying development needs (Studies I–IV).

From a practical perspective, this requires continuous data collection, analysis, and feedback processes as integral parts of operations. Technical cockpit data, observational methods, and subjective assessments all provide complementary insights into system performance. However, the collection and use of such data also raise challenges related to information security, legislation, and organisational culture (ICAO, 2002). These challenges highlight the need for legitimate, transparent, and non-punitive practices for data utilisation.

At the same time, structural constraints, such as limited organisational resources, may hinder systematic HF development in the HSW sector. These findings suggest that increased collaboration between organisations and the development of shared approaches are essential for enabling consistent, data-driven improvement of system performance.

5.3.2 Promoting learning through system-level integration

The findings indicate that improving system performance in HSW operations requires the active promotion of continuous learning across all levels of the sociotechnical system. This includes removing barriers to information flow between crew members, teams, organisational levels, and maritime organisations (Sub-studies I–IV).

However, safety reporting, a key mechanism for organisational learning, has not been effectively utilised in the HSW context (Sub-study I), reflecting broader challenges in the maritime sector (Amalberti, 2001; Berg, 2013; Schröder-Hinrichs et al., 2013;

Turan et al., 2016). Available incident data are often limited and based on incomplete analyses of HF, constraining their usefulness for learning and development. These findings suggest that the effectiveness of safety reporting depends not only on data collection but also on the quality of analysis and the visibility of organisational responses. If reporting does not lead to feedback or observable improvements, engagement with reporting systems is likely to decline (Teperi & Leppänen, 2010). Moreover, the absence of reported incidents should not be interpreted as evidence of safety but may instead indicate gaps in system understanding (Dekker & Pitzer, 2016).

Crucially, the effective use of safety reporting and other operational data depends on a culture in which reporting is perceived as legitimate and non-punitive, as noted by Qiao et al. (2021). If individuals fear blame or negative consequences, important information about system performance may remain unreported or distorted. These findings emphasise that a just (blame-free) organisational culture is a prerequisite for enabling transparent reporting, open communication, and meaningful organisational learning. In such a culture, data are used to support collective learning and system development rather than to assign individual accountability.

Developing continuous learning therefore requires a shared understanding of system performance, operational objectives, and the boundaries of normal and non-normal operations. It also requires the use of robust analytical approaches capable of supporting proactive development (Leveson, 2011; Schöbel et al., 2022; Teperi et al., 2018). Encouragingly, the findings indicate some progress in the utilisation of safety reporting in the HSW sector (Sub-study I), including increased recognition of factors supporting successful performance. However, further development is required, particularly through concrete management actions and resource allocation (Sub-study IV). Taken together, these findings suggest that learning in HSW operations must be understood as a system-level process, supported by data-driven analysis, transparent feedback, and coordinated development across organisational boundaries.

5.4 Limitations and future research

This study is interpretive in nature, and the findings were developed in close relation to the underlying theoretical framework (Puusa et al., 2020). The analysis is based on representations of HSW operations shared by different actors, reflecting a subjectivist philosophy of science (Rabetino et al., 2021). As a result, the findings are inherently context-dependent and open to alternative interpretations.

To strengthen the credibility and trustworthiness of the findings, the study applies triangulation across multiple methods and data sources. Nevertheless, triangulation does not eliminate the interpretive nature of the results. Because human activity cannot be fully observed objectively (Johnson et al., 2000), the study necessarily relies in part on subjective experience as a means of accessing the phenomenon, while acknowledging the limitations associated with such data.

This dissertation was conducted in Finland, which may raise questions about the international transferability of the findings. At the same time, Finnish waters provide a highly demanding context for coastal high-speed maritime operations and therefore offer a relevant setting for examining the cognitive and operational demands of the sector. Even so, the findings would benefit from further validation in other national and operational contexts. Study-specific limitations have been discussed in more detail in the appended articles and are therefore not repeated here.

This dissertation also identifies several important directions for future research. First, further work on the relationship and balance between Safety I and Safety II perspectives would strengthen the conceptual basis for developing the HSW maritime sector (Sub-study I). Second, research should continue to validate the competency framework and behavioural marker taxonomy developed in this dissertation, including the interrater reliability of crew competency assessment criteria (Sub-study II), while recognising that some variation in assessors' observations, evaluations, and interpretations is unlikely to be eliminated entirely (Weber & Dekker, 2017). Third, behavioural markers should be tested in other operational contexts, including larger vessels and even faster HSWs, and their relationship with observable operational outcomes should be examined more systematically (Sub-study II). Fourth, more precise identification of the relationship between mental workload and explicit performance in actual operational tasks would provide a stronger basis for the further development of the operational system (Sub-study III). Finally, longitudinal research on the effectiveness of HF development measures in maritime organisations would help identify effective solutions and avoid ineffective development trajectories (Sub-study IV).

5.5 Conclusion

This dissertation advances the understanding of HF in HSW operations by providing a domain-specific, multilevel analysis of crew performance, mental workload, and system interactions. It conceptualises the mastery of HF as a systemic and structured capability, supported by the integration of competencies, behavioural markers, workload assessment, and organisational conditions into a unified analytical framework.

The findings demonstrate that system performance and operational safety in HSW operations cannot be achieved through individual competence or isolated interventions alone. Instead, they emerge from the alignment of sociotechnical system components, including crew competencies, working conditions, organisational practices, and technological solutions. This highlights the need to move beyond individual- and error-centred approaches towards the proactive support of human performance across all system levels. The study further shows that effective mastery of HF requires the integration of both Safety I and Safety II perspectives. While traditional approaches remain necessary for understanding failures, they are insufficient for supporting everyday successful performance. A combined perspective provides a stronger basis for developing resilient operations in dynamic and uncertain environments.

From a practical perspective, the findings emphasise the importance of strengthening cooperation, shared understanding and data-informed development across the HSW operating system. This includes improving incident analysis, supporting crew resource management, enhancing workload awareness, and aligning organisational and operational practices. Without such coordinated efforts, performance remains dependent on individual capability rather than being embedded in the functioning of the system. Ultimately, the dissertation shows that human performance should be understood as a central resource for system performance. Supporting this resource requires continuous learning, systematic use of operational data, and the active development of HSW sociotechnical systems that enable safe, effective, and resilient operations.

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Appendix. Statement from the University of Vaasa Human Science Ethics Committee

Telia

SIGNATORIES

Name	Authentication method	Date
TOMMI JUHANI LEHTONEN	Strong	30.08.2022 08:14:55 UTC+03:00
VIRPI JUPPO	Strong	30.08.2022 08:19:27 UTC+03:00

Vaasan yliopisto
UNIVERSITY OF VAASA

University of Vaasa Human Science Ethics Committee

TO WHOM IT MAY CONCERN,

Researcher Mikko Lehtimäki at the University of Vaasa has asked University of Vaasa Human Science Ethics Committee to provide a description of the ethical review system for research in Finland for his research Työkuorman hallinta nopeiden työveneiden ohjaamotyöskentelyssä / Workload management in the crew performance of high-speed workboats – systemic human factors perspective.
In Finland, research with human participants must comply with the guidelines of the Finnish National Board on Research Integrity TENK *The ethical principles of research with human participants and ethical review in the human sciences in Finland. Finnish National Board on Research Integrity TENK guidelines 2019* (pdf).
University of Vaasa has undertaken to comply with TENK's guidelines. The guidelines do not cover medical research as defined by law (Medical Research Act 488/1999) or other research designs where ethical review is a separate obligation laid down by law.

According to the guidelines, research is to be conducted in such a way that the dignity and autonomy of human research participants is respected and the research does not cause significant risks, damage or harm to research participants, communities or other subjects of research.

Ethical review is to be carried out prior to gathering data, if the research contains one or more of the following factors:

1. Participation in the research deviates from the principle of informed consent. Participation is not, for example, voluntary, or the subject is not given sufficient or correct information about the research.
2. The research involves intervening in the physical integrity of research participants.
3. The focus of the research is on minors under the age of fifteen, without separate consent from a parent or carer, or without informing a parent or carer in a way that would enable them to prevent the child's participation in the research.
4. Research that exposes participants to exceptionally strong stimuli.
5. Research that involves a risk of causing mental harm that exceeds the limits of normal daily life to the research participants or their family members or others closest to them.
6. Conducting the research could involve a threat to the safety of participants or researchers or their family members or others closest to them.

Since none of the above factors is met, ethical review is not required.

In Finland, neither legislation nor TENK's guidelines require ethical review by an ethics committee for research based purely on public and published data, registry and documentary data or archive data.

25.8.2022 in Vaasa, Finland

Chair, University of Vaasa Human Science ethics committee	Secretary, University of Vaasa Human Science ethics committee

The Finnish National Board on Research Integrity TENK is an expert body appointed by the Ministry of Education and Culture and tasked with promoting research integrity and preventing research misconduct in Finland. Further information about the ethical review system in Finland is available at www.tenk.fi.

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Human factor analysis of cockpit work incidents in high-speed workboats: the mystery hidden between the lines

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ABSTRACT
This study evaluated the human factor (HF) analysis of cockpit work incidents on high-speed workboats. Although maritime safety is studied actively, information on such incidents is limited. The study examined how the Safety Investigation Authority of Finland ($n = 7$) and 11 Finnish maritime organizations ($n = 69$) analysed HFs in their incident and accident reports from 2009 to 2021. The HF Tool was used to evaluate the incident analysis and investigation methods, and safety reporting and HF investigations were found to require improvement. Teamwork and communication competencies were poorly acknowledged, and the emphasis was on the performance of individuals. Several HFs, including crew competencies and working methods, were found to play a role in incidents. Our study contributes to improving safety reporting, incident investigations and mastering HFs in maritime high-speed workboats.

KEYWORDS
accident investigation; HF Tool; high-speed workboats; human factors; maritime safety

1. Introduction

Maritime safety criticality [1] is of the utmost importance in high-speed workboats (HSWs) (Appendix 1) used for rescue operations, defence, police administration and maritime infrastructure services, as this operating environment challenges crews physically, psychologically and biomechanically [2,3]. The operations involve factors that increase complexity, changeability and uncertainty, making their identification critical to maintaining and developing safety [4,5]. The increased speeds of HSWs, time pressure [6], the demands of fast-evolving operations and multiple external factors challenge the operating system and crews' human information processing [7], especially in difficult-to-navigate waters [8].

Research data on the maritime specialty of HSWs is sparce, but practical information is more readily available [2,9–13]. Human factor (HF) analysis in the safety reporting and accident investigations of cockpit work incidents needs further improvement. Although understanding HFs is critical for safety management [14–17] and in the maritime field overall [1], it remains inadequately implemented [18].

This study examined the HSW cockpit work incident investigations of Finnish maritime organizations and the Safety Investigation Authority of Finland (SIAF). The study used the holistic HF Tool model to evaluate the HFs that they analyse [19]. It also focused on the HFs that are not identified, aiming for an overall view of the factors that affect safety [20]. This study contributes to developing the mastery of HF in high-speed maritime.

2. Human factors in HSW cockpit work

2.1. The objective of cockpit work

HSW cockpit work can be defined as the dynamically implemented, safe management of the boat in ever-changing conditions [21]. This is in line with the expression in aviation of 'aviating, navigating and communicating' [22] when following a predetermined route plan [23] and reacting to the factors encountered during sea voyages, such as other waterborne traffic [24]. The crew's main task is to manage risks [25] and avoid accidents and even catastrophic consequences [26]. The aim of cockpit work is to manage the boat's operative performance [27] and safety, effectively avoiding undesirable events and benefitting the parties involved [28–30]. In order to achieve these objectives, HFs must be mastered at all levels of activity, which are discussed next.

2.2. Mastery of HFs

This study used the systemic and multidisciplinary thinking of HF and ergonomics (HF/E) [31], which takes into account human dynamic interaction [16,29,32] with systems [33] and the HF components as a whole [31]. In this article, the term HF includes the ergonomics perspective [34].

Work in safety-critical operations requires scaling resources to meet the requirements of real work at all levels of the organization and operations [29,31], as well as understanding the diversity of human performance and the underlying factors of frontline work [35]. The interaction between technical and social components is crucial in the maritime system [36]. It can be described using the SEPTIGON model, which is based on the SHEL (Software, Hardware, Environment, Liveware) concept [37] and includes different HF levels as well as the physical environment and technology [38].

The safety criticality of operations challenges the mastery of HFs, as safety is ultimately ensured by the systems' ability to adapt to complex conditions and to learn about human performance traits in order to develop [39]. Maritime culture and safety management practices are still primarily based on the Safety I paradigm – questioning and controlling people, isolating normal activities from non-normal activities and

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eliminating individual causes of unwanted activity [29]. This perspective is technical and hierarchical; it places a great deal of trust in regulation, and sees human performance as a negative factor [18,40]. In contrast, the theoretical background of this study is related to the newer view of safety [35,41], which focuses on ensuring resilient action [42] in high-reliability organizations [43] in order to strengthen the systems' capacities to improve safety [35]. Our aim was to understand and exploit HFs more effectively, viewing people as success factors and adapting their actions to circumstances [44], rather than as the causes of intentional errors [39].

2.3. Incidents and investigations

Most maritime accidents involve navigation failures, grounding or collisions near the coast [45]. In most cases, the background factors are identifiable as HFs [46] at the sharp end [47] but also at the maritime-company level [7,45,46]. Deviations that endanger safety are usually caused by complex interactions between humans and technology [48], which is difficult to analyse due to situational uncertainty, complexity, the number of alternative outcomes and the difficulty of linear reasoning [14,20].

To improve the performance and safety of HSW crews, it is essential that they have information and learn from incidents. The required active safety reporting systems often need to be better implemented in the maritime field [49]. High-quality, holistic incident investigations [14] highlight the impact that HFs have on frontline work, and take into account how challenging it is to comprehensively analyse them [50,51], as well as the positive events and actions [19,40] in the socio-technical system.

The study hypothesizes that the traditional viewpoints of the maritime industry and its inadequately utilized safety reporting and incident investigations hinder the mastering of HFs and achieving the field's key objectives.

3. Aims

This study examined the HF analyses of incidents in HSW cockpit work in Finland from 2009 to 2021, to obtain information for improving HSW operations. The study found HFs that both strengthened and weakened the safety of operations.

3.1. Research questions

- RQ1. Which factors contributed to the incidents, according to the incident and accident reports? Which types of HF were highlighted in the recommendations issued in the reports?
- RQ2. How were the incidents investigated, and what methods were used?

4. Materials and methods

This study analysed HSW cockpit work-related investigation reports compiled by the SIAF (dataset 1: SIAF) and the incident reports of Finnish HSW maritime organizations (dataset 2: ORG) from 2009 to 2021.

In this study, incidents were defined as dangerous situations and accidents in general. The final reports of the SIAF safety investigations were called 'investigation reports', and the maritime organizations' descriptions of dangerous situations, incident reports and safety investigations were termed 'incident reports'.

4.1. Materials

In February 2022, data were requested from the HSW maritime organizations ($n = 26$) in Finland that investigated incidents as part of their operations. Research permits were granted by 22 organizations, 11 of which submitted material suitable for the study. Seven organizations reported having no suitable material available. The SIAF's investigation reports were publicly available. Data collection ended at the beginning of August 2022.

Of the 133 investigation and incident reports received, 76 were selected for analysis (SIAF, $n = 7$/ORG, $n = 69$). Fifty-seven incident reports were omitted because they addressed minor groundings during landing or approaching landing. This stage of the work was not part of the study's scope, as we were not examining the failure of technical equipment during a voyage because this did not affect the incidents. In some cases, the line separating some categorizations was very fine, and the interpretation was left to the researcher.

To avoid duplication, if the SIAF had investigated a particular accident, the maritime organization's investigation for the data was not selected. In Finland, the SIAF, which operates under the Ministry of Justice, conducts safety investigations of maritime accidents and incidents, and examines the nature of the accident, the causes and consequences of the event, the rescue operations during the accident and the authorities' actions [52].

4.2. Methods

The data were collected by studying the investigation and incident reports comprehensively as observation units. The study analysed all of the investigation methods and factors that prevented, slowed down or strengthened cockpit work, adhering to the recommendations to improve the operations.

The study summarized, classified and operationalized the data from the documents for quantitative analysis into nominal-scale statistical variables (Table 1), to be processed in Microsoft Excel version 16.90 and SPSS version 26. The analysis used a descriptive statistical method instead of statistical reasoning.

4.3. Nature of the incidents

The data were classified according to the year of the event (Table 2). The incidents occurred between 2009 and 2021, and the study focused specifically on 2018–2021 (75%). All of the HSW cockpit work incidents investigated by the SIAF ($n = 7$) had occurred between 2016 and 2020, except for one in 2009 [53]. Six incident reports did not mention the year of the incident.

The incidents were classified using the Finnish Navy's method of classifying sea damage, which is based on the event and its consequences. Ground contact means sea damage in which the vessel has slightly touched the seabed or shore but is still navigable and manoeuvrable immediately afterwards. Grounding refers to sea damage in which the vessel collides with the shore, runs aground or cannot navigate or manoeuvre after being detached from it. A collision is the collision of

Table 1. Criteria for classifying the data.

Criterion	Classification
Year of occurrence	2009–2021
Nature and consequences of incident	Ground contact
	Grounding
	Collision
	Impact
	Run-on
	Capsizing
	Other near misses or deviations
Investigation model	Linear investigation model/Swiss cheese model
	Accimap
	Safety II/holistic (as HF Tool)
	Light handling/not investigated
HF contributing to incidents (pos. and neg. impact, HF Tool 1–47 details)	Individual factors and actions
	Work characteristics
	Group characteristics
	Organizational factors
Other factors	External factors related to conditions or other factors
	Regulative factors
	Errors

Note: HF = human factor.

Table 2. Annual distribution of incidents, 2009–2021.

Year	Frequency	%
2009	3	3.9
2011	1	1.3
2014	2	2.6
2015	3	3.9
2016	3	3.9
2017	1	1.3
2018	8	10.5
2019	19	25
2020	18	23.7
2021	12	15.8
Total	70	92.1
Data on the year missing	6	7.9
Total	76	100

two or more ships in a passage, either with one another, with another ship or with equipment being towed by the ships. Impact means the collision of a ship with a quay structure or a moored ship. A run-on means the collision of a ship or its component device with a drifting, fixed or anchored object, device or vessel in the water that is not in pass. In this study, another category is associated with the capsizing of a ship in a passage and the final category relates to other near misses or deviations.

4.4. Classification of contributing factors

The study analysed the HFs that played either a positive or negative role in the incidents and the recommendations for improving operations made in the reports using the HF Tool. This tool was initially developed to implement the HF approach in the safety-critical work of air traffic management [19] and is considered a holistic, easy-to-use and positively oriented method [39]. The HF Tool has been used to learn and identify HF areas, to increase HF and safety competence, and to analytically investigate incidents [54–56]. It is based on a systemic, holistic and socio-technical understanding of the HFs that influence the mastery of complex systems through work and the development of organizations. The HF Tool is based on socio-technical theory, complemented with positive, i.e., solution-oriented, psychology, and refocuses analyses to enable the understanding and creation of factors that support individuals and organizations in their everyday operations, work and development [56].

The HF Tool focused on the socio-technical system as a whole through four levels and operational framework details (HF Tool details 1–47): individual factors and actions; work characteristics; group/team factors; and organizational levels of system safety. The model also considered HFs in terms of people's positive capacity [35], such as when operations are running smoothly [29,54], but did not describe the complex cross-connections of the system components.

The HF perspective was supplemented in the study by the following three additional categories: external factors related to conditions or other factors; regulatory factors; and operational errors. If the activity was related to several HFs mentioned in the HF Tool, the most important was selected. Each factor mentioned in the dataset as contributing to the cockpit work incident was recorded as a separate nominal-scale variable, and its frequency was analysed in all the reports of the event. The SIAF/ORG datasets were processed both separately, to enable a comparison, and together (comb.) to form an overall picture.

4.5. Investigation methods

On the basis of the model used to analyse the incidents, the reports were divided into four categories: linear investigation model/Swiss cheese model; Accimap; Safety II/holistic method; and light handling/unexplored. Light handling referred to a method in which the incident was briefly reported to the organization, and in which the organization's analysis was thin or completely absent.

5. Results

The documented HSW cockpit work incidents in Finland from 2009 to 2021 are described in the following. The article then describes the SIAF's and maritime organizations' analyses of the factors that they identified as playing a role the incidents, their recommendations to improve operations and how the events were investigated.

5.1. What kinds of incidents occur in HSW cockpit work ?

A critical proportion of incidents (69.7%) were related to ground contacts, groundings and run-ons (Table 3). The 'other events, near misses, or deviations' category (17.1%) described data from an individual organization and dealt with events that had not ultimately caused the incidents. About a tenth of the incidents were related to the risk of collision.

Next, the study assessed the HFs that were considered to have played a role in the incidents at different operational levels as well as other factors.

Table 3. Distribution of incident types.

Incident type	Frequency	%
Ground contact	37	48.7
Grounding	14	18.4
Other near miss or deviation	13	17.1
Collision danger, near miss	7	9.2
Collision	2	2.6
Run-on	2	2.6
Capsizing	1	1.3
Total	76	100

5.2. How did human factors contribute to the incidents?

The research data (comb.) contained 673 mentions of factors that were considered to have played a role the incidents (Table 4). Of these, 494 (73.4%) were negative observations and 179 (26.6%) played a positive role in the event. Only a small percentage ($n = 72$, 10.7%) of the mentions were of factors other than HFs ($n = 601$, 89.3%): external factors or other factors related to conditions ($n = 39$); regulatory factors ($n = 15$); and operational errors ($n = 18$). Only the SIAF considered the regulatory level of activity. Active human errors were mostly mentioned in the maritime organizations' data.

Of the negative factors, slightly more than half (53.3%) were classified in the HF category of 'individuals' actions and characteristics'. In the organizations' reports, the proportion of negative HFs related to individuals was significant (62.9%). In contrast, in the SIAF reports the corresponding share was half of this (31.5%). Individual-level HFs were also highlighted in terms of positive factors (SIAF 30.4%/ORG 66.9%/comb. 55.4%).

A few observations could be classified as group-level activities (comb. negative 11.3%/positive 14.7%). The SIAF investigation reports contained even fewer mentions of teamwork than the organizations' dataset (negative 6.2%/positive 1.8%), and so this was underemphasized in comparison to other HFs. The SIAF, on the other hand, considered more organizational-level activities (negative 33.8%/positive 25.0%) than the maritime organizations, which handled this level to a lesser extent (negative 7.1%/positive 5.0%).

5.3. Individuals' actions and characteristics as the cause of incidents

Slightly less than a quarter of the negative observations at the HF Tool level that were related to the actions and characteristics of individuals (Table 5) were discussed (comb.) from different perspectives such as professional competencies, skills and mastery of work processes. Problems cross-checking data sources and using navigation devices or critical information were seen as factors that played a crucial role in the incidents (41.5%). The maritime organizations addressed more problems in individuals' situational awareness or human information processing than the SIAF (SIAF 12.2%/ORG 23.8%). On the other hand, poor compliance with guidelines and agreed practices was considered more often by the SIAF (29.3%) than the organizations (14.1%). An extremely high or low mental workload was rarely recognized (SIAF 7.3%/ORG 4.9%).

Limited work experience was mentioned more often by the SIAF (9.8%) as a factor that played a negative role in activities than by the organizations (2.2%). Attitudinal factors, which are key to the safety and efficiency of operations, were minimally considered (comb. negative 6.2%/positive 0.0%).

Of the individual-level positive HFs, an essential part (comb. 46.9%) was related to crew professionalism and mastery of work ($n = 45$). In contrast, 24.5% were related to the crew adhering to pre-agreed procedures. Most of the positive mentions were made by the maritime organizations, whereas the SIAF accounted for less than a fifth of individual-level positive findings.

5.4. Work situations and how to prepare for them

More than a third (35.1%) of the negative SIAF mentions in the HF 'work activities and characteristics' category was related to the technical functionality and usability of work equipment and cockpit ergonomics (Table 6). The maritime organizations mentioned these less frequently in comparison (22.9%). In these organizations, time pressure and rushing were more often regarded as playing an adverse role in incidents (29.2% of all work activity-level and work characteristic-level details) than in the SIAF, which mentioned them only once.

