THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Towards an understanding of the consequences of technology-driven decision support for maritime navigation

Katie Aylward

Department of Mechanics and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

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KATIE AYLWARD
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Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Cover images: The cover photo embodies the transformation of ship navigation through the years. The left photo depicts two seafarers using a sextant to navigate on cargo ship FREDRIKA in Stockholm, 1943. A sextant is an instrument used for celestial navigation to determine latitude and longitude through determining the angle between the horizon and a celestial body such as the Sun, the Moon, or a star. The photo was brought to our attention by Jan Peterson, and permission to use it is granted by the Sjöhistoriska Museet through the Attrbution-ShareAlike (CC BY-SA) license. The middle photo represents a more current time in ship navigation, reflecting several elements covered within the thesis. The photo was taken by Henrik Sandsjö and depicts a woman wearing a virtual reality head set in a ship simulator. The photo on the right represents a future ship bridge generated in virtual reality. The photo was provided by project partners at the Oslo School of Architecture and Design, the photo was generated by Jon Fauske as part of the OpenAR project funded through the Norwegian Research Council.

ABSTRACT

The maritime industry is undergoing a transformation driven by digitalization and connectivity. There is speculation that in the next two decades the maritime industry will witness changes far exceeding those experienced over the past 100 years. While change is inevitable in the maritime domain, technological developments do not guarantee navigational safety, efficiency, or improved seaway traffic management. The International Maritime Organization (IMO) has adopted the Maritime Autonomous Surface Ships (MASS) concept to define autonomy on a scale from Degrees 1 through 4. Investigations into the impact of MASS on various aspects of the maritime sociotechnical system is currently ongoing by academic and industry stakeholders. However, the early adoption of MASS (Degree 1), which is classified as a crewed ship with decision support, remains largely unexplored. Decision support systems are intended to support operator decision-making and improve operator performance. In practice they can cause unintended changes throughout other elements of the maritime sociotechnical system. In the maritime industry, the human is seldom put first in technology design which paradoxically introduces human-automation challenges related to technology acceptance, use, trust, reliance, and risk. The co-existence of humans and automation, as it pertains to navigation and navigational assistance, is explored throughout this thesis.

The aims of this thesis are (1) to understand how decision support will impact navigation and navigational assistance from the operator's perspective and (2) to explore a framework to help reduce the gaps between the design and use of decision support technologies. This thesis advocates for a human-centric approach to automation design and development while exploring the broader impacts upon the maritime sociotechnical system. This work considers three different projects and four individual data collection efforts during 2017-2022. This research took place in Gothenburg, Sweden, and Warsash, UK and includes data from 65 Bridge Officers (navigators) and 16 Vessel Traffic Service (VTS) operators. Two testbeds were used to conduct the research in several full mission bridge simulators, and a virtual reality environment. A mixed methods approach, with a heavier focus on qualitative data, was adopted to understand the research problem. Methodological tools included literature reviews, observations, questionnaires, ship maneuvering data, collective interviews, think-aloud protocol, and consultation with subject matter experts. The data analysis included thematic analysis, subject matter expert consultation, and descriptive statistics.

The results show that operators perceive that decision support will impact their work, but not necessarily as expected. The operators' positive and negative perceptions are discussed within the frameworks of human-automation interaction, decision-making, and systems thinking. The results point towards gaps in work as it is intended to be done and work as it is done in the user's context. A user-driven design framework is proposed which allows for a systematic, flexible, and iterative design process capable of testing new technologies while involving all stakeholders. These results have led to the identification of several research gaps in relation to the overall preparedness of the shipping industry to manage the evolution towards smarter ships. This thesis will discuss these findings and advocate for human-centered automation within the quickly evolving maritime industry.

Keywords:

Human factors, human-automation interaction, maritime navigation, safety, automation, decision support, decision-making, sociotechnical systems, MASS

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APPENDED PUBLICATIONS

Paper I: **Aylward, K**.; Johannesson, A.; Weber, R. *et al.* An evaluation of low-level automation navigation functions upon vessel traffic services work practices. *WMU Journal of Maritime Affairs* 19**,** 313–335 **(2020)**. https://doi.org/10.1007/s13437-020-00206-y

Contribution: Katie Aylward is the main author and was supported by co-authors for subject area expertise in VTS/navigation and review and editing of the paper. The study design was already defined prior to Katie joining the project. Katie led the data collection, analysis, and paper writing.

Paper II: **Aylward, K.;** Weber, R.; Man, Y.; Lundh, M.; MacKinnon, S.N. "Are You Planning to Follow Your Route?" The Effect of Route Exchange on Decision Making, Trust, and Safety. *J. Mar. Sci. Eng.* **2020**, *8*, 280. https://doi.org/10.3390/jmse8040280

Contribution: Katie Aylward is the main author and was supported by co-authors for subject area expertise in navigation and review and editing of the paper. Katie helped with experimental design with co-authors, and led the data analysis, and paper writing.

Paper III: **Aylward, K.;** Weber, R., Lundh, M., Dahlman, J., MacKinnon, S.N. ***The Navigators' View of a Collision Avoidance Decision Support System for Maritime Navigation*.** Accepted for publication in the Journal of Navigation**.**

Contribution: Katie Aylward is the main author and was supported by co-authors for subject area expertise in navigation and review and editing of the paper. Katie developed the experimental design with co-authors, and led the data collection, data analysis, and paper writing.

Paper IV: **Aylward, K**.; Dahlman, J.; Nordby, K.; Lundh, M. Using Operational Scenarios in a Virtual Reality Enhanced Design Process. *Educ. Sci.* **2021**, *11*, 448. https://doi.org/10.3390/educsci11080448

Contribution: Katie Aylward is the main author and was supported by co-authors for subject area expertise in design and the review and editing of the paper. Experimental design was led by co-authors and Katie led the data collection, data analysis, and paper writing efforts.

Paper V: Frydenberg, S.; **Aylward, K**.; Nordby, K.; Eikenes, J.O.H. Development of an Augmented Reality Concept for Icebreaker Assistance and Convoy Operations. *J. Mar. Sci. Eng.* **2021**, *9*, 996. https://doi.org/10.3390/jmse9090996

Contribution: Katie was not involved in the technical development of the Augmented Reality application which is therefore not included within this thesis. Katie supported with the identification and development of the convoy scenario in collaboration with co-authors and end-users. Katie led the user testing data collection, data analysis and supported paper development and writing.

1. Weber, R., **Aylward, K**., MacKinnon, S.N., Lundh, M., Hägg, M. (2022). AIM Report: FP5_2020. Operationalizing COLREGs in SMART ship navigation: Understanding the limitations of algorithm-based decision support systems in traffic situations.

2. **Aylward, K**., Weber, R., MacKinnon, S.M., Lundh, M (2021). Operationalizing COLREGs in smart ship navigation: an algorithm-based decision support system study. Ergoship 2021, Busan, Republic of Korea, Western Norway University of Applied Sciences, Korea Institute of Maritime, and Fisheries Technology

3. **Aylward, K**. (2020). *Automated Functions: Their Potential for Impact Upon Maritime Sociotechnical Systems.* Licentiate Thesis at Chalmers University of Technology. Report No. 2020:01 https://research.chalmers.se/publication/515195/file/515195_Fulltext.pdf

4. **Aylward, K**., MacKinnon, S.N., Lundh, M. (2020). Preventing Unruly Technologies in Maritime Navigation: A Systems Approach. In: Stanton, N. (eds) Advances in Human Aspects of Transportation. AHFE 2020. Advances in Intelligent Systems and Computing, vol 1212. Springer, Cham. https://doi.org/10.1007/978-3-030-50943-9_53

5. Peckan, C., MacKinnon, S, N., **Aylward, K.**, Weber, R. (2019) STM Report: STM_ID3.3.2 EMSN_Test Person and Data Collection Management.

6. **Aylward, K**., Weber, R., Lundh, M., MacKinnon, S.N. (2018). *The Implementation of e-Navigation Services: Are we Ready?* Paper presented at the International Conference on Human Factors; The Royal Institute of Naval Architects (RINA), London, UK: The Royal Institute of Naval Architects; 2018.

7. Lundh, M., **Aylward, K**., Man, Y., MacKinnon, S.N. (2018). *The Human Factor in the Digital Age*. International Conference on Human Factors; The Royal Institute of Naval Architects (RINA), London, UK: The Royal Institute of Naval Architects; 2018.

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9. Lundh, M., **Aylward K**., MacKinnon, S.N., Man, Y. (2017). *On the Adaptation of the Guidelines for engine-room layout, design, and arrangement. MSC/Circ.834*. Report for Intertanko. Gothenburg, Sweden. Chalmers University of Technology

LIST OF ABBREVIATIONS

AIM	Advanced Intelligent Maneuvering
AIS	Automatic Identification System
AR	Augmented Reality
ARPA	Automatic Radar Plotting Aid
COLREGs	Convention on the International Regulations for Preventing Collisions at Sea
CPA	Closest Point of Approach
CSE	Cognitive Systems Engineering
DOA	Degrees of Automation
ECDIS	Electronic Chart Display and Information System
EMSN	European Maritime Simulator Network
EU	European Union
FMBS	Full Mission Bridge Simulator
GMDSS	Global Maritime Distress and Safety System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAI	Human Automation Interactions
HCD	Human-centered Design
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IMO	International Maritime Organization
LOA	Levels of Automation
MASS	Maritime Autonomous Surface Ships
OOTL	Out-of-the-loop
SA	Situation Awareness
SAE	Society of Automotive Engineers
SEDNA	Safe maritime operations under extreme conditions: the Arctic case
S2SREX	Ship-to-Ship Route Exchange
SME	Subject Matter Expert
SOLAS	International Convention for Safety of Life at Sea
STM	Sea Traffic Management
STS	Sociotechnical Systems
TCPA	Time to Closest Point of Approach
UCD	User-centered design
UI	User Interface
VHF	Very High Frequency
VR	Virtual Reality
VRROS	Virtual Reality Reconstructed Operational Scenarios
VTS	Vessel Traffic Services
VTSO	Vessel Traffic Services Operator
WAD	Work as done
WAI	Work as imagined

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1 INTRODUCTION

The fourth *Industrial Revolution* (I4.0), characterized by interconnectivity, smart automation, and interoperability among systems, people and the environment, is arguably the most complex and disruptive compared to past industrial revolutions (Aiello et al., 2020; Schwab, 2016). Maritime transportation represents approximately 80-90% of international world trade and employs approximately 1.9 million seafarers globally (ICS, 2020; Sepehri et al., 2021; UNCTAD, 2021). Due to the relevance of the shipping industry within the world-wide economic landscape, the technological evolutions observed in the maritime ecosystem can be described as Shipping 4.0, an all-encompassing concept, referring to the transformation of the shipping industry as part of the disruption attributed to I4.0 (Aiello et al., 2020). This transformation is fuelled by high hopes of economic, environmental and safety gains. However, the exponential pace of technology development has resulted in an ever-growing number of challenges which have resulted in a slower than expected transformation. These challenges are confounded by the fact that shipping exists within a complex sociotechnical system. Changing any aspect of a subsystem (*e.g.*, technology on a ship's bridge), will alter operator work and could cause changes in the entire system, transforming judgements, roles, relationships, and weightings for different goals (Woods & Dekker, 2000). The field of human factors and ergonomics (HF/E) is focused on the investigation of the cognitive, physical, and organizational aspects of work and is formally defined as *"the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and other methods to design in order to optimize human well-being and overall system performance*" (IEA, 2000). This thesis resides within the domain of human factors and is studied within the context of shipping as part of its transformative journey towards Shipping 4.0.

The maritime industry has a long history of considering *human factors* or the human operator as an afterthought in the design of physical spaces, and technology development (Grech et al., 2008; Lützhöft, 2004). A lack of human-centred design (HCD) in the maritime domain has introduced challenges related to human performance, workload, technology use and acceptance, and overall safety. H*uman factors*, or the incompatibility between the human operator and their environment (i.e., physical design and layout of ship's workspaces), organizational factors, and/or technology are frequently listed as the root causes of maritime accident investigations (Acejo, 2018; Grech et al., 2008; MAIB, 2021). In 2015, the pure car carrier City of Rotterdam collided with a ro-ro freight ferry Primula Seaways caused by a "relative motion illusion" because of the "innovative" bridge design which did not adhere to internationally accepted physical ergonomic principles for bridge design (MAIB, 2017). In 2017, the Nova Cura grounded in Greek waters because of a mismatch between a commonly used navigation technology and the user's skills and ability to understand it (DSB, 2017). In 2009, Chemical tanker Maria M grounded just off the coast of Gothenburg, Sweden and the causes were attributed to cultural and age differences, lack of familiarization of equipment, and a lack of intervention from the vessel traffic services (VTS) (Transportstyrelsen, 2010). These accidents highlight some of the possible incompatibilities between human operators and the systems in which they work. The human operator is a central component to successful maritime operations and a thorough understanding of their role and how they work within the system is critical to achieve safety. Many accidents could be prevented if the shipping industry adopted a more proactive approach towards safety, instead of a reactive one (Chauvin et al., 2013).

The realisation of Shipping 4.0 has revealed many outstanding issues related to human-automation interactions (HAI). HAI issues for safety critical domains have been recognised for decades (Endsley, 1995; Endsley & Kiris, 1995; Parasuraman et al., 2000) and highlighted specifically for ship navigation around 20 years ago (Lee & Sanquist, 2000; Lützhöft, 2004). While reviewing some of these classic works, it is striking to realize that while the complexity of automation has increased, the transparency of automation has decreased, and the challenges related to HAI remain the same or are even greater. While the proliferation of technology to support maritime systems is now ubiquitous, the integration and use of such technology is still in early developmental stages. The International Maritime Organization (IMO) has recently completed a regulatory scoping exercise of Maritime Autonomous Surface Ships (MASS) which is intended to monitor and maintain the pace of rapidly evolving technological developments (IMO, 2021). A major component of the MASS framework is to gain a better understanding of the role of the human operator and how it might change based on the implementation of automation. Considering HAI and adopting human-centred design practices from the beginning of MASS is critical to improve maritime safety and efficiency. This thesis does not attempt to discuss or solve all the challenges associated with the transformation towards Shipping 4.0. Instead, this work has focused on the perspective of the human operators within the maritime sociotechnical system with respect to the use of various decision support technologies for navigation and navigational assistance.

1.1 RESEARCH GAP AND PROBLEM FORMULATION

Previous research has studied the work environment and on-board practices, leading to improved theoretical and empirical developments in all aspects of maritime human factors (Costa, 2018; da Conceição et al., 2017; Hutchins, 1995; Lundh, 2010; Lützhöft & Dekker, 2002; Mallam & Lundh, 2016; Man, 2019; Praetorius, 2014b). These works have contributed towards a better understanding of work as it is done, while advocating for HCD and cautious implementation of digitalization and automation. However, the recent surge of digitalization and automation is transforming the industry faster than ever before and the exploitation of the emerging technologies have the opportunity to change shipping as we know it (Brooks & Faust, 2018; DNV GL, 2014; UNCTAD, 2019). To obtain a better understanding of Shipping 4.0, maritime stakeholders have predicted the biggest challenges facing the shipping industry, highlighting the most important aspects to consider for future research. These considerations include the current and future regulatory regime, seafarer education and training, the distribution of workload and work tasks, and most importantly how to cooperate with the next generation of smart ships, fleets, and ports (ABS, 2018; MacKinnon & Lundh, 2019; Mallam, Nazir, & Sharma, 2019; Wahlström et al., 2015; WMU, 2019). Most stakeholders consider the existence of fully autonomous, unmanned ships and a shift towards remote or shore-based operation centers a crucial part of future of maritime operations. This area of study has received significant attention and the development of artificial intelligence (AI) solutions or other algorithm-based collision avoidance systems are well underway (Veitch & Andreas Alsos, 2022; Woerner, 2016; Woerner et al., 2016; Woerner et al., 2019; Wu et al., 2021; J. Zhang et al., 2015). However, the research attention seems to be too focused into the future and largely ignores many of the practical challenges the industry needs to overcome before considering advanced AI solutions.

The knowledge gap exists in the present to near future of the shipping industry as lower levels of automation (LOA), in the form of decision support, are being developed. Despite decades of work by human factors researchers advocating to adopt HCD and user-driven solutions, the uptake and application of these findings is slow. At lower LOA, the human operator is a central part of the sociotechnical system, and an understanding of the user's work context within the operational environment and any constraints is necessary. The near future of the shipping industry will consist of a variety of sociotechnical systems involving human operators and automation, and traditional ships/ports and smart ships/ports. These combinations of human operators and technology will cause changes within all aspects of the maritime sociotechnical system, including, but not limited to, work practices, organizational environment, culture on board, training/education, safety, individual and team tasks and communication and interaction between the subsystems. There is a need for a framework that will allow for the uptake of human factors research that is accessible to maritime stakeholders which can provide tangible solutions to both the design and continuous development of technology that will support human operators.

1.2 AIM AND RESEARCH QUESTIONS

This thesis has two aims (1) to investigate how decision support will impact navigation and navigational assistance according to operators and (2) to explore how to reduce the gaps between the design and use of decision support technologies. This thesis advocates for the practitioner perspective in the design, development and implementation of automation while exploring the broader impacts upon the maritime sociotechnical system. To achieve the aim of this thesis, the following research questions are considered:

RQ 1) How do operators perceive decision support technologies for navigation?

RQ 2) (a): What are the gaps in the design process and use of decision support technologies?
(b): How to identify and close the gaps between the design and use of decision support technologies?

1.3 LIMITATIONS AND DELIMITATIONS

Delimitations are characteristics that are defined by the researcher to limit the scope and define the boundaries of the study (Simon, 2011). The delimitations of this work include:

- The field of human-automation interaction is multifaceted and can be studied from a variety of different perspectives and research frameworks. This thesis examines HAI from the operators perceived impact of decision support on operator performance and safety of navigation. The technologies assessed within this thesis are limited to those developed and tested within the three projects described in Chapter 4. There are other types of third-party decision support technologies that could potentially render different results and conclusions.
- Most of the participants, both ship and shore operators, were from European countries, predominantly Sweden.
- The discussions surrounding Vessel Traffic Services are primarily based on the Swedish VTS legislation and procedures. It is acknowledged that there are national differences in levels of authority and service provisions that could also influence the outcomes of safety of navigation.
- The context of this work is shipping which differs significantly from other transportation research domains. Although certain elements of the results can be applied to other transportation sectors, the research approach has been developed specifically for maritime research. These differences should be considered when interpreting the results.

Limitations are elements within a study that are outside of the researchers' control (Simon, 2011). The data within this thesis were collected exclusively using high-fidelity simulators. Access to ship bridges for research studies is difficult because of cost, restricted access, and safety (Lurås, 2016b). High-fidelity simulation is as close as a researcher can get to a naturalistic setting for maritime research. Although high-fidelity simulation is recognized as a valid data collection tool within the maritime industry, it is important to consider the potential impact of simulation on participant behaviour and the generalizability of the results (Dahlstrom et al., 2009). Exploratory behaviour is common in experimental settings in which people are tested in "microworlds", which are "simplified versions of a real system where the essential elements are retained and the complexities eliminated to make experimental control possible", (i.e., full-mission simulators) (Inagaki et al., 1999; Lee & Moray, 1994). In this case people explore the possibilities of automation and knowingly compromise system performance to learn how it works or behaves, which could influence how it is used (Inagaki et al., 1999; Lee & Moray, 1994; Lee & See, 2004). This is one of the limitations of simulation exercises and must be considered when interpreting the results of this work. However, given the novelty of the functions tested, simulation and virtual reality were the safest, most natural, and effective way to apply an empirical approach to answer the research questions.

