THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSPHY

Automated Functions: Their Potential for Impact Upon Maritime Sociotechnical Systems

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Gothenburg, Sweden 2020

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Report no 2020:01

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Printed by
Chalmers Reproservice
Gothenburg, Sweden 2020

ABSTRACT

The shipping industry is evolving towards an unknown and unpredictable future. There is speculation that in the next two decades the maritime industry will witness changes far exceeding those experienced over the past 100 years. The rapid development of artificial intelligence (AI), big data, automation and their impacts upon fully autonomous ships have the potential to transform the maritime industry. While change is inevitable in the maritime domain, automated solutions do not guarantee navigational safety, efficiency or improved seaway traffic management. Such dramatic change also calls for a more systematic approach to designing, evaluating and adopting new solutions into a system. Although intended to support operator decision-making needs and reduce operator workload, the outcomes might create unforeseen changes throughout other aspects 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 and challenges of humans and automation, as it pertains to navigation and navigational assistance, is explored throughout this licentiate.

This thesis considers the Sea Traffic Management (STM) Validation Project as the context to examine low-level automation functions intended to enhance operator (both Navigators and Vessel Traffic Service Operators) navigational safety and efficiency. The STM functions are designed to improve information sharing between ships and from ship to shore such as: route sharing, enhanced monitoring, and route crosschecking. The licentiate is built on two different data collection efforts during 2017-2018 within the STM Validation project. The functions were tested on two user groups: Bridge Officers and Vessel Traffic Service Operators. All testing was completed in high-fidelity bridge simulators using traffic scenarios developed by subject matter experts.

The aim of this licentiate is to study the impact of low levels of automation on operator behavior, and to explore the broader impact upon the maritime sociotechnical system. A mixed-method approach was selected to address these questions and included the following: observations, questionnaires, numerical assessment of ship behavior, and post-simulation debrief group sessions. To analyze and discuss the data, grounded theory, subject matter expert consultation, and descriptive statistics were used. The results point towards a disruption in current working practices for both ship and shore operators, and an uncertainty about the overall impact of low-level automation on operator behaviour. Using a sociotechnical systems approach, gaps have been identified related to new technology testing and implementation. These gaps relate to the overall preparedness of the shipping industry to manage the evolution towards smarter ships. The findings discussed in this licentiate aim to promote further discussions about a quickly evolving industry concerning automation integration in shipping and the potential impact on human performance in safety critical operations.

Keywords:

Human-automation interaction, maritime navigation, safety, automation, situation awareness, decision-making, sociotechnical systems, e-Navigation

ACKNOWLEDGEMENTS

I would like to extend my deepest gratitude to my supervisors Dr. Monica Lundh and Professor Scott MacKinnon. Their continuous advice, support and encouragement throughout this process have guided me through the first half of my Chalmers journey. They are always ready with chocolate, coffee, and a smile to keep me going when the going gets tough.

I want to thank everyone involved in the Sea Traffic Management Project for the incredible learning opportunity it provided. This was my first undertaking as a PhD student, and I had to learn fairly quickly how EU projects work. A special thank you to project members Reto Weber and Anders Johannesson who are my resident experts for all things navigation. I have learned so many things about maritime navigation through our discussions and observations. I truly value your feedback and wisdom. Of course, this work would not be possible without participants who are willing to share their experiences and feedback. A heartfelt thanks to you all!

Thank you to the staff at Chalmers; Lotta and Gunnel, you keep this place running smoothly and we would be lost without you. Elle, thank you for your patience while I practice my Swedish skills. Thank you to all the lecturers and simulator instructors for providing me with a deeper understanding of the maritime industry.

To my colleagues in the Maritime Human Factors Group whom I now regard as friends; this experience has been shaped by you! Thank you to Yemao, Nicole, Fredrik, Martin, Anders, Karl, and Victor for the continuous advice and encouragement. A special thank you to my Johanneberg colleagues, especially Lars-Ola, for their inclusion and helping to broaden my knowledge from the maritime industry to the automotive. I might even be infected with “systems-thinking disorder” ☺.