Assuring crew competence was more often seen as deficient by the SIAF (37.8%) than by the organizations (12.5%). A decile of the negative HFs mentioned (positive 15.8%) were related to work organization, operational procedures and competence assurance, considering crew familiarization, training and qualifications management.

About half of the positive mentions (comb.) of the organization of work activities were related to ensuring the competence of crews (45.5%, $n = 15$). Most of these were made by the SIAF, noting that the HFs related to working methods and instructions played a positive role in events. The maritime organizations had also a few positive mentions regarding the previous ($n = 9$), and these were evenly divided into factors related to the crew's division of labour, competence, working methods and the functionality of the technical equipment and environment.

5.5. Crew activities as a working group

Group/team-level HFs (Table 7) were rarely considered as playing a negative role in incidents (SIAF 6.2%/ORG 13.6%). A relatively substantial proportion of the negative mentions were related to the crew members not using their knowledge (SIAF 62.5%/ORG 65.0%). Mentions of the effective teamwork condition as well as internal communication between crew members were few (comb. negative 16.7%/positive 19.2%).

The SIAF had only one positive mention related to the success of group-level activities. As positive HFs, the maritime organizations in particular noted that the crew members used their knowledge well (40.0% of mentions). The formal structure, in line with the crew's requirements was positively emphasized (comb. 34.6%), as well as communication during the event (comb. 19.2%).

5.6. Activities of the organizations

Most of the HFs related to the activities of the organizations (comb.) could be classified as various factors of organizational and safety culture (negative 76.9%/positive 85.0%) (Table 8).

Based on the mentions (comb.) at the organizational level, further analysis of inadequate safety culture found

Table 4. Factors contributing to incidents.

	Dataset											
	Combined ($n = 76$)				Organizations ($n = 69$)				SIAF ($n = 7$)			
Factor contributing to incidents	DFT	HFT	*n*	%(*n*)	DFT	HFT	*n*	%(*n*)	DFT	HFT	*n*	%(*n*)
HFs, negative observations												
Individuals' actions and characteristics	44	10	226	53.3	43	10	185	62.9	14	8	41	31.5
Work activities and characteristics	28	6	85	20.0	21	6	48	16.3	17	6	37	28.5
Group-level factors	11	4	48	11.3	10	4	40	13.6	4	3	8	6.2
Organization-level factors	29	6	65	15.3	10	1	21	7.1	23	6	44	33.8
Total	*112*	*26*	*424*	*100.0*	*84*	*21*	*294*	*100.0*	*58*	*23*	*130*	*100.0*
HFs, positive observations												
Individuals' actions and characteristics	25	8	98	55.4	22	7	81	66.9	9	5	17	30.4
Work activities and characteristics	16	4	33	18.6	6	4	9	7.4	13	4	24	42.9
Group-level factors	7	4	26	14.7	7	4	25	20.7	1	1	1	1.8
Organization-level factors	13	4	20	11.3	6	2	6	5.0	9	3	14	25.0
Total	*61*	*20*	*177*	*100.0*	*41*	*17*	*121*	*100.0*	*32*	*13*	*56*	*100.0*
Other negative factors												
External factors related to conditions or other factors	10	Intentionally empty	39	Intentionally empty	10	Intentionally empty	32	Intentionally empty	5	Intentionally empty	7	Intentionally empty
Regulative factors	9	Intentionally empty	13	Intentionally empty	0	Intentionally empty	0	Intentionally empty	9	Intentionally empty	13	Intentionally empty
Errors	2	Intentionally empty	18	Intentionally empty	2	Intentionally empty	16	Intentionally empty	1	Intentionally empty	2	Intentionally empty
Other positive factors												
Regulative factors	2	Intentionally empty	2	Intentionally empty	0	Intentionally empty	0	Intentionally empty	2	Intentionally empty	2	Intentionally empty

Note: DFT = distinct factors named; HF = human factor; HFT = HF Tool details 1–47; SIAF = Safety Investigation Authority of Finland.

Table 5. Individuals' actions and characteristics that contribute to incidents.

	Dataset											
	Combined				Organizations				SIAF			
Individuals' actions and characteristics	Neg.	%	Pos.	%	Neg.	%	Pos.	%	Neg.	%	Pos.	%
Competence, mastery of work	53	23.5	46	46.9	44	23.8	41	50.6	9	22.0	5	29.4
Situation awareness (perception, memory, decision-making, response/execution)	49	21.7	9	9.2	44	23.8	9	11.1	5	12.2	0	0.0
Working in accordance with instructions and agreed procedures	38	16.8	24	24.5	26	14.1	20	24.7	12	29.3	4	23.5
Understanding the bigger picture/overall situation	30	13.3	1	1.0	26	14.1	0	0.0	4	9.8	1	5.9
Being proactive, examining preconceptions and assuring assumptions	13	5.8	2	2.0	12	6.5	2	2.5	1	2.4	0	0.0
Workload (overload/minimal workload) and means of managing it	12	5.3	5	5.1	9	4.9	1	1.2	3	7.3	4	23.5
Vigilance, alertness, fatigue symptoms	6	2.7	4	4.1	6	3.2	4	4.9	0	0.0	0	0.0
Life situation, anxiety, level of (long-term) stress	3	1.3	0	0.0	3	1.6	0	0.0	0	0.0	0	0.0
Age; quality and quantity of work experience	8	3.5	7	7.1	4	2.2	4	4.9	4	9.8	3	17.6
Health, work ability	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Motivation, attitudes	14	6.2	0	0.0	11	5.9	0	0.0	3	7.3	0	0.0
Emotional state and reactions, mood	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Total	226	100.0	98	100.0	185	100.0	81	100.0	41	100.0	17	100.0

Note: Neg. = negative observations; SIAF = Safety Investigation Authority of Finland; Pos. = positive observations.

Table 6. Work activities and characteristics.

	Dataset											
	Combined				Organizations				SIAF			
Work activities and characteristics	Neg.	%	Pos.	%	Neg.	%	Pos.	%	Neg.	%	Pos.	%
Quality and content of work; work demands	2	2.4	0	0.0	2	4.2	0	0.0	0	0.0	0	0.0
Quantity of work; time pressure, having to rush	15	17.6	0	0.0	14	29.2	0	0.0	1	2.7	0	0.0
Work organization, work distribution, job descriptions; clarity	12	14.1	5	15.2	11	22.9	3	33.3	1	2.7	2	8.3
Usability and functionality of devices, software, technology	22	25.9	4	12.1	11	22.9	1	11.1	11	29.7	3	12.5
Procedures and instructions; functionality, clarity and keeping up-to-date	12	14.1	9	27.3	4	8.3	2	22.2	8	21.6	7	29.2
Opportunities to influence one's work and working conditions	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Feedback on work, professional appreciation	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Opportunity/ability to evaluate and improve one's work processes	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Assuring competence (training, exercises, other ways of learning)	20	23.5	15	45.5	6	12.5	3	33.3	14	37.8	12	50.0
Work hygiene factors, physical work environment, working conditions, occupational hygiene factors (noise, ventilation, lighting, temperature; layout)	2	2.4	0	0.0	0	0.0	0	0.0	2	5.4	0	0.0
Total	85	100.0	33	100.0	48	100.0	9	100.0	37	100.0	24	100.0

Note: Neg. = negative observations; Pos. = positive observations; SIAF = Safety Investigation Authority of Finland.

Table 7. Poorly identified group-level factors.

	Dataset											
	Combined				Organizations				SIAF			
Group-level factor	Neg.	%	Pos.	%	Neg.	%	Pos.	%	Neg.	%	Pos.	%
Shared understanding of situation among all group members	7	14.6	2	7.7	7	17.5	2	8	0	0	0	0
Knowledge of all group members is used	31	64.6	10	38, 5	26	65	10	40	5	62.5	0	0
Communication within group (e.g., misunderstandings, misinterpretations and mishearing are corrected)	8	16.7	5	19.2	6	15	5	20	2	25	0	0
Structure and cohesion of group, group dynamics (social relations, atmosphere, mutual support)	2	4.2	9	34.6	1	2.5	8	32	1	12.5	1	100.0
Communication between different groups (deck, engine room, vessel trafic service, pilot, tugboats, icebreakers, harbour, other ships); model maritime glossary; language skills	0	0.0	0	0.0	0	0	0	0	0	0	0	0
Information flow, communication practices, including change of watch, change of shift	0	0.0	0	0.0	0	0	0	0	0	0	0	0
Decision-making in group (e.g., role of watch officer)	0	0.0	0	0.0	0	0	0	0	0	0	0	0
Total	48	100.0	26	100.0	40	100.0	25	100.0	8	100.0	1	100.0

Note: Neg. = negative observations; Pos. = positive observations; SIAF = Safety Investigation Authority of Finland.

Table 8. Organization-level HFs that support crews.

Organization-level factor	Dataset											
	Combined				Organizations				SIAF			
	Neg.	%	Pos.	%	Neg.	%	Pos.	%	Neg.	%	Pos.	%
Management and leadership; structure, styles	4	6.2	1	5	0	0.0	1	16.7	4	9.1	0	0.0
Organization/safety culture	50	76.9	17	85	21	100.0	5	83.3	29	65.9	12	85.7
Cooperation between different organization levels and units (e.g., office, ship, technology, quality and safety, manning)	3	4.6	0	0	0	0.0	0	0.0	3	6.8	–	0.0
Understanding ship safety as a whole throughout the shipping company's management	1	1.5	0	0	0	0.0	0	0.0	1	2.3	0	0.0
Decisions made (including resources, personnel, equipment)	5	7.7	1	5	0	0.0	0	0.0	5	11.4	1	7.1
Change management (personnel, systems)	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0
Cooperation with partners, e.g., shipping companies, authorities	2	3.1	1	5	0	0.0	0	0.0	2	4.5	1	7.1
Company's support for ship operations (SMS/DPA)	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0
Total	65	100.0	20	100.0	21	100.0	6	100.0	44	100.0	14	100.0

Note: HF = human factor; Neg. = negative observations; Pos. = positive observations; SIAF = Safety Investigation Authority of Finland; SMS/DPA = safety management system/designated person ashore.

that deficiencies in risk management (24.6%) contributed to the occurrence of events. Difficulties in the cooperation and communication between organizational levels, harmful hierarchies and crew leadership styles, and work-as-done/imagined conflicts (23.1%) were almost as often seen to play a negative role in events.

Structural problems in the organization of HSW activities in certain administrative branches were seen as a challenge that weakened the ability to operate safely (16.9%). Problems in safety reporting and learning from errors were seen to play a role in incidents in about a decile of organization-level mentions. However, their share of all the negative factors was still minimal (1.7%). Inadequate situational speed control stood out in the data as a factor that facilitated incidents (15.4%), which may be related not only to the competencies of the crews but also to an operating culture that is harmful to safety.

5.7. What kinds of recommendations were issued in the incident reports?

The SIAF and maritime organizations had 71 different ($n =$ 119) recommendations for improving maritime safety and operational development in their reports (Table 9). Most of these (95.8%) were related to HFs. In addition, the SIAF issued three recommendations for improving regulation. The distribution of the SIAF recommendations was twofold, highlighting the levels of work activities/characteristics and organizational factors (45.5%/45.5%).

In its recommendations, the SIAF did not address group or individual factors to a great extent. In contrast, the maritime organizations made more recommendations for group-level HFs (25.0%, $n = 23$), and about a third were related to the activities of individuals (33.7%, $n = 31$). The importance of leveraging the shared knowledge of crew members was raised repeatedly (comb. 54.2% of group-level HFs). The observation that the knowledge of all crew members should be utilized more effectively was emphasized.

The majority of the organizations' recommendations regarding individual-level HFs were related to improving competence and the mastery of work and working in accordance with instructions/procedures (77.4%). In order to improve work activities (comb.), the competence of the crews (42.9%), developing working methods and instructions (28.6%) and increasing the functionality and usability of the technical equipment (19.0%) were considered essential. Some recommendations related to mental workload management were also made ($n = 2$). Time pressure, which was closely related to this factor, was not considered.

Only around 7% of the recommendations were related to the physical work environment and the usability of technology. No recommendations related to the activities behind these factors were made, such as the empowerment of employees, cooperation and management between different levels of the organization, and decision-making regarding technical solutions. The most important part of the recommendations at the organizational HF level dealt with the management, organizational and safety culture, and the improvement of maritime safety (93.8%). The organizations made some recommendations regarding organizational development (6.5%). In contrast, 80% of the SIAF recommendations at the organizational level were related to organizational and safety culture factors.

Table 9. Recommendations made in incident reports.

	Dataset											
	Combined (n = 76)				Organizations (n = 69)				SIAF (n = 7)			
Recommendation	DRN	REC	n	%(n)	DRN	REC	n	%(n)	DRN	REC	n	%(n)
Related to HFs												
Individuals' actions and characteristics	17	6	32	28.1	17	6	31	33.7	1	1	1	4.5
Work activities and characteristics	26	5	42	36.8	21	5	32	34.8	7	3	10	45.5
Group-level factors	9	5	24	21.1	8	4	23	25.0	1	1	1	4.5
Organization-level factors	16	4	16	14.0	6	3	6	6.5	10	2	10	45.5
Total	68	20	114	100.0	52	18	92	100.0	19	7	22	100.0
Related to regulations	3	Intentionally empty	5	Intentionally empty	0	Intentionally empty	0	Intentionally empty	3	Intentionally empty	5	Intentionally empty

Note: DRN = distinct recommendations named; HF = human factor; n = Recommendations classified by HF Tool levels and related to regulatory development; REC = recommendations by HF Tool details 1–47; SIAF = Safety Investigation Authority of Finland.

Table 10. Distribution of investigative methods.

Investigative method	Frequency	%
Linear investigation model/Swiss cheese model	8	10.5
Accimap	6	7.9
Safety II/holistic (as HF Tool)	2	2.6
Light handling/not investigated	60	78.9
Total	76	100

Note: HF = human factor.

5.8. How were the incidents investigated? What methods were used?

In the majority of the cases (comb. 78.9%), the investigations were general, and more thorough investigations that were in line with known investigative models were not carried out on the basis of the documents (Table 10). However, commonly used investigative models (21.1%) were also used. As a rule, the SIAF used the Accimap method (85.7%) in its investigations. The majority (87.0%) of the investigations conducted by the organizations were either general or no actual investigation was carried out. The HF Tool model was used twice (2.6%).

6. Discussion

This study evaluated the SIAF's and maritime organizations' analysis of HSW cockpit incidents in Finland from 2009 to 2021. The results showed that the HF analysis of incidents in the field still requires improvements. However, it is constantly evolving.

6.1. HFs behind the incidents

HFs were recognized as playing a significant role in incidents, as is evident in the maritime sector [7,18,46] and in safety research [1,15–17,35]. Although the analysis focused on negative observations, it also identified HFs that supported the activity. Several dimensions of the HF analysis should be developed. Many pivotal HFs that affected operations were not evaluated, which meant that the documents had to be interpreted by reading 'between the lines' [51]:

- HFs were understood through individuals, as is often the case in the maritime sector [40]. Especially in the organizations, individuals' successes and failures were generally seen as contributing to incidents, which shifted responsibility from the management to the front line. Problems cross-checking data sources by crew members were emphasized. Group-level HFs, such as crew communication, are challenging to analyse and were scarcely addressed, even though they were prerequisites for safety and efficiency in these challenging and complex operational environments [57–59]. The successes related to teamwork that were mentioned were often related to fulfilling formal requirements, which is in line with the Safety I paradigm [29].
- Competence assurance and working methods were the HFs that were considered to play a role in operations (negative/positive). Considering the fields' individual viewpoints on HFs, we propose that the pivotal crew competencies and the procedures reflecting them are analysed and developed, to ensure effective resource management and consideration in safety investigations.
- Multitasking and time pressure were seen as harming operations, but mental workload was not explicitly addressed.

We propose that the concept and management of workload is considered in more detail in maritime HSWs.

- HFs related to the technical and information environment were rarely mentioned, despite the role they play in crew performance. However, the SIAF paid relatively more attention to these HFs. Technical aspects should be emphasized more clearly in socio-technical operations.
- The SIAF more accurately identified organizational HFs, such as crew structuring and work experience, as being behind the operational levels. The maritime organizations seldom mentioned organizational HFs but supported the SIAF findings, which in turn were essential to the field from an outside perspective.
- Many of the HFs identified were related to the human consequences of actions, as situational awareness, e.g., can be both a factor and an effect. Nevertheless, the HSW field should seek to analyse these dependencies more closely to promote a proactive approach and reduce reactivity.
- The organizations' recommendations often focused on improving individuals' performance by developing their professional skills or mastery of their work and following instructions and procedures, reflecting the norm-based emphasis [55]. Many of the recommendations were related to developing and adopting working methods. However, the organizations emphasized group-level HFs, which are significant to resource management, in their recommendations to a greater extent than they were considered in the incident reports. The SIAF mainly focused on organizational-level activities and work activities/work characteristics. The absence of group-level recommendations by the SIAF raised legitimate questions: would developing this level of HFs not be essential?

6.2. Investigations and investigation methods

The number of incident reports from the organizations was low, given that a few thousand (depending on the estimate) HSWs are actively used in Finland. The annual data distribution indicated that it is likely that not all incidents were investigated, or that the data had not been available for the study. Most of the organizations did not use the well-known methods of accident analysis or comprehensive analysis, perhaps because of their challenging nature [14,20,50,51] and the apparent lack of resources and expertise in terms of HFs. The number and quality of investigations rose towards the end of 2009–2021, in line with findings from other safety-critical fields [56]. This also took into account the possibility of increased incidents. The SIAF used the Accimap method extensively [60], which affected the quality of the analysis.

6.3. Development of investigations and future research

Systemic mastery of HFs must be promoted in HSWs maritime [29,41], instead of focusing on the activities of individual crew members. The results showed that individualistic thinking is harmful, and that the operating culture is unlikely to be considered fair [61]. Organizations need adequate methods for developing safety reporting and investigations, and to proactively develop operations on the basis of analytical data [40,61,62]. Further research on crew competencies is needed to promote crew performance in the HFs at different levels of operations, and investigations need to consider them carefully. The current paradigm shift in safety research (Safety I–II) offers an opportunity for change, and to effectively combine the aspects of safety thinking [18].

6.4. Limitations

This study did not manage to provide an overall picture of safety in HSW cockpit work because: the total number of incidents and work performance were most likely completely unknown; the incidents had been reported, documented or investigated at different times over the years; or reports were not available for the study. Overall, the timelines of the incidents were unknown, and no attempt had been made to artificially place the chains of events in a time-ordered form. Interpretation of the results should take into account that the data were gathered in Finland only.

6.5. Ethics

In its ethical statement dated August 25, 2022, the Human Science ethics committee of the University of Vaasa considered that no ethical review was required for this study. Several foundations supported the implementation of the study. The funders did not participate in the planning of the research; the collection, analysis or interpretation of the data; the writing of the research report; or in the selection of the publication to which to offer the research article.

7. Conclusion

Most HSW voyages in Finland are carried out with enormous professionalism and without incident. Any incidents that do occur should not be considered part of normal operations [32], and may be more of an indication of safety management problems. Utilizing the socio-technical HF Tool model, we examined how maritime organizations and the SIAF analysed how HFs contribute to cockpit work incidents and made recommendations related to them to improve operations. The challenges we identified concerned HF analysis, incident reporting and investigations. Teamwork and communication in particular were poorly recognized HFs behind the incidents. Several other HFs were emphasized and should be considered when attempting to better understand HFs and promoting a proactive operating culture in the socio-technical system of HSWs.

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Disclosure statement

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Appendix 1. Definition of a high-speed workboat

In this study, a high-speed workboat (HSW) meant a professional boat of 5.5–24 m in length [64], moving at a speed of more than 20 knots, without using the ground effect or getting out of the water [65]. The boat has a sliding or semi-sliding hull and is used for professional, trade or non-recreational purposes. It can also be used to respond to an oil spill or as a fire or police boat [66]. The IMO's high-speed craft (HSC) is a term used to describe the operational profile of HSWs. Warships and troop carriers were included in the scope of this study, although they are not included in the definition of the IMO's HSC vessels [65], as these often operate faster than other traffic and their speed is occasionally used as a tool to avoid a collision. Active measures that are in violation of water transport regulations are also sometimes required to avoid a collision [67].

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Developing behavioural markers of high-speed workboat crews' competencies

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ABSTRACT
This study defines the competencies, structured as behavioural markers, that lead to an excellent performance by high-speed workboat crews in cockpit work and can promote maritime safety and operational efficiency. A need to better understand crew performance in cockpit work has been identified in this maritime specialty. The behavioural marker taxonomy is based on aviation standards, further reasoned by human factor models and maritime knowledge. It was formed utilizing content analysis and validated at the prototype level using observation data from actual cockpit work. The tested behavioural markers modelled crew behaviours in eight competency areas. This study contributes to improving crew and operative performances and safety, and to developing socio-technical systems in the field. The study also reveals further research topics for supporting cockpit and bridge crews in safety-critical high-speed maritime environments.

KEYWORDS
behavioural markers; cockpit work; high-speed workboats; human factors; maritime safety

1. Introduction

As the operational environment of high-speed workboat (HSW) cockpit work is challenging and fast paced [1,2], safety [3–5] is a crucial issue in the crews' performance. HSWs (defined in Appendix 1) are used in rescue, defence and police operations, as well as in other maritime environments, such as those critical for the security of supply and the energy sector.

The impact of human factors (HFs) [6] on operations in the maritime industry [7] is insufficiently known, although it is constantly evolving [8]. Despite the information obtained from safety research [9–12], shortcomings have been highlighted in HSWs, especially in the group work and resource management of cockpit work [13]. The crew competencies essential for effective resource management have not been specified. The non-technical skills [9] required for performing operations [10] such as those in safety-critical sectors are particularly poorly understood and insufficiently supported [11].

This study defines the behavioural markers (BMs) of HSW crew competencies as vital to crew performance and achieving cockpit work objectives. BMs refer to a taxonomy of the key skills associated with effective, safe job performance in a given operational environment and illustrate them using example behaviours [12]. BMs help develop sharp-end work and positively influence background processes such as regulations, working methods [14,15], training and performance requirements [16–18] and human–machine interface optimization [19].

1.1. Cockpit work – objectives and working as a team

HSW cockpit work objectives have been defined [13, p.1] as:

> the safe management of a boat in ever-changing conditions [20], which is in line with the definition in aviation – 'aviating, navigating and communicating' [21] to follow a predetermined route plan [22] – and reacting to factors encountered during the voyage, such as other waterborne traffic [23].

The aim of cockpit work is operative performance [24] and the safety of the parties involved [5,16], which requires detecting and reacting to threats [25]. The efficiency of operations considers the limited time for executing tasks [3,25,26]. The results are affected by resources [27], the demands of the situation and the task and ability of crews to return to normal operations after adverse situations [28].

On HSWs, cockpit work requires a high level of resource management and teamwork to advance common goals [29], utilize determinants and carry out cognitive, verbal and behavioural tasks and processes [30]. Crews form an effective team when they dynamically and interdependently combine their roles to promote interaction and to achieve goals [18,31].

Group work has been described as, e.g., input–process–output–process [32], work phases or interpersonal activity [30]. The results of work are visible or related to human reactions [29], efficiency and the achievement of goals [33]. They are incorporated into background activity, and modifying frontline teamwork's input factors and features [10,32,34]. In reality, crews are complex, adaptive and dynamic entities that interact with the operating environment [35,36]. This process perspective has also been criticized for ignoring emergence [30] and the non-linearity of teamwork [37], whereas others have noted that grouping human activities gives structure to the interrelationships and feedback mechanisms involved in processes [38].

To promote teamwork and resource management in cockpit work, the demands placed on crews must be detailed [39]. In this study, these requirements were structured according to competence areas as BMs, the formation of which is discussed in the following.

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Table 1. Examples of behavioural marker taxonomies.