1.4 STAKEHOLDERS

The academic society is a stakeholder for this work, as this thesis contributes towards new knowledge development in human factors. Knowledge contributions have been made towards the use of decision support technology in a safety critical domain, including a proof-of-concept framework for the utilization of augmented reality (AR) and virtual reality (VR) in the development of new technology. This knowledge can be applied to any transportation or safety critical domain.

The maritime industry is complex and consists of distributed, yet interconnected stakeholders. Key maritime stakeholders include ship owners, ship builders, international and national regulatory bodies, classification societies, seafarer unions, ship and shore-based operators, port authorities, technology developers, insurance and legal companies, designers, researchers, and maritime academies. Increasing digitalization and automation will have an impact on these stakeholders to a varying degree. There is hope that these wider audiences can be reached by this work to contribute towards a more general discussion about safety at sea. Working at sea is still considered a risky profession, and the risks will continue to grow as new technology disrupts the way seafarers perform their work. Hopefully, this thesis can provide a heightened awareness of the more hidden elements of the maritime transport chain and showcase the importance of seafarers.

While findings and discussion in this thesis should provide relevant information to all these stakeholder groups, three primary stakeholder groups and one secondary group are identified based on the appended papers. The first stakeholder group includes the operators, the end-users in the technology utilization. The thesis papers studied the practitioners, and the results discuss their experiences and perspectives in relation to new technology implementation. The second stakeholder group includes researchers within any transportation sector facing the challenges and uncertainties associated with human-automation interactions. The final group is technology developers. Human-automation interaction and user-centered design are central concepts in this thesis, which could potentially provide useful insights for technology development, especially in the maritime domain.

1.5 OUTLINE OF THE THESIS

This thesis consists of seven chapters and five appended articles. This chapter is the introduction which has provided a general overview of the research problem, identified the research questions, discussed the limitations, and identified the intended stakeholders. Chapter 2 will provide the reader context of the shipping domain, with supporting literature from important works in the field. Chapter 3 is the frame of reference which explains the theoretical frameworks for which this thesis has drawn from. Chapter 4 is the research approach which provides an overview of the entire research process, including the philosophical worldview, information about the three projects, and a description of the methods adopted throughout the work. Chapter 5 is a summary of the results from the appended five articles. Chapter 6 is the discussion chapter which answers the RQ's, then explores theoretical and practical aspects of maritime human factors. Chapter 7 is the conclusion which brings forward the most important elements of this thesis work.

2 THE SHIPPING CONTEXT

This chapter will describe the maritime domain which is the context for this research. This work has had a primary focus on maritime navigation, and a secondary focus on the vessel traffic services. This chapter will provide (1) a general description of merchant shipping (2) the role of the human element, (3) existing research on e-Navigation and MASS (4) detailed descriptions of navigation and VTS and (5) the regulatory framework for both maritime navigation and VTS.

2.1 MERCHANT SHIPPING

The work included within this thesis is studied in the context of merchant shipping. Merchant shipping is characterized as watercraft that transports passengers or cargo (Costa, 2018; Lützhöft, 2004), thereby excluding naval ships/military operations, and pleasure crafts. More specifically, this work considers merchant ships within The International Convention for the Safety of Life a Sea (SOLAS). Examples of types of ships included within the classification for this thesis are oil tankers, bulk carriers, general cargo, passenger ferries, cruise liners, and container ships. Today, the merchant shipping industry is responsible for 80-90% of all maritime trade and the compound annual growth in maritime trade is expected to grow at an annual rate of +2.4% between 2022 and 2026 (UNCTAD, 2021). There are approximately 1.9 million seafarers employed globally, operating on over 74,000 vessels (UNCTAD, 2021).

Given the shipping industry's critical role in transporting goods, any disruptions can have major consequences. International maritime world trade has been put in the spotlight twice over the last two years. The COVID-19 pandemic triggered what's been called a "seafarer crisis" causing thousands of seafarers to be stranded on ships because of COVID-19 restrictions. Inexperienced, or overworked crew members and stressful working conditions likely resulted in higher risk of safe navigation during this period (UNCTAD, 2021). Then in March 2021, the fragility of maritime trade was showcased when one of the world's largest container ships, Ever Given grounded in the Suez Canal blocking the entire passage causing a severe bottleneck (UNCTAD, 2021). The Ever Given grounding exposed how the consequences of the safety/economic trade-off and the result of poor navigation practices can have severe impacts on world trade. These events highlighted the vulnerability but also the complexity of the shipping industry with a particular emphasis on the human element and ship safety.

2.2 THE HUMAN ELEMENT AND MARITIME SAFETY

Research and practice to improve maritime safety has increased over the last decades, yet seafaring is still considered a challenging and dangerous occupation (Acejo, 2018; Brooks & Faust, 2018). The maritime industry, similar to other safety critical industries, has typically defined safety as the absence of accidents or incidents, an approach also known as Safety-I (Hollnagel & Leonhardt, 2014). Unfortunately, a Safety – I lens has led an industry to cite "human factors", "human error" or the "human element" as the root cause in anywhere from 70-96% of maritime accidents (Han & Ding, 2013; Hetherington et al., 2006; Rothblum, 2000; Sanquist, 1992). However, these figures are generated based on rigid, non-standardised incident reporting systems with predefined categories, which generally fail to consider the complexity of the maritime sociotechnical system (Wróbel, 2021). Work today is complex and distributed between human operators and technology, resulting in multi-causal accidents or incidents.

Additionally, there has been little emphasis on what humans do right and how they prevent accidents from happening every day, also known as the Safety-II concept (Hollnagel & Leonhardt, 2014). Therefore, the highly cited percentages of human error as root contributors to accidents should be interpreted with caution.

In response to the high attribution of human error to accidents, an industry-wide “solution” has been to reduce human involvement by increasing automation-based support, (Hetherington et al., 2006) particularly of navigation systems. Although it is assumed that many of these systems have led to improvements in maritime safety, they have also altered typical “navigation tasks” and the role of the human operator (da Conceição et al., 2017; Lützhöft, 2004; Lützhöft & Dekker, 2002). A review of accidents between 2002-2016 identified that collisions, close quarters situations and contact represented 35.8% of accident types and groundings were the second most frequent at 17.0% (Acejo, 2018). The most common reported “immediate cause” for collisions, which refers to factors that directly led to the accident, was an inadequate lookout (24.6%). The most common contributary cause, which refers to factors that created conditions which led to the immediate cause of the accident was the “ineffective or inappropriate use of technology” representing 31% of collisions (Acejo, 2018). Similar values were reported for groundings, with 39% having a contributory cause of “ineffective or inappropriate use of technology”. Although many factors contribute to collisions and groundings, it is impossible to ignore the influential role of technology in maritime accidents. While not the specific context of the thesis (i.e., merchant shipping), the US Navy has switched from touch screen systems back to physical throttles with more traditional control systems after two collisions involving USS John S. McCain and USS Fitzgerald caused major damage and fatalities (DoN, 2017). The introduction of touch screens came from the desire to incorporate new technology without considering the other problems it might create, resulting in a more complex, poorly understood system. Another review of ship accidents (collisions, grounding, and allisions) between 1973 and 2018 attempted to understand if and how the causes of accidents have changed over the last 45 years. The results revealed that the causes remained essentially the same throughout this time period, even with the adoption of navigational aids and more advanced technologies, calling into question their use (Chen et al., 2022).

2.3 NAVIGATION

2.3.1 Regulation of Navigation

The IMO is the regulatory body responsible for the safety of navigation at sea. The IMO has three conventions which cover all aspects of navigational safety: (1) The International Convention for the Safety of Life at Sea, 1974 (SOLAS) (IMO, 1974); (2) The Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREG) (IMO, 1972); and (3) The International Convention on Standards, Training, Certification and Watchkeeping for Seafarers, 1978 (STCW) (IMO, 1978, 2011). In addition to the formal regulations set by the IMO, there are also rules and guidance provided by classification societies (e.g., ABS, Lloyds Register, DNV-GL), Oil Companies International Marine Forum (OCIMF), and INTERTANKO to further enhance safety at sea.

2.3.2 Practice of Navigation

Ship navigation involves planning, managing, and directing a ships voyage which is achieved through good seamanship, professional knowledge and judgement, and the application and use of various technologies (AMSA, 2019). Navigation is a complex activity consisting of distributed teams and knowledge, dynamic high-risk situations, and a heavy reliance on effective communications between team members (Bailey et al., 2006). To mitigate negative incidents in traffic situations, navigators are bound to follow The International Regulations for Preventing Collisions at Sea (COLREGS) which are the 'rules of the road' for ships and other vessels at sea. The first set of statutory rules for preventing collisions at sea came into force in 1846 and consisted of two rules for steam vessels (Cockcroft & Lameijer, 2012). Today, there are 41 rules which set out the conduct for navigators and help determine for example, which ship is the "stand on" and "give-way" and what are the correct actions (IMO, 1972). As defined by IMO Resolution A.893(21) Guidelines for Voyage Planning, there are four elements of a voyage plan (IMO, 2000).

1) Appraising all the relevant information
2) Planning the intended voyage
3) Executing the plan taking account of prevailing conditions
4) Monitoring the vessel's progress against the plan continuously

This thesis has primarily focused on one aspect of navigation, monitoring, which is defined by IMO Resolution A.893(21) as:

> "5.1 The plan should be available at all times on the bridge to allow officers of the navigational watch immediate access and reference to the details of the plan.
> 5.2 The progress of the vessel in accordance with the voyage and passage plan should be closely and continuously monitored. Any changes made to the plan should be made consistent with these Guidelines and clearly marked and recorded."

Monitoring the voyage includes among other things, keeping the schedule, monitoring the weather forecast, attending to any new navigation-warnings, and determining their possible implications, checking for any cargo related items (e.g., checking the lashings), ballast water management, etc. To create a boundary based on the type of decision support assessed throughout this work, monitoring can be divided into two sub-categories, collision avoidance and groundings or allisions (Figure 1). The type of decision support studied has focused on new developments and aids for both collision avoidance and avoiding grounding and allisions.

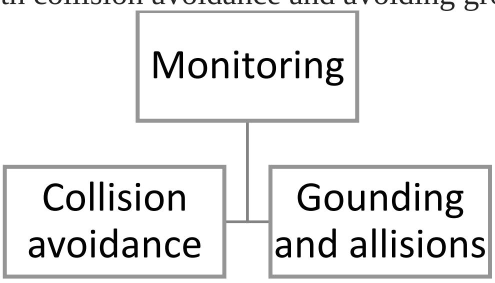

Figure 1 Elements of monitoring relevant for this thesis

The term seamanship is an important concept in maritime navigation which has both formal and informal associations. Formally, seamanship is written in International Regulations, including COLREG Rule 8 (Action to Avoid collision) (a) "*Any action taken to avoid collision shall, if the circumstances of the case admit, be positive, made an ample time and with due regard to the observance good seamanship"(IMO, 1972)*. In practice, it is associated with the ability of seafarers to work safely, and involves a combination of professional knowledge, pride, and common sense (Kongsvik et al., 2020). Even though the term seamanship is adopted throughout international regulations, and is widely used in everyday language, there still remains a lack of agreement surrounding what good seamanship actually means (Kongsvik et al., 2020). The more informal associations of seamanship have been characterized *as informal rules,* defined as deviations from the formal rules given situation-dependent interactions between ships. The use of *informal rules* appears to be the most common among ferries operating in local waters, for example ferries in Dover Strait (Chauvin & Lardjane, 2008; Rowell, 2020). The existence of these two rule systems today can cause misunderstanding, uncertainty, and potentially lead to accidents (Chauvin et al., 2013). The introduction of more information, and automated functions on some ships and not others may further exploit the differences between informal and formal rule adherence.

2.3.3 Arctic Navigation

Papers IV and V have a particular focus on Polar navigation. As glacial ice melts and regions become more accessible for longer periods of the year, there is projected to be increased shipping activity in polar areas (Kennedy et al., 2013). Ship operations in Polar waters introduce additional hazards to an already challenging work environment including extreme environmental conditions, technology limitations, a lack of accurate navigational information, ice-specific knowledge, possible communication "blackouts", and longer waiting times for rescue (Aylward et al., 2021; Rogers et al., 2020). The IMO recognized the specific challenges faced by ships operating in polar waters, and in 2017 the Polar Code consisting of goal-based regulations came into force (IMO, 2014b). The Polar Code is designed to enforce maritime safety and the security of the environment and while this was a step in the right direction there is a lot more work to do to ensure these goals can be achieved. Papers IV and V contribute towards an exploration of the technological solutions which could be adopted to improve the work situation for navigators operating ships in ice-covered waters.

2.4 NAVIGATIONAL AIDS

The Global Navigation Satellite System (GNSS) including Global Positioning System (GPS) are used to establish and update the ship's position, and velocity by automatic means. To support the navigator in ascertaining if a risk of collision exists, ARPA (Automatic Radar Plotting Aid) and AIS (Automatic Identification System) are mainly used. ARPA is a radar with capability to track and obtain information about plotted targets such as (among others) the Closest Point of Approach (CPA) and the Time to CPA (TCPA). AIS is an automatic tracking system in which ships transmit information about a ship's name, position, size, course, speed, and more to other AIS receivers (IMO, 2015). AIS can be depicted on both the radar and the Electronic Chart Display and Information System (ECDIS) and is regarded as a useful source of information to that derived from other navigational systems (including radar) and therefore an important 'tool' in enhancing situation awareness in traffic situations (IMO, 2015). ECDIS is a geographic information system that offers route charting and planning as an alternative to paper nautical charts (MAIB, 2021). Other technologies on a ship's bridge include Global Maritime Distress Safety System (GMDSS) which is an automated emergency signal communication for ships using satellites to prevent unanswered distress calls, and Very High Frequency (VHF) radio which is used to communicate between ships and between ship and shore. These technologies have impacted the practice of navigation and redirected the responsibility of the navigator to assume more cognitive responsibilities including planning and monitoring as opposed to more manual tasks including position fixing on paper charts (Conceição et al., 2017; Grech & Lutzhoft, 2016).

The carriage required technologies today (e.g. AIS, ARPA, ECDIS) are meant to support navigators with access to more information about surrounding targets, geography, bathymetry, etc., however, newer, automated technologies have wider impacts on navigation practices, as they are used by human operators which can change the role and skills of seafarers leading to unexpected outcomes (Chen et al., 2022; Orlikowski & Barley, 2001). The Marine Accident Investigation Branch (MAIB) and the Danish Maritime Accident Investigation Board (DMAIB) studied ECDIS use and its practical applications from the user perspective (work as done) versus the intention of performance standards and ECDIS design (work as imagined). ECDIS is widely regarded as a technology which has improved navigational safety through its ability to provide real-time geo-positioning, supposedly improving operator situational awareness. ECDIS is also intended to decrease the workload associated with updating paper charts (MAIB, 2021). However, the MAIB and DMAIB report identified many problematic areas associated with ECDIS use. Three of the main challenges were identified as:

- *"ECDIS requires significant cognitive resources to use its functions, which has contributed to a minimalist approach by its users.*
- *ECDIS use continues to be framed and audited within the context of paper chart practices with Flag State, PSC, and SIRE inspections often not recognizing new ways of working such as the use of radar information overlay to verify position.*
- *Users are trained to distrust the ECDIS and continuously verify the ship's position by alternative means. However, significant discrepancies are rarely encountered" (MAIB, 2021).*

These findings, in addition to several other human-automation incompatibilities related to, distracting alerts and alarms, "official and unofficial workarounds", and the complexity of the user interface, highlight the importance of thoughtful human-centered design and technology integration (MAIB, 2021). During an informal interview with an Instructor at Chalmers University who recently transitioned from sailing to teaching, he described ECDIS as the technology that revolutionized navigation, yet described the transition towards more automated systems as "incomplete" (Ernstsson, 2022). He described a mismatch between the "old versus new" in relation to both practice and procedure creating a potentially dangerous conflict. His comments directly mirror the results from the ECDIS inquiry and point towards deeper rooted system problems with increasing automation on the bridge.

2.5 DIGITALIZATION AND AUTOMATION IN THE MARITIME INDUSTRY

The shipping industry remains more traditional and lags behind other transportation sectors such as aviation, rail, and automotive in terms of adopting and implementing new technologies, largely because of regulatory restrictions (MacKinnon & Lundh, 2019; Mallam & Lundh, 2013; Mallam, Nazir, & Sharma, 2019; Man, Lundh, et al., 2018; Schager, 2008). However, the recent surge of digitalization and automation is disrupting the industry faster than ever before and the exploitation of the technologies emerging within the maritime industry have the opportunity to influence navigation as it is currently understood and practiced (Brooks & Faust, 2018; DNV GL, 2014; UNCTAD, 2019). According to Kitack Lim, Secretary-General of the IMO, changes within the maritime industry over the next 10 to 20 years will see as much change as we have experienced over the past 100 years (Brooks & Faust, 2018).

2.5.1 e-Navigation

To address technology development for maritime applications, the IMO adopted the e-Navigation strategy implementation plan (2015-2019). e-Navigation is defined as “the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment” (IMO, 2014a). Therefore, the efforts of e-Navigation were primarily focused on digitalisation, or the conversion of analog information to a digital format. The goal of e-Navigation was to improve safety by reducing errors, while also increasing the efficiency of ship and shore operations. One of the key concepts of this implementation plan was that the initiative must be led by user needs (IMO, 2014a). Several European Union projects including MONALISA (Swedish Maritime Authority, 2018), MONALISA 2.0, and the Sea Traffic Management (STM) Project (Sea Traffic Management, 2018) were among the first to address safety concerns and try to understand the practical implementation of e-Navigation. These projects generated digitalised solutions including information exchange between ships and between ships and shore (Aylward, 2020; STM, 2019).

Research dedicated to further understanding the e-Navigation concept found that human-centered design (Costa, 2018; Costa, Jakobsen, et al., 2018; Costa & Lützhöft, 2014; Gernez, 2019) and participatory design (Costa, 2016; Mallam et al., 2017; Man, Lützhöft, et al., 2018), paired with a systems approach using mixed methodologies, are necessary to better assess the impact of e-Navigation concepts (Aylward et al., 2018; Baldauf et al., 2011; Baldauf & Hong, 2016; Burmeister et al., 2014). The author’s Licentiate thesis focused specifically on findings from the STM project. The results indicate that navigators had a positive attitude towards incorporating STM or similar functions into their work practices. They perceived that the functions could improve safety and efficiency, primarily through “freeing up time” to plan, respond, or tend to other tasks (Aylward, 2020). There was an obvious value in increasing information exchange between ships and between shore for navigation practices. However, the findings also pointed towards a growing list of operational challenges facing the maritime industry throughout the adoption of new technologies. One of these challenges is the communication system between ships and between ships and shore. VHF radio is the pillar of maritime communications today (Costa, Lundh, et al., 2018b; Praetorius, 2014a), and the utilization of another form of communication or information exchange will have consequences, including some operators being “out-of-the-loop” while agreements are made through another means of communication. The simple addition of more information could complicate the VTS-navigator interaction and the general communication structure of navigational assistance.

Operational challenges also included the human-automation interaction and the regulatory environment. Technology that is being developed to support human decision-making should be designed based on the human needs and grounded in the “work as done” instead of “work as imagined” (de Vries, 2017; Hollnagel, 2017a). Concepts related to human-automation interaction will be further described in Chapter 3. The pace of technology development on board and ashore has created both regulatory and liability challenges (Mallam, Nazir, & Sharma, 2019). Carey (2017) outlined the legal and regulatory barriers to autonomous ships and identified some of the major unresolved issues: 1) the lack of human presence on board may render the vessel unseaworthy according to current regulation 2) the ability for companies operating autonomous ships to comply with COLREGs as they are written today 3) the role of the seafarer/shipmaster will no longer exist and the duties will more than likely move to shore (Carey, 2017; MacKinnon & Lundh, 2019). Although the barriers described by Carey are related to autonomous ship(s) operations, the results from the recent work indicate that those barriers are also relevant for lower-intermediate levels of automation (Aylward, 2020; Mallam, Nazir, & Sharma, 2019).