To my dear Chalmers friends; this group includes, but is not limited to, Maria, Maja, Bea, Elin, Nefelli, Amanda, Andrei, and Dinis. You have all helped to make this process fun and rewarding and helped brighten the darkest of Swedish days. I´m so thankful our paths have crossed.

Finally, I want to especially thank my family and friends in Canada, USA, and Sweden for their continuous support throughout this journey. I’d like to express special gratitude to my mom who came to my rescue in Sweden following an unfortunate sport’s injury and made it possible for me to continue my studies from my couch. She even got to learn about grounded theory and situation awareness☺.

Paper A: The Implementation of e-Navigation Services: Are we Ready?

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.

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Paper B: An evaluation of low-level automation navigation functions upon Vessel Traffic Services work practices

Aylward, K., Johannesson, A., Weber, R., MacKinnon, S.N., Lundh, M. (2019), *An evaluation of low-level automation navigation functions upon Vessel Traffic Services work practices*

Paper accepted with minor revisions to World Maritime University (WMU) Journal of Maritime Affairs.

Paper C: "Are you planning to follow your route?": the effect of route exchange on decision-making, trust, and safety.

Aylward, K., Weber, R., Man, Y., Lundh, M., MacKinnon, S.N. (2020). *"Are you planning to follow your route?": the effect of route exchange on decision-making, trust, and safety.*

Paper submitted for consideration to a peer reviewed journal.

Katie Aylward is the first and main author of all appended articles. The articles were developed with the support and advice of co-authors.

ADDITIONAL PUBLICATIONS

1. Aylward, K., MacKinnon, S.N., Lundh, M. (2020). *Preventing unruly technologies in a maritime context: a human-centered approach*. Paper to be presented at the 11th International Conference on Applied Human factors and Ergonomics (AHFE). July 2020.

2. 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

3. 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.

LIST OF ABBREVIATIONS

AIS	Automatic Identification System
ARPA	Automatic RADAR Plotting Aid
COLREGs	Conventions on the International Regulations for Preventing Collisions at Sea
CSE	Cognitive Systems Engineering
EDCIS	Electronic Chart Display and Information System
EMSN	European Maritime Simulator Network
EU	European Union
GMDSS	Global Maritime Distress and Safety System
HAI	Human Automation Interactions
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
ICS	International Chamber of Shipping
IMO	International Maritime Organization
LOA	Levels of Automation
MASS	Maritime Autonomous Surface Ships
OOTL	Out-of-the-loop
OOW	Officer of the Watch
SA	Situation Awareness
SAE	Society of Automotive Engineers
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
VHF	Very High Frequency
VTS	Vessel Traffic Services
VTSO	Vessel Traffic Services Operator

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1 INTRODUCTION

The shipping industry is responsible for approximately 80-90% of the international world trade, employing around 1.6 million seafarers globally (Hetherington, Flin et al. 2006, ICS 2020). Seafaring is considered to be a high-risk occupation with unique health and safety challenges (Hetherington, Flin et al. 2006, Brooks and Faust 2018). Historically, the heightened risks stem from the following: demanding working conditions required to run and maintain a ship, unpredictable long hours of shift work causing fatigue, the isolation of being on a ship, the constantly changing work crew and distributed tasks within a team, and the high stress navigational situations. These factors relate to the physical, cognitive, and organizational aspects of a job which when grouped together are called "human factors" (Ross 2009). Human factors is 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 licentiate thesis resides within the domain of human factors and is studied in the context of shipping.

1.1 BACKGROUND

For decades, the shipping industry has cited "human factors" or the "human element" as the leading cause (approximately 85%) of maritime accidents (Sanquist 1992, Hetherington, Flin et al. 2006, Han and Ding 2013). In response, an industry-wide solution has been to reduce human involvement by reducing manning and increasing automation, particularly of navigation systems (Hetherington, Flin et al. 2006). While many of these systems have improved maritime safety, they have also altered typical "navigation tasks" and the role of the human operator (Lützhöft and Dekker 2002, Lützhöft 2004, da Conceição, Dahlman et al. 2017). Implementing new technologies in a sociotechnical system requires a careful assessment of the human-automation relationship. It is critical that the technology is properly tested and introduced safely and purposefully otherwise, as we have learned from other industries, accidents can and will happen as a result (Lee and Moray 1992, Lee and Moray 1994, Lee and See 2004, Lützhöft 2004, Lee 2008).