Model	Author(s)	Industry	Description
NOTECHS NTS	Van Avermaete [45]	Aviation	NTS of multi-pilot aircrew, considering interconnectedness with technical skills
Evidence-based training	EASA [14], based on IATA [25]; ICAO [46]	Aviation	Skills, attitudes and knowledge needed by crew to master situations and prepare for changing, unpredictable situations
Prototype taxonomy	Kontogiannis and Malakis [47]	Air traffic services	Strategies that controllers use to cope with complexity
ANTS Anaesthetists' NTS	Fletcher et al. [41]	Health care	NTS important for good anaesthetic practice
The nuclear team skills taxonomy	O'Connor et al. [48]	Nuclear industry	Team skills required by nuclear power plant operation team members
NTS (in BMs)	O'Connor and Max Long[49]; da Conceiçlo et al. [50]; Saeed et al. [51]	Maritime industry	NTS of bridge teams and deck officers
	Fjeld et al. [44]	Maritime industry	Literature review 'NTS used by ships' bridge officers in connection with navigation'

Note: ANTS = anaesthetists; BM = behavioural marker; EASA = European Union Aviation Safety Agency; IATA = International Air Transport Association; ICAO = International Civil Aviation Organization; NTS = non-technical skills.

1.2. Defining behavioural markers

Crews' requirements can be structured into competencies and measurable BMs [27] that are needed in technical or non-technical work phases and can be linked to work performance [12,40]. BMs should be simple, comprehensible, usable, valid, sensitive and reliable [12]. They are combined with assessment scales used by trained and calibrated assessors. However, calibration is not always consistently implemented in all assessments [41], as in this study.

BMs have been defined in several safety-critical fields (Table 1). The historical BM ground-breaker was the University of Texas' Behavioral Markers taxonomy [42], which was used to construct the Line Operations Safety Audit (LOSA) [43]. BM models have clarified how non-technical skills are managed in the maritime industry, but detailed descriptions of BMs, particularly with regard to human interaction within crews, are still scarce [44].

Competency-based learning pedagogy related to the use of BMs promotes competencies and continuous development [52] and has been utilized in the maritime sector [53], yielding mixed results [54]. Training and assessment tools still need to be adapted for the maritime industry [44,55,56], due to different operationalization in different fields [9]. This requires applicable methods [12], understanding of HFs [9,49,57] and sector-specific information [58]. This study took these requirements into consideration when implementing the aviation BMs in the HSW maritime industry.

2. Aims

This study examined the BMs of critical HSW crews' cockpit work competencies by modelling crew performance. The taxonomy was tested using observation data from actual operations.

The research questions were as follows:

RQ1. What are the critical crew competencies and BMs in HSW cockpit work?

RQ2. How does the BM taxonomy prototype structure the activities of the crew?

3. Materials and methods

This study utilized content analysis to form a taxonomy prototype of the BMs of critical HSW crews' competencies. The BMs were tested utilizing recordings of observations during actual operations. The study process consisted of four phases (Table 2).

Table 2. Study process.

Phase	Description
Forming the taxonomy prototype	Document analysis
Forming the assessment principle	Synthesis of STCW, NOTECHS NTS and EBT principles
Observations	Development of data recorder for observations in actual cockpit work. Also used in Lehtimäki and Teperi ([85]). Observations of actual sea voyages
Testing the taxonomy	The crews' observed and technically recorded behaviours were analysed, compared to BMs and classified as 'acceptable' or 'unacceptable' based on the assessment principle (see Section 3.2.2 and Table 6) The testing revealed missing and non-functional BMs and the need to improve their content, grammar and mutual order The functionality and fluency of the assessment principle were tested The taxonomy prototype was developed and finalized based on test results

Note: BM = behavioural marker; EBT = evidence-based training; NTS = non-technical skills; STCW = International Convention on Standards of Training, Certification and Watchkeeping for Seafarers Code.

3.1. Materials

3.1.1. Data for taxonomy prototype

The BMs were formed on the basis of the materials and perspectives presented in Table 3. Other data were also employed, as presented in Table 4.

3.1.2. Observation data

Technically recorded observation data from actual cockpit work were gathered to test and develop the BMs. The first author of this article (later 'researcher') conducted the observations in sea areas and inland waters in five Finnish HSW maritime organizations in the autumn of 2022. Data were also used from a voyage during which the recording technology was tested.

The observation cases ($N = 6$) were selected to comprehensively represent the HSW field. The crews used different cabin boat classes, technical designs and working methods,

Table 3. Materials for the BMs.

Material	Source	Description
BM taxonomies		
EASA taxonomy	EASA [14]	Characteristics and behaviours of human activity leading to good performance, essential for executing a task [38]. Nine competency categories: (KNO) application of knowledge; (PRO) application of procedures and compliance with regulations; (COM) communication; (FPA) aeroplane flight path management – automation; (FPM) aeroplane flight path management – manual control; (LTW) leadership and teamwork; (PSD) problem-solving – decision-making; (SAW) situation awareness and management of information; (WLM) workload management; including 73 BMs
NOTECHS non-technical skills	Van Avermaete [45]	Describing original non-technical skills for aviation: attitudes and behaviours not directly related to management of aircraft or systems and use of standard operating procedures [14,45]. Four categories: cooperation; leadership and managerial skills; situation awareness; and decision-making; including 15 elements and 39 BMs
HF models		
CRM	EASA [59]	Concept to ensure optimal utilization of technical, information and human resources in safety-critical fields [34]; improving leadership, communication, human performance and safety in a systemic and resilient way [14]; including 21 themes handling EASA competencies and other HFs
BRM	STCW Tables A-II/1 and 2 (IMO) [53]	CRM for maritime industry [60]. Knowledge, skills and attitudes, three categories: maintaining a safe navigational watch; applying leadership and teamwork skills; and using leadership and managerial skills (last of which is assigned to masters or mates of ships with 500 gross tonnage or over). Categories structured into levels that describe competence, understanding and professionalism in slightly different ways. Levels divided into competence assessment criteria (14 pcs)
HF Tool	Teperi [61]	Systemic concept, based on description of HFs on four levels of socio-technical system: individual factors and actions; work characteristics; group/team factors; and organizational factors; levels include 37 details
Maritime sources		
Documents	HSW organizations ($N = 5$)	Procedures, formal requirements and guidelines ($n = 28$), including cockpit work-related mentions ($n = 118$). Data request made in May 2022 on basis of research permits granted by organizations between December 2021 and April 2022
Incident analysis	Lehtimäki and Teperi [13]	Factors ($n = 112$) that have positively or negatively affected HSW incidents in Finland ($n = 76$)
Regulation in Finland	Agreements, laws, decrees and official regulations	Workshop to select dataset held by Finnish Transport and Communications Agency Traficom and Regional State Administrative Agency for Western and Inland Finland in December 2022. Researcher finally selected eight regulations aimed specifically at cockpit work from entire dataset (28 pcs)
Cockpit work-related technical skills	STCW Table A-II/3 (IMO) [53]	Three competency categories: plan and conduct a coastal passage and determine position; maintain a safe navigational watch; and manoeuvre ship and operate small ship power plants. Categories include seven levels and 23 BMs

Note: BM = behavioural marker; BRM = bridge resource management; CRM = crew resource management; EASA = European Union Aviation Safety Agency; HF = human factor; HSW = high-speed workboat; IMO = International Maritime Organization; STCW = International Convention on Standards of Training, Certification and Watchkeeping for Seafarers Code.

which the researcher studied before commencing observations [58]. The observed sea voyages were carried out for research purposes only. The organizations that granted the research permit selected the crews to be observed. Observations are described in more detail in Section 3.2.

3.2. Methods

3.2.1. Forming the taxonomy prototype

The BMs were formed on the basis of document analysis (Table 3), which evaluated the cockpit work contents of the datasets (BM taxonomies, HF models, maritime sources) and their relationships. The data were first broken down into parts and simplified during the open coding process. They were then grouped using axis coding on the basis of the European Union Aviation Safety Agency (EASA) taxonomy [14], using the basic structure of BMs. The EASA competencies of 'Flight path management automation' and 'Flight path management – manual control' were combined and modified as one competency category, called 'Route plan management', which was then further divided into 'Route planning' and 'Route plan control' subcategories.

The data were continuously compared to the EASA taxonomy (Table 5), other datasets were derived in the selective coding phase and the final BMs were developed and verified. Existing BMs were cited or modified, data synthesized or new BMs were formed. The data were processed in Microsoft Excel version 16.90.

Figure 1 shows the relationships between the datasets and the finalized BMs in competency categories. The figure includes the cumulatively coded parts of the datasets (total 592 pieces) that rationalized the BMs (17 pcs), were modified or combined (231 pcs), or were used as complementary justification (344 pcs).

Figure 2 illustrates the relationship between the coded parts (277 pcs) of the datasets, employed as a concept-level justification for the BMs.

The BMs were operationalized into HSW by ensuring that they were suitable for preventing common HSW cockpit work incidents [13], they considered critical technical skills in cockpit work (facilitated by International Convention on Standards of Training, Certification and Watchkeeping for Seafarers Code [STCW] Code Table A-II/3 [53]) and they complied with regulations in Finland.

The taxonomy was structured as two levels: primary BMs and complementary BMs, the latter of which consisted of 26 primary BMs. Both levels could be utilized to assess the user's choice. The BMs were numbered at three levels (e.g.,

Table 4. Other sources used to form the behavioural markers.

Behavioural marker(s)	Source	Reference
1.7.5 Avoiding 'heads-down' situations by communicating if necessary3.4 Involving crew in sea voyage planning and feedback7.3 Ensuring sufficient time to carry out assigned task without unnecessary sense of urgency	Active Pilot Monitoring Working Group, 2014	[62]
2.2.2 Communicating actively and adequately	Helmreich and Foushee, 34	[34]
2.2.3 Avoiding extra communication	Broom et al., 2011	[63]
2.3 Effectively using description of work phases	Active Pilot Monitoring Working Group, 2014; Gillespie, 2013	[62,64]
2.5 Confirming that recipient demonstrates understanding of message2.5.2 Addressing monosyllabic responses2.5.3 Making sure the message is understood correctly2.6.2 Not answering monosyllabically	Federal Aviation Administration (FAA), 2005	[65]
3.8 Monitoring compliance with a route plan in a timely manner, taking necessary measures	Klampfer et al., 2001; da Conceiçlo et al., 2017; Active Pilot Monitoring Working Group, 2014	[12,50,62]
4.2 Proposing solutions and expressing opinions without questioning authority	Klampfer et al., 2001; Saeed, 2017	[12,51]
4.4.1 Leading the crew and not shirking responsibilities	Ginnet, 66	[66]
5.1 Identifying problems and contributing factors together with crew	Orasanu, 67	[67]
6.3 Maintaining situation awareness of crew and their capacity to carry out the mission6.4 Being aware of one's own functional capacity and communicating its impact on work	Teperi, 61; Flin et al., 2003	[61,68]
7.11 Reacting to indications of a harmfully high or low workload for the crew	International Labour Organization (ILO), 2021; Hollnagel, 16; Siegel and Schraagen, 69	[6,16,69]

1.1.1: competency, primary BMs, complementary BMs). Footnotes for practitioners were also justified and attached to the BMs to refine the content, but they are not reported in the article.

3.2.2. Forming the assessment method

The intention was not to evaluate all of the competencies or BMs simultaneously. The behaviour assessment principle was synthesized (Table 6) to recognize safe and sufficiently effective crew performance [14,53]. The Venn model in the evidence-based training concept [24] was used to specify when the criteria had been exceeded, and the threat and error management level was measured by how often the targeted necessary behaviour was repeated in the competence area and how well it was implemented when necessary. Competence was rated on two tiers [45].

3.2.3. Observations

The observation data were technically recorded and analysed retrospectively. A data recorder was developed for the study (Zilar Security Systems, Finland) (Figure 3), which recorded the following on a timeline (Figure 4): several video cameras; HSW movement factors on a map application; cockpit communication; and subjective mental workload data measures (Lehtimäki and Teperi [85]).

The crews were entrusted with implementing the route plan created by the researcher, except for one case in which the crew carried out operational tasks. The crews were instructed to use at least 90% of their boat's top speed or > 40 knots, but to maintain a safe situational speed. The crews were observed, as in Lehtimäki and Teperi [85], for almost 10 h, from before departure to arrival at the port, over a distance of 269 nautical miles (376 waypoints) and at an average speed of 28 knots (mean speed range 17–34 kn). The external conditions were mild (mean wind 5 m/s, visibility 49 km, dry weather, dark or light). The researcher carried out the observations but did not participate in working in the cockpit.

3.2.4. Testing and developing of taxonomy

The BMs (draft 1.15, completed in June 2023) were tested using the observational data. In testing, the researcher analysed the crews' technically recorded activity 'second by second', also utilizing the repetitions of the recording. All of the crews' observable behaviours were compared to BMs. The assessment method introduced earlier (Table 6) was used, and the behaviours were analysed by 'how often the targeted necessary behaviour was repeated in the competence area and/or how well it was implemented when necessary'. When the crew acted according to a particular BM on 'at least minimum

Table 5. Datasets related to EASA taxonomy.

	Dataset							
EASA competency (BM)	CRM	BRM	NOTECHS NTS	HF Tool	DOC	FAC	STCW	REG
Application of knowledge (7)	0/7	0/7	1/7	+	5/7	2/7	4/7	4/7
Application of procedures and compliance with regulations (7)	1/7	3/7	1/7	+	5/7	4/7	4/7	4/7
Communication (10)	+	+	0/10	+	5/10	3/10	0/10	1/10
Flight path management automation/manual control (8)	1/8	1/8	0/8	+	6/8	5/8	5/8	6/8
Leadership and teamwork (11)	+	+	8/11	+	6/11	3/11	0/11	2/11
Problem-solving – decision-making (9)	+	+	5/9	+	2/9	5/9	0/9	0/9
Situation awareness and management of information (7)	+	+	3/7	+	3/7	5/7	1/7	4/7
Workload management[a] (10)	+	3/10	5/10	+	5/10	4/10	1/10	2/10

[a]EASA BM 3.5 incorporated into workload management (originally nine BMs).
Note: '+' indicates content applicable to EASA BMs at a concept level. BM = behavioural marker; BRM = bridge resource management; CRM = crew resource management; DOC = maritime documents; EASA = European Union Aviation Safety Agency; FAC = factors behind high-speed workboat incidents; NTS = non-technical skills; REG = high-speed workboat cockpit work regulations in Finland; STCW = International Convention on Standards of Training Certification and Watchkeeping for Seafarers Code.

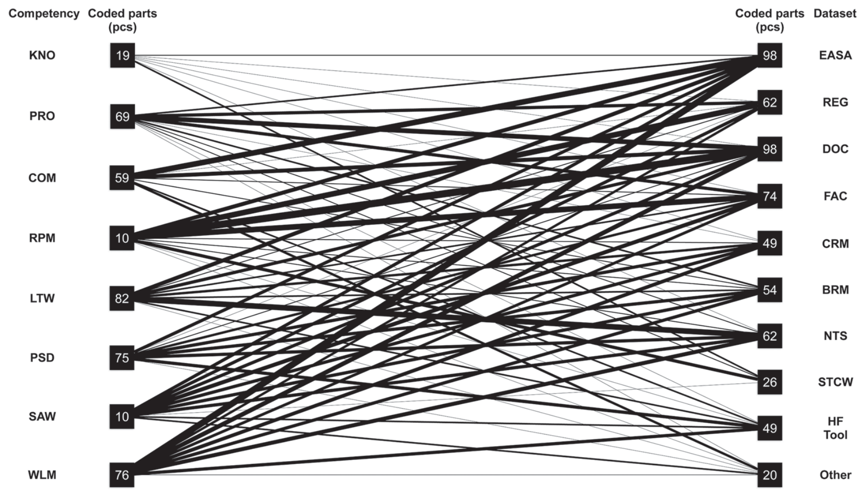

Figure 1. Primary rationale behind behavioural markers. Note: BRM = bridge resource management; COM = communication; CRM = crew resource management; DOC = maritime documents; EASA = European Union Aviation Safety Agency; FAC = factors behind high-speed workboat incidents; KNO = application of knowledge; LTW = leadership and teamwork; NTS = NOTECHS non-technical skills; Other = references presented in Table 4; PRO = application of procedures; PSD = problem-solving and decision-making; REG = high-speed workboat cockpit work regulations in Finland; RPM = route plan management; SAW = situation awareness and management of information; STCW = International Convention on Standards of Training Certification and Watchkeeping for Seafarers Code; WLM = workload management.

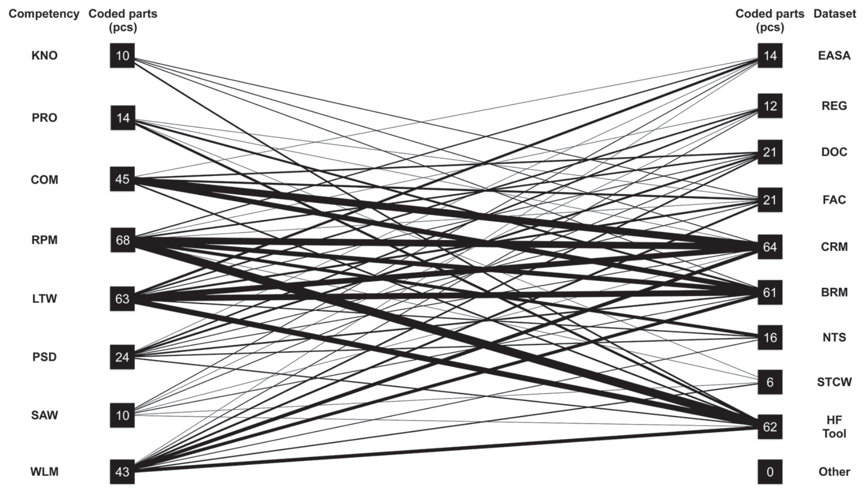

Figure 2. Concept-level rationale behind behavioural markers. Note: BRM = bridge resource management; COM = communication; CRM = crew resource management; DOC = maritime documents; EASA = European Union Aviation Safety Agency; FAC = factors behind high-speed workboat incidents; KNO = application of knowledge; LTW = leadership and teamwork; NTS = NOTECHS non-technical skills; Other = references presented in Table 4; PRO = application of procedures; PSD = problem-solving and decision-making; REG = high-speed workboat cockpit work regulations in Finland; RPM = route plan management; SAW = situation awareness and management of information; STCW = International Convention on Standards of Training Certification and Watchkeeping for Seafarers Code; WLM = workload management.

Table 6. Assessment principle.

Parameter	How often does the target behaviour recur if necessary?		How well is the target behaviour implemented when necessary?	Result of assessment	Assessment of competence
Negative mark	Target behaviour is rarely or hardly ever repeated	and/or	Inefficiently	Crew showed little or none of the necessary behaviour. The action led or could have led to an unacceptable deterioration in safety	Unacceptable
Positive mark	Target behaviour is repeated at least intermittently	and/or	Minimum acceptance	Crew demonstrated required behaviour to at least a minimum acceptable level and the action did not lead to any deterioration in safety	Acceptable
Usage	Score kept by marks		Marked positive or negative		
Source	Paraphrasing Venn model (EASA) [14]		Paraphrasing Venn model (EASA) [14]	Paraphrasing IATA [24]; EASA [14]	Van Avermaete [45]
General principle	Safe, sufficiently effective performance considered sufficient (STCW, Part A, Chapter I) [53]				

Note: EASA = European Union Aviation Safety Agency; IATA = International Air Transport Association; STCW = International Convention on Standards of Training Certification and Watchkeeping for Seafarers Code.

Figure 3. Data recorder.

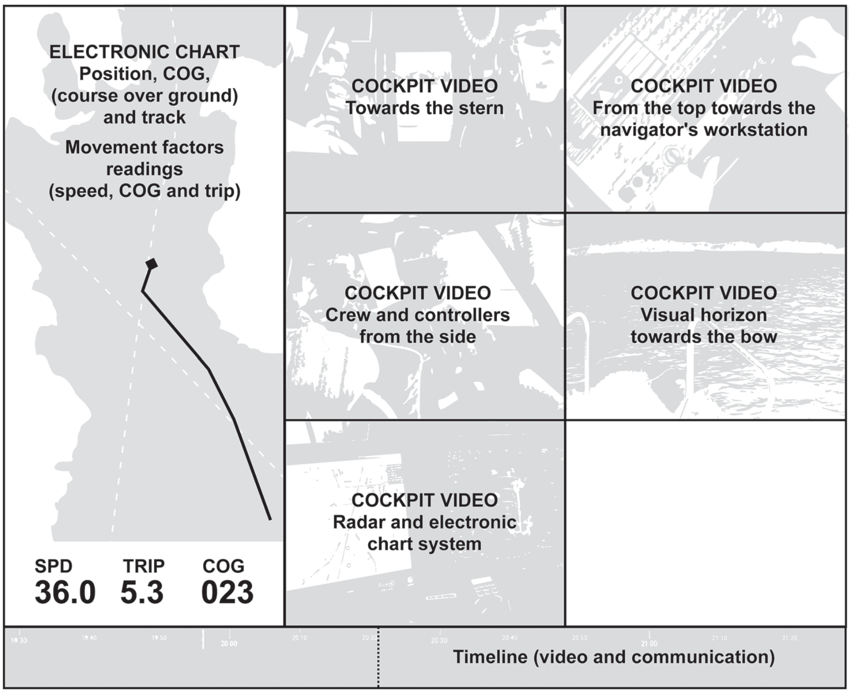

Figure 4. Data recorder timeline. Note: COG = course over ground; SPD = speed; TRIP = distance travelled.

acceptable level and the action did not lead to any deterioration in safety', it was assessed as 'acceptable' and recorded with a positive mark on a paper form, based on the BMs. When the behaviour was repeated 'inefficiently' and 'led or could have led to an unacceptable deterioration in safety', it was considered 'unacceptable' and a negative mark was recorded. In the BMs testing, only observable behaviour was classified as 'acceptable' or 'unacceptable'. Missing behaviours were not recorded.

Testing ensured that the crews' recorded activity modelled actual behaviour rather than the norms that guided it [14,70]. During the testing, the researcher developed the taxonomy by reacting to missing and non-functional BMs and improving the content, grammar and mutual order of the BMs. The functionality of the assessment principle was also tested assessing the fluency of its use. This process enabled us to finalize the taxonomy prototype (version 1.18). In this version, one overlap and one contradiction of BMs were observed during the peer

Table 7. Taxonomy prototype behavioural markers in eight competency areas (version 1.18).