2.5.2 Maritime Autonomous Surface Ships (MASS)

In an evolution of the e-Navigation concept, and a step further towards automation, the IMO undertook the Maritime Autonomous Surface Ship (MASS) scoping exercise from 2017 to May 2021. The purpose was to investigate the safety, security, and environmental impacts of autonomous ships and to review existing and further evolve pertinent IMO regulations for MASS. The IMO working group had agreed upon four degrees of autonomy which are currently the industry standard in terms of referring to levels of automation (IMO, 2018)

- Degree one: Ship with automated processes and decision support: Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.
- Degree two: Remotely controlled ship with seafarers on board: The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.
- Degree three: Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.
- Degree four: Fully autonomous ship: The operating system of the ship can make decisions and determine actions by itself.

Today, most research initiatives prioritize projects which hypothesize a future with remote operations (MASS Degree 2/3) similar to the MUNIN concept (Man et al., 2015), or full autonomy (MASS Degree 4), leading to substantial research gains towards the development of collision avoidance algorithms (Perera & Batalden, 2019; Ramos et al., 2020; Ramos et al., 2019; Ramos et al., 2018; Woerner, 2016; Woerner et al., 2016; Woerner et al., 2019; R. Zhang & Furusho, 2016). These works have attempted to quantitatively evaluate and implement the subjective nature of the COLREGs (IMO, 1972) through various approaches including optimization methods, reinforcement learning, fuzzy-logic, neural networks, and Bayesian networks (Porres et al., 2021; Woerner et al., 2019). As machine learning and more advanced neural networks are developed, the potential for collision avoidance systems should be further advanced. However, while human operators remain in control of the ship there are many challenging research and practical implementation problems which remain unresolved. Even in human-centered research, there is an underlying assumption these wicked problems, including incorporating seafarer experience, and seamanship into artificial intelligence, can be resolved (Porathe, 2021; Ramos et al., 2020; Ramos et al., 2019). While it is necessary to investigate the future of MASS Degrees 2-4, the only way to safely achieve this is through a systematic sociotechnical approach. Caution must be exercised surrounding assumptions of future maritime systems to ensure that the important roles of the human operator are prioritized and remain an integral part of the system. MASS Degree 1 which includes decision support systems for navigation is the next systematic step towards smarter ships. This thesis aligns with MASS Degree one, Degree’s two, three and four are outside the scope of this work (Figure 2).

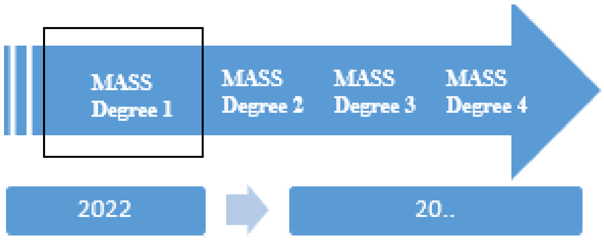

Figure 2 Timeline showing this research within the MASS framework

While work to develop solutions for MASS Degrees 2-4 is well underway, there are fewer research efforts studying decision support from the operator's perspective, as described in MASS Degree 1. Few collision avoidance decision support systems have been developed and tested on end-users over the last decade. Two examples are NAVDEC or navigation decision supporting system, first of its type on the market originally proposed in 2012, and Multi-ARPA (MARPA) (Ożoga & Montewka, 2018; Pietrzykowski & Wołejsza, 2016). NAVDEC plans maneuvers for the navigator that comply with COLREGs and is based on predefined distances and times (to closest approach to ship traffic) while MARPA provides the navigator information on safe headings and operates based on an algorithm designating direct hazards for the Own Ship (OS) for the set of maneuvers in a traffic situation. Both studies highlighted the potential of decision support systems for navigation while underlining the challenges of developing accurate algorithms given the challenging operational environment of ships (Ożoga & Montewka, 2018). These research initiatives are few and far between, demonstrating a clear gap in research related to decision support for navigation activities and the potential influences it may have on work as it is done. Decision support systems should improve the safety of navigation; however, the reality is that any additional technology added onto the bridge can have unwanted or surprising consequences (Bainbridge, 1983).

There are vast possibilities for new technologies, especially artificial intelligence (AI), big data and robotics. However, it is increasingly difficult to anticipate the potential impact these technologies will have on the maritime sociotechnical system (Woods & Dekker, 2000). Furthermore, humans evolve more slowly than the technology they use making it critical to understand the compatibility with the other elements in the sociotechnical system. The role of education and training are critical elements to consider throughout this transition period towards smarter ships. The role of the seafarer is expected to change through the introduction of more automated systems, and many anticipate that most seafaring duties will be moved shore-side (Porathe et al., 2020). There is a need to align the regulations with the needs of seafarers through continuous education to ensure they are properly equipped to handle the inevitable changes of Shipping 4.0 (Chan et al., 2022; Ghosh, 2017). The implementation of technology must be purposeful and intentional, otherwise, as we have learned from other industries, accidents can and will happen as a result (Lee, 2008; Lee & Moray, 1992, 1994; Lee & See, 2004; Lützhöft, 2004).

2.6 VESSEL TRAFFIC SERVICES (VTS)

2.6.1 The Regulation of VTS

The IMO Guidelines for Vessel Traffic Services have been recently revised from the previous resolution A.857(20) 1997 because of the many organizational, operational and technological developments globally that have changed the maritime domain (IMO, 2022). In terms of governance, IMO Resolution A.1158(32) provides guidelines and criteria for VTS operations which are associated with SOLAS Regulation V/12; however, there remain national differences in how VTSs are organized (A. Brödje et al., 2013; IALA, 2021; IMO, 1974). These national differences include varying levels of authority and service provisions. In an attempt to standardize these differences, the IALA VTS Committee provides the most current and accurate information related to VTS operations, technologies, and VTS training (IALA, 2021).

2.6.2 The Role of Vessel Traffic Services (VTS) in Navigational Assistance

As defined by the newly adopted IMO Resolution A.1158(32), VTS means “services implemented by a government with the capability to interact with vessel traffic and respond to developing situations within a VTS area to improve safety and efficiency of navigation, contribute to the safety of life at sea and support the protection of the environment” (IMO, 2022). The new IMO Resolution is intended to be more concise, easier to interpret, and internationally adaptable. The purpose of VTS is to mitigate the development of unsafe situations through; providing timely and relevant information on factors that may influence ship movements and assist on-board decision-making, monitoring and managing ship traffic to ensure the safety and efficiency of ship movements, and respond to developing unsafe situations (IMO, 2022).

Trained VTS Operators (VTSO) monitor the traffic in real time and obtain information from various sources. Included among these sources are VHF radio communications, radar and AIS, weather sensors and reports, navigational warnings and instructions from Maritime Authorities and Port Authorities (IALA, 2021). A VTSO uses this information, in addition to their experience and knowledge, to generate an overview of the VTS area and traffic image. Like navigation, which has both formal and informal rules (Chauvin & Lardjane, 2008), local VTS areas have their own accepted “norms” based on familiarity with ship traffic and other non-technical communication factors that will allow VTSOs to achieve success (Costa, Lundh, et al., 2018b). The VTSO communicates with ships via VHF radio to provide information or assistance to a ship in the area, as deemed necessary, for example, aiding in transfer through a narrow passage. The time between when the VTSO observes a potentially dangerous situation to when they establish contact with the vessel in danger is usually relatively short, often a few minutes or less (Praetorius, 2014a). The VTS is an integral part of the maritime traffic system and must be considered as part of the sociotechnical system.

3 THEORETICAL FRAMEWORKS

This chapter will describe the concepts which create the theoretical framework for this thesis. First, a description of the sociotechnical system and its boundaries is provided, highlighting the most important system elements relevant to this research context. Next, the *work as done (WAD) versus work as imagined (WAI)* framework (Hollnagel, 2012, 2017b) is described with a discussion surrounding existing gaps, application, and importance in the maritime industry. Finally, the framework for the level of automation applicable to this thesis is described, accompanied with human-automation interaction concepts and their impacts upon decision making.

3.1 SYSTEMS PERSPECTIVE

A system consists of interdependent parts (elements or components) which interact with each other to form an integrated whole, in which the whole is greater than the sum of its parts (Dul et al., 2012; Skyttner, 2005; Von Bertalanffy, 1968). General Systems Theory (GST) emerged as the opposition to a reductionist view. A reductionist view breaks down complex things into simpler, or individual components, also known as an analytic approach (Skyttner, 2005). A reductionist approach or studying singular elements within a system is what led the maritime industry to have such fragmented understanding of the human's role in the ship as a system. In 1967, Walraven identified this issue in the maritime domain,

> *"Design must be seen as an integrated problem, and not as a number of independent part problems. It is moreover extremely useful to have discussion between builder, user, and designer"* (Walraven, 1967).

Although the benefits of an integrated approach were identified over 50 years ago, a reductionist approach is still widely applied to research problems in the maritime domain. There remain few examples in which the builder, user, and designer truly work together. A systems or holistic approach studies the entire system and the interactions between the system components (Vicente, 2013). GST is criticized for being too vague and lacking accepted definitions; however, it allows the researcher to gain a broader perspective of the complex elements within a system to include all relevant factors (Von Bertalanffy, 1968). Systems are abstract, and in order to evaluate a system, the system´s environment must be defined by the researcher, called a system boundary (Skyttner, 2005). The system boundaries applicable to this thesis are described below.

Sociotechnical systems (STS) is a branch of GST which can be defined as "integrating of the social requirements of people doing the work with the technical requirements needed to keep the work systems viable with regard to their environment" (Fox, 1995). STS are goal-driven and should be described in terms of their subsystems: technical subsystem, personnel subsystem, work design subsystem/procedures, and the environment (Davis et al., 2014). Koester (2007) developed "The SEPTIGON Model" (Figure 3) specifically for the maritime sociotechnical system (Grech et al., 2008; Koester, 2007). This model includes all the elements of a typical sociotechnical system including: Society and culture, the Physical Environment, Practice, Technology, Individual, Group and Organizational Environment Network (Grech et al., 2008; Koester, 2007). The aim of this model was to advocate for a more holistic approach to study the interaction and relationships between the individual elements or nodes. The individual papers within this thesis generally examined micro-level (individual-technology) systems, however, as the work progressed, the focus evolved to a meso-level (individuals as part of technical processes or organizations) to explore the holistic impact of technology on work practices, procedures and shipping in general (Dul et al., 2012; Rasmussen, 2000).

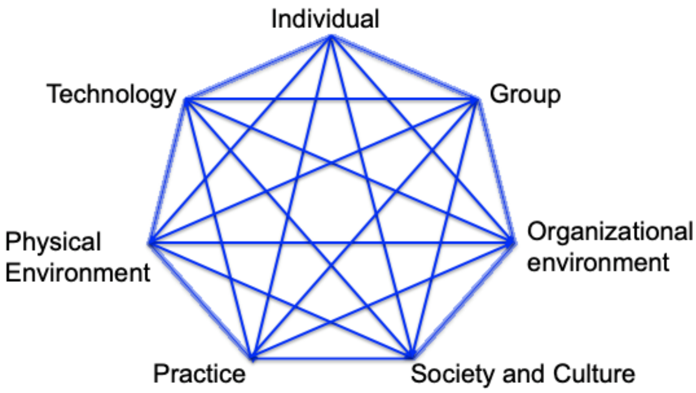

Figure 3 The SEPTIGON sociotechnical system model. Figure created by (Koester, 2007)

Figure 3 shows the most relevant system interactions in relation to this thesis. The most obvious interactions are those between the *technology (automation)*, *individual*, *organizational environment network, and practice* nodes. The nodes that were least explored in this thesis work include *group*, *society and culture*, and *physical environment*. The individual studies did not explore the interaction between bridge team members, or other group/team activities throughout the data collections. Paper I explored interactions between ship and shore, however, the results contribute more towards the other nodes in the sociotechnical system. The physical environment was also not prioritized as articles I-III were conducted in a simulator, and articles IV and V were conducted in VR. Society and culture were considered from a broader perspective; however, the results do not contribute explicitly towards this node.

Maritime human factors researchers have been advocating for a more systemic approach towards new technology integration (Costa, 2018; da Conceição et al., 2017; de Vries, 2017; Lützhöft, 2004; Man, 2019; Praetorius, 2014b). In maritime operations, ship and shore-based operators work together, amid different tasks and work structures to achieve common safety and regulatory goals (Costa, Lundh, et al., 2018a). Introducing a change in the level or type of automation, or the number of actors within a subsystem (i.e., on a ship's bridge) will cause changes in the entire system. transforming judgements, roles, relationships, and weightings of different goals (Woods & Dekker, 2000). It is the factors, relationships, and processes that emerge in the intersection between the various components (people, technology, and work) that is the interesting unit of analysis (Woods & Hollnagel, 2006).

Sociotechnical system models are increasingly being applied within the field of human factors to describe work (de Vries, 2017; Praetorius et al., 2015; Relling et al., 2019), inform better design and improve safety (Andersson et al., 2011; de Vries & Bligård, 2019). Examples of STS models are Activity Theory, Cybernetics, Joint Cognitive Systems, Cognitive Systems Engineering (CSE), and Resilience Engineering. The benefits of these models are that they provide a platform to discuss the existing challenges of a particular work practice(s) with various stakeholders. Results from studies adopting STS models were used as part of the literature search and development of the theoretical framework for this thesis yet were not applied throughout the individual studies within this work. It can be argued that these sociotechnical models, although useful for visualization, lack practical use and application (also a common criticism in the field of HF/E) (Nuutinen, Savioja et al. 2007, de Vries and Bligård 2019). There is a need to better understand how to study, define, and evaluate STS.

3.2 WORK AS DONE (WAD) VERSUS WORK AS IMAGINED (WAI)

Work is messy, variable, and complex, yet systems achieve safety because people within systems are flexible, adaptable, and resilient (Hollnagel, 2012). WAI is the idealized view of work and is based on procedures and prescriptive practices that are written by management, designers, and authorities; it is the belief of what *should* happen at work (Hollnagel, 2012). WAD is what actually happens including workarounds of prescribed procedures in order to cope with the complexity of the work environment (Hollnagel, 2012). In complex systems there is usually a gap between WAD and WAI which translates to a gap between the sharp-end (operators or end-users) and the blunt end (management or authorities) (Hollnagel & Leonhardt, 2014). To close the gap between WAD and WAI, there is a need to change the approach towards safety. Human operators should not represent the threat within the system, instead their behaviour and work should be better understood, which will improve system functioning. Although this alternative approach to safety is becoming more prevalent in the maritime industry (Praetorius et al., 2015; Turan et al., 2016), it is not widely applied and the industry remains reactive, and predominantly technology driven.

3.2.1 Closing the Gap Between WAD and WAI: Design

The work to close the gap between WAD and WAI is challenging because maritime navigation and navigational assistance exist within a safety-critical sociotechnical system, defined as a system that with any failure could result in a loss of life, significant property damage, or damage to the environment (Friedman, 2002; Knight, 2002; Lurås et al., 2015; Schønheyder & Nordby, 2018). Human factor research encourages participatory and inclusive approaches to design, but there has been an oversight to fully support and integrate design practitioners in its processes. Furthermore, reports on many HF methods and tools tend to be published for academic and scientific audiences only, while the intended users are practitioners, service providers, or mariners (in this case). This situation has led to very little uptake regarding research results and applications for both new techniques and user-centred solutions (Shorrock & Williams, 2016). The HF and design domains remain slightly disjointed, leading to a research-practice gap in the maritime industry. This has contributed to the widening of the WAD/WAI gap and left the maritime industry lagging behind other transportation domains (Mallam, Nazir, & Renganayagalu, 2019).

A central concept that must be achieved to close the WAD/WAI gap is user-centred design (UCD) and human-centred design (HCD). Although many practitioners use these concepts interchangeably, it is important differentiate between them. User-centred design is a sub-theme of HCD and is focused on a deep analysis of the target audience/ end-users. HCD, includes UCD but has a broader focus and is defined as a systems design approach which aims to make interactive systems more useable through the application of human factors/ergonomics and usability knowledge and techniques (ISO, 2019). This thesis advocates that the more broad, all-encompassing HCD framework is necessary to close the WAD/WAI gap. Despite decades of research advocating for HCD for maritime applications, the problems remain the same (Gernez, 2019; Grech & Lutzhoft, 2016; Lützhöft, 2004; Mallam et al., 2017). Automated systems continue to be developed that “assist” with navigational tasks, yet because a systems perspective is not applied, inadvertently, more complicated systems are developed (Aylward, 2020;

Aylward et al., 2020; MAIB, 2021). Designing relevant solutions for maritime applications requires access to the user context while also maintaining awareness of the rapid development of new design concepts (Kristiansen & Nordby, 2013).

To achieve HCD there is a need to go beyond the application of a singular method, framework, or tool. Instead, a collaborative, interdisciplinary, and more systemic or holistic approach to safety and design is needed. Collaborative design is the process by which actors from different disciplines disseminate knowledge about the design process to achieve a shared understanding and use this collective understanding to create new products or designs (Kleinsmann et al., 2007). Systemic design is the integration of systems thinking and human-centred design to assist designers with complex design projects (e.g., a ship's bridge) (Lurås, 2016b). The adoption of these more collaborative, systemic, user-centred approaches in the maritime industry requires early bottom-up intervention, flexible and iterative processes involving an interdisciplinary team. There is also a need to consider the use of alternative methods and tools to capture both quantitative and qualitative data to obtain a clearer understanding of WAD.

3.2.2 Closing the Gap Between WAD and WAI: Technology

The current, standard technology for maritime education and training (MET), and experimental testing is a full mission bridge simulator (FMBS), regulated by the Standard for Training, Certification and Watchkeeping for Seafarers (STCW) convention in the 2010 Manila amendments to the STCW Convention and Code (IMO, 1978). FMBS, or high-fidelity simulators, have proven to be extremely useful for research studies and the training of future mariners (Sellberg, 2017, 2018). Although providing an effective means of research and training, there is a long list of limitations associated with the use of FMBS, including cost, availability, and lack of flexibility. Further, these simulators do not commonly facilitate human-centered design processes (Kristiansen & Nordby, 2013). As a solution to these limitations, immersive technologies, including AR, VR, and extended reality (XR), have created a new space for advanced maritime research and training applications (Mallam, Nazir, & Renganayagalu, 2019).

AR superimposes information on top of a person's view in any environment. AR technology is becoming increasingly viable for maritime use, although still considered in the early stage of development (Frydenberg et al., 2021; Nordby et al., 2020). AR is interesting for maritime applications because it allows the user to maintain a heads-up position which is an integral component of maritime navigation. VR is a computer-generated simulated experience that is achieved through a VR headset. VR solutions have recently gained traction within maritime applications, including efforts from classification societies (e.g., Lloyd's Register) and maritime startups (e.g., Immerse) (Markopoulos et al., 2019). Maritime stakeholders are recognizing the potential benefits associated with more flexible and cost-effective solutions that can be used for maritime training, research, and development (Markopoulos & Luimula, 2020). Although immersive technology has been available for decades, it has not been fit for use in real-world maritime applications and is therefore not widely implemented (Mallam, Nazir, & Renganayagalu, 2019). Although the use of immersive technologies in the maritime domain is still novel, there is a need to search for alternative, flexible solutions to understand work, and test new technology to achieve HCD. These emerging technologies provide additional tools to close the gap between WAD and WAI.