Primary behaviour	Complementary behaviour
Application of knowledge (KNO)	
0.1 Demonstrating practical knowledge of boat systems and their interaction	
0.2 Demonstrating knowledge of applicable operational guidelines	
0.3 Demonstrating knowledge of physical operating environment	
0.4 Demonstrating knowledge of information on key applicable regulations	
0.5 Demonstrating knowledge of key themes of CRM	
Application of procedures and compliance with regulations (PRO)	
1.1 Applying appropriate operating instructions and working methods	
1.2 Following SOP for cockpit work in work phases	
1.3 Deviating from SOP or operating instructions to ensure safety or for some other justified reason	1.3.1 Identifying and justifying the need for deviations together
	1.3.2 Deviating and returning to SOP by communicating together
1.4 Supervising in the use of standard procedures and addressing deviations	
1.5 Using boat's systems and equipment correctly and monitoring their status and functionality	1.5.1 Using the organization's standardized data display settings
1.6 Acting in accordance with regulations	
1.7 Effectively observing sea terrain	1.7.1 Arranging and ensuring continuous lookout
	1.7.2 Taking ships and other objects into consideration
	1.7.3 Anticipating objects behind the obstruction of vision
	1.7.4 Communicating lookout observations between the crew
	1.7.5 Avoiding 'heads-down' situations by communicating if necessary
1.8 Giving way and preventing collisions	1.8.1 Determining the movement factors of other vessels
	1.8.2 Acting with clearly visible intentions and avoiding harmful traffic behaviour
	1.8.3 Giving way before near misses arise
	1.8.4 Giving way as a group effort
	1.8.5 Ensuring the impact of giving way measures
1.9 Manoeuvring the boat to the starboard edge or within one third of fairway area whenever possible	
Communication (COM)	
2.1 Identifying recipient's readiness and ability to receive information	
2.2 Appropriately choosing what, when and to whom to communicate	2.2.1 Identifying the information that is necessary to communicate at any given time
	2.2.2 Communicating actively and adequately
	2.2.3 Avoiding extra communication
2.3 Effectively using description of work phases	
2.4 Communicating clearly, accurately and concisely	2.4.1 Ensuring sufficient volume is used
	2.4.2 Sharing messages as needed (rhythms)
	2.4.3 Making effective use of non-verbal communication
2.5 Confirming that recipient demonstrates understanding of message	2.5.1 Requiring closed communication loop (notification if message not replied to)
	2.5.2 Addressing monosyllabic responses
	2.5.3 Making sure the message is understood correctly
	2.5.4 If necessary, expanding communication to ensure understanding
2.6 Actively listening and demonstrating understanding of message	2.6.1 Replying to messages using closed communication loop
	2.6.2 Not answering monosyllabically
	2.6.3 Indicating when message is not perfectly heard or understood
	2.6.4 Expanding communication until message is understood correctly
2.7 Asking relevant and effective questions	
2.8 Using organization's standard communication approach	2.8.1 Using standard terms and phrases
	2.8.2 Using common working language correctly enough to ensure safety and that instructions are followed
Route plan management (RPM)	
Route planning (RPL)	
3.1 Planning route before starting sea voyage or new mission	
3.2 Making high-quality route plan that contains necessary information	
3.3 Efficiently using permanent route plans or route library	
3.4 Involving crew in sea voyage planning and feedback	3.4.1 Involving crew in route planning and planning of sea voyage
	3.4.2 Providing a high-quality, effective briefing before departure
	3.4.3 Providing a high-quality, efficient debriefing after sea voyage

(*continued*).

Table 7. Continued.

Primary behaviour & Complementary behaviour	
Route plan control (RPC)	
3.5 Monitoring compliance with route plan in a timely manner, taking necessary measures	3.5.1 Detecting deviations to route plan whilst managing other tasks and distractions
	3.5.2 Ensuring implementation of correct steering line in future work phases
	3.5.3 Communicating result of monitoring and ensuring common understanding of situation
	3.5.4 Efficiently correcting steering line as a team effort
	3.5.5 If necessary, reducing speed or stopping boat to ensure compliance with route plan
3.6 Deviating deliberately from route plan, if necessary to ensure maritime safety and/or critical task performance	3.6.1 Identifying and justifying the need to deviate from route plan
	3.6.2 Implementing a temporary deviation from the route plan by communicating together
	3.6.3 If necessary, making a new route plan and briefing the crew
3.7 Effectively using information sources to follow route plan	3.7.1 Emphasizing most useful source of information at any given time
	3.7.2 Interpreting information correctly
	3.7.3 Validating movement factors by cross-checking at least two sources of information
	3.7.4 Using visual views and manoeuvring signs as sources of information
	3.7.5 Using technical systems and equipment as sources of information
	3.7.6 Ensuring that display settings are optimized efficiently and dynamically
3.8 Steering boat accurately, smoothly and safely in accordance with situation	
3.9 Using automation in the right work phases	3.9.1 Using autopilot in suitable work phases and conditions
	3.9.2 Closely monitoring the operation of automation
	3.9.3 Detecting deviations in operation of automation and effectively addressing them
Leadership and teamwork (LTW)	
4.1 Encouraging participation and promoting an open atmosphere	4.1.1 Asking for suggestions for solutions
	4.1.2 Asking more than telling
	4.1.3 Avoiding competition and emphasizing the crew rather than the individual
	4.1.4 Focusing on what is right instead of who is right
4.2 Proposing solutions and expressing opinions without questioning authority	
4.3 Considering the initiatives and suggestions of others	4.3.1 Reacting to initiatives and proposals
	4.3.2 Giving reasons if initiative or proposal cannot be implemented
	4.3.3 Objectively considering initiatives despite differences of opinion
4.4 Showing initiative and determination in leadership and indicating the direction of action	4.4.1 Leading the crew and not shirking responsibilities
	4.4.2 Clearly indicating the task, direction of action and objective to the crew
	4.4.3 Contributing to the success of the task
4.5 Taking responsibility for decisions and actions	4.5.1 Showing initiative and ensuring that the task is successful
	4.5.2 Communicating uncertainties, deviations and safety
	4.5.3 Refusing to complete a task if lacking the required skills and experience
	4.5.4 Obeying instructions and commands
4.6 Giving and receiving constructive feedback	
4.7 Dealing with and resolving conflicts constructively	4.7.1 Behaving calmly in cases of conflict
	4.7.2 Proposing solutions to conflicts
Problem-solving and decision-making (PSD)	
5.1 Identifying problems and contributing factors together with crew	
5.2 Obtaining accurate, reliable information for decision-making	5.2.1 Showing a positive drive to acquire knowledge and encouraging others to do the same
	5.2.2 Reserving sufficient time for acquiring information
	5.2.3 Obtaining information from the crew
	5.2.4 Obtaining information from the cockpit's information sources
	5.2.5 Acquiring information from outside the boat

(*continued*).

Table 7. Continued.

Primary behaviour & Complementary behaviour	
5.3 Identifying and considering suitable alternatives together	
5.4 Identifying, assessing and managing threats and errors in timely manner together with crew	
5.5 Continuing to work tirelessly to solve problem and ensure safety	
5.6 Comprehensibly informing crew of content of decisions and expectations regarding tasks and standards	
5.7 Jointly monitoring consequences of decision and, if necessary, changing the policy	
5.8 Adapting to situations that have no instructions or procedures	
5.9 Demonstrating resilience and ability to act in unforeseen situations	
Situation awareness and management of information (SAW)	
6.1 Monitoring boat movements and systems	6.1.1 Reacting without delay to problems, deviations and changes
	6.1.2 Ensuring shared situation awareness about boat movements and systems through communication
6.2 Collecting information on operating environment	6.2.1 Taking information into account and reacting to it without delay
	6.2.2 Ensuring shared situation awareness about operating environment through communication
6.3 Maintaining situation awareness of crew and their capacity to carry out the mission	6.3.1 Considering the human needs of the crew and communicating them when necessary
	6.3.2 Asking the crew about their operational capability and monitoring any noticeable changes
	6.3.3 Dimension expectations in relation to crew capacity and its changes
6.4 Being aware of one's own functional capacity and communicating its impact on work	
6.5 Ensuring the reliability of information and related errors and reacting to deviations by communicating	
6.6 Using an alternative information source when original is unavailable or unreliable	
6.7 Reacting to indications of impaired situational awareness	
6.8 Creating contingency and emergency plans for different situations on basis of risk assessment	
Workload management (WLM)	
7.1 Concentrating on task and on matters important for work phase	
7.2 Planning, prioritizing and scheduling tasks efficiently	
7.3 Ensuring sufficient time to carry out assigned task without unnecessary sense of urgency	
7.4 Managing situational speed safely and efficiently	7.4.1 Using situation speed that is in proportion with the anticipated strain of the situation
	7.4.2 Defining situational speed as a group decision based on performance
	7.4.3 Implementing speed changes as a separate work phase, and allocating sufficient time
	7.4.4 Ensuring that speed changes great enough to have a real impact on workload (speed reduction) or operational efficiency (speed increase)
7.5 Monitoring and identifying crew's need for help, offering and providing assistance	
7.6 Requesting assistance if necessary and accepting it when offered	
7.7 Delegating tasks efficiently when needed	7.7.1 Ensuring sufficient division of labour
	7.7.2 Ensuring that delegated tasks are carried out in accordance with objectives
	7.7.3 If necessary, giving the crew additional guidance to perform a task
7.8 Completing the assigned tasks according to the objectives	
7.9 Ensuring efficient recovery from interruptions, disturbances, deviations and faults	
7.10 Using automation in the right work phases in terms of workload management	7.10.1 Avoiding the use of autopilot during monotonous operations
	7.10.2 Changing control system only in low-workload work phases
7.11 Reacting to indications of a harmfully high or low workload for the crew	

Note: CRM = crew resource management; SOP = standard operating procedure

Table 8. Primary behavioural markers not identified in testing.

BM no.	Behavioural marker
1.3	Deviating from SOP or operating instructions to ensure safety or for some other justified reason
2.1	Identifying when the recipient is ready and able to receive information
3.6	Deviating from route plan if necessary
3.10	Using automation in suitable work phases
4.4	Showing initiative and determination in leadership and indicating direction of action
4.7	Dealing with and resolving conflicts constructively
5.8	Adapting to situations that have no instructions or procedures
5.9	Demonstrating resilience and ability to act in unforeseen situations
6.8	Creating contingency and emergency plans for different situations on basis of risk assessment
7.6	Requesting assistance if necessary and accepting it when offered
7.8	Completing assigned tasks in accordance with objectives

Note: BM = behavioural marker; SOP = standard operating procedure.

Table 9. Crew behaviours by competency, observed in taxonomy testing.

Competency area	Positive[a] (*n*)	Negative[b] (*n*)	Combined[c] (*n*)
Application of knowledge (BMs in this competency area were not specifically tested)	6	2	8
Application of procedures and compliance with regulations	100	89	189
Communication	127	127	254
Route plan management	109	131	240
Leadership and teamwork	73	4	77
Problem-solving and decision-making	8	30	38
Situation awareness and management of information	38	36	74
Workload management	29	55	84
Total	490	474	964

[a] Crew demonstrated required behaviour to at least a minimum acceptable level and the action did not lead to any deterioration in safety (assessment of competence: acceptable).
[b] Crew demonstrated target behaviour inefficiently, the action led or could have led to an unacceptable deterioration in safety (assessment of competence: unacceptable).
[c] Positive and negative marks combined.
Note: BM = behavioural marker

review phase of the study, which were corrected before the publication. The change did not affect the expressed justifications of BMs or the validity of the BM testing.

4. Results

This section presents the taxonomy prototype and its test results.

4.1. RQ1. What are the critical crew competencies and BMs in HSW cockpit work?

The BMs were finalized in April 2025. The taxonomy consisted of eight competency categories, structured as 66 primary BMs and 86 complementary BMs (Table 7).

4.2. RQ2. How does the BM taxonomy prototype structure the activities of the crew?

Using the BMs enabled efficient classification of the observed crew activity. Although all of the targeted behaviours could be classified as BMs, not all BM behaviours were observed. As the research strategy did not contain testing of the competency area of 'Application of knowledge', it remained mostly unproven.

Testing showed that 51 of the 62 primary BMs (and/or complementary BMs in the area) of the taxonomy covered all of the observed crew behaviour necessary for effective crew performance. However, other BMs not subject to the observations were also relevant to crew performance and were added to the taxonomy (Table 8).

Detailed complementary BMs were typically used when available. In summary, 32.5% of the markings ($n = 313$) were aimed at primary BMs, compared to the 67.5% of markings ($n = 651$) aimed at complementary BMs, of which 66% were labelled.

4.2.1. Using the taxonomy prototype

A prerequisite for an accurate analysis was technical recordings, which would enable one to repeatedly watch a specific part of the observation data timeline. Recording observations on paper forms was efficient in office conditions, but familiarization with the structure required effort.

4.2.2. Competency-specific observations

The BMs modelled the activities that promoted or hindered crew performance. Testing showed that BMs that promoted crew performance were often repeated (51%) (Table 9). However, almost half of the observed crew behaviours (49%) hindered crew performance.

There were few crew behaviours in the category 'Application of knowledge', as they were recorded, as in other competencies, only by observable actions. In this category, critical to practical crew performance, the assessments would also require questionnaires or specified tasks to gather data about the realization of the competency. BMs related to 'Communication' and 'Route plan management' were recorded the most frequently, followed by competency in 'Application of procedures and compliance with regulations'. In several categories, the distribution of positive and negative entries was even, with some exceptions as follows: in 'Leadership and teamwork', behaviour was positive; observations of competency in 'Problem-solving and decision-making' were more often negative than positive, but the number of observations was low; and the BMs connected to 'Workload management' were often negative (65%).

5. Discussion

This study defined the BMs of crew competencies in a taxonomy prototype for modelling crew performance in HSW cockpit work. The taxonomy was based on aviation knowledge, reasoned with HF concepts and operationalized using maritime-specific information. The BMs were tested using observation data and validated at a prototype level.

The study complemented previous research on maritime BM taxonomies and contributed to assessing and supporting crew performance, developing the socio-technical system of HSWs and improving maritime safety.

5.1. RQ1 critical crew competencies and behavioural markers in HSW cockpit work

Firstly, the study revealed a need to better understand crew performance in maritime HSWs. Despite contradictions, the aviation standards [14,45] provided a foundation for evolution, supported by reasoning using HF models [14,53,61]. Operationalizing BMs in a maritime context [56] prevented the needless use of practices from other industries [60].

In their review article, which partly inspired this study, Fjeld et al. [44] argued that the descriptions of bridge crew skills needed improvement and that new models should ensure sufficient coverage, detail and relevance when describing human activity, and pay particular attention to non-technical skills such as crew interaction. We propose that this study's detailed BMs confirmed this, but also complemented the previous research, even though the target was the specialized area of HSWs. Previous studies have focused on non-technical skills [49–51,71], but we did not separate them from technical skills in this study, as they were both prerequisites for safety and efficiency [25,44,46] and were difficult to divide [45].

We claim that the taxonomy BMs formed an entity promoting crew performance, considering the diversity of human activity [72] and despite the lack of analysis of BM interactions [44]. The basic idea of the taxonomy was facilitating effective resource management and crew cooperation, and to create the right attitude for this [14,25,46] that was lacking in individual-centred and technical-oriented maritime situations [7,73]. Knowledge of the mastery of HF was improved by integrating 'Crew resource management knowledge' as a compulsory component to crew training, as in merchant shipping [53]. Standard operating procedures were considered a fundamental prerequisite for efficient crew performance, considering the transitions with non-linear methods [74]. Unlike the primaries of non-technical skills [45], a separate communication competency was justified by the threats and development needs in the field [13]. Ensuring the effective use of route plans and controlling the outcome was carefully planned to facilitate the use of resources. Interpersonal activities, including leadership in teams [34,48,56,68], were highlighted and complemented previous maritime BMs [44]. Encouraging analytical, process-based [75] group decision-making [67,76] promoted intuitive perspectives, which are essential in rapidly changing situations [77]. Shared situation awareness [78] was highlighted over individual perspectives. Workload management – crucial for unified, proactive actions – was included as a competency area and suggested as a development target in the maritime industry [44].

Because teamwork is non-linear [37], the competencies, which all promoted crew cooperation and proactive resource management, were not organized as a process, although helpful illustrations were available [38].

5.2. RQ2 behavioural marker taxonomy structuring the activities of the crew

Secondly, the BMs modelled all of the observed behaviours essential for competent cockpit work crew performance. The researcher did not observe all of the BMs, but eliminating any of them was unjustified. Behaviours in certain competence areas were generally less noticeable, which was predictable [9].

The BMs described actual work according to the principles pursued [12] and testing revealed differences between crews. Using BMs enabled us to identify explicit behaviours that promoted or hindered crew performance. We also observed a possible dependence in the taxonomy behaviours, and deviations in the visible outcomes that could facilitate supporting the crews [45]. However, the study's results were reported on the group level, and individual crews were not compared.

Despite the simple and detailed expressions of the prototype BMs, operators need to understand the underlying phenomena [41] and their evaluation principles so as to ensure fairness and accuracy. Using the BMs enabled effective behaviour analysis of the cockpit recordings. In actual operations or real-time simulations, the researcher or practitioner should examine only a range of BMs.

5.3. Practical contribution

To conclude, the trainers in high-speed maritime organizations may use the taxonomy BMs to assess and develop crew competencies, the crews may enhance their self-reflection and the organizations may improve training systems [9,14,41,46]. The taxonomy could be used to enhance safety management, synchronize organizational levels [12], optimize the interaction between socio-technical components [79], and improve incident investigations [41] and standard operating procedures. The study's strategic benefit was related to future research and development [44] of the maritime industry.

5.4. Limitations and future research

When forming and testing the BMs, we sought content validity using all possible means [80], but further validation and proof of inter-rater reliability remains a topic for further research [12]. The number of cases for observation was reasonably low, which affects generalization. The crews may have overemphasized normative behaviour during the observations [12]. The qualitative data required interpretation by the researcher when developing the BMs, because some contents lacked precise boundaries. We suggest that future research should use international data, and that the researchers cooperate with each other.

5.5. Ethics

All of the materials were processed confidentially in accordance with the requirements of the target organizations and the agreements made with the parties involved. The participants were informed of the study's objectives on 20 May 2022 (request for data for organizations) and 30 August 2022 (study information sheet for observational participants). A privacy notice was created in connection with the evaluation. The University of Vaasa Human Science Ethics Committee confirmed, by its decision submitted on 30 August 2022, that no ethical review was needed for the research.

6. Conclusion

To summarize, the taxonomy prototype and BMs created a comprehensive framework for crew competencies in HSW cockpit work. The taxonomy was based on the systemic aviation standard [14], and was further justified by HF models [53,59,61] and maritime materials. Several areas requiring improvement were identified in the HSW maritime area. The competencies formed an entity that can be used to mitigate these by developing crew cooperation and resource management. We believe that our extensive synthesis of the datasets and testing of the BMs validated the model at the prototype level.

The scientific contribution of this study complements the chain of previous maritime BM taxonomies. The taxonomy prototype facilitated the analysis of the interaction between socio-technical system components in order to improve operative performance [24] and safety [5,16]. Practitioners can use the taxonomy prototype to develop several levels of HSW cockpit work operations.

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Appendix 1. Definition of an HSW

A high-speed workboat (HSW) refers to a professional boat [81] 5.5–24 m in length that moves at a speed of more than 20 knots without using the ground effect or exiting the water [84], has a sliding or semi-sliding hull and is employed for professional or trade purposes; or a vessel intended for non-recreational purposes. An HSW can also be used in an oil spill response team, by a fire brigade or as a police boat [82]. The International Maritime Organization (IMO) uses the term 'high-speed craft' (HSC) to describe the operational profile of HSWs [84]. Warships and troop carriers were included in the scope of this study, although they are not included in the IMO's definition of HSC [84], as these often operate faster than other traffic, and their speed is occasionally used as a tool to avoid collisions. Active measures that violate water transport regulations are sometimes also required to avoid a collision [83].

Workload in cockpit work on high-speed workboats: How to improve crew performance

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Case Report

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Abstract

This study examined the mental workload (MWL) of cockpit work on high-speed workboats' (HSWs), as the crews of these boats are exposed to harmfully high and low MWL, which are both detrimental to safety and performance. MWL was measured during observed, real-life voyages using an experimental subjective Likert scale that assessed cognitive reserve capacity that could then be compared to retrospective NASA TLX data. The crews were interviewed about the factors that affected their MWL during voyages and the need to improve MWL management in the sociotechnical system of the HSWs. The MWL measures were sensitive to cognitive load variations and suitable for measuring MWL in the maritime field. The crews' MWL, but on the other hand cognitive reserves were repeatedly reported as low. Crew competencies in particular were seen to improve workload management, which was especially weakened by insufficient skills, the technology used, its usability, and the cockpit layout. The interviewees made proposals for how to enhance MWL management. The results contributed to improving MWL management and the mastery of human factors in HSWs and small-craft operations.

1. Introduction

High-speed workboats (HSWs) (Annex 1) are used in safety-critical rescue, military and police operations and for maintaining critical maritime infrastructure. Cockpit work on board HSWs is performed 'in all conditions' and often in challenging sea terrains, causing significant cognitive and physical demands for operators (Dobbins et al. 2010; Ullman et al. 2024).

This case study aimed to support crew performance in the cockpit work on board HSWs by improving the management of mental workload (MWL). Despite MWL management being an essential skill for HSW crews (XX and XX B, under review), information on MWL and applicable measurement methods have not been available, unlike, for example, in the case of high-speed crafts (e.g., Kartoglu et al. 2023). This study utilized the Human Factors (HF) perspective (CIEHF 2021) to better understand and manage HSWs as sociotechnical systems (Wilson 2014). The need to improve the mastery of HFs by creating new information and developing concrete measures has been identified in several safety-critical sectors (Teperi 2012; Teperi et al. 2017, 2023), including the maritime sector (Schröder-Hinrichs et al. 2012; Teperi et al. 2019) and the specialized area of HSW (XX and XX A, under review).

This study used a condensed Likert version of the Modified Bedford Pilot Workload Scale to measure MWL during actual cockpit work operations. The results were compared with retrospective NASA TLX (unweighted) measurements (Hart and Staveland 1988). Crew interviews provided additional data on MWL factors and the development of MWL management.

1.1. Why study mental workload in HSWs?

In research on safety-critical fields, MWL (Young et al. 2015) describes the amount of attention a person exerts to meet the criteria for a task (Young and Stanton 2005). The concept refers to a person's psychological state (Wulvik et al. 2020), the individual 'human cost' of the task (Hart 1986; Hart and Staveland 1988), or the amount of mental work required to complete a task in a certain amount of time (Longo 2015). MWL describes a multifaceted phenomenon, the description of which has been harmonized as: 'MWL represents the degree of activation of a finite pool of resources, limited in capacity, while cognitively processing a primary task over time, mediated by external stochastic environmental and situational factors, as well as affected by definite internal characteristics of a human operator, for coping with static task demands, by devoted effort and attention' (Longo et al. 2022).

HSW crews often multitask (Jokinen et al. 2021), although they are also exposed to monotony. In complex situations (Paxion et al. 2014), when the crew have to simultaneously carry out several tasks under uncertain conditions (Hancock and Chignell 1988; Evans 2008), there is a risk of excessive MWL and a loss of situational awareness (Endsley and Jones 2016). Planning and preparation may be limited by complexity and time pressure, the crew's cognitive reflection can collapse, and control can become opportunistic, as actions are defined by circumstances and continue through trial and error (Hollnagel 2002; Porathe 2018). Harmfully low MWL can result in similar consequences (Casner and Gore 2010).

1.2. Mental workload and crew performance

Individuals' cognitive capacity and attention to focus on the task varies (Schneider and Shiffrin 1977; Patten et al. 2006; Klein et al. 2010; Paxion et al. 2014). Human performance can also vary independently of MWL (Pauzie 2014), because it can be maintained by making extra effort to accomplish a task (Hart and Staveland 1988; Yeh and Wickens 1988), depending on the capacity limits of personal information processing (Kahneman 1973). Cognitive load can impair human performance slowly (O´Donnel and Eggemeier

1994; Kantowitz 2000), but also catastrophically abruptly (Norman and Bobrow 1975; Lysaght et al. 1989). However, automated or repetitive tasks pose the risk of attention- and concentration -related problems (Casner and Gore 2010) and a reduced sense of presence (Rajapakse and Emad 2021). If MWL is moderate, human performance is more likely to remain optimal (Yerkes and Dodson 1908; Lysaght et al. 1989).

MWL management is the continuous and proactive work of maritime organizations at all levels (Hollnagel 2014; Blandford et al. 2014) and an integral part of the crews' competencies that are essential to ensure safe and efficient work (Mansikka et al. 2019). The HF discipline has shifted from defining and measuring MWL towards improving practical MWL management (Young et al. 2015) and evaluating systems as a whole (Dekker and Hollnagel 2004). However, safe operations require knowledge of human performance and actual MWL (Mansikka et al. 2019), which is why there is a need for new information on HSW operations.

1.3. How to measure mental workload

Cognition-related factors are complexly cross linked (Klein et al. 2003), and measuring MWL is not problem free (Hart and Staveland 1988; Dekker and Hollnagel 2004; Casner and Gore 2010). MWL can be measured on the basis of performance of primary or secondary tasks, available capacity, subjective experience, or psychophysiological reactions. However, none of these tools is a 'silver bullet' of validity (Johanssen et al. 1979; Casner and Gore 2010; Dekker and Nyce 2015; Matthews et al. 2020), and therefore, it is often justified to use several measurement techniques simultaneously (de Waard 1996; Wulvik et al. 2020). When selecting a measurement method, the intrusiveness, sensitivity, diagnostics, validity, implementation of data storage, and sufficient acceptance of the method by the target persons should be considered (Eggemeier et al. 1991; Rubio et al. 2004).

Accurate physiological MWL measurements are not possible in HSW cockpits, as harsh movements can cause physiological reactions that easily distort the results (Mansikka et al. 2019), unlike in simulated maritime environments (Gould et al. 2009; Lochner et al. 2018a). On the other hand, commissioning secondary tasks during actual operations would jeopardize safety. In this study, MWL measurement was based on subjective experience, a method that has proven to produce valid results compared to physiological measurements (Matthews et al. 2015; Mansikka et al. 2019), and despite criticisms, is 'true' from the individuals' point of view (Moray et al. 1979). A condensed version of the subjective Modified Bedford Pilot Workload Scale (Roscoe 1984) was used, based on the target person's assessment of their capacity for secondary tasks (Casner and Gore 2010). The MWL measurements were repeated retrospectively using the NASA TLX technique (unweighted), taking into consideration (1) mental demands, (2) physical demands, (3) temporal demand, (4) the person's own performance, (5) effort and (6) frustration level (Hart and Staveland 1988).

2. Aims

The aim of the study was to produce new information on crews' MWL in cockpit work on board HSWs. MWL was measured in observed, real-life operations and compared to retrospective NASA TLX data. The crews were interviewed on the factors that affected their MWL on voyages and the needs to improve MWL management.

2.1. Research questions (RQs)

RQ1. How can subjective measures be applied when measuring MWL in cockpit work on board HSWs (Likert scale, based on estimates of reserve capacity and unweighted NASA TLX)?

RQ2. What kind of MWL does cockpit work on board HSWs cause for crews?

RQ3. What factors affect MWL and how can MWL management be improved, according to the crews?

We hypothesized that better knowledge of the MWL in HSW operations will help maritime organizations improve crew performance and the safety of cockpit work on board HSWs.

3. Material and methods

This case study utilized qualitative and quantitative methods to research the MWL of cockpit work on board HSWs (Table 1). Actual operations were observed, and the crews' MWL was measured during sea voyages using an experimental, subjective Likert scale and retrospectively using NASA TLX. Information on the factors that influence MWL and on how to improve MWL management was obtained by interviewing crew members. Supplementary questionnaires were also used to collect information from the crews.

Table 1
Study process.

Work phase	Additional information
	Crews (n = 5), Crew members (n = 10)
Development of data-collecting system	A prototype model for gathering data from actual cockpit operations. Used previously (XX and XX, unpublished observations B)
Development of experimental Likert scale for MWL	For use during real operations. Adapted from Modified Bedford Pilot Workload Scale, based on estimate of crew reserve capacity
Questionnaire 1	Crew background variables (before observation)
Observations	Actual sea voyages (n = 5), Likert scale MWL measurements (n = 210)
Questionnaire 2	Complexity of observed sea voyage (retrospectively)
Questionnaire 3	Working conditions in HSW cockpit (retrospectively)
NASA TLX measurements	Use of recordings from voyages (retrospectively)
Crew interviews	Factors that affect MWL and proposals for improving MWL management (retrospectively)

The MWL data were analysed and compared using descriptive methods and statistical inference. Information on MWL, the crew's views on the factors that influence it, and their proposals to improve MWL management were discussed.

3.1. Observations

The observations were carried out in sea areas and inland waters in five Finnish HSW maritime organizations in the autumn of 2022. We observed the cockpit work of five crews over a distance of 269 nautical miles (376 waypoints), at an average speed of 28 knots (mean speed range 17–34 kn), with HSWs passing a new waypoint every 1.5 minutes on average. The external conditions were mild (mean wind 5 m/s, visibility 49 km, dry weather). The crews used different boat classes, technical designs and cockpit work operating methods.

The crews were told the time of the observation in advance. The organization's contact person participated in the route planning with the researcher, but did not inform the crew of the route plan beforehand, except in two cases. The crews were entrusted with implementing the route plan created by the researcher, except in one case, in which the crew carried out operational tasks. The crews were instructed to use at least 90% of the boat's top speed or more than 40 knots, but a safe situational speed. The activities were scrutinized from the before-departure to the post-voyage stage, which was observed to varying degrees.

3.2. Crew background variables and difficulty of the voyages

A questionnaire was used to investigate the crew members' background variables before the observed sea voyages. The results are reported in such a way that the crew members cannot be identified (Table 2). The correlation of background variables with the phenomena studied was not analysed.

Table 2
Crew background variables

Crew member background variable	Description of results
HSW cockpit work experience	Ranging from six months to over ten years
HSW cockpit work training	Ranging from very minor to extensive. Half of the crews had trained in a simulator or actual operations to some extent (13–33 times) or very much (at least 34 times) every year. The rest reported practising a little (1–5 sessions) or irregularly (irregular breaks between workouts).
Life situation	Mostly care- and stress-free, with one exception
'Recent' sleep pattern	At least moderate, satisfactory
Alertness	At least good
Perceived cumulative workload before observation	Mainly low, with two exceptions
Motivation to strive for safety	At least good
Motivation to strive for good crew performance	At least good, with one exception

In the retrospective questionnaires, three crews reported that the observed voyage had been easy in terms of the cockpit work demands; one voyage was reported as demanding, and another was described as being in between easy and demanding. Other water traffic was sparse on all the voyages. The crews did not have to concentrate on tasks other than the cockpit work, such as radio communications, planning or carrying out an operational task, or communicating with command-and-control systems. However, on one voyage, the organization's primary task was carried out at the same time.

3.3. Likert scale used for on-voyage measurements

A simplified version of the 10-step Modified Bedford Pilot Workload Scale (Roscoe 1984) was used during the observed voyages. The scale was experimentally condensed by forming five-step, ordinal-scale Likert observation values with verbal equivalents on the Bedford scale (Gall et al. 2003) (Table 3), and was defined as a 'Likert scale' in the study. The five-step scale has also been previously used in an Instantaneous Self-assessment designed for taking measurements during real work (Tattersall and Foord 1996) in the maritime sector (Lochner et al. 2018b), as have various other MWL/Likert scales in general (Orlandi and Brooks 2018).

Table 3
Development of Likert scale.

Original Modified Bedford Pilot Workload Scale values categorized	Verbal description of new combined categories	Response options in reverse order for the Likert scale question: Could you take on a greater burden? (time/capacity to handle additional tasks)
1–2	Piece of cake / there is more than enough time for secondary tasks	No (burden could only be increased occasionally or not at all)
3–4	There is enough time to easily complete secondary tasks	Hardly (little could be done to increase the burden)
5–6	From time to time there is enough time to complete secondary tasks	Now and then (burden could be increased from time to time)
7–8	There is little or no time to complete secondary tasks	Yes (the burden could be increased)
9–10	There is almost no extra capacity, or it would be impossible to maintain performance	A great deal (the burden could be increased considerably)

The functionality of the data-collecting system and the Likert scale was tested in real HSW cockpit work in August 2022 before the data acquisition, and the results were retrospectively compared to the NASA TLX (unweighted raw) measurements. In the test measurements (n = 41) on one voyage, the dependence of the Likert scale and the NASA TLX results was significant (rS= –,663), and the monotonous dependence was very significant (p = 0.000).

3.4. NASA TLX measurements

The NASA TLX (unweighted) measurements were conducted after the voyages. The crew members were instructed to use the NASA TLX and describe their perceived MWL at all the Likert scale measurement points (n = 210), using the recording. The results were mainly processed as unweighted values because the measurement situations during the voyage differed, and because this made the research process more straightforward without compromising the quality of the measurement results (Hart 2006). In this article, the abbreviation NASA TLX refers specifically to the unweighted values. The interdependence of the Likert scale and NASA TLX results was analysed using Spearman correlation analysis.

3.5. Recording the observation data

The data-recording system prototype developed for the study allowed the researcher to avoid harmful communication, crew members influencing each other's results, and extensive interference with the primary task (Fig. 1). The system: (1) recorded subjective MWL data, also on a timeline, (2) used several video cameras, (3) recorded the boat movement factors in a map application, and (4) recorded cockpit communication.

The crew members described their perceived subjective MWL at the researcher's request on route sections immediately after the turning area of the waypoints and between the waypoints in medium and long route sections. When the researcher pressed a button on his terminal, the response units attached to the crew members' arms emitted a continuous beep. In response, the crew members gave an estimate of their MWL using their unit switches (5 pcs) that corresponded to the Likert scale values, which were constantly visible in the cockpit (Fig. 2).

Requests and responses were recorded in the central unit (sequence number and time for the researcher's question, response time, and MWL values). Sometimes, the respondents found it difficult to hear the response unit's beep, but then another crew member pointed out the beep, enabling an answer. Nine MWL measurements were rejected because of a missing response.

3.6. Interviews and questionnaires

Retrospectively, the crews participated in interviews (five in total, 09:32:13), covering (1) the characteristics of the voyage, (2) the factors that influenced their MWL, and (3) recommendations for improving MWL management (Annex 2). Short thematic surveys supplemented the interviews, focusing on the complexity of the observed voyage and the features and working conditions of the HSW cockpit (Annex 3). The interviewees' descriptions of the factors that affected MWL (pos/neg) and their development proposals for MWL management were simplified, grouped, and coded into quantitative data, which were analysed as such. We also compared the responses of the navigators and helmsmen.

The competency-based HFs identified from the interview data were classified using a prototype model, which described precursor competencies and behavioural markers for crew performance in the cockpit work of HSWs (XX and XX B, under review) (Table 4). This model was originally based on the principles of competence assessment in civil aviation.

Table 4
Crew competencies in cockpit work on board HSWs, a prototype model (XX and XX B, under review)

Competency	
KNO	Application of knowledge
PRO	Application of procedures and compliance with regulations
COM	Communication
RPM	Route plan management
LTW	Leadership and teamwork
PSD	Problem-solving and decision-making
SAW	Situational awareness and management of information
WLM	Workload management

Non-competency-based HFs were classified using a sociotechnical HF Tool (Annex 4), which has previously been used to identify HF (Teperi 2012). This HF Tool has been used in several safety-critical fields (Teperi et al. 2015 in aviation, 2017 in the nuclear field, 2023 in the railway sector).

4. Results

Next we describe the results: (1) the correlation between the MWL measurements during the voyages (Likert scale) and retrospectively (NASA TLX), (2) MWL experienced by the crews (Likert scale and NASA TLX) (3) factors that affected MWL during the voyages (interviews) and (4) proposals for improving MWL management (interviews).

4.1. Correlation between Likert scale and NASA TLX

The Likert ordinal-scale measurements ranged from 1 to 5 (mode 2–5). The crews reported MWL as unweighted NASA TLX ranging from 0.00 to 70.83 (mean 7.9–42.8), classes 80–100 having no values at all. As a rule, except in one case, the correlation between the Likert scale and NASA TLX measurement results varied from moderate to notable (Table 5). In one case, the correlation could not be calculated due to the similarity of the results, but both measures reacted similarly.

Table 5
Correlation between Likert scale and NASA TLX.

					Spearman's rho **Correlation significant at 0.01 level (2-tailed)**
Voyage	Meas. (N)	Crew member	rS	Sig. (2-tailed)	Monotonic correlation
1A	31	A	–.870	< .001	Powerful
		B	–.481	< .006	Moderate
1B	23	A	–.677	< .001	Notable
		B	–.247	.256	Insignificant
2	51	A	–.703	< .001	Notable
		B	–.447	< .001	Moderate
3	46	A	–.502	< .001	Moderate
		B	–.655	< .001	Notable
4		A/B	All the Likert scale measurements (13 pcs) were the same in the responses, dependency factors cannot be calculated using the Spearman ordinal correlation coefficient		
5	46	A	–.565	< .001	Moderate
		B	–.650	< .001	Notable
Total (N)	197				
1A = first part of observed sea voyage 1 1B = second part of observed sea voyage 1					

Despite strong correlations, the results had to be interpreted with caution due to their contradictions. For example, the navigators reported at least high MWL twice as often as the helmsmen (Likert scale), but the difference was significantly smaller in the NASA TLX measurements. The helmsmen more often perceived MWL as very low than the navigators (NASA TLX), which was not confirmed by the Likert scale results.

4.2. Mental workload of crew members

The crew members often reported very low or low MWL, which can be as detrimental to performance as harmfully high MWL. Physical demands were perceived as very low, affecting the unweighted NASA TLX averages and reducing diagnosticity to cognitive load. For more than half of the NASA TLX measurements, the crews reported very low MWL, and the efforts required to ensure performance were not considered significant. The Likert scale measurements showed very low MWL less frequently (%N = 26.7%). However, in easy external conditions, at a moderate speed, and without operational tasks, the crew members' MWL was often at least high (16% Likert scale), and they reported that there was little need for additional requirements. In the NASA TLX results, however, only 1.0% of the measurements fell into the corresponding categories.

The mental demand values (NASA TLX) were often higher than the NASA TLX average, as shown in the example (Fig. 3). The Likert scale results were possibly more comparable to the NASA TLX values that measured mental demands (7.4% at least high MWL). The navigators, for example, reported a tenfold difference between mental requirements and the NASA TLX average.

When a single sea voyage with a significantly different work profile was removed from the data, at least high mental demands (NASA TLX) were reported in almost 16.0% of the TLX measurements. In more than a third of the Likert scale measurements, the crew members felt that the cognitive demands could have been increased a little, or not without problems.

4.2.1. Likert scale results

The crews' MWL was more often very low (26.7%) than very high (1.9%) (Table 6). However, in 16.0% of the measurements, MWL was perceived as high or very high. On one voyage, the crew members reported a very low perceived workload (value of 5).

Table 6
Likert scale results describing high/very high and very low MWL.

			Likert scale values					
Voyage	Meas. (N)	Crew member	1–2 (N)	1–2%(N)	1 (N)	1%(N)	5 (N)	5%(N)
			High or very high	High or very high	Very high	Very high	Very low	Very low
1A	31	A	3	9.7	0	0.0	13	41.9
		B	0	0.0	0	0.0	0	0.0
1B	23	A	8	34.8	1	4.4	10	43.5
		B	0	0.0	1	4.4	0	0.0
2	51	A	5	9.8	0	0.0	15	29.4
		B	1	2.0	0	0.0	21	41.2
3	46	A	8	17.4	0	0.0	10	21.7
		B	21	45.7	6	13.0	5	10.9
4	13	A	0	0.0	0	0.0	13	100.0
		B	0	0.0	0	0.0	13	100.0
5	46	A	21	45.7	0	0.0	2	4.4
		B	0	0.0	0	0.0	10	21.7
Total (N)	210		67	16.0	8	1.9	112	26.7

1A = first part of observed sea voyage 1

1B = second part of observed sea voyage 1

Likert scale value 1 = Burden could only be increased occasionally, or not at all

Likert scale value 2 = Little could be done to increase the burden

Likert scale value 5 = Burden could be increased considerably

4.2.2. Unweighted NASA TLX results

To enable comparison of the Likert scale and NASA TLX values, the NASA TLX results were divided into five equal categories: 0–20 (very low), 25–40 (low), 45–60 (moderate), 65–80 (high), 85–100 (very high).

High or very high MWL was reported in only 1.0% of the measurements, but mental demands were more often perceived as at least high (7.4%) and time pressure was perceived to increase MWL in 5.0% of the measurements. The crew members felt that they had to make an effort to achieve their own performance level and meet the requirements either a lot or very much in only 4.3% of the measurements. Significant feelings of frustration were expressed in 1.2% of the measurements.

Next, we describe the results of the combined NASA TLX class 65–100 (high – very high WL) (Table 7).

Table 7
NASA TLX results describing high or very high MWL (values 65–100).

Voyage	Meas. (N)	CM	MEN		PHY		TEM		PER		EFF		FRU		NASA TLX	
			N	%(N)	N	%(N)	N	%(N)	N	%(N)	N	%(N)	N	%(N)	N	%(N)
1A	31	A	2	6.5	0	0	2	6.5	2	6.5	2	6.5	0	0.0	1	3.2
		B	3	9.7	0	0	0	0.0	2	6.5	1	3.2	0	0.0	0	0.0
1B	23	A	3	13.0	0	0	3	13.0	4	17.4	4	17.4	3	13.0	1	4.3
		B	9	39.1	0	0	5	21.7	2	8.7	1	4.4	2	8.7	2	8.7
2	51	A	12	23.5	0	0	11	21.6	2	3.9	8	15.7	0	0.0	0	0.0
		B	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
3	46	A	2	4.4	0	0	0	0.0	0	0.0	2	4.4	0	0.0	0	0.0
		B	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
4	13	A	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
		B	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
5	46	A	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
		B	0	0.0	0	0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Tot. (N)	210		31	7.4	0	0.0	21	5.0	12	2.9	18	4.3	5	1.2	4	1.0

1A = first part of observed sea voyage 1

1B = second part of observed sea voyage 1

CM = Crew member

MEN = Mental, PHY = Physical, TEM = Temporal, PER = Performance, EFF = Effort, FRU = Frustration

The crew members reported a very low MWL in 58.1% of the measurements (comb. NASA TLX class 0–20) (Table 8). Physical demand was perceived as very low (85.2%), but very low mental demand was perceived almost half as often (41.2%). Achieving one's own level of performance was viewed quite critically (64.1%), and moderate effort was needed to achieve one's own level of performance (61.9%).

Table 8
NASA TLX results describing very low MWL (values 0–20).

Voyage	Meas. (N)	CM	MEN		PHY		TEM		PER		EFF		FRU		NASA TLX	
			N	% (N)	N	% (N)	N	% (N)	N	% (N)	N	% (N)	N	% (N)	N	% (N)
1A	31	A	12	38.7	31	100	15	48.4	16	51.6	17	54.8	27	87.1	16	51.6
		B	0	0.0	1	3.2	1	3.2	0	0.0	0	0.0	1	3.2	0	0.0
1B	23	A	8	34.8	23	100	7	30.4	8	34.8	8	34.8	5	21.7	4	17.4
		B	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
2	51	A	18	35.3	51	100	32	62.7	30	58.9	25	49.0	50	98.0	29	56.9
		B	20	39.2	51	100	44	86.3	44	86.3	37	72.6	49	96.1	43	84.3
3	46	A	29	63.0	43	93.5	33	71.7	31	67.4	29	63.0	34	73.9	30	65.2
		B	44	95.7	46	100	46	100	44	95.7	45	97.8	46	100	46	100
4	13	A	13	100	13	100	13	100	13	100	13	100	13	100	13	100
		B	11	84.6	13	100	13	100	13	100	13	100	13	100	13	100
5	46	A	7	15.2	40	87.0	25	54.3	31	67.4	27	58.7	46	100	18	39.1
		B	11	23.9	46	100	26	56.5	39	84.8	46	100	38	82.6	32	69.6
Tot. (N)	210		173	41.2	358	85.2	255	60.7	269	64.1	260	61.9	322	76.7	244	58.1

1A = first part of observed sea voyage 1

1B = second part of observed sea voyage 1

CM = Crew member

MEN = Mental, PHY = Physical, TEM = Temporal, PER = Performance, EFF = Effort, FRU = Frustration

4.2.3. Workload of navigators and helmsmen

The MWL of the navigators and helmsmen were evaluated separately. As their roles were not defined in the same way in one crew, this case was excluded from the analysis. The navigators reported high or very high MWL more often (22.8%) in the Likert scale measurements than the helmsmen (11.2%). No corresponding difference was observed in the NASA TLX values, although the navigators perceived high MWL or very high mental demand more often (9.6%) than the helmsmen (6.1%).

4.3. Interviews

It seems that dozens of different factors (47 pcs), classified into six HF Tool details and eight competency categories of the earlier presented prototype model, positively impacted MWL and its management during the sea voyages (Table 9). The competency-based factors (NAV 82.1%/HELM 79.1%) were emphasized. Competencies in (1) communication, (2) route plan management, (3) leadership and teamwork, (4) situational awareness and management of information and (5) workload management were mainly seen to have the most positive impact on the outcome.

Moderate external conditions seemed to decrease MWL. These findings were classified in the HF Tool, a detail that describes the demands of the work (20.). Although external factors are not actual HF, they do influence the demands of the work and MWL through decisions.

According to the navigators, 40.3% of the factors that positively affected MWL were related to predicting work phases, successful monitoring, and the efficient use of data sources. The helmsmen emphasized competencies in *leadership and teamwork* as well as *situational awareness* and *management of information* more than the navigators. The views of the navigators and helmsmen differed significantly in the two crews, but were parallel in the three crews (Spearman's rho,780 < .943).

Table 9
HFs that positively affected crews' MWL during sea voyages.

Voyage	**1**		**2**		**3**		**4**		**5**		**Mean**	
	NAV	HELM	NAV	HELM	NAV	HELM	NAV	HELM	NAV	HELM	NAV	HELM
Competencies %(n)												
KNO	5.3	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	2.8	0.0
PRO	0.0	0.0	7.7	0.0	0.0	7.7	0.0	0.0	0.0	0.0	1.4	1.6
COM	21.1	25.0	15.4	21.4	10.0	7.7	8.3	0.0	16.7	12.5	15.3	16.1
RPM	31.6	25.0	30.8	21.4	30.0	7.7	16.7	14.3	27.8	25.0	27.8	19.4
LTW	21.1	16.7	15.4	14.3	10.0	23.1	0.0	28.6	16.7	18.8	13.9	19.4
PSD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	0.0	1.4	0.0
SAW	10.5	16.7	7.7	7.1	0.0	15.4	0.0	14.3	5.6	12.5	5.6	12.9
WLM	0.0	0.0	15.4	14.3	30.0	15.4	25.0	0.0	11.1	12.5	13.9	9.7
Other HFs classified by the HF Tool %(n)												
1. Competence, conceptual mastery of work	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0
20. Quality and content of work, work demands	10.5	8.3	7.7	7.1	0.0	7.7	8.3	28.6	16.7	6.3	9.7	9.7
23. Technology, machines; usability and reliability	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	4.2	0.0
28. Training: contents. effectiveness, opportunities to participate	0.0	0.0	0.0	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6
29. Work hygiene factors, physical environment (noise, illumination, air condition, temperature, layout)	0.0	0.0	0.0	7.1	0.0	7.7	16.7	14.3	0.0	12.5	2.8	8.1
33. Structure and cohesion of group (atmosphere, group dynamics, mutual support)	0.0	0.0	0.0	0.0	0.0	7.7	0.0	0.0	0.0	0.0	0.0	1.6
Competency-based mentions classified by HCS (n = 108)	17	11	12	11	9	10	6	4	15	13	100.0%	100.0%
Other HFs mentions classified by HF Tool (n = 26)	2	1	1	3	1	3	6	3	3	3		
KNO = application of knowledge, PRO = application of procedures, COM = communication, RPM = route plan management, LTW = leadership and teamwork, PSD = problem-solving and decision-making, SAW = situational awareness and management of information, WLM = workload management												
NAV = navigator, HELM = helmsman												

Voyage	1		2		3		4		5		Mean
HFs mentions total (n = 134)	19	12	13	14	10	13	12	7	18	16	
KNO = application of knowledge, PRO = application of procedures, COM = communication, RPM = route plan management, LTW = leadership and teamwork, PSD = problem-solving and decision-making, SAW = situational awareness and management of information, WLM = workload management											
NAV = navigator, HELM = helmsman											

The competency-based factors had a significantly smaller negative impact on crew MWL (NAV 39.1%/HELM 50.0%) than on the other HFs (Table 10), divided into five competency categories. The helmsmen emphasized deficiencies in the competency areas of *communication* and *workload management* that had adversely affected MWL during sea voyages to a greater extent than the navigators. The crews reported that the *usability of technical equipment* (HF Tool category 23.) and the *work hygiene factors* and *physical environment* (HF Tool 29.) often negatively affected MWL (NAV 46.9%/HELM 39.3%).

Table 10
HFs that negatively affected crew MWL during sea voyages.