3.2.3 Closing the Gap Between WAD and WAI: Organizational Environment

The maritime industry is unlike other transportation sectors. The safety culture, number and role of stakeholders, and regulatory framework make for a complex operational environment. The safety culture on board ships remains hierarchal including a network of people with diverse demographics holding various responsibilities. There is a need to have both experienced and inexperienced operators in user studies as there is a great need to reduce the gap between the "old vs new" mentality. The stakeholders range from the operators on board ships, to the regulatory body of IMO, each with different representations of how work should be done versus how it is done. This is partially attributed to the fact that the current state of regulation for maritime operations is prescriptive and presents barriers for achieving safety goals in the maritime industry. To move forward, there is a need to re-evaluate the operational environment and find solutions that allow for a more harmonized approach to safety and efficiency. One innovative solution that has been developed to address the lack of standardization in maritime workspaces is the OpenBridge project (Nordby et al., 2020; Nordby et al., 2019). OpenBridge is a Norwegian based open-source user-friendly solution which can be implemented into existing equipment, resulting in cost effective, immediate improvements in the organizational environment.

3.3 DECISION-MAKING AND AUTOMATION

Understanding how people make decisions has important consequences for automation development. Decision-making generally includes four elements (1) a person must select one option from several alternatives (2) there is some amount of information available with respect to the option (3) the timeframe is relatively long (longer than a second) (4) the choice is associated with uncertainty (Wickens et al., 2003). Early research in cognition originated in the 1950's by George Miller which focused on information processing theory and contributed towards working memory capacity and information chunking (Miller, 1956). In 1976, Neisser developed the Perceptual Cycle Model (PCM) for decision making which highlighted that both schemata (or mental models/templates) and available information from the world will direct decision making (Neisser, 1976). This model advanced the idea that information processing and cognitive processes extend beyond the individual and are grounded in the context of the environment in which they occur (Plant & Stanton, 2015). In 1983 Rasmussen developed the skill, rule, knowledge (SKR) levels of cognitive control, which describes how people with differing levels of expertise handle a decision-making situation (Rasmussen, 1983). The SKR model remains one of the most influential contributions in human factors and has supported the development of error classification frameworks.

Rationality is a core component of many of the early decision-making theories which means that performance has been evaluated relative to a normative set of alternatives, and that an action outside of the normative model could be considered an "error" (Flach, Feufel, et al., 2017; Kahneman & Klein, 2009; Man, 2019). The heuristics and biases (HB) paradigm contrasted these earlier decision theories, finding that people rely on heuristics as opposed to algorithmic strategies even when these strategies deviate from optimal judgements (Kahneman & Klein, 2009; Klein, 2008). The HB approach demonstrates a sceptical attitude towards expertise, as studies have found major discrepancies between expert judgement (Kahneman & Klein, 2009). Around the mid 1980's research in complex and safety-critical environments increased dramatically, shifting from laboratory-based experiments to dynamic natural settings (Flach, Stappers, et al., 2017; Man, 2019). During this time, researchers from various field settings of decision-making came together and managed to agree on the fact that *"people were* *not generating and comparing option sets, people were using prior experience to rapidly categorize situations"* (Klein, 2008). This era introduced Klein's Naturalistic Decision Making (NDM) research approach which focuses on complex decision-making and the role of experience and pattern recognition which provide essential information to react to a situation (Klein, 2008). The NDM approach is based on field studies within safety critical domains (e.g., Navy, fire-fighters, airline pilots, nurses) and grounded in qualitative assessments.

Recent research has proposed blending paradigms and using elements from each to contribute towards a more holistic understanding of complex systems. John Flach describes what he calls "muddling-through" (or trial and error) as a process to find solutions to complex problems as a middle point between 'intuitive' and 'deliberative' processes (Flach, Feufel, et al., 2017). This approach focuses on a shift from trying to understand how people rationalize information through internal processes, towards trying to improve how humans pick up information (Flach, Stappers, et al., 2017). This approach aligns with systems thinking and is more appropriate for distributed teams instead of individual people. There are numerous decision theories, and each one has its merits and limitations. It seems that people adopt different decision processes depending on the combination and complexity of risk, uncertainty, time, and available choices to solve the situation. It can be summarized that decision-making will involve; an assessment of the situation through acquiring information and cues, awareness of the situation (mental representation) through situation assessments about what the cues mean, knowledge of appropriate course of action, and awareness of potential consequences of action(s)/inaction (Cook et al., 2007; Wickens et al., 2004). This thesis has taken elements from various theoretical frameworks, particularly information-processing as it is applicable to HAI research, and the NDM framework in the collection of qualitative data to try to better understand how automation might impact decision making. The framework for human-automation interaction by Parasuraman et al. (2000) discussed in section 3.4 has been criticised as being too basic to describe human cognition particularly because it neglects intuitive cognition (Patterson, 2017). However, it is acknowledged by Parasuraman et al. (2000) that the information-processing description adopted within the framework is a gross simplification of decision-making (Parasuraman et al., 2000).

3.4 HUMAN-AUTOMATION INTERACTION

The interactions between humans and technologies are situated within the theoretical framework of HAI. HAI research within safety-critical domains such as medicine, nuclear, and transportation have increased considerably in the 1990s and early 2000s (Hancock et al., 2013; Janssen et al., 2019; Parasuraman & Riley, 1997; Pazouki et al., 2018; Sheridan & Parasuraman, 2005). These works highlight HAI considerations driven by more advanced technologies and reiterated the importance of a better understanding of the classic human-automation challenges, captured in Bainbridge's (1983) seminal paper the "ironies of automation". This section will describe HAI as the theoretical frame of reference for the appended papers.

Automation is a central concept studied in this thesis which has been defined in many ways, incorporating diverse taxonomies, levels, and functions depending on the contextual application. *Autonomy* or *autonomous systems* are also mentioned throughout the thesis. It is important to differentiate between the two concepts automation and autonomy. In this thesis, there is a focus on the human-automation relationship and the definition proposed by Parasuraman et al. (2000) is applied:

> *"Automation refers to the full or partial replacement of a function previously carried out by a human operator. This implies that automation is not all or none, but can vary across a continuum of levels, from the lowest level of fully manual performance to the highest level of full automation"* (Parasuraman et al., 2000).

The concepts *autonomy* or *autonomous systems* are referring to systems which have a high level of self-sufficiency, self-directedness, and freedom to make their own choices without the involvement of a human operator (Bradshaw et al., 2013; Vagia et al., 2016). Autonomy is aligned with unmanned, autonomous ships (MASS Degree 4) which is outside the scope of the individual studies within the thesis. However, the potential of autonomy and autonomous systems is referenced in Chapter 6 in relation to the future of the maritime sociotechnical system.

Human-automation interaction (HAI) can be defined as how humans interact with automation in complex and large-scale systems, characterized by the way humans control and receive the information from automation (Mattsson, 2018; Sheridan & Parasuraman, 2005). Many industry stakeholders have defined HAI through the use of a Levels of Automation (LOA) or Degrees of Automation (DOA) scales which usually range anywhere from 0-10, 0 = no automation to 10 = fully autonomous, and mixed human-automation task allocations in between (Endsley & Kiris, 1995; Kaber, 2018; Parasuraman et al., 2000; Vagia et al., 2016). The benefits of using LOA scales for automation are generally attributed to having a common language to discuss human performance related factors (Lee, 2018; Man, 2019). For example, in the automotive industry, the Society of Automotive Engineers (SAE) have adopted a six-level scale in which each level describes the function allocations and level of control between the system and human operator (SAE, 2021; Vagia et al., 2016). In this context, level 2, and level 3 automation (or low-mid level automation) present transfer of control issues in which the driver or user must be in-the-loop or brought back into the loop quickly. This level of automation will have an impact on human performance including; situation awareness, mental model development, decision-making and timely execution affecting overall safe use of automation (Creaser & Fitch, 2015). In 2016, Vagia et al. completed a review of the various LOA´s proposed since the 1950´s which outlined the most common taxonomies presented in the literature which include Sheridan and Verplank´s ten level model (Sheridan & Verplank, 1978), Endsley´s four level LOA model (Endsley, 1987), and Parasuraman et al. four different classes of input functions (Parasuraman et al., 2000; Vagia et al., 2016). This review highlighted the many approaches available to define and understand automation across various industries, including a suggestion to revisit the concept of adaptive or adaptable automation.

The conceptualization of automation using DOA or LOA has been criticized as a simplified, reductionist approach (Bradshaw et al., 2013) which does not consider the complexities of the system to which it is applied (Lee, 2018). These taxonomies presume a siloed system, where various states of automation cannot co-exist within a system. Although these criticisms are noted, it is also imperative that industry stakeholders have a common language to guide automation development which is aligned with human capabilities and limitations. Therefore, the four-level model proposed by Parasuraman, Sheridan and Wickens (2000) of human information processing and automation capabilities is selected to describe the categorization of automation discussed in this thesis (Parasuraman et al., 2000). This model was selected because various levels or degrees of automation can be applied to each input function level, and one system can have different levels of automation across all four dimensions. It is a flexible, non-linear framework that can be used to discuss automation and addresses many of the limitations highlighted by LOA critics. This approach is summarized in Table 1 which provides a framework to discuss the potential implications of low-level automation on human performance.

Table 1 Input functions and description including examples related to the shipping context[1]

Input Functions	Description	Explanation	Human Information Processing Stage
Level 1	Information acquisition	The task of sensing, monitoring, and registering data *(e.g., organization of incoming information on ship´s ECDIS)*	Supporting human sensory process
Level 2	Information analysis	The act of performing all the processing, predictions, and general analysis tasks *(e.g., provide navigator time and distance to come back to route)*	Working memory and inferential processes
Level 3	Decision selection	Decision and action selection are the act of selecting between different decision alternatives *(e.g., manoeuvring suggestions)*	Augmentation or replacement of human selection of decision options with machine decision-making
Level 4	Action implementation	Acting on decisions or commanding new actions, being practically the final stage of the actual execution of action choice *(e.g., machine selects best route and accepts it)*	Different levels of machine execution of the choice of action, and generally replaces the human command

For the context of this thesis, levels one to three of input functions; Information acquisition, information analysis, also grouped together and called "information automation" and decision selection are applicable, and level four (action implementation) is outside the scope of this work. The different types of automation can be classified as *decision support*. This thesis is investigating three different decision support systems, STM, AIM and SEDNA (see Chapter 4 for description).

Within this framework, the level of automation can also vary across functional dimensions within the different degrees as shown in Table 2. The functionality within the different decision support systems varied. For example, AIM had the highest LOA as the system provided suggestions to operators as to how to proceed based on surrounding traffic information. STM had the lowest LOA, as the information was exchanged between operators and displayed digitally. STM did not require higher functioning algorithms or additional information from sensors. SEDNA acquired and analysed more information than manually possible from the surrounding environment and displayed this information virtually. Table 2 provides a summary of the type and level of automation explored throughout the thesis within the HAI framework.

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[1] Table *adapted from Parasuraman et al., 2000 in the "explanation" column to include relevant examples of automation studied in this thesis.*

Table 2 represents the type of automation studied in this thesis and is not describing the desired or recommended type of human-automation allocation for navigation.

Table 2 The type and level of automation provided by the decision support systems studied in this thesis

Decision Support Systems	**Information Acquisition**	**Information Analysis**	**Decision Selection**	**Action Implementation**
STM (ship-to-ship route exchange)	Manual sharing of data, the operator must choose to share their route with other ships.	Based on shared data, the projected future course of a ship will show when the two routes would intersect if both ships were to follow on their current course and speed.	N/A	N/A
	LOA: Low	LOA: Medium		
AIM	System gathers information about surrounding ship traffic including speeds, and distances.	Analysing data from other ships actions to determine which ship is stand-on or give-way.	Present the operator with manoeuvring suggestions (*e.g.*, reduce speed, or change course)	N/A
	LOA: High	LOA: High	LOA: Medium	
SEDNA	Augmenting and integrating existing information with new information from sensors about the surroundings of the ship.	The different AR solutions can show the operator potential dangers, status of other ships in a convoy through a heads-up display.	N/A	N/A
	LOA: High	LOA: Medium		

3.5 AUTOMATION AND HUMAN PERFORMANCE

The purpose of introducing automation into a workplace is generally to improve system performance and reduce human-related errors often associated with workload and situation awareness, however, the outcome often causes more complex problems. The "ironies of automation" which Lisanne Bainbridge wrote about almost 40 years ago remain remarkably accurate today (Bainbridge, 1983; Strauch, 2017). The "ironies of automation" suggest that the more advanced a control or automated system is, the more important the role of the human operator. The two major ironies related to the removal of the human operator from the system are that: (1) the system design errors are a major source of operating problems and (2) the designer leaves the operator with the tasks that they don´t know how to automate or operate (Bainbridge, 1983). These ironies have not been resolved and as automation is becoming increasingly more complex, the role of the human operator is often diminished or not considered, jeopardizing system safety (Strauch, 2017).

There is an extensive body of HAI research within safety-critical industries including military operations, healthcare, aviation, nuclear, and transportation domains (Endsley, 1987, 2017b; Hancock et al., 2013; Jenkins et al., 2008). This research has led to a more thorough understanding of the potential benefits of automation for human performance, while also highlighting the challenges of increasing automation within safety critical systems. These challenges, if not addressed, result in various forms of human-automation errors including; decreased situation awareness, automation biases, information overload, complacency, and/or skill degradation (Bainbridge, 1983; Endsley & Kiris, 1995; Kaber et al., 1999; Lee & Moray, 1994; Lee & See, 2004; Lützhöft & Dekker, 2002; Parasuraman & Wickens, 2008). Recent works have identified that these challenges are more prevalent than ever today in technology-driven industries (Janssen et al., 2019; Kaber, 2018; Woods, 2016). These human performance constructs will be discussed in the following section in relation to decision support automation.

3.5.1 Situation Awareness

A concept that is both highly applied and vigorously debated in cognitive science is situation awareness (SA), what it is and how to measure it (Bakdash et al., 2022; Salmon, Stanton, et al., 2009). The debate hinges on how people view SA either as a product or a process (Stanton et al., 2001). One of the most frequently cited definitions was proposed by Mica Endsley (1995), suggesting that SA is

> *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future"* (Endsley, 1995).

This approach has three levels which can be broken down into: Level 1 SA: perception, Level 2 SA: comprehension, and Level 3 SA: projection (Endsley, 1999). This approach to SA incorporates many cognitive processes as seen in traditional information-processing models and has been dubbed as SA "in-the-mind" (Endsley, 1995). Endsley´s framework has been criticized for being strictly linear (Sorensen et al., 2011; Stanton et al., 2010), however, Endsley argues that this is a misunderstanding of the three-level model, and it should be interpreted as ascending levels of SA (Endsley, 2015). Endsley further clarified some common misconceptions indicating that this approach can explain human behaviour in complex systems (Endsley, 2015).

Two alternative approaches to define and evaluate SA include the engineering approach and the systems or distributed SA approach (Stanton et al., 2010). The engineering or technology-focused approach, means that displays, sensors, maps, etc. have SA (i.e., a navigation display contains SA for a pilot) (Ackerman, 1998; Jenkins et al., 2008). Within this view, it is understood that SA is achieved through various technologies providing SA to the operator, indicating that SA can be in the device as well as the person, or "in-the-world" (Ackerman, 1998; Stanton et al., 2010). This is the approach held predominantly by the public, end-users, and technology manufacturers. A systems approach to SA originated from Hutchins' distributed cognition movement (Hutchins, 1995; Salmon, Stanton, et al., 2009; Stanton et al., 2006). The term Distributed Situation Awareness (DSA) is used within complex sociotechnical systems to describe how people work together, and how information bonds people and technology together (Salmon, Walker, et al., 2009; Stanton et al., 2010; Stanton et al., 2006). DSA views SA as an emergent property that resides between the elements of a system, and not in the heads of the individual operators (Stanton et al., 2017). This approach is based on the assumption that SA information exists and is distributed within the people (team) but also the tools used to accomplish their goals (i.e., navigation equipment), also known as SA “in-interactions” (Salmon, Stanton, et al., 2009). The DSA approach is the most complex and comprehensive in terms of measurement and analysis. The DSA approach, although thought to be beneficial to evaluate sociotechnical systems was not considered throughout this thesis work.

There are criticisms associated with each approach to SA. However, the important aspect of SA is that the selected definition, measurement tools, and analysis align with the approach chosen, i.e., “in-the-mind”, “in-the-world”, or “in-interaction” (Stanton et al., 2010). This thesis is theoretically grounded in Endsley’s three-level model, or SA “in-the-mind” to better understand how decision support could impact an operators’ understanding, comprehension, projection and the eventual decision making in a situation. SA was subjectively measured and discussed within each article and is a central concept throughout this thesis. However, it is important to acknowledge the role of the engineering approach to SA. The concept of SA is popular in the maritime community, and it is a common marketing strategy to promote “SA-technologies” which claim give the operator SA. Therefore, it is probable that SA “in-the-world” view is held by most of the participants included in these studies which could be reflected in the results when they described their experiences with decision support technologies.

3.5.2 Trust, Reliance, and Complacency

Perceived trust and reliance in automation strongly influences automation usage (Lee & See, 2004; Parasuraman & Riley, 1997). Trust is a construct in which a human considers the reliability, truth, and ability of automation and experiences some level of vulnerability in developing expectations towards the automation (Lee, 2008; Lee & See, 2004). It is recognized that trust and reliance evolve in a complex way which include personal history, cultural and organisational factors (Lee & See, 2004). In 1997, Parasuraman & Riley discussed why automation often fails to perform as expected and identified challenges related to automation use, misuse, and abuse (Lee, 2008; Parasuraman & Riley, 1997). Automation bias occurs when human operators over-trust or over-rely on automated aids, even when they are imperfect (Parasuraman & Manzey, 2010). An example of an automation bias is automated cueing, also known as attention guidance, which is when an operator fails to detect important cues outside of the automated cues, leading to decreased performance in target detection (Wickens et al., 1999). Automation biases can lead to an inadequate assessment by the operator of the available information, leading to misplaced trust, resulting in the misuse of automation. Similarly, automation complacency occurs when operators fail to monitor an automated system as needed because of the belief that the automation is more reliable than it is (Crocoll & Coury, 1990; Merritt et al., 2019). Conversely, under-trust in automated aids leads to disuse occurring when operators fail to engage automation when it could enhance performance, leading to an increase in workload and time pressures (Lee, 2008; Lee & Moray, 1992; Lee & See, 2004).

Within the transportation sector there are examples in which people have either misused or disused automation leading to major accidents, usually as a result of the mismatch between the human operator’s expectations of the automation capabilities and limitations (Endsley, 2017a, 2017b). Recently, Tesla’s Autopilot, a partially automated driving system (SAE Level 2), has been receiving negative attention because of accidents in which users have over-trusted the automation, leading to use outside the intended operational design specifications (Endsley, 2017a; Morando et al., 2021). In the maritime domain, a classic example is the grounding of

The Royal Majesty cruise ship which occurred following a satellite navigation failure causing the vessel to drift off track (Lützhöft & Dekker, 2002). A detailed analysis of this accident revealed how the introduction of automation changed the task it was meant to support, allowing for unforeseen errors and automation surprises (Lee & Sanquist, 2000; Lützhöft & Dekker, 2002).

3.5.3 Information Automation and Decision Automation on Human Performance

Introducing new LOA technology into a sociotechnical system will alter the interaction between system elements and change the way work is done. The impact of automation on human performance has been studied extensively as discussed in the previous sections. However, the impacts on human performance also depend on the function or task (i.e., information automation, action selection or action execution) that automation is applied (Endsley, 2017b; Parasuraman et al., 2000). Endsley (2017) summarized the most relevant research related to the effect of autonomy applied to the stages of task performance across different LOA taxonomies. Endsley's perspectives, in addition to the relevant literature, are discussed in relation to human performance (Endsley, 2017b).

Information automation is intended to support human cognitive processes in decision-making, providing the most useful information to the operator. Altering the manner of information retrieval for an operator will impact information processing, perception and decision-making (Endsley, 1995). High levels of information automation and information-cuing systems are valuable and should create improved performance if the system and information sources are correct and reliable but create poor performance when incorrect (Endsley, 2017b; Parasuraman et al., 2000). However, reliability and certainty are difficult to guarantee particularly for maritime applications (i.e., collision avoidance algorithms) because most systems are still in the early stages of development, validation, and implementation. High levels of information automation have also been associated with reduced mental workload (Parasuraman et al., 2000), decreased time to make a decision (Crocoll & Coury, 1990), and improved SA (Endsley, 1999). Based on Endsley's three-level SA model, information automation can benefit SA, workload, and performance from systems that present the relevant information (Level 1 SA), and integrate the information needed for comprehension (Level 2 SA), and projection (Level 3 SA) (Endsley, 2017b). It is suggested that SA is generally higher with lower to intermediate LOA, as the operator is still in-the-loop, or at least on-the-loop, and exhibits an enhanced ability to respond to system failures, compared to higher LOA (Kaber et al., 2000; Parasuraman & Manzey, 2010).

Decision selection departs from information acquisition and analysis as it requires the operator to evaluate the potential outcomes of the situation based on the acquired information (Parasuraman et al., 2000). This evaluation will depend on the operators' ability to gather, handle, process, and comprehend the information from either manual sources or the automated information (Ramos et al., 2019). Throughout this thesis, the level of automation for decision automation is categorized as "low" meaning the operator is completely responsible for final decision selection and outcome action. The exception is for the AIM decision support system which is categorized as "medium-level" as the system provides route suggestion alternatives to the operator to evaluate and make a final decision. When the user has a high engagement during decision selection (low-medium LOA), there is less of a decision-bias problem and decision support can improve human performance (Endsley, 2017b). However, high levels of automation at this stage can also introduce new cognitive demands (Lee & Sanquist, 2000) and have been associated with reduced situational awareness, complacency, and skill degradation

(Parasuraman et al., 2000). Decision selection is a critical step in the decision-making process; therefore, the level and type of automation should be carefully considered.

For even higher LOA, including high levels of automation for decision selection and action performance, there appears to be an *automation conundrum* which happens when the LOA is increased, along with its reliability and robustness leading the human operator to have a reduced SA and therefore reduced ability to take over a system in a failure (Endsley, 2017b). This result is attributed to the out-of-the-loop (OOTL) operator, which is caused by a loss of SA when monitoring or overseeing automation (Bainbridge, 1983; Endsley, 2017b; Kaber et al., 2000). Although this is important to further investigate, it is outside the scope of the human performance considerations within this thesis.

4 RESEARCH APPROACH

This chapter provides an overview of the procedures adopted to achieve the results and conclusions throughout this thesis. This chapter describes (1) the philosophical worldview and overall research approach (2) a description of the different projects and procedures of each paper included within the thesis (3) research design and data collection (4) methodological tools including data collection and analysis processes. Details of the methodology for each study can be found in the appended papers.

4.1 PHILOSOPHICAL WORLDVIEW

Philosophical assumptions consist of a basic set of beliefs that guide inquiries which can be described as a researcher's worldview (Creswell & Clark, 2017). Understanding the researcher's worldview provides the reader insight into the researcher's preconceptions which have influenced choice of methods, data collection and analysis, and the overall research process (Crotty, 1998). The epistemological basis of human factors (HF) relates to what we know, how we know it, and what are the implications for practice and research (Meister, 1991). HF as a scientific discipline is inherently a systems science, studying human performance (behaviour) and interactions with various systems and their elements to optimize human well-being and system performance (IEA, 2000). The field draws on theory and knowledge (experimental, empirical, and experiential) from other disciplines including but not limited to, engineering, cognitive science, and design (Meister, 1991). HF research tends to be explanatory having much success in describing a particular phenomenon, yet as an action-oriented discipline sometimes lacks the utility of knowledge (i.e., what to do with it) (Meister, 1991). The research journey described within this thesis attempts to provide contributions towards both explanatory and action knowledge ("is that so, what next?" – borrowed from Margareta Lützhöft who borrowed from her Professor Erik Hollnagel, who learned from one of his mentors (Lützhöft, 2004)), through explaining the research problem and proposing solutions based on the empirical results from the appended articles.

The educational background and work experience of a researcher is relevant as it can provide insight into the development of a researcher's worldview. The author's educational and work experience prior to the PhD were primarily rooted in physical HF for maritime applications. During the PhD work over the last five years, the focus has drifted from physical ergonomics towards cognitive ergonomics, human-automation interaction, and a growing interest in qualitative inquiry. The PhD program has provided opportunities to support various projects exploring the role of automation in the maritime industry as discussed throughout this thesis. The goal is to advocate for better designed maritime systems with a human-centred approach to improve the working conditions, safety, efficiency, and productivity for operators. This diverse work and educational experience have focused primarily on problem-centred applied research with a real-world application. Therefore, a pragmatic mixed methods approach has been used to address the research problems. Pragmatism is widely adopted by mixed methods researchers as it provides flexibility in the research process given that there is no commitment to one philosophical paradigm or worldview. This approach has an emphasis on methods that work best for the research questions, allowing for various types of data collection, analysis, and interpretation (Creswell & Clark, 2017; Johnson et al., 2007).

4.2 RESEARCH APPROACH: MIXED METHODS

The methodological approach describing the development of this work follows a convergent design which is when a researcher combines both qualitative and quantitative data to obtain a more complete understanding of the research questions or problem (Creswell & Clark, 2017). The use of the convergent design aligns with the assumptions of pragmatism which encourages flexibility and finding the right methods for the research problem. Based on the Creswell and Clark (2017) notation system for core mixed methods design, this thesis would be considered as "QUAL + quant = converge" results. In this case the overall intent of the researcher is to converge or compare the results from both types of data, with a particular emphasis placed on qualitative data (Creswell & Clark, 2017). Qualitative research was selected as the primary approach as it allows the researcher to obtain both inner and common experiences from participants and seeks to describe and understand the phenomenon being studied (Corbin & Strauss, 2015; Silverman, 2011). The quantitative data collected throughout this thesis is primarily in the form of descriptive statistics. The quantitative data were used as an objective measure of certain variables to compare or contrast with the qualitative data. For example, the frequency of communication interactions between navigators and VTS operators, the frequency of COLREG breaches, and ship distances. A summary of the methodological approach for the appended papers is provided in Table 3.

4.3 DESCRIPTION OF THE PROJECTS AND PROCEDURES

4.3.1 Project A: Sea Traffic Management (STM) - Thesis Papers I and II

The STM Validation Project (2014-EU-TM-0206-S) was a European Union (EU) funded project aimed at validating the STM concept and its applications (IMO, 2014a; STM, 2019). The STM concept proposed a holistic approach with the aim to connect and update the maritime world (ships, ports, vessel traffic services, service providers, shipping companies) in real time through digital information exchange and standardized infrastructure. The STM Validation Project used a large-scale testbed, the European Maritime Simulator Network (EMSN) to demonstrate the STM concept in both the Baltic and Mediterranean Seas. The EMSN is a network of simulator centres enabling testing of STM concepts in complex traffic situations while using real operators. The STM services were made up of different information sharing tools between ships and between shore. The STM Validation Project generated interesting findings from both the perspective of navigators and VTS operators.

4.3.1.1 Procedures for Paper I: STM (VTS)

This paper explored the impact of the STM functions from a Vessel Traffic Services (VTS) perspective. The goal of this paper was to understand how communications and interactions between ship and shore would impact VTS operations. The following decision support functions were tested: **Shore-to-Ship Route Exchange (Receiving route suggestions from shore):** This function allows the VTS to send a suggested route to the ship, to be reviewed by the bridge team and then either accepted or rejected. This function can be used in various situations, for example, if several vessels are warned to avoid a certain area, the shore centre can plan a route based on all available information and directly send this route to the vessel. **Chat Function:** A standalone communication software similar to other programs such as Skype, or WhatsApp which is integrated on the same station as the ECDIS. This function allows text communications with other STM enabled ships or VTS stations.

Data were collected over four non-consecutive weeks in 2017 and 2018 in the EMSN testbed. Sixteen VTS operators participated at simulated VTS stations (at Chalmers University, Sweden or Warsash Maritime Academy, UK) and participated in two, 1.5-hour simulator exercises; one in the English Channel, and one in the Baltic. The VTSOs were not given any specific instructions related to the use of the STM functions versus traditional communication means (*e.g.,* VHF). This approach was selected to represent a more realistic situation so that the VTSOs were not ¨forced¨ to use the STM services, and instead would use the services based on their time, ability, and interest.

Data collection included observations that assessed the frequency and type of interactions between the ship and VTS, and post-test questionnaires to assess user experience. An experienced VTS instructor (and co-author) observed and recorded all direct interactions between the vessels and the VTS, and VTSOs and their equipment. During the baseline simulations, VHF radio was the only available method of communication between the ship and VTS. In the STM simulations, there were several STM tools (*e.g.*, VHF, chat function, and route suggestion from shore to ship) to actively interact with the ships. The use of these three functions is considered as *direct interactions with ships*. The observer used pre-determined taxonomies (i.e., name of STM function, names of vessels, etc.) to populate an experimental data collection spreadsheet to capture systematically and chronologically the data. All details about the direct interactions were also recorded including who initiated the interaction, when it occurred, and if there was miscommunication. This information was collected for both Baltic, and English Channel scenarios.

4.3.1.2 Procedures for Paper II: STM (Nav)

This paper explored the impact of ship-to-ship route exchange (S2SREX) on decision-making and navigational safety. **S2SREX** provides the navigator with a route segment consisting of the next 7 waypoints of the monitored route of another vessel. Route segments are broadcasted through AIS and give additional information to the presently available data obtained by radar/ARPA and AIS. Nothing in the S2SREX information exonerates the navigator from applying the COLREGs. Data were collected over four days in October 2018 at two simulations centers (Chalmers University and Warsash Maritime Academy). Each simulation center followed the same protocol for all aspects of the experimental protocol. STM subject matter experts (SMEs) developed six different traffic scenarios each lasting approximately 15-20 minutes. The scenarios can be grouped into two types of traffic situations: (1) Meeting/overtaking and (2) Crossing and general traffic situations and are fully described in Paper II.

A total of twenty-four participants were included, twelve at CTH and twelve at WMA. For each scenario, a baseline and decision support trial were conducted by twelve different test participants. The main difference between baseline and the experimental condition was that the participants had access to an ECDIS with decision support. A simulator instructor and a human factors specialist observed the trials from the simulator instructor’s station. After each simulation scenario, the participants filled in a brief post-scenario questionnaire regarding their perceived performance and opinions about the scenario and the STM functions. At the conclusion of the data collection there was an open-ended questionnaire debrief which included semi-structured interviews to obtain information related to the participants overall perceptions and experiences of the decision support. During the debrief, the scenarios were replayed to help the participants remember what happened and discuss the outcomes. The purpose of this exercise was to probe the participants to think about how the decision support influenced their decision-making processes and how it could impact safe navigation practices. Quantitative data (e.g., distance from ships, closest point of approach) were collected from simulator trial files to assess the ship movements in relation to the COLREGs.

4.3.2 Project B: Advanced Intelligent Manoeuvring Project - Thesis Paper III

The research, funded by the Swedish Maritime Competency Centre called Lighthouse aimed to understand the effect of an algorithm-based collision-avoidance decision support system on decision making and navigation. The Advanced Intelligent Manoeuvring (AIM) decision support system was developed and marketed by Wärtsilä (https://www.wartsila.com). The system covers all working cycles of navigation, including situation monitoring, problem detection, suggesting a manoeuvre and monitoring execution of the manoeuvre based principally on geometrical calculations, the system assumes that the other ships keep their course and speed. The decision support system provides graphical solution(s) to solve the traffic situation either by changing course or speed with an additional possibility to "play ahead" (visualize the manoeuvre on the ECDIS) the manoeuvre before executing it. For reason of property rights and commercial considerations, Wärtsilä did not disclose the algorithms employed by the decision support system, disclosing that it is based on COLREGs, anti-grounding (nautical chart information), the manoeuvring capabilities of the ship using AIM and normal behaviour of ships according to historical AIS data previously collected in the specified geographies. The suggested environment of use is in open waters or in relatively uncongested waterways as the decision support follows COLREGs more strictly than typical vessel traffic may do in congested areas.

4.3.2.1 Procedures for Paper III: AIM

Paper III explored the navigators' view of a collision avoidance decision support system. The study included nineteen Swedish navigators and followed a within-subject design. Three simulation traffic scenarios captured meeting, crossing, and overtaking situations and included three manned bridges (Alpha, Bravo and Charlie). The experimental design consisted of trials which had no decision support (baseline) and decision support (AIM). The study lasted for approximately four hours including the pre-scenario familiarization and post simulation debrief interviews. Three scenarios were completed during each test period, lasting approximately 25 minutes each and the participants were never exposed to the same scenario in both conditions. The order in which the scenarios were tested, along with the level of the independent variable were randomized to reduce any potential order effect. Qualitative data were collected through collective debrief and interviews.

4.3.3 Project C: The SEDNA Project - Thesis Papers IV-V

The "Safe Maritime Operations under Extreme Conditions: the Arctic case" (SEDNA) project, was a European Union Horizon 2020 funded research program (no.723526). This work is based on a work package that was specifically investigating the challenges of Arctic navigation with one of its aims to design a "human-centred Safe Arctic Bridge". The SEDNA project removed the constraints of regulation and existing technological solutions, and instead applied human-centred design thinking throughout the project's life cycle to develop, test, and apply novel concepts for navigation practices. The removal of these constraints allowed this work to develop user-driven solutions using augmented and virtual reality. Papers IV and V report on the HCD and collaborative process used to produce and demonstrate workplace design proposals for ships' bridges using virtual reality-reconstructed operational scenarios (VRROS). Within the development of the VRROS, AR concepts were developed and tested on end-users. Figure 4 illustrates the overall research approach to Papers IV and V. The approach can be divided into two primary methods: (1) Design of the AR application and (2) Usability testing of AR application and VRROS. As the second author on Paper V, the candidate's contribution was towards method 2.

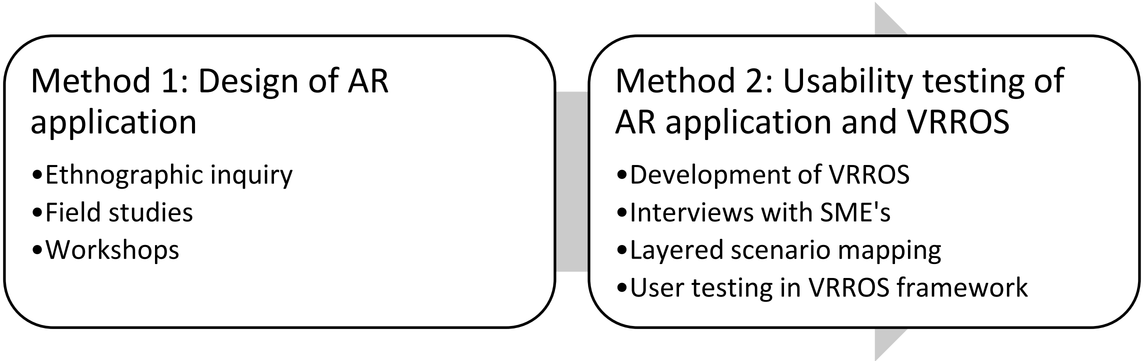

Figure 4 Summary of the approach to Papers IV and V

4.3.3.1 Procedures for Paper IV: SEDNA 1

This article reports on the process of developing VRROS and describes how VRROS can be used as a tool both for concept development (augmented reality and other types of technology) and as a tool to bring together stakeholders in a joint process. A pragmatic approach was adopted throughout this work, utilizing several different qualitative methods and tools to develop and test the VRROS. The process started with an ethnographic inquiry to understand the users' context on board a ship's bridge. This led to the identification of critical and common operations that could be useful for developing operational, VR scenarios. Next, the scenarios were developed through interviews with SMEs using the layered-scenario mapping technique and data from the FMBS to create a realistic scenario in VR. Finally, the scenarios were tested on end-users through a think-aloud protocol in which the data was sent directly back to the design team to improve the VRROS. In total 22 professional mariners experienced the VRROS. This process is summarized in Figure 5.

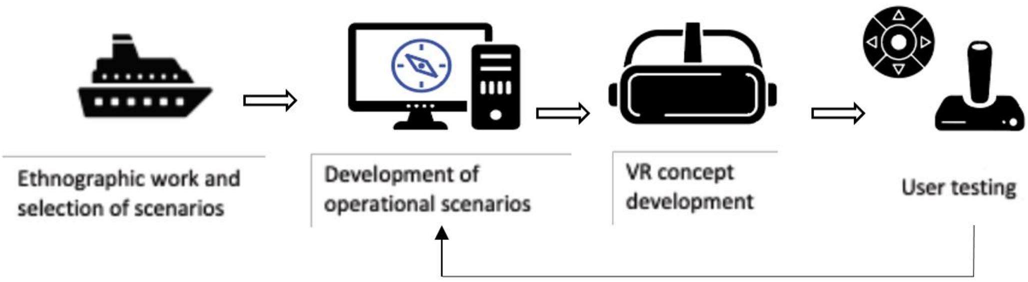

Figure 5 Summary of the methodological approach for Paper IV

4.3.3.2 Procedures for Paper V: SEDNA 2

This paper reports on the user testing of an augmented reality user interface concept for an icebreaker convoy operation. The user testing was completed at Chalmers University and seven professional mariners evaluated the convoy scenario (Figure 6). The vessel followed a predefined path, so the participants were not able to control the ship or affect how the scenario unfolded. Instead, they were encouraged to evaluate the AR solutions. Two HF researchers were present throughout the data collection to observe, record participants' answers, and assist with the VR controls and manoeuvring through the scenario. The participant first completed a tablet-based demographic pre-test questionnaire followed by the convoy scenario which lasted for approximately 60 minutes. Qualitative data were obtained through a think-aloud protocol including both concurrent and retrospective verbal reports. The concurrent report involved the participants speaking out loud throughout the scenario as they encountered a specific AR solution. They spoke about what they saw and were probed with pre-determined specific questions about each AR feature if needed. The retrospective verbal report was completed post-scenario and required the participants to reflect on their experiences. Finally, a post-test questionnaire was administered at the end of the test day, which asked specific questions about the usefulness of the AR technology and attempted to obtain a quantitative assessment of the user's overall experience using the technology.

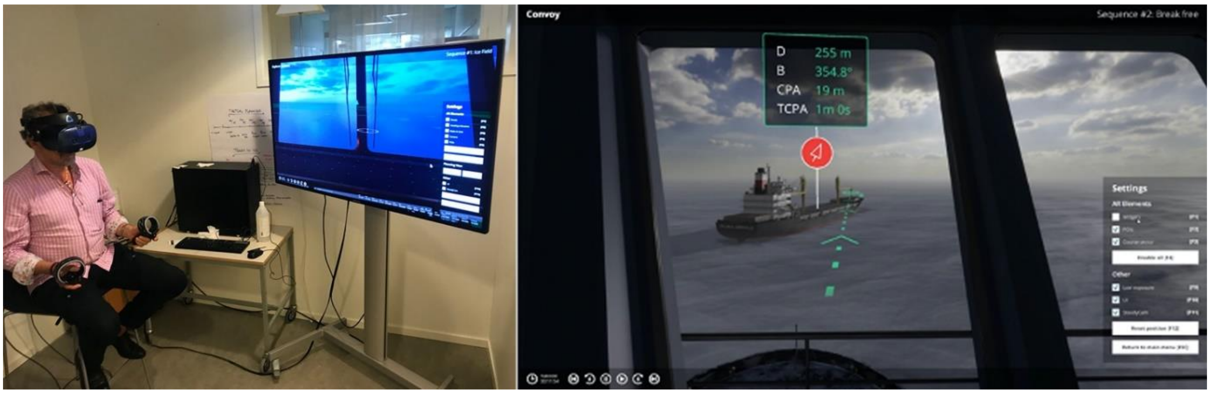

Figure 6 (Left) An exocentric perspective in VR/AR test set-up showing how the researcher can monitor both the users' behavior and have the same visuals as the user in VR on the TV screen. (Right) A screen capture of the egocentric perspective of what the user sees in the VRROS during the convoy scenario.