Voyage	1		2		3		4		5		Mean	
	NAV	HELM	NAV	HELM	NAV	HELM	NAV	HELM	NAV	HELM	NAV	HELM
Competencies %(n)												
KNO	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.3	11.1	3.1	3.6
PRO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COM	6.5	11.1	0.0	25.0	7.7	25.0	0.0	0.0	14.3	11.1	6.3	14.3
RPM	6.5	0.0	0.0	0.0	15.4	25.0	0.0	0.0	14.3	11.1	7.8	7.1
LTW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PSD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SAW	12.9	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	6.3	3.6
WLM	19.4	22.2	16.7	50.0	15.4	0.0	0.0	0.0	0.0	22.2	15.6	21.4
Other HFs classified by HF Tool %(n)												
2. Situational awareness (perception, memory, decision-making, response/execution)	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0
7. Vigilance, alertness, fatigue symptoms	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0
20. Quality and content of work, work demands	12.9	22.2	8.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8	7.1
23. Technology, machines; usability and reliability	16.1	22.2	25.0	25.0	38.5	0.0	100.0	0.0	42.9	44.4	26.6	25.0
24. Procedures, regulations, norms; usability, validity	0.0	0.0	8.3	0.0	0.0	0.0	0.0	0.0	14.3	0.0	3.1	0.0
28. Training: contents, effectiveness, opportunities to participate	0.0	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6
29. Work hygiene factors, physical environment (noise, illumination, air condition, temperature, layout)	16.1	11.1	41.7	0.0	23.1	25.0	0.0	100.0	0.0	0.0	20.3	14.3
Competency-based mentions classified by HCS (n = 39)	15	3	2	3	5	3	0	0	3	5	100.0%	100.0%

KNO = application of knowledge, PRO = application of procedures, COM = communication, RPM = route plan management, LTW = leadership and teamwork, PSD = problem-solving and decision-making, SAW = situational awareness and management of information, WLM = workload management

NAV = navigator, HELM = helmsman

Voyage	1		2		3		4		5		Mean
Other HFs mentions classified by HF Tool (n = 53)	16	6	10	1	8	1	1	2	4	4	
HFs mentions total (n = 92)	31	9	12	4	13	4	1	2	7	9	
KNO = application of knowledge, PRO = application of procedures, COM = communication, RPM = route plan management, LTW = leadership and teamwork, PSD = problem-solving and decision-making, SAW = situational awareness and management of information, WLM = workload management											
NAV = navigator, HELM = helmsman											

The majority of the MWL management development proposals that the crews made were competency based (NAV 64.3%, HELM 78.6%). The proposals focused on all eight competencies (defined in Table 2), emphasizing *route plan management*, *situational awareness and management of information*, and *workload management* (NAV 49.3%, HELM 57.1%). The navigators reported that about a quarter (26.9%) of the areas that required improvement were related to the features of cockpit work routines, such as the steering team's tasks and the division of tasks. However, the navigators also drew attention to specific needs in the content of the working methods used and the training and practising of cockpit work.

5. Discussion

We studied crews' MWL in the cockpit work of HSWs, utilizing observations of real operations, subjective MWL measurements, crew interviews and supplementary questionnaires. The results discussed below could be used to develop crew performance and safety in the area of HSWs in the maritime field.

5.1. Likert scale and NASA TLX measurements

The tested Likert scale, which was based on the assessment of individual cognitive reserve capacity, and the NASA TLX (unweighted), which considered the external and internal factors that affect crew members (Hart and Staveland 1988), were suitable tools for measuring MWL in actual HSW operations and responded to varying cognitive demands, providing information for analysing different work phases. Although the Likert scale/NASA TLX correlation was significant in most cases, because of the contradictions, interpretations had to be made with caution, and the different measurement scales and class intervals of the meters, as well as the detected perspective variation 'on sea and land' had to be considered.

Communicating cognitive reserve capacity (Likert scale) 'on-voyage' was a viable way to measure MWL in actual cockpit work, considering the uncertainties in the Likert scale experiment. The more diagnostic NASA TLX was also expected to be well suited, especially if recordings were available. In general, comprehensive cockpit data are essential for high-quality HF analysis. Future studies should consider weighted NASA TLX measurements for identifying primarily cognitive loads.

5.2. Workload of crew members

MWL was an individual experience, and significant variations were observed among sea voyages, crews, crew members and measuring points, which reinforced previous knowledge (Hancock and Chignell 1988) and the wide variation in individual efforts, resource use, and strategies (Hart and Staveland 1988). As with the MWL data, low perceived MWL in particular had to be treated with caution, as it could indicate a monotony, an excellent operational strategy (Casner and Gore 2010), uncompleted work phases (Matthews and Reinerman-Jones 2017), or perhaps overly positive reports in measurement situations (Paulhus and Vazire 2007).

Based on the research results, the crew members' MWL was more often very low or low than very high. However, it was at least high quite often; even without an operational task, with crews feeling that increasing cognitive requirements would not be desirable. The removal of one deviant observed case from the data revealed even higher MWL values for the other cases. Mental demands were emphasized over physical demands.

Considering previous knowledge (Yerkes and Dodson 1908; Lysaght et al. 1989; Matthews and Reinerman-Jones 2017) and the results of this study, moderate crew MWL should be considered the aim when attempting to improve cockpit work in HSWs in the future. Both detrimentally low and high MWL work phases can lead to, at least as prolonged, poor crew performance and should be recognized as ‘windows’ for developing the work.

5.3. Factors that affected MWL management

The factors that had a positive impact on MWL management revolved around efficient resource management, and were mostly competency based. These should be encouraged in operations. The crews emphasized anticipating situations, communicating and ensuring shared situational awareness related to route plan control, the external operating environment, information displays, and crew member's’ ability to function. Competencies in managing workload and mastering situational awareness and information were highlighted, unlike the use of standard operating procedures, which possibly reflects their rare use in the field.

The impact of deficient competencies on MWL was similar to that of other HFs in the sociotechnical system, highlighting the importance of the technology used, its usability, and the cockpit layout. The unobstructed vision of information displays, and the effortless use of floodlights were not self-evident in modern HSWs, and this created unnecessary load. Low-quality route plans and the availability of information were often seen as additional MWL factors. Communication problems, inadequate division of duties and working methods of the steering team, excessive situational speeds, and poor recovery from deviations increased MWL and occasionally caused time pressure.

5.4. Improvement of MWL management

The interviews revealed that attention should be paid to cockpit resource management and crew competencies: no single ‘silver bullets’ emerged. In particular, communication, shared situational awareness, and competencies in MWL and route plan management required attention, in line with the earlier identified critical factor of use of information in the maritime field (Lützhöft et al. 2011) and the ‘bottleneck’ in high-speed maritime in particular (Olsson and Jansson 2006). Dynamic situational speed control was seen as a critical factor for crew MWL. Rushing, time pressure, and an unnecessary sense of urgency were seen as requiring attention in the operating culture of HSW maritime organizations, for example, in the work phase of starting an operational task.

In addition to crew competencies, proposals were made regarding HFs at all levels of the sociotechnical system, in terms of the functionality of the system, the availability of information, the division and methods of labour, and sufficient training, which reflected the choices made by the maritime organizations and entire administrative branches when organizing operations.

5.5. Limitations and future research

The present sample of observations and measurements was small, the cases differed, and the results could not fairly be generalized. The experimental Likert scale metrics needs to be further validated. The ‘red-line’ (Grier et al. 2008) of the crew members' individual MWL was not defined. The crew members reported that their MWL was not affected by the Likert scale’s items, although they inevitably occasionally were (Tattersall and Foord 1996).

This exploration of MWL revealed further research topics: MWL during operational missions, at higher speed ranges, in more severe external conditions, and in the organizations’ larger high-speed vessels. The links between perceived MWL and crew performance provided important information for improving crew competencies and sociotechnical HSW systems.

5.6. Ethics

All the materials were processed confidentially in accordance with the requirements of the target organizations and the confidentiality agreements made. Before observation, we ensured that the persons concerned understood that the research results would be reported at group level so that no individuals or organizations could be identified (Casner and Gore 2010). The participants were informed of the study’s objectives on 20.5.2022 (request for data from organizations) and 30.8.2022 (study information sheet for observation participants). Those who participated in the observation signed their written consent to participate in the study. A privacy notice was also drawn up in connection with the evaluation. The University of Vaasa’s Human Science Ethics Committee confirmed, by their decision submitted on 30.8.2022, that no ethical review is needed for the research.

5.7. Conclusion

This study examined the measurement, realization and management of MWL in cockpit work on board HSWs. Real-time operations were observed in geographically demanding Finnish waters. Subjective methods were used to identify the crews’ MWL. A Likert scale, based on the assessment of individual cognitive reserve capacity and retrospective NASA TLX, were found to be suitable for measuring and determining the MWL in actual HSW operations.

Based on the results, the crew's MWL was more often low than very high. However, their cognitive reserve capacity was also challenged. Mental demands were greater than physical demands. The factors considered to positively impacted MWL were efficient resource management and were mainly competency based. Other HFs in the sociotechnical system, in addition to inadequate competencies, were also seen as detrimental to crew workload. The crews' proposals revealed that resource management and crew competencies should be emphasized to improve the MWL management.

These research results can help maritime organizations further improve MWL management in cockpit work and better understand human performance. The focus should be on moderate levels and avoiding both harmfully high and low, and both momentary and prolonged MWL. We recommend encouraging pivotal crew competencies and developing other HFs in the sociotechnical system, such as working methods, standard procedures, training, and technical equipment, to enhance resource and MWL management. We suggest that the use of more diverse procedures could both reduce harmfully low MWL and improve resource management.

Declarations

The authors report that they have no competing interests to declare.

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Figures

Figure 1

Data-recording system.

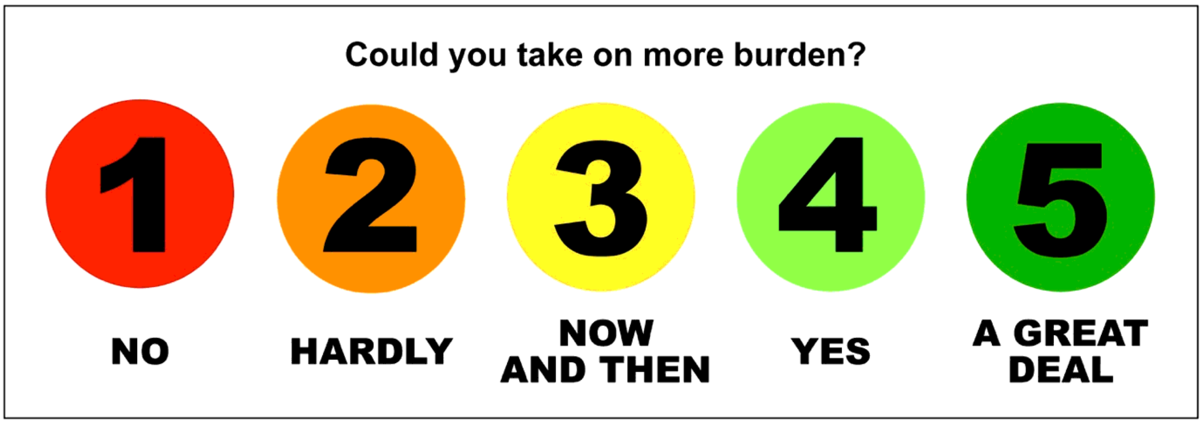

Figure 2

Likert scale visible in cockpit during observations.

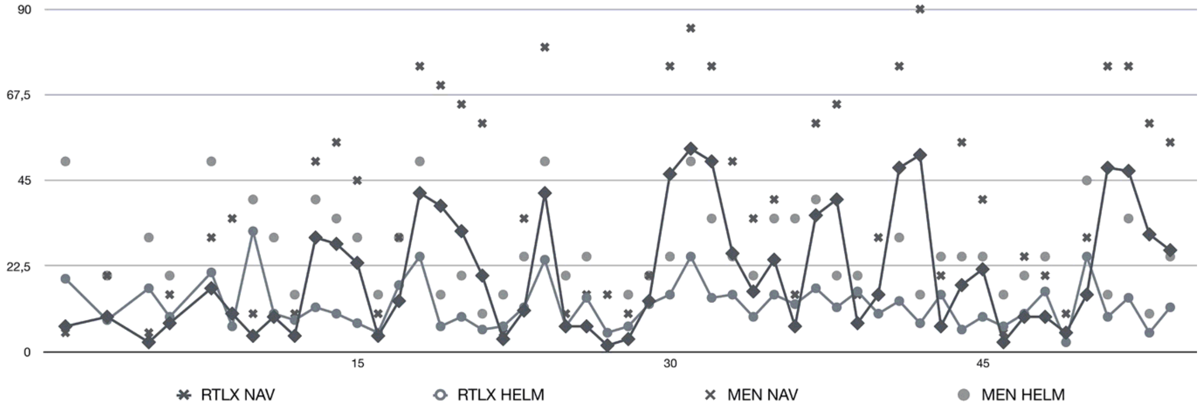

Figure 3

Example of higher mental demand values than NASA TLX average.

Supplementary Files

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- Annexes.docx

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Supporting high-speed workboat crew performance with blunt-end human factors

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Abstract: Work and organisational factors (blunt-end factors) have been recognised as key features of maritime crew performance. In the case of high-speed workboats (HSWs), evidence of how blunt-end human factors (HF) are managed is lacking. This paper examined the HFs that particularly need addressing to enhance crew performance support. We obtained data from operators (n = 281) at four levels of Finnish HSW organisations (n = 5) using a questionnaire created by utilising observed phenomena affecting crew performance and the HF Tool. Results show that despite the current availability of HF knowledge, a practical shift is needed from Safety-I perspectives to the proactive and effective use of crew resources, enhanced crew competencies, unified technical solutions and procedures, and a fairer operating culture. All organisational levels in HSW organisations agreed on the areas that will need development in the future. The study's results contribute to improving the mastery of HF in the high-speed maritime sector.

Keywords: high-speed workboats; HSWs; human factors; maritime safety; crew performance; HF tool; work and organisational factors; cockpit work; high-speed maritime; crew resource management.

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1 Introduction

Cockpit work in high-speed workboats (HSW) (Annex 1) is safety-critical work and constantly challenges crew performance. HSWs are utilised in rescue, defence and police operations, as well as in other maritime environments, some of which are essential for the security of supply and the energy sector. These operations, the success of which is particularly topical due to the current unstable global situation, are carried out under dynamic, complex and uncertain conditions (Norros, 2014) and are influenced by human factors (HFs) (ILO, 2021) at various levels of the sociotechnical system (Wilson, 2014).

Systematic mastery of HF is still lacking in the maritime sector (Teperi et al., 2019b), making the development of operations challenging, despite the progress made in recent years (EMSA, 2022). In line with Safety-I thinking (Hollnagel, 2014) HSW maritime safety has focused on the activities of individuals at the 'sharp end' (Flin et al., 2013; Lehtimäki and Teperi, 2025a), and HFs have remained neglected at the 'blunt-end' levels of maritime organisations (Puisa et al., 2018). In this study, the sharp end refers to HSW crews. The blunt end refers to the background levels of maritime organisations, such as the sociotechnical sectors responsible for providing support for crews and making decisions regarding, for example, the practical implementation of the latest research findings that affect crews (Dekker, 2014).

This study utilised the proactive facet of Safety II to address the safety and resilience of HSW maritime organisations (Hollnagel, 2014; Hollnagel and Nemeth, 2022). We obtained the data using a phenomenon-based questionnaire (Lehtimäki and Teperi, 2025a, 2025b, 2025c) that we distributed in HSW organisations to explicitly identify the critical HFs that should be proactively improved at the blunt end of operations to better support crew performance in the cockpit work. We used the HF Tool concept to break down the HFs in the questionnaire (Teperi, 2012).

1.1 Mastery of HFs in HSW maritime organisations

International maritime agreements have made it mandatory to consider HFs, and this has contributed positively to the sector's development (EMSA, 2022), at least at certain organisational levels (Turan et al., 2016). HF requirements have not yet been fully extended to HSW operations (Lehtimäki and Teperi, 2025a, 2025c), despite regulation being a critical safety factor in the maritime sector (Fenstad et al., 2016). However, ever-increasing regulation can also have harmful effects (Størkersen et al., 2017).

HF has been researched in the maritime sector (Chauvin et al., 2013; Gould et al., 2009; Hetherington et al., 2006; Kee et al., 2017; Qiao et al., 2021; Schröder-Hinrichs et al., 2012; Wahl and Kongsvik, 2017, 2018; Wrobel, 2021), but human needs and ergonomic requirements (ISO, 2019; IMO, 2019) continue to be rarely met. This causes unnecessary crew adaptation to technology (Danielsen et al., 2021, 2022) and, for example, critical deficiencies in bridge crews' situational awareness (Sandhåland et al., 2015). Moreover, HF research on HSW operations (Dobbins et al., 2008, 2009, 2010; Forsman et al., 2012; Forsman, 2015; Lehtimäki and Teperi, 2025a, 2025b, 2025c; Ullman et al., 2024, 2025) has not yet lead to HF knowledge being fully applied to support crew performance.

In line with modern safety thinking (Dekker, 2015; Le Coze, 2022), maritime crew support should be based on a systemic capabilities perspective rather than pushing individuals to their limits and beyond (Haavik et al., 2017; Kongsvik et al., 2020). To ensure safety and resiliency, HFs should be systemically utilised and continuously developed in sociotechnical operations (Hollnagel, 2016; Vicente, 1999; Wilson, 2014). The system levels of maritime organisations have been described by, for example, the SEPTIGON model (Koester, 2007), which is based on the software, hardware, environment, liveware (SHEL) concept (Hawkins, 2016). In this study, we analysed HFs using the HF Tool concept to enable us to consider the different levels of HSW operations (Teperi et al., 2015) and to facilitate holistical support of crew performance (Kongsvik et al., 2020).

We propose, based on previous knowledge, that more practically implementing HF knowledge in the HSW field would increase support of crews, lead to a fairer operating culture (Dekker, 2017), and foster a continuous ability to learn from practices, deviations and incidents, which is essential for system performance (Biggs and Russell, 2024; Schein and Schein, 2016). Such improvements are still sorely needed in the maritime sector (Oltedal and McArthur, 2011; Turan et al., 2016) and in the HSW field (Lehtimäki and Teperi, 2025a).

1.2 Support of crew performance

To better support HSW crews, maritime organisations must utilise detailed knowledge of the tightly intertwined crew competencies (Fan and Yang, 2023; Harris et al., 2021) and the HFs that underlie crew performance (Fjeld et al., 2018; Flin et al., 2013; ICAO, 2013). Crew competencies are most often dependent on other HF components and their interactions (ILO, 2021), and understanding this is vital for crews to receive support at different sociotechnical system levels (Wilson, 2014).

The competencies that are especially vital for crew collaboration have defined by the crew resource management (CRM) concept (Cooper et al., 1980; Helmreich et al., 1999), which considers HF in the planning of work and the promotion of safety (Blandford et al., 2014), together with technical subsystems (Mansikka et al., 2019). CRM has evolved over several generations (Harris et al., 2021) and is widely used and variously applied in safety-critical fields (Alavosius et al., 2017; Griffioen et al., 2021; Salas et al., 2006), including the maritime sector (Fjeld et al., 2018; Grech et al., 2008; Hetherington et al., 2006; IMO, 2011; International Convention on Standards of Training et al., 2011; Wahl and Kongsvik, 2018). HSW crew performance in cockpit work has previously been defined in terms of competencies and behavioural markers in the CRM concept, and have based on aviation standards (EASA, 2023). This is illustrated in Table 1 (Lehtimäki and Teperi, 2025c).

Table 1 Crew competencies in HSW cockpit work

Competency
Application of knowledge
Application of procedures and compliance with regulations
Communication
Route plan management
Leadership and teamwork
Problem-solving and decision-making
Situation awareness and management of information
Workload management

Source: Lehtimäki and Teperi (2025c)

This study methodically used knowledge on competency-specific crew behaviours and HF perspectives in the HSW field (Lehtimäki and Teperi, 2025a, 2025b, 2025c) to gather information from HSW organisations and to identify the blunt-end HFs that need practical improvement so that better support can be provided for crews. The paper contributes to increasing the impact and implementation of previous maritime HF research in the HSW maritime field, and to increasing shared perspectives across different organisational levels, which is essential for developing HF (Schein and Schein, 2016). Harmonising views is also crucial for safety management (ICAO, 2021), but is often lacking in the maritime sector (Puisa et al., 2018). This affects detrimentally decisions regarding the allocation of resources (Teperi, 2012; Teperi et al., 2018). 'Work-as-imagined' decision-making (Hollnagel, 2014) in the planning of HSW work must be reduced, because the professional identity of seafarers includes the aspiration to 'get work done' (Nævestad et al., 2018), and formalities that are poorly adapted to other sociotechnical system components do not contribute to procedural compliance (Bye and Aalberg, 2020).

2 Aims

This case study examined the critical HFs that should be developed at the blunt end of operations to improve support of crew performance in HSW cockpit work. The purpose of this paper is to encourage HSW maritime organisations to apply previous maritime HF knowledge and legitimise management decisions for practical measures on the basis of information obtained from different levels of HSW organisations.

2.1 Research question (RQ)

Which critical HFs need to be enhanced to improve the practical blunt-end support of crew performance in HSW cockpit work?

3 Material and methods

We utilised a phenomenon-based semi-structured questionnaire to address the critical HFs that need to be addressed in the sociotechnical system of HSWs to improve maritime organisations' blunt-end support of crew performance in cockpit work. Table 2 describes the study process.

Table 2 Study process: work phase, description, and additional methodological information

Work phase	*Description*	*Additional methodological information in this study*
Defining the gap		
Description of nine phenomena that challenge crew performance in the cockpit work of HSWs	Based on information on competency-specific crew behaviours (Lehtimäki and Teperi, 2025c), and how mental workload is managed in the cockpit work of HSWs (Lehtimäki and Teperi, 2025b), and safety reporting practices in the field (Lehtimäki and Teperi, 2025a)	Table 5
Questionnaire		
Structured questions	Based on the nine phenomena. Response options (33 pcs.) were developed on the basis of the HF Tool concept (Teperi, 2012), in order to break down the HFs in the system of HSWs.	Table 4, Annex 2
Open-ended questions	An open-ended question with a similar structure was attached to each phenomenon (9 pcs.).	Table 4
Completion of questionnaire	On organisational levels (n = 4) of Finnish HSW maritime organisations (n = 5), number of respondents (n = 281).	Table 3
Data analysis	The analysis identified similar views across the responses of the different organisational levels, and further analysis was conducted using descriptive statistical methods.	Section 3.4, Section 4.1
Structured questions	Statistical reasoning (Spearman's rho correlation analysis) and descriptive methods for quantitative data from the structured responses.	Section 3.1.1
Open-ended questions	Qualitative analysis of open responses.	Table 6

3.1 Participants

The data were gathered from five Finnish HSW organisations operating in the rescue, defence and pilotage sectors, which are pivotal to national comprehensive security (Security Committee, 2025). These organisations covered a wide range of HSW operations in sea areas and inland waterways, and used varying HSWs. The cockpit work in organisations was conducted in navigationally demanding water areas, also internationally, covering approximately 11,000 nautical miles of narrow fairways and more than 35,000 maritime navigational aids (FTIA, 2024).

The data were collected using a semi-structured electronic questionnaire (Webropol Survey Reporting Platform) administered between May and October 2024, which encompassed both blunt- and sharp-end organisational levels (Table 3). A census approach was attempted, with all personnel in the defined roles across the five organisations invited to participate via an internal memo. Significantly fewer people worked at the blunt end of the organisations than in the crews. Thus, the number of respondents at the blunt end was inevitably smaller than the number of crew members. The proportion of respondents from the study population was estimated to be 20.0%, but this estimate excluded data from one organisation.

Table 3 Organisational levels, examples of roles and number of respondents

Blunt-end level	*Examples of roles*	*Description/tasks*	*n*	*% (n)*
Headquarters	Managing director, commander of maritime staff, director of maritime organisation, safety manager	Management, policies, synchronisation of organisational levels and cooperation, resources, safety management	25	8.9
Operational level	Head of training, operations manager	Work processes, methods, training	26	9.2
Technical level	Technical manager, technical specialist, procurement specialist	Design, procurement and maintenance of equipment, technology, equipment and technical systems	25	8.9
Sharp-end level				
Crews	HSW crew members	Sharp-end work in cockpits	205	73.0
Total			*281*	*100.0*

3.2 Questionnaire

3.2.1 Synthesising the phenomena

As a starting point, we synthesised the phenomena (9 pcs.) that challenged HSW crew performance (Lehtimäki and Teperi, 2025a, 2025b, 2025c). The questionnaire data addressed the critical HFs that needed improving to mitigate these phenomena. The phenomena were reasoned on the basis of previous studies of HF mastery in the HSW maritime context (Table 4):

1. Eight of the phenomena (Q1–Q8) focused on crew competency areas, which were presented by comparing summaries of critical HSW crew competencies and behavioural markers with observations of their real-life implementation (Lehtimäki and Teperi, 2025c).
2. Data on the realisation and management of the mental workload of HSW crews were utilised to further justify the phenomenon (Q8) in this HF area (Lehtimäki and Teperi, 2025b).
3. Data on the incident and accident analysis practices in the HSW maritime field in Finland (Lehtimäki and Teperi, 2025a) were used to condense the safety reporting phenomenon (Q9).

Table 4 Questionnaire structure: questions, phenomena that challenge crew performance, structured and unstructured questions

Question	*Phenomena that challenge crew performance*	*Structured questions*	*Open-ended questions*
	Q1–8: crew competency phenomena Q9: safety reporting phenomenon	Which background factors (choose 5–10 HF details) should particularly be improved, in order to…	Describe in your own words, how…
Q1	KNO: Operating instructions and working methods do not always enable cockpit resources to be shared efficiently (crew, technical systems, information = 'maritime / crew resource management').	… improve cockpit work's standard and working methods? The aim is to efficiently use the crew, technology and information.	…standard and working methods should be improved. (*
Q2	PRO: The use and application of the organisation's standard procedures in cockpit work vary.	… enable the maritime organisation to better help crews consistently and efficiently use standard and working methods?	…the uniform, efficient use of standard and working methods could be supported.
Q3	COM: Inadequate cockpit communication hampers crew performance.	… improve cockpit communication among crews?	…crew cockpit communication could be improved and supported.
Q4	RPM: The use of route plans and route monitoring need improvement.	… help crews make use of route plans and monitor routes?	… crews could be helped to utilise route plans and monitor routes.
Q5	LTW: As a resource, crew teamwork receives little attention and individual performance is overemphasised.	… promote crew teamwork?	… crews' teamwork could be promoted.
Q6	PSD: Decisions are often made on the basis of 'gut instinct', and it would be useful to look into the facts, options and risks together.	… support and improve crew decision-making?	… crew decision-making could be supported.
Q7	SAW: Information available from the boat's systems and from outside, as well as from crew members, is often underutilised and not always shared among the crew. The technical design of boats is not always conducive to the availability of information or the formation of shared situational awareness.	… improve access to and the sharing of information among crew members?	… the access to and sharing of information among crew members could be improved.
Q8	WLM: Workload management is not always proactive, and crew members' harmfully high or low workloads may be ignored/neglected.	… improve crew workload management?	… crews' workload management could be supported and improved?
Q9	Safety reporting is used inefficiently to improve cockpit work (e.g. number of reports, quality of investigations).	… make safety reporting practices more supportive of crew safety and improvement of performance?	… safety reporting could be improved?

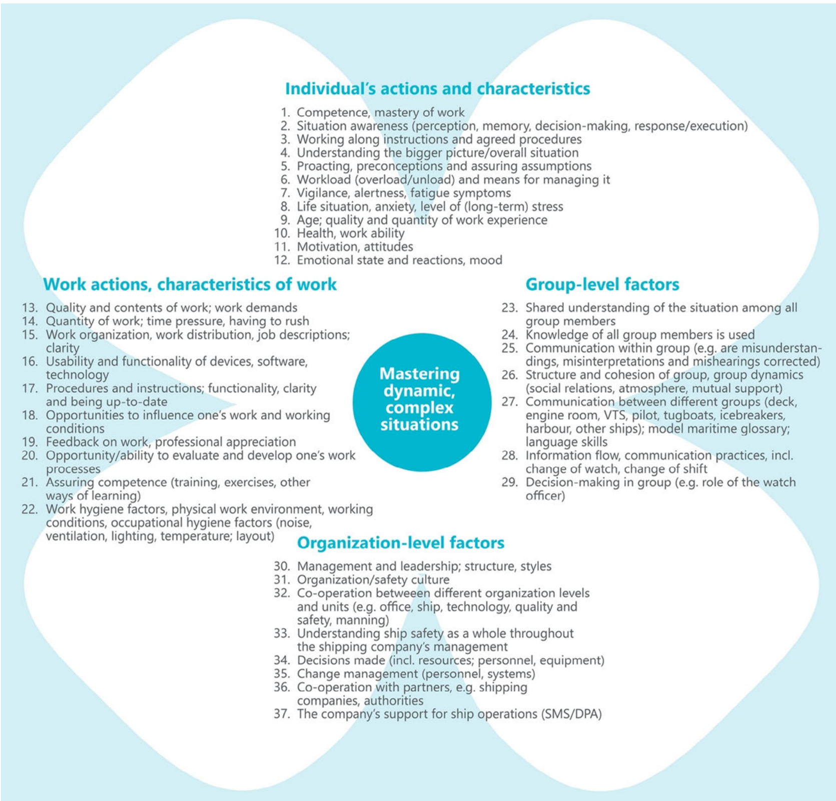
Notes: KNO = application of knowledge, PRO = application of procedures, COM = communication, RPM = route plan management, LTW = leadership and teamwork, PSD = problem-solving and decision-making, SAW = situational awareness and management of information, WLM = workload management.
*This question remained invisible to the respondents.

3.2.2 Structured and open-ended questions

The questionnaire was based on the HF Tool. The respondents were asked to select the critical HFs (5–10 pcs.) that should be developed with actions from the blunt end to better support crew performance. The response options, the same for each question, were created using the HF Tool (Teperi, 2012) operationalised into maritime context (Teperi et al., 2018) (Figure 1) to enable addressing HFs in the responses.

The HF Tool is a theoretical framework and practical model (Figure 1), developed for implementing HF informed thinking and practices to safety management systems of safety critical industries (Teperi, 2012). It has been especially used for learning and analysing relevant HF in incident reporting and analysis (Teperi et al., 2015, 2017) and for developing organisational learning and safety culture (Teperi et al., 2023). The HF Tool deals with interactions among four system levels (inter- and intra-organisational, group, work, and individual levels), and the specified details describing each level in detail (for example, decision-making and use of resources at the organisational level). The application of the HF Tool has been studied and published in various fields: Air traffic management, the nuclear industry, and the railway (Teperi, 2012; Teperi et al., 2017, 2023); the maritime industry (Teperi et al., 2018); aviation maintenance (Teperi et al., 2019a); and the construction industry (Nykänen et al., 2020).

Figure 1 HF Tool adapted to the maritime industry (see online version for colours)



Source: Teperi et al. (2016); paraphrasing Teperi et al. (2015)

To improve the questionnaire design, the HF Tool details (originally 37 pcs.) were condensed into 33 response options (HFs) by adapting 17 HF Tool details and combining four details (see Annex 2). Response options for individual-level HFs were presented last in the questionnaire to avoid unnecessary emphasis, given the current situation in the HSW maritime field (Lehtimäki and Teperi, 2025a).

The structured questionnaire data consisted of mandatory nominal scale responses (Table 5). Open-ended question attached to each phenomenon (9 pcs) asked the respondents to describe in their own words how the crew's performance could be better supported in terms of the phenomenon in question.

Table 5 Questionnaire data: descriptions and numbers

Description of structured question data	*Number*
Respondents	n = 281
Structured questions (Q1–Q9)	9
Structured response options	33
Selected response options per question (mean)	7
Selected response options (total)	n = 17,677
Description of open-ended question data	
Open-ended questions (Q2–Q9)	8
Open-ended responses (headquarters 12%, operational level 11%, technical level 7%, crews 70%)	n = 502

Notes: The responses to one open-ended question (Q1) on the developing standard operating procedures were not received because the question remained invisible to the respondents. However, the respondents reported Q1-related human factors in other question areas, which reduced the detrimental effect of this.

The questionnaire was first tested by a focus group and then modified. The number of structured response options posed challenges for some test respondents, but detailed data were considered crucial, and reducing the number of responses was considered acceptable. At the beginning of the questionnaire, the respondents were introduced to the concepts and elements that would be covered. The questionnaire was available in both Finnish and Swedish.

3.3 Data analysis

The questionnaire data were combined and analysed at the group level, in accordance with the consent of the HSW organisations. The structured data were processed in Microsoft Excel 16.90 and SPSS version 29, and were analysed by phenomenon, organisation level, and HF tool level. The analysis used statistical reasoning (Spearman's rho correlation analysis) to identify the differences between the responses of the organisational levels. The views were similar across the responses of the different organisational levels, and further analysis was conducted using descriptive statistical methods. Aggregated variables were used to compare the relative distribution of the structured responses.

The open-ended responses were first broken down into parts and simplified during the open coding process. They were then grouped, using axis coding, on the basis of structured question-response options (Table 6). The disaggregated responses were summarised to eliminate duplication and to facilitate the identification of key content. The open responses were eventually condensed into larger entities of four HF clusters, which were also utilised to analyse the structured questionnaire data.

Table 6 Analysis of open responses: (1) initial responses, (2) broken-down and coded responses, (3) simplified responses, (4) combined, condensed responses and (5) HF clusters based on the responses

	Analysis process of open responses	*Open-ended questions based on eight phenomena*								*Total*
		Q2	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q9*	
1	Initial responses	81	84	65	60	56	50	51	55	502
	Headquarters	*12*	*11*	*8*	*7*	*7*	*6*	*5*	*6*	*62*
	Operational level	*6*	*8*	*7*	*8*	*7*	*5*	*6*	*7*	*54*
	Technical level	*6*	*7*	*4*	*3*	*3*	*3*	*6*	*3*	*116*
	Crews	*57*	*58*	*46*	*42*	*39*	*36*	*34*	*39*	*351*
2	Broken-down and coded responses (coding based on structured question-response options)	161	160	136	119	106	92	81	85	940
3	Simplified responses, duplication removed	22	23	22	22	21	18	23	16	167
4	Combined condensed responses (Q2–Q9)									30
5	HF clusters, based on responses									4

Notes: Data description by question and as total.
Open-ended Q1 remained without responses, because the questions were not visible in the questionnaire.

The responses to the open-ended questions on safety reporting (Q9) were processed separately, as they did not correlate with the competency-based phenomena (Q2–8) due to their different theme.

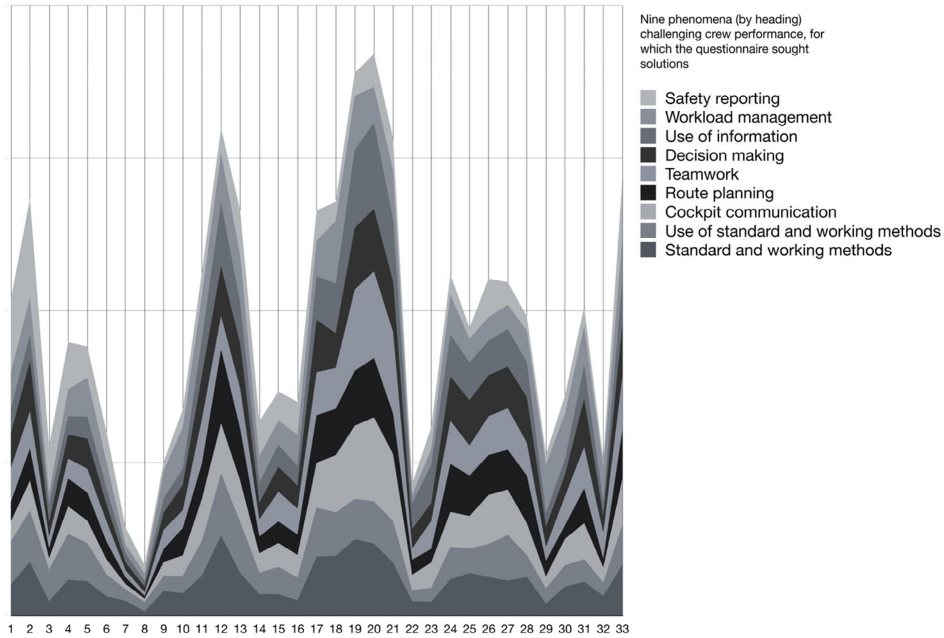
4 Results

4.1 Structured responses reflecting needs for improvement

The structured questions' (Q1–Q9) response options (33) were subject to choice (n = 17,677). We combined the relative proportions of the organisational level responses and first divided them by the HF Tool levels: *Organisational factors* (18%), *Work characteristics* (32%), *Group/team factors* (20%), and *Individual factors and actions* (30%).

The distribution of the responses was multi-peaked (Figure 2). The responses to the different questions were very similar. The monotonous dependence of responses (Spearman's rho correlation analysis) on the questions was ($p = <.001$) most commonly strong ($r_S = 0.800–0.915$) and at least significant ($r_S = 0.670–0.743$). The workload management responses correlated slightly less ($p = 0.001–0.011$) with the other responses (rS = 0.437–0.596). The responses to the safety reporting question (Q9) did not correlate to any great extent with the responses to the other questions.

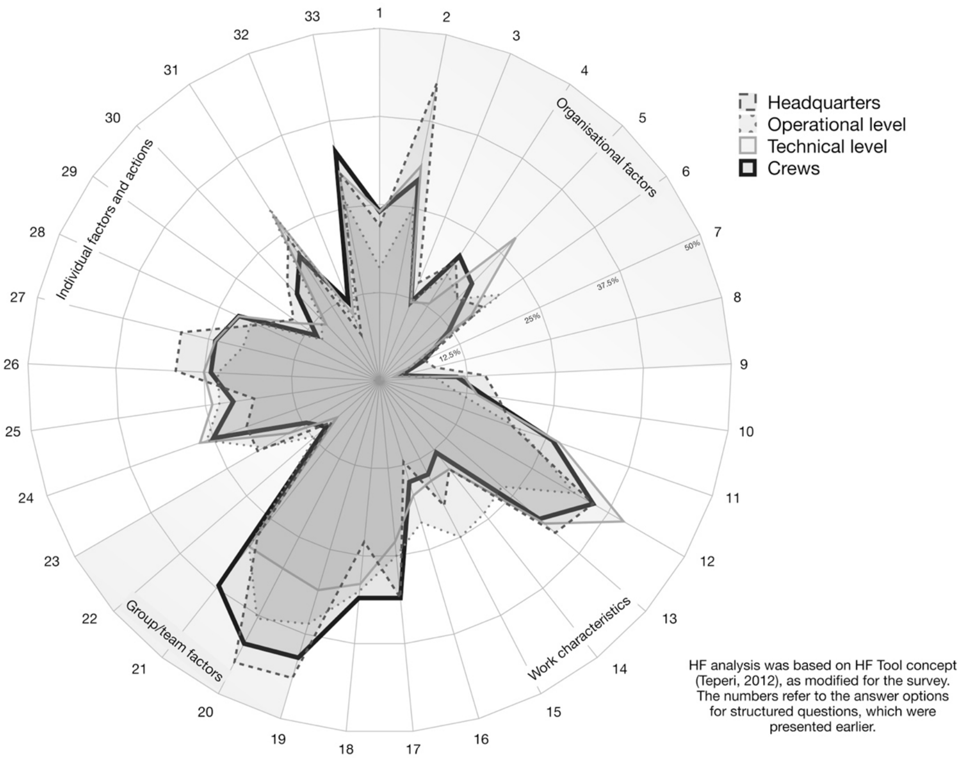
Figure 2 HFs in need of improvement to mitigate phenomena (9) affecting crew performance (Table 5), presented in structured responses % (N)



1. Management and leadership in organisation: structure, styles
2. Organisational/safety culture
3. Co-operation and communication between different units and hierarchy levels (office, vessel, technology, quality and safety, manning, etc.)
4. Understanding the reality of cockpit work and safety factors as a whole in management
5. Decisions concerning resources, personnel, equipment
6. Change management (personnel changes, systems)
7. Co-operation with partners (other organisations, educational institutions, research, public authorities, command centres)
8. Support of operations (safety management system/designated person ashore, Standby operator)
9. Content and meaningfulness of work; e.g. related to competencies
10. Amount of work: time pressure, haste and sense of urgency (in one's role)
11. Work distribution, work organisation, job roles
12. Functionality and usability of hardware, software and other technology
13. Working methods and instructions; functionality, clarity and timeliness
14. Being able to influence one's own work
15. Feedback on work, professional esteem/appreciation
16. Opportunities and ability to analyse and develop one's work processes
17. Ensuring competence (training, exercises, other ways of learning)
18. Physical work environment, working conditions, occupational hygiene factors (noise, air conditioning, lighting, temperature, layout)
19. Crew resource management (teamwork, team leadership, ensuring shared situational awareness, group decision-making, crew members as a resource, etc.)
20. Communication within the group (e.g. correcting misunderstandings, misinterpretations and mishearings)
21. Crew structure and group dynamics (social relations, atmosphere, mutual support)
22. Communication among different partners (vessel traffic system, pilot, tugs, icebreakers, ports, other vessels and units, command centres); model nautical vocabulary, language skills
23. Information flow (shift change)
24. Competence, conceptual mastery of work in one's role
25. Management of situational awareness (perception, memory, management of information, decision-making, response/execution)
26. Compliance with instructions, agreed procedures and regulations
27. Understanding entirety of factors affecting cockpit work
28. Preconceptions, assurance and checking; assumptions
29. Proactive workload management, response to harmfully high and low workloads
30. Understanding of crew performance and functional limitations (life situation, worries, stress, mood, alertness, fatigue, ability to concentrate on work, age)
31. Quantity and quality of work experience
32. Health and work ability of crew members
33. Motivation, attitudes

Monotonous dependence (Spearman's rho) was strong (p = <.001, rS = ≥ 0.8) in the responses to structured questions at the different levels of the maritime organisations (Figure 3). Thus, the views of the organisational levels were all similar.

Figure 3 Relative number of structured responses by organisational level



4.2 Clusters of human factors

As the HFs presented in the structured responses and proposed as being in particular need of improvement to mitigate the nine phenomena challenging crew performance were very similar, they were discussed together. In reporting the results, the highlighted HF areas were condensed into four HF clusters (Table 7). The responses to the question on safety reporting (Q9) formed a separate cluster, based on a different theme.

Next, we present the HF clusters' proposals for improving the support of crew performance. Tables 7–10 present the relative proportions of the structured responses in descending order, and the open responses support the reporting of the results. The HFs (numbers 1–33, based on structured questions' response options) to which the responses were addressed are indicated in the text by parentheses (e.g. '33').

Table 7 Structured responses classified as four HF clusters: cluster number, cluster label, description, response options and numbers

Cluster number	*Cluster label*	*Description*	*Response options (33 pcs.)*	*n*	*%(n)*
1	Crew and sharp-end CRM	Crew characteristics and 'sharp-end' CRM, mastery of work and ensuring competencies	10, 19, 20, 21, 22, 23, 25, 28, 29, 30, 32, 33, 9, 17, 24, 26, 27, 31	9,485	60%
2	Tools and methods	Working methods, physical and technical environment	11, 12, 13, 18	2,832	18%
3	Organisation and cooperation	Management, leadership and operating culture, engagement, collaboration and support	1, 2, 4, 5, 6, 3, 7, 8, 14, 15, 16	3,587	23%
	Total, Clusters 1–3			15,904	100%
4	Safety reporting		1–33	1,773	100%
	Total, Clusters 1–4			17,677	100%

4.2.1 Cluster 1: crew and sharp-end CRM

The structured responses classified into the *Crew and sharp-end CRM* HF cluster (60% of all responses) highlighted the need to improve and ensure CRM and crew competencies (47% of responses in cluster) (Table 8). The open responses revealed that promoting a better understanding of the factors that affect cockpit work and human performance was considered essential for supporting crews. (33) A common safety-friendly attitude and a good crew atmosphere were seen as pivotal factors for safe operations. (19) To improve CRM, the respondents wished that crew interaction, sense of responsibility and participation would be encouraged more; they also wanted more (23, 28) proactive work phases and better risk management. (20) According to the respondents, open, standardised, high-quality crew communication would enable foresight, cross-checking and sound decisions. (26) The requirement that crews comply with procedures, orders and regulations during all work stages was deemed more important than individual ways of acting. (25) The promotion of shared situational awareness and foresight was seen as the objective of reducing assumptions and ensuring high-quality decisions. (29) To improve proactive mental workload management, the respondents proposed identifying stressful situations in advance, as this could ensure that the crew had operational capability and sufficient capacity for dealing with changing situations.