4.4 RESEARCH DESIGN AND DATA COLLECTION

This thesis work has been supported by project-based, applied research studying solutions to real-world problems. Participants were fully informed of the procedures and risks of the experiments and provided electronic and written Informed Consent prior to the start of the simulations. The experiments complied with the requirements of Article 28 of the EU General Data Protection Regulation (2016/679) regarding protection for physical persons in the processing of personal data. Each participant was assigned a unique identification number (ID) prior to arrival, which was used for the questionnaires throughout the studies to maintain confidentiality. This research was deemed not to fall within the scope of the Swedish Ethical Review Act because there was no: processing of sensitive personal data, processing of personal data regarding violations of the law, or experiments performed with the purpose to affect a research participant physically or mentally, or research that includes an apparent risk of injuring the research participant either physically or mentally. Therefore, an ethical review was not required for any of the studies included within this thesis. A summary of the methodological approach for the appended papers is provided in Table 3.

Table 3 Summary of the methodological approach for each paper

Paper	Project	Approach	Testbed	Methodological Tools	Analysis Method	Number/ Role of Participants
I	A	Mixed methods	Full-mission bridge simulators	➢ Post-simulation questionnaires ➢ Observations ➢ SME review ➢ Communication analysis	➢ Descriptive statistics ➢ Comparative analysis related to the frequency of interaction ➢ Frequency of use of STM functions	16 VTS Operators
II	A	Mixed methods	Full-mission bridge simulators	➢ Post-scenario Questionnaires (per scenario and per day) ➢ Video playback of scenarios ➢ SME consultation ➢ Simulator data capture	➢ Descriptive statistics ➢ Frequency analysis of ship distances ➢ Frequency analysis of COLREG breach	24 Professional mariners
III	B	Qualitative	Full-mission bridge simulators	➢ Debrief and collective interviews	➢ Thematic analysis	19 Professional mariners or master mariner students
IV	C	Qualitative	VR/AR test environment	➢ Layered scenario mapping ➢ Think aloud technique	➢ Thematic analysis	22 Professional mariners or master mariner students
V	C	Mixed methods	VR/AR test environment	Method 1: Design ➢ Field studies ➢ Design of AR application ➢ Layered scenario mapping Method 2: Usability testing ➢ Think aloud technique ➢ Post-test questionnaire	➢ Summary of qualitative data ➢ Descriptive statistics	7 Professional mariners

4.4.1 Research Testbeds

4.4.1.1 Full Mission Bridge Simulator (FMBS)

A Wärtsilä full mission bridge simulator was used as the testbed for data collection for studies described in Papers I-III. Simulation is increasingly being used for research, training, and continuing education in a wide range of disciplines (e.g., medicine, transportation). Simulation technologies have continuously developed both hardware and software systems to create highly naturalistic and immersive experiences, also known as high-fidelity simulation (Massoth et al., 2019). High-fidelity simulators are commonly used for training officers, maritime pilots, VTS operators and for practicing safety critical operations (Sellberg, 2017, 2018). Simulation for maritime education and training is regulated by the Standard for Training, Certification and Watchkeeping for Seafarers (STCW) convention in the 2010 Manila amendments to the STCW Convention and Code (IMO, 1978; Sellberg, 2017). The data within papers I, II and III were collected using a FMBS (Figure 7 left). Paper III included an additional stand-alone screen for the AIM system (Figure 7 right).

Figure 7 (Left) High-fidelity ship´s bridge simulator at Chalmers University of Technology (Right) The test-set up for Paper III with the additional decision support screen.

4.4.1.2 Virtual Reality Experiment

Papers IV and V collected data in a virtual reality environment. VR, as a testbed in the maritime domain, is more immature compared to other industries, for example, industrial (i.e. maintenance and assembly tasks, procedural training, etc.), safety and emergency preparedness (Renganayagalu et al., 2021), healthcare, firefighting, and other means of transportation (e.g., aviation, aerospace). However, the maritime industry has the potential to benefit from VR and immersive technologies as an alternative flexible, cost-effective solution compared to FMBS. There have been several research initiatives within the last few years which aim to determine the possibilities of VR in the maritime sector particularly for maritime education and training (MET) (Hjellvik et al., 2019; Mallam, Nazir, & Renganayagalu, 2019; Markopoulos & Luimula, 2020; Renganayagalu et al., 2021). The VR test set-up in Papers IV and V was configured so that the researchers held the same visual field as the participants in VR through the large TV screen (Figure 8). This allowed for seamless communication between participant and researcher during the data collection.

Figure 8 Virtual reality user testing setup.

4.5 METHODOLOGICAL TOOLS

To increase trustworthiness of the data, triangulation was used (Olsen, 2004). Triangulation can be defined as mixing data types and methodologies to obtain more diverse standpoint or deeper understanding of research questions (Denzin, 2012; Olsen, 2004). The following methodological tools were used to study the research questions.

4.5.1 Qualitative Interviewing

Qualitative interviewing can be described simply as various forms of asking questions and listening to the respondent's answers. The goal of the qualitative interviews has been to derive interpretations and meaning from the participants experiences (Warren, 2001).

4.5.1.1 Post simulation debriefing and collective interviews

Debriefing is known as the "heart and soul" of simulation experiences (Rall et al., 2000). It is a common approach used in simulator studies as it integrates theoretical knowledge with practical experience to obtain a detailed overview of the simulated exercise (Fanning & Gaba, 2007; Rall et al., 2000; Sellberg, 2017). It is a platform or tool to codify tacit knowledge, to better understand WAD. In papers II and III, the debrief and interviews overlapped which allowed the researchers to provide more detailed information and feedback to the participants about the purpose of the study, while also providing feedback and a learning opportunity for the participants. The interviews allowed the test participants to provide an account of their experiences, both positive and negative in a non-bias environment (Patton, 2002). The interview facilitation style was intermediate, meaning the facilitator had a pre-defined list of open-ended questions designed to guide the discussions to ensure certain topics were covered consistently or probe participants to provide input when necessary (Fanning & Gaba, 2007). In certain cases, the discussions were paired with video playback to jog the participant's memory to recall specific traffic scenarios or interactions with the technology.

4.5.1.2 Think-aloud protocol

User testing was completed in Papers IV and V. The primary method to obtain user feedback in Papers IV and V was through a qualitative assessment called the think-aloud protocol or technique. The think-aloud protocol allowed the participants to verbalize their thoughts while completing a specific task, so that the researcher could gain insight into their decision outcomes (Fan et al., 2020). Both concurrent and retrospective verbal reports were completed throughout the data collection (van den Haak et al., 2003). The concurrent reports involved the participants speaking out loud throughout the scenario about what they saw and were challenged with pre-determined questions, if necessary. The retrospective verbal report was completed post-scenario and required that the participants reflect upon their experience, while they were probed by the researchers on elements of the data collection experience.

4.5.1.3 Informal discussions

The author does not have a background as a master mariner, yet navigation is the subject of study. To achieve a coherent description and analysis of this context one must immerse themselves in the field which includes, listening, observing, and constantly gathering information. During the data collection efforts, industry meetings and conferences, teaching and even lunchroom chats there have been countless informal conversations which have provided insight and enrichment to this research. Although informal conversations were not used as a primary method, they have been used to supplement and perhaps enhance data collected from the primary methods (Swain & Spire, 2020).

4.5.2 Layered-scenario Mapping Technique

Layered-scenario mapping was a method used to develop the scenarios in Papers IV and V. The layered-scenario mapping technique provided a framework to physically map out and discuss the critical aspects of the scenario including; the vessels position, mode of operation, the actors involved, communication (when and to whom), position on the bridge, equipment used, and the information and functionality necessary to carry out each task (Lurås, 2016a). This technique was completed based on information from accident reports from the Maritime Accident Investigation Branch (MAIB), and then discussed amongst the SEDNA SMEs to determine additional relevant information to the accident or convoy operation. Once the research team was satisfied with the map, it was taken on board a local icebreaker and used as a validation and communication tool to ensure all information was captured, and new insights were recorded.

4.5.3 Observations

Observations are one of the most valuable data collection methods in trying to understand or verify what practitioners actually do compared to what they say or think they do (Wickens et al., 2003). Observations are a key component of qualitative data collection to gain an understanding of "cognition in the wild" or naturalistic decision making (Hutchins, 1995). Observations were completed throughout all the data collections by SMEs and human factors specialists. These were often supplemented with video and audio recordings. In Paper I, the observer used pre-determined taxonomies (i.e., name of STM function, names of vessels, time, etc.) to capture the observations as efficiently as possible. Using taxonomies during observation is helpful to be able to condense the data and create meaningful descriptions of the observations (Wickens et al., 2003). In Papers IV and V, HF specialists observed the participants throughout the entire VR scenario. The test setup allowed the HF specialists to have the same viewpoint as the participants through the TV screen, while also observing their body language and movements. Any interesting observations were noted and added to the participant's observation records. Observations as a standalone method are generally not sufficient to understand the observed phenomenon (primarily cognitive tasks) and these were always complemented with other methodological tools.

4.5.4 Audio and Video Recording

Audio and visual recording was used for several aspects of data collection. Paper IV utilized audio capture when only one researcher was available during the data collection to ensure no details of the think-aloud protocol were missed. Audio-visual materials of the participants were captured during the simulator scenarios for Paper III. The purpose of recording these data were to understand how the participants interacted with the additional AIM screen, particularly in cases when it was difficult to understand the other captured data (e.g., interviews, questionnaire responses, or ship maneuvering). In many cases participants believe they are doing something when they in fact are not (WAD vs. WAI) and audio-visual material can help provide evidence of this (Hollnagel, 2012). Further, the ability to review footage allows for more freedom during data collection for researchers to facilitate and immerse themselves in the interview or data collection experience (Patton, 2002).

4.5.5 Questionnaires

Questionnaires can be classified as both qualitative and quantitative methods depending on whether the question is open or close-ended. Both types of questions were administered throughout Papers I, II and IV to measure operator perceptions. A basic demographic questionnaire was always administered prior to the data collection to obtain information about the sample, which sometimes asked the participants about their attitudes towards technology. Several post-scenario questionnaires were used to understand the participant's subjective rating and perception of the technologies tested. The questions were related to safety, perceived situation awareness, trust, risk, reliance, workload, and usefulness of technology. The close-ended questions included multiple choice, dichotomous questions, and various types of scaling questions. Two different online survey software tools were used to develop the surveys, Qualtrics (QualtricsXM, © 2019, Provo, Utah, USA, https://www.qualtrics.com), and Survey Monkey (Momentive software company, California, United States, https://www.surveymonkey.com).

4.5.6 Literature Study and Review

Conducting a literature search and review can be characterized as a methodology. Onwuegbuzie and Frels (2015) discuss that a literature review does not begin and end at the primary research study, rather it is a part of the entire research process (Onwuegbuzie & Frels, 2015). The literature reviewed and included within this thesis has contributed towards the development of the research questions, theoretical framework, methods and procedures, analysis, and future research directions. This component within the research process has resulted in the ability to understand and contribute to the existing gaps in knowledge within the studied field.

4.5.7 Simulator Data

Paper II used a software developed by Wärtsilä called NTPro https://www.wartsila.com/voyage/simulation-and-training/ntpro-5000-simulator to capture quantitative data from the ship movements. NTPro provides the user with automatically generated log files for each simulation. The data includes positions, speeds, position of targets, and rudder angles.

4.5.8 Subject Matter Expert (SME) Consultation

Throughout papers I-V, SMEs were involved in all project stages, from the initial development of the experimental design to the final review of the results. SMEs were consulted to improve researcher understanding during observations and analysis, and to improve questionnaire quality (Olson, 2010). SMEs are also contributing authors Papers I, II, and III and provided invaluable contributions towards Papers IV and V.

5 RESULTS

This chapter identifies the results from the five appended papers that will focus the discussions and conclusions in the next chapter of this thesis. Figure 9 presents an overview of how each paper has contributed towards answering the RQs.

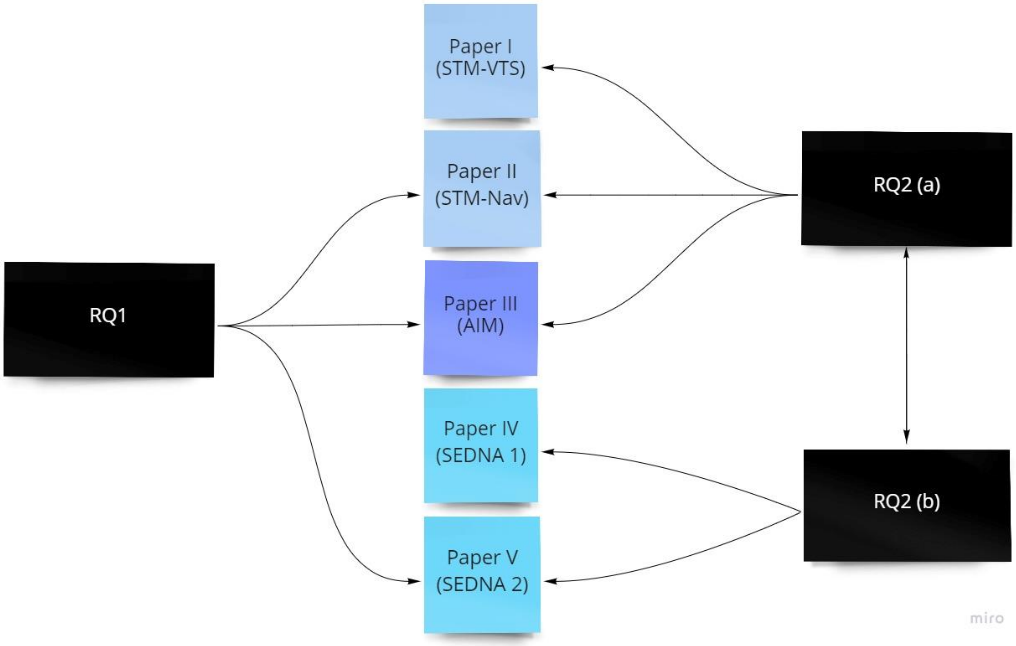

Figure 9 Summary of how the research questions connect to the papers

5.1 PAPER I RESULTS

The results from Paper I are about the VTS perspective and are considered in addressing RQ 2(a). The aim of Paper I was to evaluate the impact of information acquisition and information analysis decision support functions upon VTS operators. The most interesting findings are related to how communication or interaction could change between ships and VTS with the introduction of STM services (and presumably other decision support functions). The types of decision support functions were divided into two categories, indirect and direct interactions. Indirect interactions refer to tools used by the VTSO for planning and predicting traffic independently with their software, without directly communicating with the ship (this analysis is not included in the thesis but can be found in Paper I). Direct interactions refer to functions which allow the VTSO and ship to communicate between each other. In the baseline, the only means of direct interaction was VHF radio and in the STM trials, direct interactions included VHF, chat, and route suggestions from shore (a description of these functions can be found in section 4.3.1.1).

A comparison was completed of direct interactions between ships and VTS in the baseline and the STM trials. In both traffic scenarios, the total number of direct interactions increased (Figure 10). Although the total number of direct interactions increased from the baseline (VHF only) simulations to the STM simulations, the VHF communication decreased in both scenarios (this can be visualized by comparing the striped, blue bar with the solid blue bar).

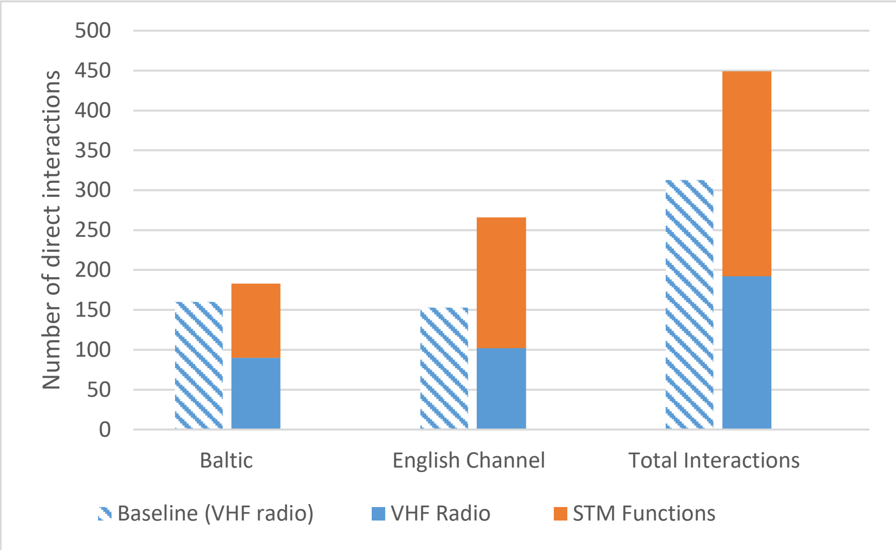

Figure 10 The number of direct interactions between ship and shore in both baseline (VHF only) and STM conditions (VHF and STM)

Results further indicate that decision support might impact operator performance through their workload. VTS operators-initiated interactions approximately 50% more often compared to the baseline (Table 4). This result points towards a more active VTS compared to the regulated carriage required equipment deployment. Several factors must be considered when interpreting the results on the overall impact on VTS work practices and performance. Compared with current navigation practices, the STM functions (i.e., route sharing, route review) can be utilized hours in advance, reducing stress upon arrival in port. This study was completed during a 1.5-hour simulation which could not take into consideration the continuous workflow of a VTSO. In real life, information sharing between ship and shore would be continuous, and the work would be distributed more optimally so that the VTSO can observe, intervene, and share information much earlier in advance.

Table 4 Initiation of interaction from ship or VTS operator

Who initiated interaction?	**Baseline**	**STM**
Ship Initiated	153	132
VTS Initiated	160	317

5.2 PAPER II RESULTS

The results from Paper II help answer RQs 1 and 2(a). The aim of this paper was to understand the impact of the ship-to-ship route exchange (S2SREX) on operators' perception of decision-making, trust, and overall safety. The results provide insight into understanding "work as done" or what the operators did, through a quantitative analysis. The quantitative assessment was completed to assess the positions of the ships in relation to CPA, distance when taking actions, and adherence to the COLREGS. The results from the numerical assessment show that in all cases when the operators used S2SREX, they acted with a greater distance from other ships, and ended up with a larger resulting CPA (NM) compared to baseline conditions (Table 5). COLREGs were breached more frequently in all scenarios when S2SREX was used compared to baseline conditions. While there were no collisions, the project navigation SME did not consider this to decrease safety limits.

Table 5 Quantitative assessment of baseline and experimental conditions

All scenarios	**Distance when acting (NM)***	**Resulting CPA (NM)***	**Breach of COLREG**
No S2SREX	3.6	0.9	2
with S2SREX	4.1	1.1	11
Means in meeting/overtaking scenarios 1, 2 and 4			
No S2SREX	2.4	0.7	0
with S2SREX	2.6	0.9	3
Means in crossing scenarios 3,5 and 6			
No S2SREX	4.4	1.1	2
with S2SREX	5.2	1.3	8

*NM is Nautical Miles

5.2.1 Perception of S2SREX

To understand the participants' perceptions of the S2SREX function, a questionnaire was completed at the end of each scenario. The participants were asked about their perceived situation awareness, and the potential impact of this decision support system on decision-making. From the operators' understanding of SA, 95.8% of participants believe that the S2SREX function improved their SA, and 67.6% of participants made a decision based on the information from the function. These values represent a clear perceived value in the ability to see other ships' intended routes. In addition to the post-scenario questionnaires, there was an end of the day questionnaire which asked more generic questions about navigation practices, trust, overreliance, and risk. These results include 24 responses from all 24 participants and are presented in Table 6. These results show that the participants value S2SREX and placed a high level of trust in the function, generally believing it has the potential to improve navigational safety. However, there are concerns related to the risks of over-reliance and potential misinterpretation of information. These concerns show potential consequences for navigation practices, communication between ships, and the ability for the existing regulatory framework to handle a new type of automation, even at the lowest level.

Table 6 Frequency distribution of end of the day questionnaires

Navigational Tendencies	**N**	**Extremely Unlikely**	**Somewhat Unlikely**	**Neither likely nor unlikely**	**Somewhat Likely**	**Extremely Likely**
Knowing the monitored route is broadcasted, do navigators follow their routes to a higher extent? (i.e., less willing to deviate from their route?)	24	1 (4.2%)	4 (16.7%)	10 (41.7%)	9 (37.5%)	0 (0%)
Tendency for a shift towards using the ECDIS (with S2SREX information) instead of ARPA/visual means when ascertaining the risk of collision?	24	0 (0%)	5 (20.8%)	2 (8.3%)	16 (66.7%)	1 (4.2%)
Trust		**Never**	**Sometimes**	**About half of the time**	**Most of the time**	**Always**
Do you consider S2SREX information as trustworthy?	24	0 (0%)	4 (16.6%)	3 (12.5%)	(66.7%)	1 (4.2%)
Risk and overreliance		**No risk**	**Low risk**	**Medium Risk**	**High Risk**	**Extremely High Risk**
Is there a risk that navigators put over-reliance in S2SREX?	24	0 (0%)	2 (8.3%)	8 (33.3%)	12 (50%)	2 (8.3%)
Is there a risk for misinterpreting data obtained from S2SREX?	24	0 (0%)	3 (12.5%)	12 (50%)	8 (33.3%)	1 (4.2%)

5.3 PAPER III RESULTS

The results from Paper III are directed towards answering RQ's 1 and 2(a). The aim of Paper III was to understand the navigators' perspective of employing a collision avoidance decision support system for navigation. This paper adopted a qualitative approach using interviews and a thematic analysis to understand the benefits and challenges of a collision avoidance decision support technology from the participant's perspective.

5.3.1 The human-automation Interactions

From an information processing perspective, the decision support system aided operators with information acquisition, information analysis, and decision selection. The system provides Level 1-3 of input functions from the automation framework and supports Levels 1-3 of SA.

- Level 1 (information acquisition & perception) organizing incoming data from surrounding ships
- Level 2 (information analysis & comprehension): mathematically predicting the most optimal route and the optimal time to act
- Level 3 (decision selection & projection): the system provides suggested manoeuvres to solve a traffic situation.

The navigators' indicated that decision support could positively impact their performance it supported their weaknesses (e.g., visualization and computation), allowing them to use their strengths (seamanship) to have a more accurate perceived situation awareness. The navigators also described the decision support as a tool which could confirm or challenge their existing mental model. Some participants likened the automation to human characteristics including "buddy", "co-pilot", and "consultant". Other participants used more direct descriptions; including "option generator", "thought checker", and "confirmation tool".

As a decision support system, the operator ultimately decides on the execution of the navigation manoeuvre. Understanding how the operator interacts with and uses the system is extremely important to ensure the system is used safely. The participants identified that there are risks related to complacency and over-reliance in the suggestions provided by the system, particularly for novice or inexperienced navigators. The participants also warned against implementing additional "tools" on the bridge without integrating existing bridge systems (*e.g.*, ECDIS) and ensuring navigators have an adequate understanding of the systems.

5.3.2 The Practice-Organizational Environment Interaction

The results indicate that seafarers are concerned about the potential impacts that collision avoidance decision support might have on navigation practices. The decision support system employed in this data collection evaluated navigational situations based primarily on mathematical calculations derived from the COLREGs. However, safe navigation is achieved through good seamanship, informal agreements, experience, and adherence to the formal rules (COLREGs). Adding decision support or increasing information exchanged between ships could complicate basic navigational scenarios which could otherwise be solved easily.

There were also concerns related to de-skilling and a potential loss of the "art of navigation" with the introduction of higher levels automation. There was an almost unanimous agreement that core navigational knowledge should remain an essential part of seafarer education in the foreseeable future. These challenges were identified as a problem even at this low-level of automation, where the operator is still in full control of the operational decisions. The results indicate that the challenges described in this paper could be much greater if not addressed in the early stages of MASS development.

5.4 PAPER IV RESULTS

The results from Paper IV address RQ 2 (b). The aim of Paper IV was to describe the design process and user testing through a framework called virtual reality reconstructed operational scenarios (VRROS) (Figure 5). This framework practiced the human-centred design principles that are widely discussed, but rarely implemented, in the maritime industry. This process connected end-users, designers, and human factor specialists in a joint process. Qualitative data were collected throughout the project and are summarized through a thematic analysis. The result was a framework for a design process, which explores how operational scenarios could be used as a tool for both concept development and user testing. The results reveal that VRROS can support maritime design processes through collaborative work and flexible solutions which were achieved through thinking "outside the box". A summary of the findings can be found in Table 7.

Table 7 Summary of thematic analysis from developing and testing the VRROS framework

Main Theme	Evidence
VRROS supporting maritime design processes	• Designing for safety-critical operations requires that designers have specialized knowledge in the specified domain, which is hard to obtain. VRROS allow a faster exposure and an understanding of a particular context. • Operational scenarios provide a collaborative, flexible opportunity to support the maritime design process. • VRROS have the potential to support new work practices in MET and to promote interdisciplinary work.
Sub-Themes	**Evidence**
VRROS as a collaborative tool	• Can be used as a strategic tool to create past, existing, or future scenarios. • Allow people from all disciplines to capture the essence of the working environment. • VRROS can be used as a support to make long-term decisions or to simulate an existing or future scenario, or concept. • There is a need for new methods and practices in the maritime domain; this paper provides a new approach to MET. • Technology today allows for interdisciplinary work to be completed more easily than ever before. • Developing novel concepts and solutions that are wanted and needed by end-users is impossible without an interdisciplinary team. • Novel concepts and new technologies could be tested first by using VRROS to check basic usability, prior to their implementation in real life. This could improve safety by allowing users to be involved much earlier in the design process, reducing many of the problems associated with new technologies on ships.
Flexibility of the process	• Ability to make design changes immediately (if necessary) to a scenario using cloud/remote technology. • Possibility to recreate any ship bridge design, and to test any concept or task. • Compared to FMBS, VR is inexpensive. • As VR is further developed, it will become less expensive and more adaptable. • Repeatable scenarios can support experimental studies and training efforts.
Potential of VRROS	• VRROS have the potential to help with MET for navigators, engineers, new cadets, experienced mariners, design students, and even project members who have not yet been exposed to a maritime environment. • No participants experienced any form of malaise while using the VR headset, even those participants prone to simulator or motion sickness.

5.5 PAPER V RESULTS

The results from Paper V support the discussion of RQ's 1 and 2 (b). The aim of Paper V was to test an AR concept for Icebreaker assistance and convoy operations on end-users. This was a ¨proof of concept¨ exercise of the VRROS framework developed in paper IV. In contrast to the technology-first approach within the maritime industry, this framework explores a user driven design process and AR concepts which were developed specifically for this operational context. Ice navigation requires focus on the visuals, feel of the ship, feedback from the engines, and ice movements according to ship movements. Today in a convoy operation, there is a high risk of miscommunication and misunderstanding within the inter and intra-ship communications. The AR concept would allow the navigator to stand on the bridge wing to look out the window while also being able to see the critical operational information about each ship in the convoy, along with others present on the bridge. When asked if the AR concepts could reduce the risk of a convoy-related accident, six out of seven participants agreed that the risk of an accident would be reduced, and one participant was torn between the benefits and risks of the technology.

The participants were optimistic about the further development of AR, indicating that the potential risks of information overload and distracting visuals should not be underestimated, particularly in high-traffic areas. The participants strongly advocated that these types of solutions must be flexible and customizable for individual operators and for specific operations (e.g., convoy). Some of the AR solutions (widgets) caused confusion for the operators, which reiterated the importance of a continuous collaborative design process. These comments were reported directly back to the design team and the next iteration of the AR solution was easier to understand. This process reflected the flexibility, adaptability, and collaborative benefits of this framework as described in Paper IV. The participants also highlighted interesting future developments for VRROS and AR concepts for training, and exposure particularly for less experienced operators. Given the complexity of convoy operations, using VR as a tool to provide cadets with exposure to this type of situation could be very beneficial. Overall, the user-testing revealed that the AR concept demonstrated potential to improve safety during convoy operations in Arctic waters. The primary benefits highlighted by the participants were that the AR concept can integrate currently distributed information, decrease the chance of miscommunication within and between ships, and possibly improve operator SA.

6 DISCUSSION

The purpose of this research program has been to understand how decision support is used and perceived for navigation and navigational assistance. This chapter begins with a short summary of the work, followed by the identification of the results critical to answer the research questions. The discussion then proceeds with a broader lens examining the impact of automation and decision support on the wider maritime sociotechnical system and suggestions as how to move forward towards a safer maritime industry. This chapter is finalized with a discussion about the methodological choices and overall research.

6.1 GENERAL SUMMARY

The transformation of the shipping industry as part of Shipping 4.0 is well underway (Aiello et al., 2020). The use of decision support for maritime navigation is one of the first steps in the journey towards MASS. Lower levels of decision support require active involvement from the human operator in decision selection and full responsibility for action implementation. Understanding how decision support is used by operators and its potential impacts on the maritime sociotechnical system represent the growing knowledge gaps addressed in this thesis. The outcome of this work has shown that operators perceive that decision support will impact their work, but not necessarily as expected. There is a need to better understand work as it is done from the user's perspective. This can be achieved through an interdisciplinary, user-driven, flexible, and iterative approach. This process will help reduce the gaps between WAD and WAI and hopefully improve the usefulness of maritime technologies, as this is critical to achieve safety and efficiency in the shipping industry. The research questions are answered in the following sections.

6.2 ANSWERING THE RQ'S

6.2.1 RQ1

RQ1: How do operators perceive decision support technologies for navigation?

RQ1 is intended to elucidate how operators perceive the utility of decision support technologies for navigation. This answer is related to their perception of how decision support might impact their performance, SA, and overall safety. The data used to answer this question is gathered from 50 practitioners (see Papers II, III and V) which has led to a thematic analysis approach to understand how operators perceive different types of decision support.

Results from Papers II (STM-Navigation), III (AIM) and V (SEDNA) have identified how decision support could impact both negatively and positively their performance, decision-making and work as it is performed. Decision support could contribute towards improved performance as (1) the operator is actively involved in the decision process with access to additional information about other ships, keeping them in-the-loop (2), the technologies gathered and computed relevant information which was then visualized showing potential outcomes of navigational situations, supporting, or possibly biasing information processing and perceived SA. The results also suggest that decision support could have negative outcomes including (1) human-automation interaction issues related to trust, reliance, and complacency

(2) decision making in basic navigational scenarios might become more complicated in the existing regulatory framework.

6.2.1.1 Positive perceptions

The level of automation that includes decision support technologies studied in this thesis allow the operator to remain in the loop as they are responsible for the outcome decision and action execution. This type of HAI can be categorized as “agent-generated proposals”, where agent is interchangeable for automation (van de Merwe et al., 2022). For this type of automation, transparency and system opacity, or communication to the user about how, what, and why, information is being presented, is important (Helldin, 2014; Lee, 2008; Westin et al., 2016). For agent-generated proposals, recent research has shown positive effects of automation transparency on operator performance, SA, and mental workload (to a lesser extent) (van de Merwe et al., 2022). Greater transparency means there is greater understanding and predictability of the system allowing the operator to better evaluate whether to use the information instead of trying to evaluate why it was presented. In Paper II, the participants were positive towards exchanging information between ships, as this could improve their SA by reducing assumptions about other ships intentions. The inability to anticipate the actions of another ship is another causal factor in ship collisions (Langard et al., 2015; Wickens et al., 2020), therefore, the use of route sharing, and suggested route manoeuvres was described as positive. In Paper V, the operators believe that the AR information could lead to improved SA, and overall safety. The AR information was greatly appreciated because it was context specific and based on real convoy operations and user input.

From an information processing perspective, decision support automation is intended to support human sensory processes, working memory and inferential processes (Parasuraman et al., 2000). The different decision support systems achieved this through functions which organized incoming information from distributed input sources (supporting Level 1 SA, perception), analysed the information through computation (supporting Level 2 SA, comprehension), and visualized the potential outcomes of a situation (supporting Level 3 SA, projection) (Endsley, 1995). These tasks can be challenging for human operators, particularly visualization and computation (Endsley, 2017b; Lee, 2018). Therefore, the additional support of visualization and computation through either route exchange (Paper II), route suggestion (Paper III), or augmented reality concepts (Paper V) was perceived positively by users and thought to contribute to improved perceived SA and overall decision making. In Paper III, the decision support was described as having “blunt” functionality which through mathematical calculations, provided support through a strict application of the COLREGs. The navigators believe that even this basic, blunt functionality has an important role in the safety of navigation.

6.2.1.2 Negative perceptions

Papers II and III suggests that the integration of information systems should be prioritized instead of adding/overlaying of new functions or systems, a sentiment that was echoed in the Application and Usability of ECDIS report (MAIB, 2021). There are ongoing efforts to adopt standardization for navigation systems in the OpenBridge project (Nordby et al., 2019) (Chapter 2), and efforts to advocate for the integration of information in existing ship navigation systems using grouping patterns (Vu et al., 2022). The results from Papers II and III indicate a need for additional user testing prior to implementation to reduce the exposure to automation biases and automation complacency. The content, format, interface and usability of technology have a powerful impact on trust, even if this is not associated with the true capabilities of the system (Corritore et al., 2003; Lee & See, 2004). Results from Paper II reveal that the operators placed a high level of trust in the information, yet identified a high risk of over-reliance on information, and a medium-high risk of misinterpreting information from the decision support (Table 6). Paper III identified similar risks of complacency depending on how the decision support system is used. For example, the operators indicated that a higher level of system transparency (*e.g.*, how, and why suggestions were presented) would be desirable to be able to evaluate the information from a more informed perspective as there is a hesitancy to trust and rely on a "black box" system. Simultaneously, they identified a risk of over-trusting systems and failing to thoroughly evaluate the navigational situation suggestion, particularly in novice navigators. These issues related to trust, reliance, and other HAI concepts are rarely considered in the maritime domain, and there is a need for additional research to understand the eventual operator interactions with the automation in the early stages of its development.

Maritime accident data indicates that 56% of collisions at sea are caused by violations to the COLREGs (Liu et al., 2016; Ramos et al., 2019; Statheros et al., 2008). The results from Paper II found that although operators acted earlier and with a larger distance (CPA) to other targets, COLREGs were breached more often when decision support was used compared to baseline trials (Table 5). Although SMEs did not determine any unsafe situations, there is a need to understand what this means for navigational safety and integration of future automated technologies. Similar results were identified in Paper III where decision support seemed to complicate the decision-making process, possibly leading to false assumptions about other ships' intentions. These decision support systems project a future state of events which is based on accurate input data and the assumption that ships are following the data they are broadcasting. In Paper III participants indicated that seamanship and the COLREGs are heavily intertwined and referred to seamanship as "a floating abstract norm". The use of seamanship throughout the COLREGs, raised concerns about how seamanship, a term difficult to define in practice can be applied by an algorithm. The ship scenarios in Paper III were designed to be simple, involving only three-ships, however, live traffic situations would be far more complex and dynamic. There was little need for seamanship, or informal agreements, as the solutions were primarily rule-based as defined in the COLREGs. Many operators indicated that they probably wouldn't use this functionality in busy waterways. Testing decision support in more complex, challenging traffic situations is necessary to understand how their decision making and understanding of the traffic situation is impacted.

There are elements within each of the decision support systems studied throughout this thesis that should be further developed and considered for long term implementation. However, the decision to automate previously manual functions must be evaluated from a more holistic assessment (Parasuraman et al., 2000) and understanding of work as it is done (Hollnagel & Leonhardt, 2014).

6.2.2 RQ 2(a)

RQ 2 (a) What are the gaps between the design and use of decision support technologies?

RQ1 has identified how the operators perceive decision support technologies which has provided insight into the gaps between the design or intended function of decision support and their use in practice. Papers I (STM-VTS), II (STM-Navigation), and III (AIM) provide evidence towards a discrepancy between the system task description (WAI) and the everyday work (WAD) (Hollnagel, 2017b). The results indicate that technology intended to improve the operator's job and provide support may complicate, confound, or disrupt decision-making and communications processes. Marketing of decision support should not target inexperienced operators and should only be used by more skilled and well-trained operators.

6.2.2.1 Complicated decision-making

Formal rules and procedures for maritime operations should describe how work should be done; yet studies in the maritime context repeatedly demonstrate that mariners and VTSOs succeed in their goals (i.e., safe navigation) differently than formally prescribed procedures and rules (Anders Brödje, 2012; Costa, Lundh, et al., 2018b; Man, 2019; Praetorius, 2014b). The decision support system studied in Paper III is intended by the manufacturer to close the skill gap between individual operators to support the less competent/skilled operator. The results show that the operators perceived the role of the decision support system as a basic "buddy" or "blunt" option generator which could be used as a confirmation tool. This description led to most navigators believing that the individual's skill and knowledge of COLREGs was even more important and that this support should only be used by the most skilled/experienced operators. Similar findings were reported in Paper II, it seems that the grey zone of "safe navigation" is much larger than it previously was. If all ships are following the COLREGs with similar technology onboard, then the risk should be reduced unless certain ships deviate from the accepted rules. However, the addition of a route exchange, or route suggestion services allows for assumptions about other ships, a more complex interaction involving trust, reliance, and acceptance of information from the technology (Tables 5 and 6).

6.2.2.2 Disruptions in communication

Ideally, decision support systems should enhance SA, keep operators in-the-loop, and improve performance/outcomes. Unfortunately, the intended use is not always the reality in practice. Paper I tested several alternative means for VTSOs to share information, monitor traffic, and ¨chat¨ with ships. These technical solutions will change the way ship and shore operators interact with one another. The interactions between ship-shore increased when decision support was available compared to the baseline (Figure 10) and the increase was attributed to the VTS operators initiating contact with ships (Table 4). While the total frequency of ship-shore interactions increased, the VHF interactions decreased (Figure 10). Decreasing VHF communications and replacing it with another means of communication (i.e., chat) could considerably disrupt the ship-shore and ship-ship communication and feedback loop. All existing research studying work practices of VTSOs, bridge officers (or both) focus on VHF radio as the foundation of maritime communications as it was the only available means of communication (Anders Brödje, 2012; A. Brödje et al., 2013; Anders Brödje et al., 2010; Lützhöft, 2004; Lützhöft & Dekker, 2002; Praetorius, 2014b; Praetorius et al., 2015). VHF radio conversations are used by VTSOs and surrounding traffic to obtain important information, the status onboard other ships, and a general shared awareness and common ground of the surrounding traffic (Anders Brödje, 2012). A ¨chat¨ function, for example, could isolate the conversation between two parties (i.e., two ships or ship and VTS) which could change or disrupt the existing communication practices. A further disruption may be an increase in operator workload if they had to repeat information to other ships, while considering the possibility of typos or redundant/obsolete information. Whether the disruptions are positive or negative, it is important to better understand how this type of decision support will affect the actors, teams, and organization within the sociotechnical system(s). Further research is needed to better understand the role of the VTS and their place in MASS Degree 1 and 2 as certain responsibilities may shift towards the shore.