Table 8 HF Cluster 1 – *Crew and sharp-end CRM*: response option and number, questions and summaries of numbers

No.	*Response option*	*Q1*	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q1–Q8 (%)*	*Q1–Q8 (n)*
20	Communication within the group (e.g.. correcting misunderstandings, misinterpretations and mishearings)	11%	8%	12%	10%	12%	9%	13%	6%	10%	974
19	Crew resource management (teamwork, team leadership, ensuring shared situational awareness, group decision-making, crew members as a resource, etc.)	11%	8%	11%	9%	11%	9%	12%	9%	10%	958
21	Crew structure and group dynamics (social relations, atmosphere, mutual support)	8%	8%	10%	7%	11%	7%	9%	8%	9%	820
33	Motivation, attitudes	8%	8%	7%	8%	8%	8%	7%	7%	7%	697
17	Ensuring competence (training, exercises, other ways of learning)	9%	10%	7%	8%	6%	8%	6%	6%	7%	691
24	Competence, conceptual mastery of work in one's role	5%	6%	5%	8%	6%	6%	6%	6%	6%	591
26	Compliance with instructions, agreed procedures and regulations	6%	7%	7%	7%	5%	6%	5%	4%	6%	550
27	Understanding the entirety of factors that affect cockpit work	5%	9%	7%	7%	6%	6%	6%	4%	6%	573
31	Quantity and quality of work experience	5%	4%	5%	6%	6%	7%	5%	6%	6%	533
28	Preconceptions, assurance and checking; assumptions	6%	4%	5%	8%	5%	7%	5%	5%	6%	525
25	Management of situational awareness (perception, memory, management of information, decision-making, response/execution)	6%	5%	5%	7%	4%	7%	6%	4%	5%	510
30	Understanding crew performance and functional limitations (life situation, worries, stress, mood, alertness, fatigue, ability to concentrate on work, age)	4%	4%	4%	2%	4%	3%	2%	7%	4%	373

Notes: Relative proportions of structured responses in descending order
Q1 = developing standard and working methods
Q2 = promoting use of standard and working methods
Q3 = promoting crew cockpit communication
Q4 = supporting route plan management
Q5 = promoting teamwork
Q6 = promoting crew decision-making
Q7 = supporting the use of information
Q8 = supporting workload management

Table 8 HF Cluster 1 – *Crew and sharp-end CRM*: response option and number, questions and summaries of numbers (continued)

No.	*Response option*	*Q1*	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q1–Q8 (%)*	*Q1–Q8 (n)*
10	Amount of work: time pressure, haste and sense of urgency (in my role)	3%	3%	3%	5%	2%	4%	2%	7%	4%	347
23	Information flow (shift change)	2%	3%	4%	2%	4%	3%	6%	3%	3%	306
29	Proactive workload management, response to harmfully high and low workloads	2%	3%	2%	3%	2%	3%	2%	8%	3%	277
32	Health and work ability of crew members	3%	3%	2%	1%	4%	2%	2%	6%	3%	272
9	Content and meaningfulness of work; e.g. related to competencies	4%	3%	2%	2%	3%	3%	2%	4%	3%	266
22	Communication among different partners (vessel traffic system, pilot, tugs, icebreakers, ports, other vessels and units, command centres); model nautical vocabulary, language skills	2%	2%	2%	2%	2%	3%	4%	1%	2%	222
	Total (%)	100	100	100	100	100	100	100	100	100	
	Total (n)	1,231	921	1,242	1,117	1,332	1,259	1,239	1,144		9,485

Notes: Relative proportions of structured responses in descending order
Q1 = developing standard and working methods
Q2 = promoting use of standard and working methods
Q3 = promoting crew cockpit communication
Q4 = supporting route plan management
Q5 = promoting teamwork
Q6 = promoting crew decision-making
Q7 = supporting the use of information
Q8 = supporting workload management

Table 9 HF Cluster 2 – *tools and methods*: response option and number, questions and summaries of numbers

No.	*Response option*	*Q1*	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q1–Q8 (%)*	*Q1–Q8 (n)*
12	Functionality and usability of hardware, software and other technology	36%	32%	26%	36%	21%	29%	34%	24%	30%	852
18	Physical work environment, working conditions, occupational hygiene factors (noise, air conditioning, lighting, temperature, layout)	27%	23%	30%	23%	26%	20%	26%	31%	26%	727
13	Working methods and instructions; functionality, clarity and timeliness	19%	27%	22%	25%	25%	26%	21%	23%	23%	663
11	Work distribution, work organisation, job roles	18%	18%	22%	17%	28%	25%	19%	22%	21%	590
	Total (%)	100	100	100	100	100	100	100	100	100	
	Total (n)	407	353	352	382	294	318	351	375		2832

Notes: Relative proportions of structured responses in descending order
Q1 = developing standard and working methods
Q2 = promoting use of standard and working methods
Q3 = promoting crew cockpit communication
Q4 = supporting route plan management
Q5 = promoting teamwork
Q6 = promoting crew decision-making
Q7 = supporting the use of information
Q8 = supporting workload management

Table 10 HF cluster 3 – *organisation and cooperation*: response option and number, questions and summaries of numbers

No.	*Response option*	*Q1*	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q1–Q8 (%)*	*Q1–Q8 (n)*
2	Organisational/ safety culture	20%	16%	15%	16%	16%	20%	13%	13%	16%	585
1	Management and leadership in organisation: structure, styles	12%	13%	10%	10%	15%	14%	12%	13%	12%	448
4	Understanding the reality of cockpit work and safety factors as a whole in management	14%	14%	14%	14%	9%	10%	9%	10%	12%	417
5	Decisions concerning resources, personnel, equipment	13%	12%	11%	14%	10%	12%	11%	14%	12%	438
15	Feedback on work, professional esteem/appreciation	8%	8%	12%	11%	13%	10%	11%	9%	10%	359
16	Opportunities and ability to analyse and develop one's work processes	6%	7%	11%	10%	11%	9%	10%	11%	9%	333
14	Being able to influence one's own work	8%	7%	9%	8%	8%	7%	10%	10%	8%	293
6	Change management (personnel changes, systems)	7%	7%	7%	9%	9%	7%	8%	9%	8%	283
3	Co-operation and communication among different units and hierarchy levels (office, vessel, technology, quality and safety, manning etc.)	5%	10%	6%	5%	5%	6%	9%	4%	6%	224
7	Co-operation with partners (other organisations, educational institutions, research, public authorities, command centres)	6%	4%	3%	3%	3%	3%	5%	3%	4%	130
8	Support of operations (SMS/DPA, Standby operator)	1%	3%	2%	1%	2%	2%	3%	3%	2%	77
	Total (%)	100	100	100	100	100	100	100	100	100	
	Total (n)	485	598	369	375	426	456	372	506		3587

Notes: Relative proportions of structured responses in descending order.
Q1 = developing standard and working methods
Q2 = promoting use of standard and working methods
Q3 = promoting crew cockpit communication
Q4 = supporting route plan management
Q5 = promoting teamwork
Q6 = promoting crew decision-making
Q7 = supporting the use of information
Q8 = supporting workload management
SMS/DPA = safety management system/designated person ashore

4.2.2 Cluster 2: tools and methods

The distribution of the structured responses classified into the *tools and methods* HF cluster (18% of all responses) by response option was even (Table 9). The open responses showed that for different boat classes, (12) technical solutions such as software and hardware and (18) cockpit layout should effectively and consistently support access to information, teamwork, group decision-making, and use of standard operating procedures (SOP). In particular, (12) technical solutions were seen as essential for supporting the planning and monitoring of routes. (18) The need for low noise levels or functional communication systems in cockpits was highlighted, as effective resource management was impossible without crew communication. (13) It was expected that well-documented SOPs would be part of normal operations and meet the requirements of actual work in routine and abnormal situations. SOPs should support the management of crews' resources and information, cross-checking, shared situational awareness, and the management of workload in complex situations. The respondents wished SOPs would be as similar as possible for the different boat classes but that their unique requirements would also be considered. (11) Better division of tasks and labour among crews was seen as being linked to SOPs. Replacing individual work with cooperation, mutual support and efficient use of resources was considered essential.

4.2.3 Cluster 3: organisation and cooperation

Of the responses classified as belonging to the *organisation and cooperation* HF cluster (23%) (Table 10), 40% focused on operating culture, leadership and the different forms of cooperation between the actors in the maritime organisations. (2) To develop a safety culture and atmosphere, it was considered that transparency, impartiality, shared respect and, in particular, blame-free attitudes needed to be increased at all levels of the organisation. Better justification of continuous teamwork and uniform operating methods was considered essential, and a prerequisite for proactive risk management. One respondent described the need for change thus: 'We shouldn't admire Chuck Norris-style action in the cockpits anymore'.

(1) A desired change in the management of operations was that it would require the use of common practices and SOPs as well as an atmosphere conducive to teamwork through consistent engagement, setting an example and monitoring the achievement of objectives. (3) Organisational levels should also communicate more effectively with each other and coherently contribute to objectives. (4, 5, 6, 7, 8) To ensure good-quality cooperation and decisions, all those involved should have a common understanding of the reality of cockpit work. Poor correspondence between formal requirements and the reality of the work was considered highly detrimental. To guarantee continuous development, an atmosphere that encourages participation and opportunities to develop work processes was considered crucial (27%).

4.2.4 Cluster 4: safety reporting

The *Safety reporting* HF cluster contained responses related to the development of learning about deviations and events (Table 11). (2) To increase and ensure the development of information through safety reporting, priority was given to promoting an open, supportive, error-tolerant and blame-free culture. According to the respondents, all levels of the organisation should participate in reporting, including near misses and positive observations. All reports, including anonymous reports, should be treated as essential information. The respondents saw a shared attitude and understanding among the management and the crew as a key goal and believed there should be no need to fear the consequences of mistakes. The system's functionality had to be based on a constant desire to identify even minor deviations and to learn and develop. (1) Leadership and motivation should ensure a sufficient number of reports.

(24) According to the responses, the entire crew should be helped to understand the importance of safety reporting and be aware of current safety observations. (17) The training system should, according to the respondents, ensure that all operators have sufficient skills to prepare safety reports and to process results. (19) The respondents also felt that all crew members should be allowed to express their views on the course of events. (4) Those processing reports and investigating events at the organisational level should have a better understanding of the reality of the work to avoid conflicts. (13) According to the respondents, reports would be easier to analyse if they were based on uniform criteria. The analysis should also include recommendations for improving risk management on the basis of events and the measures taken. If the safety report is considered unfounded, this should be justified. (3) The reports should always be examined and promptly communicated to the crews. The system was only considered motivating or functional if information was available on how notifications were processed or if concrete results were visible. (9) Information on incidents should also, according to the respondents, be shared among maritime organisations.

Table 11 HF Cluster 4 – *Safety reporting*: response option and number summaries of numbers

No.	*Response option*	*Q9 (%)*	*Q9 (n)*
2	Organisational/safety culture	10%	183
1	Management and leadership in organisation: structure, styles	8%	134
33	Motivation, attitudes	6%	107
4	Understanding the reality of cockpit work and safety factors as a whole in management	5%	87
3	Cooperation and communication among different units and hierarchy levels (office, vessel, technology, quality and safety, manning etc.)	5%	87
13	Working methods and instructions; functionality, clarity and timeliness	5%	83
26	Compliance with instructions, agreed procedures and regulations	4%	70
14	Being able to influence one's own work	4%	65
20	Communication within the group (e.g.. correcting misunderstandings, misinterpretations and mishearings)	3%	61
16	Opportunities and ability to analyse and develop one's work processes	3%	61
21	Crew structure and group dynamics (social relations, atmosphere, mutual support)	3%	60
5	Decisions concerning resources, personnel, equipment	3%	58
6	Change management (personnel changes, systems)	3%	56
17	Ensuring competence (training, exercises, other ways of learning)	3%	55

Notes: Relative proportions of structured responses in descending order.
Q9 = question nine
SMS/DPA = safety management system/designated person ashore

Table 11 HF Cluster 4 – *Safety reporting*: response option and number summaries of numbers (continued)

No.	*Response option*	*Q9 (%)*	*Q9 (n)*
15	Feedback on work, professional esteem/appreciation	3%	54
12	Functionality and usability of hardware, software and other technology	3%	46
19	Crew resource management (teamwork, team leadership, ensuring shared situational awareness, group decision-making, crew members as a resource, etc.)	2%	43
11	Work distribution, work organisation, job roles	2%	43
27	Understanding all the factors that affect cockpit work	2%	41
23	Information flow (shift change)	2%	41
24	Competence, conceptual mastery of work in one's own role	2%	37
31	Quantity and quality of work experience	2%	36
18	Physical work environment, working conditions, occupational hygiene factors (noise, air conditioning, lighting, temperature, layout)	2%	35
30	Understanding crew performance and functional limitations (life situation, worries, stress, mood, alertness, fatigue, ability to concentrate on work, age)	2%	33
10	Amount of work: time pressure, haste and sense of urgency (in one's role)	2%	33
7	Cooperation with partners (other organisations, educational institutions, research, public authorities, command centres)	2%	32
28	Preconceptions, assurance and checking; assumptions	1%	26
25	Management of situational awareness (perception, memory, management of information, decision-making, response/execution)	1%	20
22	Communication among different partners (vessel traffic system, pilot, tugs, icebreakers, ports, other vessels and units, command centres); model nautical vocabulary, language skills	1%	20
29	Proactive workload management, response to harmfully high and low workloads	1%	19
9	Content and meaningfulness of work; e.g. related to competencies	1%	17
32	Health and work ability of crew members	1%	15
8	Support of operations (SMS/DPA, standby operator)	1%	15
	Total	100%	1,773

Notes: Relative proportions of structured responses in descending order.
Q9 = question nine
SMS/DPA = safety management system/designated person ashore

We now turn to the main discussion of the study.

5 Discussion

We studied the critical HFs that the blunt end of HSW maritime organisations should develop to be able to better support crew performance in cockpit work. The findings highlight that the operators in the HSW organisations anticipated a shift towards better crew collaboration, improved proactive use of resources, and a blame-free operational culture. The results support previous findings that have shown that crew performance is highly dependent on the surrounding sociotechnical system (Kongsvik et al., 2020), and that the critical HSW crew competencies required for crew performance (Lehtimäki and Teperi, 2025c) cannot be supported in isolation from other system components and their interactions (ILO, 2021). The paper contributes to the practical application on HF and especially bridge crew skills, which have been deemed necessary to improve in maritime (Fjeld et al., 2018) and in studies executed in the HSW field (Lehtimäki and Teperi, 2025c).

5.1 Improving crew resource management

Firstly, the respondents wanted a better understanding of the factors underlying human performance in the HSW field. This was not surprising, as this is still lagging in the maritime sector (Turan et al., 2016). A shift from individualistic perspectives (Safety-I) (Hollnagel, 2014) to proactive and effective CRM (Cooper et al., 1980; Helmreich et al., 1999) was expected to improve foresight and risk management at all levels of HSW operations. Measures to foster a safety-friendly attitude, crew interaction and sense of responsibility were seen as prerequisites for effective crew performance.

The respondents expected extensive CRM training to enhance crew performance by improving the crew members' interaction skills, increasing mutual support, helping dismantle crew hierarchy, and encouraging the adoption of proactive perspectives. HSW organisations ought to invest more to CRM training and then assure that the training targets all levels of the HSW organisations (Griffioen et al., 2021), that the content is adapted to the context (O'Connor, 2011; Wahl and Kongsvik, 2018) and connected to actual operations (Röttger, 2016), and that it uses detailed descriptions of the behaviours affecting crew performance (Griffioen et al., 2021; Fan and Yang, 2023). These descriptions, which outline the crew competencies of knowledge, skills and attitudes, especially in HSWs (Lehtimäki and Teperi, 2025c), will inform and prepare stakeholders to effectively increase resilience (Patriarca et al., 2018) in operations.

5.2 Tools and methods to support crews

Secondly, according to the respondents, the consistency of operations needs to be improved by using cockpit work's SOPs in both routine and abnormal situations. This can be achieved through explicit management decisions and engaging operators. These findings support the practical application of CRM perspectives, as CRM training cannot be effective without adherence to high-quality SOPs, which provide a standard reference for the crew's tasks (EUROCONTROL, 2004). The respondents expected a working paradigm shift from methods tailored by constantly changing crews and different boat classes to common perspectives, but on a continuum, building high-level competency in the use of SOPs. In modern seamanship, 'tinkering' with SOPs should be possible in dynamic situations, but 'tailoring' them, by making permanent changes to operations or approving a practical drift from common standards, should not be accepted (Haavik et al., 2017).

The content of SOPs was expected to facilitate a continuous flow of analytical group decision-making and provide criteria for monitoring and suspending operations. As in other maritime research (Bye and Aalberg, 2020), the respondents expected SOPs to be continuously improved (Nævestad et al., 2018), and designed together with operators (Rajapakse et al., 2019), based on work-as-done (Hollnagel, 2014), to manage cognitive workload (Blandford et al., 2014) and foster the use of information and shared situational awareness in routine and complex situations.

Thirdly, as is often the case in the maritime field, sub-optimised technical solutions have made it challenging to utilise SOPs and cockpit resources effectively (Danielsen et al., 2021). They hinder adaptation to SOPs, unlike in the standardised conditions of civil aviation (Haavik et al., 2017). The results show that HSW technical equipment is often designed for a different environment and their usability could be better. Even essential functions can cause unnecessary cognitive load. Technical systems should be 'designed for situational awareness' (Endsley and Jones, 2016), and according to the respondents, they should more effectively support access to information, teamwork, group decision-making, route planning and the monitoring of routes.

The results regarding technical resources in the cockpits highlighted how in modern maritime, the 'distributed capabilities of seafarers' (Kongsvik et al., 2020) are holistically integrated into the functionality of the sociotechnical system. Technical facilities should be integrated into maritime organisations' high-level strategies, like the human-technology interaction in real-world operations. According to Haavik et al. (2017), in HSW operations, modern seamanship cannot be expected from only crews: crew performance must be seen as being created by the conditions of a larger sociotechnical system.

5.3 Maritime organisations' role in supporting crew performance

Finally, the findings confirmed those of previous research: if systemic performance is to be ensured in operations, all the decisions and measures concerning responsibility taken by maritime organisations (Turan et al., 2016) should be justified from the perspective of effective CRM and the use of cockpit resources at all operational levels (Kongsvik et al., 2020).

However, the traditional emphasis on individual seamanship in the HSW field is still a long way from enhanced systemic performance, unity and resource sharing. This study shows that blame and misfunctioning feedback mechanisms have made it difficult for HSW operators to improve group decision-making in cockpits. For continuous learning to occur, the obstacles to a fair culture (Dekker, 2017) must be removed, and a shared safety-friendly attitude and crew participation in risk management should be promoted. Conflicting features in the operating culture have hindered the collection of information, analysis through safety observations, and joint learning and development, a finding which is in line with previous knowledge on the maritime sector (Oltedal and McArthur, 2011; Turan et al., 2016) and the HSW maritime field (Lehtimäki and Teperi, 2025a). The HSW field must collect more data, including positive observations (Hollnagel, 2014), analyse them using high-quality methods, and utilise them in a concrete way to continuously develop the sociotechnical system and adopt more standardised solutions (Haavik et al., 2017).

As a positive implication, and partly contrary to expectations, the results revealed that the views of the different organisational levels regarding which HFs need to be developed in the future to support crew performance were ultimately similar, which is essential, and promising in terms of improving mastery of HF (Schein and Schein, 2016; ICAO, 2021). However, many practical measures were still only just being implemented, although the perspectives aligned. Cooperation and communication among organisational levels requires substantial improvement, which is typical in the maritime sector (Puisa et al., 2018). Clear decisions by HSW organisations' management regarding HF development strategies were seen as a prerequisite for improving operations and use of cockpit resources in the future. This was proposed by the organisations' technical sector in particular.

5.4 Ethics, limitations and future research

All the materials were processed in accordance with the requirements of the target organisations, and the results were reported on a group level. A privacy notice was drawn up in connection with the evaluation. The University of Vaasa's Human Science Ethics Committee confirmed, in its decision submitted on 30 August 2022, that no ethical review was required for this research. The authors state that this study was conducted without any ties to commercial interests.

As a limitation, the classification of HFs also required interpretation by the researcher. The fact that the number of people working on the blunt end of target organisations was smaller than the number of HSW crew members caused a relative imbalance between the questionnaire respondents. Analysing the data on a group level prevented the breakdown of organisation-specific differences, which weakened the level of detail in these areas. Another limitation of the study was that the significant synchronisation of views between the respondents from different organisations was not further analysed, leaving legitimate questions unanswered for future studies. Despite the potential for improvement in the more complex statistical analysis, we feel that our choice of method was acceptable. The statistical analysis of more complex causal relationships between the HFs is something for future studies to examine.

Topics raised for future research were improved support for crew competencies, the effectiveness of HSW-specified CRM training, the integration of CRM principles into SOPs, managing the paradigm shift from Safety-I to Safety II in HSW organisations, and finally, connecting HF research to practical operations. Future research should also use international data.

5.5 Conclusions

In this study we addressed the critical HFs that should be improved to enhance practical blunt-end support of crew performance in HSW cockpit work. Based on results, the main prerequisite for improving operations is increasing the basic understanding of HF and the factors underlying crew and systemic performance. Enhanced crew collaboration, proactive use of sociotechnical resources, and a blame-free operational culture were expected by the organisational levels in HSW organisations. Although these requirements have already been identified in safety-critical sectors, they still need to be internalised more effectively in the HSW maritime field.

Despite the extensive knowledge of HF produced by maritime research, practical implications still need improvements. The conservative maritime sector urgently requires more research, development and innovations to form bridges between academic HF studies and practical operations. A contribution of this study was that upcoming decisions in HSW organisations should be based on holistic perspectives, with more sophisticated HF knowledge and synchronised resource management. There is a deep connection between a blame-free and less hierarchical operating culture and unified perspectives regarding operations and maintaining crew performance. This makes it essential to make explicit decisions to increase HF/CRM training at all operational levels. Prevailing coherence of views at HSW organisational levels makes it possible to enhance critical synchronisations between organisation levels. The HFs highlighted in this study, should be concretely addressed in HSW organisations to develop safety, performance, and efficiency of operations.

Declarations

The authors report that they have no competing interests to declare. The first author holds the position of consultant in the target field in Finland, but this did not affect the selection of cases, data gathering, or analysis.

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Appendix

Annex 1. Definition of an HSW

A high-speed workboat refers to a professional boat (EUROFINS, 2016) of 5.5 to 24 metres in length, that moves at a speed of more than 20 knots without using the ground effect or exiting the water (IMO, 2000), has a sliding or semi-sliding hull, and is employed for professional or trade purposes; or a vessel intended for non-recreational purposes. It can also be used in an oil spill response, by the fire brigade, or as a police boat (Finlex Data Bank, 2009). The IMO uses the term HSC (high-speed craft) to describe the operational profile of HSW. Warships and troop carriers were included in the scope of this study, although they are not included in the IMO's definition of an HSC vessels (IMO, 2000), as these often operate faster than other traffic, and their speed is occasionally used as a tool to avoid collisions. Active measures that violate water transport regulations are also sometimes required to avoid a collision (Olsson and Jansson, 2006).

Annex 2. Questionnaire response options and operationalisation of HF tool details (17 pcs.)

Option number	*Structured questionnaire response option in the questionnaire*	*Detailed description of the operationalisation of the HF Tool (original detail number in parentheses)*
	Organisation-level factors	
1	Management and leadership in organisation: structure, styles	Added 'in organisation' (30)
2	Organisational/safety culture	
3	Cooperation and communication between different units and hierarchy levels (office, vessel, technology, quality and safety, manning, etc.)	Added 'and communication' (32)
4	Understanding the reality of cockpit work and safety factors as a whole in management	Added 'reality of cockpit work', highlighting understanding 'work-as-done' in the field (33)
5	Decisions concerning resources, personnel, equipment	
6	Change management (personnel changes, systems)	
7	Cooperation with partners (other organisations, educational institutions, research, public authorities, command centres)	Changed examples (in parentheses) (36)
8	Support of operations (safety management system/designated person ashore, standby operator)	Changed examples (in parentheses) (37)
	Work actions, characteristics of work	
9	Content and meaningfulness of work; e.g. related to competencies	Emphasis on the meaningfulness of the work and its demands in relation to competence (13)
10	Amount of work: time pressure, haste and sense of urgency (in one's role)	Added 'in one's role' focusing the answer on the respondent's own work role. Added 'sense of urgency' (14)
11	Work distribution, work organisation, job roles	
12	Functionality and usability of hardware, software and other technology	
13	Working methods and instructions; functionality, clarity and timeliness	
14	Being able to influence one's own work	
15	Feedback on work, professional esteem/appreciation	
16	Opportunities and ability to analyse and develop one's work processes	
17	Ensuring competence (training, exercises, other ways of learning)	

Notes: CRM = crew resource management; SA = situational awareness

Annex 2. Questionnaire response options and operationalisation of HF tool details (17 pcs.) (continued)

Option number	*Structured questionnaire response option in the questionnaire*	*Detailed description of the operationalisation of the HF Tool (original detail number in parentheses)*
	Work actions, characteristics of work	
18	Physical work environment, working conditions, occupational hygiene factors (noise, air conditioning, lighting, temperature, layout)	
	Group-level factors	
19	CRM (teamwork, team leadership, ensuring shared situational awareness, group decision-making, crew members as a resource, etc.)	Generated option that described crew cooperation as a whole (23, 24, 29). including 'team work and leadership'
20	Communication within the group (e.g. correcting misunderstandings, misinterpretations and mishearings)	
21	Crew structure and group dynamics (social relations, atmosphere, mutual support)	Emphasis on 'crew'. Discussed 'cohesion' as part of group dynamics (26)
22	Communication among different partners (vessel traffic system, pilot, tugs, icebreakers, ports, other vessels and units, command centres); model nautical vocabulary, language skills	Removed 'deck/engine', added 'units, command centres' (27)
23	Information flow (shift change)	
	Individual's actions and characteristics	
24	Competence, conceptual mastery of work in one's role	Meaning 'in respondent's role' (1)
25	Management of SA (perception, memory, management of information, decision-making, response/execution)	Emphasised 'management' of SA, added 'management of information' (2)
26	Compliance with instructions, agreed procedures and regulations	Added ' regulations' (3)
27	Understanding entirety of factors affecting cockpit work	Referring to factors affecting cockpit work (4)
28	Preconceptions, assurance and checking; assumptions	
29	Proactive workload management, response to harmfully high and low workloads	Modified to denote momentary mental workload (6)
30	Understanding crew performance and functional limitations (life situation, worries, stress, mood, alertness, fatigue, ability to concentrate on work, age)	Option, covering understanding the limitations of performance and functional capacity (7, 8, 12)
31	Quantity and quality of work experience	
32	Health and work ability of crew members	Added 'crew members' (10)
33	Motivation, attitudes	

Notes: CRM = crew resource management; SA = situational awareness