6.2.3 RQ 2(b)

RQ 2 (b) How to identify and reduce the gaps between the design and use of decision support technologies?

The gaps between the design and use of new technologies (decision support) are addressed in RQ 2 (a). These gaps have been possible to identify through understanding how operators perceive two different decision support systems that were developed through top-down, technology-driven processes, instead of bottom-up and user-driven. It is evident that involving users at the end of a design process will introduce challenges in how the system is used (Costa, 2018; Gernez, 2019; Grech & Lutzhoft, 2016). An understanding of WAD is necessary to reduce the unexpected outcomes and discrepancies between the design and use of new technology (Hollnagel, 2017b; Hollnagel & Leonhardt, 2014). Paper IV (SEDNA) presented a user-driven, interdisciplinary framework which can be adopted to identify and reduce these gaps (Table 7 and Figure 5). Paper V (SEDNA) was a "proof-of-concept" exercise which tested the VRROS framework. The results show that AR is a welcomed technology for maritime operations because of the ability to integrate important operation specific information and access it from around the bridge. Operators found that this technology has the potential to improve SA and overall safety during polar convoy operations.

Identifying the gaps in the design and use of decision support technology is challenging and closing these gaps is difficult. The framework presented in Paper IV begins with the user's context which was assessed through an ethnographic inquiry to understand how work is done (Table 7). This process developed solutions that are needed by the operator in specific operational contexts, an approach unique from most other decision support solutions marketed today for navigation and navigational assistance. The use of VR provides a flexible, iterative, cost-effective, and interdisciplinary working space for stakeholders (Renganayagalu et al., 2021). The feedback loop is continuous between users and designers to improve solutions based on user feedback. In this framework VR was used to test AR solutions, representing only two possible combinations of technologies from the ever-growing immersive reality industry.

Paper V identified that the AR concept could reduce several of the risks associated with convoy operations in ice-covered waters. This operational-specific information was derived from the user's context and designed according to their needs. Having access to relevant operational-specific information all around the bridge in a heads-up display allowed operators to check around the ship for physical environment changes. The concepts developed in Paper V were a step towards a reduced gap between WAD and WAI. There are always risks with adding more information or new technology to a work task (Lee, 2018), therefore, the participants believe that if AR will become more common on-board, there is a need for the solutions to be adaptable between operators. This framework is a starting point which combines currently available solutions to practice HCD, as shown in Paper V. This approach can be seen as a "plug-and-play" system which can support any sort of human performance testing, including eye tracking, SA assessments, workload evaluation, and team interactions. It also allows for repeatable scenario-based testing which will improve the reliability and validity of using AR/VR systems in the maritime domain (Menck et al., 2013). Moving towards the approach presented in Papers IV and V will reduce the gaps between the design and use of new technologies for maritime applications.

6.3 SYSTEMS PERSPECTIVE: DECISION SUPPORT AND MARITIME STS

Zooming out from the individual research questions is necessary to consider the wider impacts of decision support on the maritime STS. *"Sociotechnical theory is as concerned for the experience of humans within systems as it is with the system's ultimate performance"* (Walker et al., 2008). This thesis has explored beyond the individual-technology node interactions within a STS (Grech et al., 2008). The data shows that the top-down, technology-first approach to develop assistive technology is not working. The intentions of the technology manufacturers do not match the needs of the users, resulting in an increasing gap between WAD and WAI. Closing the gap between WAI and WAD requires thinking beyond a singular method, framework, or approach. A true systems perspective may be achieved if design, and technology development for maritime applications are (1) driven by user needs (2) based on WAD (3) developed within an interdisciplinary team and as part of an iterative, continuous design and development process (4) communicated between stakeholders and (5) the design and development process should utilize technology that is flexible, time and cost efficient (AR/VR). While a challenging methodological framework, it should improve the opportunities for new technologies to emerge within a larger STS.

6.3.1 Maritime Safety

Chapter 2 summarized research which investigated the causes of maritime accidents, highlighting the contributary role of technology (Acejo, 2018; Chen et al., 2022). Certain elements of navigation have and will continue to become more automated, resulting in some positive outcomes for safety. For example, users believe that ECDIS has reduced workload compared to manual plotting (MAIB, 2021), and information automation for navigation can free up time for operators to complete other navigational tasks (Aylward, 2020). This thesis work builds on this limited body of work studying lower levels of automation (decision support), and early adoption of MASS and found that while some functionality of decision support may enhance safety, there could be equally as many unexpected and potentially unwanted outcomes. These outcomes will change the interactions between all the elements within the SEPTIGON model (Grech et al., 2008), resulting in changes for individual operators, teams, operational environment, regulatory environment, and how the STS achieves safety. Therefore, while the goal of decision support is to increase safety and improve operator performance, this thesis provokes the question whether this is really the case?

How operators achieve safety within complex STS is critical to understand (Flach, Feufel, et al., 2017; Hollnagel & Leonhardt, 2014). To do this, there may be a need to re-evaluate how we approach the current challenges in the maritime industry including; a true shift towards systems-based "information age" thinking (Walker et al., 2008), extending our conceptualization of what constitutes a system (Davis et al., 2014), re-evaluating how to measure human performance metrics within STS (Stanton et al., 2015), and focusing greater efforts on the understanding interactions between agents and humans (Behymer & Flach, 2016). In terms of understanding safety, there is already a shift towards Safety II, focusing on positive outcomes and an understanding that performance variability is not a threat (Hollnagel, 2017b). To meet the demands of Shipping 4.0, a shift in approaching safety is considered as an important step towards a safer future. The VRROS framework presented in Papers IV and V is just one example of how it is possible to safely develop and test technology that is cost efficient, flexible, and available today. VR is quickly evolving (Renganayagalu et al., 2021), and although AR may be a long way away from being approved for on-board use, the utility of immersive technologies for maritime safety cannot be ignored.

6.4 FUTURE OF SHIPPING 4.0 (FUTURE RESEARCH NEEDED)

There exists a conflict between the push towards autonomy and the pull by maritime industry stakeholders. The exponential rate of technology development presents difficulties in anticipating the future of maritime operations (Aylward, 2020; Mallam, Nazir, & Sharma, 2019). This thesis has identified gaps between WAD and WAI that will impact the *near* future of a mixed human-automation STS. These gaps motivate research areas and questions that should provide direction for future research. A mixed methods approach should be adopted in future research to obtain a more holistic assessment of the research problems. Although by no means exhaustive, future research areas/questions can be grouped into regulation, standardization, and the future seafarer.

6.4.1 Regulation

This thesis has highlighted that decision support may complicate decision making within the existing regulatory framework. The shift towards higher levels of MASS seems to be outgrowing the prescriptive nature of the COLREGs (WMU, 2019). In addition to challenging the way STS are described and evaluated, there may need to re-define the existing regulatory frameworks towards goal/performance-based outcomes. The findings within this thesis contribute towards a discussion about the formal and informal regulations. In Paper I, the communications and interactions between ships and shore changed. The question remains as how will changing communication between ship-shore impact navigational situations on a larger scale? Do the current regulations governing VTS, and navigation allow for such changes? In Paper II, having decision support caused mariners to break more formal rules (COLREGs). This was the result of the addition of simple or low-level automation consisting of route sharing. Moving towards higher levels of automated technologies involves the development of algorithm-based solutions to work within human-operated and regulated environments. Questions remain about existing regulation; are the COLREGs in their current form the most appropriate to address the upcoming mixed human-automation state or would it be better to develop new regulations? Will decision support cause mariners to break more formal rules and rely more heavily on seamanship/informal rules? The informal and formal systems in maritime traffic systems already exist today, so the addition of automated technologies will likely exploit these differences. There is a need to address these questions which are relevant now while the uptake of such technologies is still mostly a discussion and not widely implemented. Future research should consider the upcoming mixed human-automation types and levels, working together in the same system and how this should be regulated (Dominguez-Péry & Vuddaraju, 2020; Endsley, 2017b; Janssen et al., 2019).

6.4.2 Standardization

Standardization has been a long discussed and disputed topic in the maritime industry. The advent of Shipping 4.0 brings with it a host of challenges, many circling around how standardization should be addressed. The lack of standardization allows for a “vacuum of space” (Man, Lundh, et al., 2018) in which manufacturers and service providers continue to develop solutions that are not integrated. Lützhöft’s (2004) ethnographic doctoral thesis work concluded that the bridge systems are poorly integrated from both human and technical perspectives, and human operators must bridge these gaps through co-operation, co-ordination and compromise (Lützhöft, 2004). Almost twenty years later Papers II and III have shown that mariners are hesitant to accept new decision support functions while existing systems remain non-integrated (Aylward et al., 2020). The OpenBridge project is an example of how it is

possible to design consistent user interfaces across multi-vendor systems, which include user-interface guidelines that are available open-source (Nordby et al., 2020). The OpenBridge navigation systems were used in Papers IV and V and participants were all in agreement that consistent user interface design is a necessary next step towards overall ship safety (Aylward et al., 2021; Frydenberg et al., 2021).
The issue of standardization extends beyond onboard navigation systems. The shipping industry has been criticized for its lack of transparency and inability to agree on industry-wide definitions, particularly for the levels and types of automation (OneSea, 2022). The MASS framework defining four degrees of autonomy while helpful, are limited in detail and thereby usefulness in developing regulatory frameworks. Stakeholders within the maritime industry have adopted their own interpretation of autonomy for ship functions with varying degrees of detail (ABS, 2022). While still at this early stage of MASS Degree 1, definitions across the industry should be standardized. There is also an argument that the levels of automation themselves may be too siloed and cannot meet the complexity of the systems (Kaber, 2018). There is a lot of future research needed to find solutions to address standardization within Shipping 4.0. If standardization is to become a reality, the standards must be resilient enough to withstand the rapid growing future technology landscape and consider how work will evolve.

6.4.3 Future Seafarers

The skills, training, and role of the *future seafarer* has been identified as a high priority for IMO (IMO, 2021). The future competencies of seafarers and their role within the maritime ecosystem has been an important area of research interest over the last decade (Baldauf et al., 2019; HVL, 2021; Kim & Mallam, 2020; Mallam, Nazir, & Renganayagalu, 2019; Man et al., 2015). The IMarEST MASS Special Interest Group (MASS SIG) has an ongoing investigation attempting to understand the role, skills, and responsibilities of the "future seafarer" while also identifying the major gaps to better prepare the industry for the next 10-30 years. This working group identified that *"the starting point for automating functions and tasks is to capture the tacit knowledge of human seafarers who currently operate vessels. This must be understood before the technology can be fully developed"* (Meadow, 2019), a task which this thesis attempted to support with. This work also questioned the human and machine interface status for various roles on board (i.e., administration, physical maintenance, etc.) for the years 2030 and 2050, highlighting that the role of the human operator whether on shore or on board will remain critical in maritime operations (Meadow, 2019). Today there is a feeling of uncertainty and insecurity for workers in the maritime industry. This situation is driven by business cases to increase efficiency and the blame culture in the maritime industry (Miyoshi et al., 2022). This attitude represents a valid concern and one that resonates strongly with workers in industries that are introduced to increasingly automated systems (Brynjolfsson & McAfee, 2014).

The role of the seafarer has already changed and will continue to evolve. The data obtained throughout this thesis contributes towards this complex discourse to highlight that the role of the seafarer during MASS Degree 1 must not be ignored. The simple addition of decision support does not equate to clear improvements in performance, instead, there is a possibility of skill degradation, complacency and more complex HAI challenges (Lee & Sanquist, 2000). The future seafarer will most likely possess a more diverse set of technical and non-technical skills than today, including increased focus on IT solutions (MacKinnon & Lundh, 2019; WMU, 2019). How to define, educate and maintain these skills remain challenging research questions. Papers IV and V highlight the potential of immersive technologies to support training and skill development. There is a need to take advantage of the existing technologies to build solutions that are based on user needs. These adopt a human-centered approach and are highly essential throughout the transition towards the future shipping industry.

6.5 METHODS DISCUSSION

This thesis adopted a pragmatic exploratory approach towards understanding the research questions. Understanding complex human phenomenon requires approaching the problem from various perspectives. The mixed methods approach of this thesis included some quantitative data, but the results are heavily based in qualitative inquiry. The drift towards the adoption of qualitative methods was natural in the research process. There is a need for the greater use of qualitative methods to move towards HCD solutions and understanding how work is done onboard. Traditionally, in human factors research, performance is measured quantitatively through standardized questionnaires (*e.g.,* NASA-TLX (workload), SAGAT, SART (SA)) or similar (Endsley et al., 1998; Salmon, Stanton, et al., 2009). However, operator performance is difficult to measure and there have been inconsistencies within and between methods (Salmon, Stanton, et al., 2009). When using standardized questionnaires, it is suggested to include other types of methods including qualitative interviews. The studies throughout this thesis evaluated safety critical operations, and interrupting the flow of work was not desirable, therefore, more nonintrusive, naturalistic methods were chosen (Stanton et al., 2015). As part of natural decision making (NDM) theory, experts are evaluated primarily based on qualitative measures, including observations, peer feedback and performance judged as a comparison between operators (Kahneman & Klein, 2009).The primary benefits of using qualitative data were to:

- Capture the richness and holism of a person's experience
- Obtain "thick descriptions" that are vivid
- The ability to collect data over a sustained period, going beyond "how many times"(Miles, 2020; Patton, 2002)

Different means of qualitative inquiry were utilized to obtain results from various perspectives. For example, SME consultation was used consistently throughout all papers as a "quality check" to ensure accuracy of navigational information, experimental set up, and interpretation of the results. However, given the closeness of the SMEs to the research process it may be difficult to objectively provide a non-biased perspective. Therefore, informal discussions with maritime stakeholders who were not directly involved in the research process were used as a supplementary method. These methods complimented the results from participant interviews and allowed for a broader perspective in understanding and interpreting the data. This thesis demonstrated the discrepancies between WAD and WAI using mixed methods, however, future studies should consider a deeper qualitative investigation into why there are differences between WAD and WAI. The framework provided in this thesis could allow for a deeper evaluation into any element of the findings and afford replication of results and validation of research activities.

To yield meaningful results for qualitative research, it is important to consider the quality of the data analysis. Reliability and validity are most associated with quantitative data, while "trustworthiness" is the equivalent term used in qualitative research to evaluate the traceability and verification of the analysis (Nowell et al., 2017). This research adopted a thematic analysis to analyse the data, which followed the Braun and Clarke (2006) six step process (Familiarization of data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and writing the report) (Braun & Clarke, 2006). In addition to following a procedure, two researchers were always involved in the qualitative analysis to improve the objectivity of the data analysis. Two software programs, MAQDA and NVivo were used to increase transparency, and traceability of the results. The qualitative analysis was considered complete when saturation was reached (Miles, 2020). The methodology is described in detail in each of the appended papers and summarized in this thesis to encourage repetition of the experimental design.

The selection of participants can influence the quality of the research. Purposive sampling, also known as judgment sampling, is a non-random technique used when the researcher needs the participants to have certain qualities, skills, knowledge, or experience (Silverman 2011, Etikan, Musa et al. 2016). In all studies purposive sampling was used to recruit professional mariners (active or recently active masters, mates, officers, and maritime pilots and VTS operators), or fourth year master mariner students as test participants. Participants were recruited through various social media platforms, professional maritime organizations, maritime academies, and word of mouth. Part of the data was collected during the COVID-19 pandemic which caused recruitment to be limited primarily within Chalmers for Papers IV and V. It is possible that this limitation yielded different results than if the sample was taken more broadly from Swedish maritime organizations. This situation also resulted in having more fourth year Master Mariner students than originally anticipated. While this could be considered a limitation, it is also acknowledged that to obtain more holistic results and achieve a better understanding of WAD, the population sampled should include a wide range of ages and experience (Hollnagel & Leonhardt, 2014). Papers IV and V pre-test questionnaire queried about experience with VR, and attitude towards automation. However, a consideration for future research in similar studies would be to include more questions about the participants' history, experience, interest, and attitude towards technology and automated solutions. It is possible the participants´ exposure and familiarization with gaming, computers, and technology in general influences their acceptance of automation in navigation practices. The potential impact this could have on the results would be interesting to better understand.

Ecological validity is defined as the extent to which the research findings can be generalized to real-world settings (Creswell & Clark, 2017). The use of simulation for each of the studies has provided the closest naturalistic situated setting for research, aside from being on board a ship. Mariners are familiar with simulator exercises for training purposes, and fulfil the STCW convention's requirements (IMO, 2011; Sellberg, 2018). However, the individual papers have tested "ideal" situations of all ships sailing in an area equipped with the same functions, knowledge (i.e., familiarization), level of training, and a heightened level of safety given the context of the study (i.e., simulation). When the technologies are further developed, there is a need to determine the transferability of the results to reality.

7 CONCLUSIONS

This thesis has addressed two aims (1) an investigation of how decision support will impact navigation and navigational assistance according to operators and (2) an exploration as to how to reduce the gaps between the design and use of decision support technologies. This thesis has focused on how work is done, and results are discussed from a sociotechnical system perspective. The main findings from this thesis are:

- Decision support technologies will change work as it is performed, in different ways than anticipated. The positive aspects of decision support for navigation and navigational assistance are associated with the technology supporting cognitively challenging tasks, visualizing relevant information about surrounding traffic, and keeping operators in-the-loop, contributing to a better perceived SA.
- Some of more negative outcomes of the use of decision support are that operators perceive that decision support functions may encourage risky behaviours, complicate decision-making, shift workload from ship to shore, and introduce a multitude of HAI issues.
- This thesis found gaps between the intended design/purpose and use of decision support technologies in practice. The gaps and unexpected outcomes associated with the introduction of decision support are attributed to the systems being developed from a top-down design process instead of bottom-up, grounded in the user's perspective and based on WAD.
- From a systems perspective, decision support will impact the role of the seafarer, the interaction between ships, the interactions between ships and shore, communication practices, conformance to the COLREGs and overall navigation practices.
- The decision support systems tested throughout this research should carefully consider their target users. This work has shown that there is a higher risk if the systems are used by inexperienced operators and should primarily be considered for use by more skilled and well-trained operators. Participants expressed concerns around decision support systems being used for decision-making, something they are not designed to do.
- Maritime research should prioritize interdisciplinary work, systems-thinking, and a shift beyond the current reactive, technology-first approach. The VRROS framework is one example of how to meet these challenges. Relevant technologies such as VR, AR and mixed reality are proposed as viable tools for automation design, development and testing for maritime applications. These technologies are flexible, adaptable, and cost effective.

There is a need for a deeper investigation of how different levels and types of automation will impact all the elements of the maritime sociotechnical system. This thesis has identified several challenges associated with automation design and development that are necessary to consider. If these challenges resulted from the introduction of low-level decision support/ MASS Degree One, how is the future development of automation going to evolve? Now is the time to address these challenges so that the future design, development, and implementation of automation for maritime applications is useful. This thesis has provided several solutions to meet the challenges which should be considered to close the gaps between WAD and WAI. As the industry evolves towards increasingly automated solutions, the system will continue to become more complex. Thus, to maintain safe and efficient maritime operations we must commit to a dynamic discovery process as it will likely become even more challenging to unravel the complexities of the maritime sociotechnical system.

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