Unfortunately, the maritime industry has a more "tech" focused, or engineering approach to technology development and implementation which rarely prioritizes the human element (Hetherington, Flin et al. 2006, Grech, Horberry et al. 2008, Ross 2009, Praetorius, Kataria et al. 2015, Grech and Lutzhoft 2016). The "ironies of automation" which Lisanne Bainbridge wrote about almost 40 years ago remains remarkably accurate today (Bainbridge 1983, Strauch 2017). Increasing automation can lead to typical human-automation errors including; automation biases, situation awareness, information overload, mode confusion, and complacency (Bainbridge 1983, Lee and Moray 1994, Endsley and Kiris 1995, Kaber, Omal et al. 1999, Lützhöft and Dekker 2002, Lee and See 2004, Parasuraman and Wickens 2008, Conceição 2018).

In order to address technology development, the International Maritime Organization (IMO) formally adopted e-Navigation and published their strategy for developing an implementation plan, which was completed between 2015-2019. The scope of e-Navigation is "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" (International Maritime Organization 2014). One of the key concepts of this implementation plan is that the initiative must be led by user needs, including both seafarers and shore side services. The overall goal of e-Navigation is to improve safety by reducing errors, while also increasing the efficiency of ship and shore operations (International Maritime Organization 2014, Costa 2016, van de Merwe, Kähler et al. 2016, Costa, Holder et al. 2017).

Research dedicated to further understanding the e-Navigation concept found that human-centered design (Costa and Lützhöft 2014, Costa, Holder et al. 2017, Costa 2018, Costa, Jakobsen et al. 2018, Gernez 2019) and participatory design (Costa 2016, Mallam, Lundh 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 (Baldauf, Benedict et al. 2011, Burmeister, Bruhn et al. 2014, Baldauf and Hong 2016, Aylward, Weber et al. 2018). 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 2017). Therefore, studying human-automation interaction from an interdisciplinary approach (i.e. through psychological, sociological, ecological lenses, (as proposed by Man (2019)) is more critical than ever as we try to understand the potential impact new technologies will have on "work as done" in the maritime sociotechnical system (Man 2019).

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 (Schager 2008, Mallam and Lundh 2013, Man, Lundh et al. 2018, MacKinnon and Lundh 2019, Mallam, Nazir et al. 2019). However, the recent surge of digitalization and automation is transforming the industry faster than ever before and the exploitation of the technologies emerging within the maritime industry have the opportunity to change shipping as we know it (DNV GL 2014, Brooks and Faust 2018, 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 and Faust 2018).

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 and 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. These considerations include: the current and future regulatory regime, seafarer education and training, the distribution of workload and work tasks, and most of all how to cooperate with the next generation of smart ships, fleets, and ports (MacKinnon and Lundh 2019).

1.2 HUMAN-AUTOMATION INTERACTION

Human Computer Interaction (HCI) and Human Automation Interaction (HAI) research within safety-critical domains such as medicine, nuclear, and transportation have increased dramatically in the 1990s and early 2000s (Parasuraman and Riley 1997, Sheridan and Parasuraman 2005, Hancock, Jagacinski et al. 2013, Pazouki, Forbes et al. 2018, Janssen, Donker et al. 2019). Many industry stakeholders have described human-automation interaction with the adoption of a Levels of Automation (LOA) scale. The scales usually range anywhere from 0-10, from 0 = no automation to 10 = fully autonomous, and mixed human-automation task allocations in between (Endsley and Kiris 1995, Parasuraman, Sheridan et al. 2000, Vagia, Transeth et al. 2016, Kaber 2018). 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 (Vagia, Transeth et al. 2016, Rødseth and Nordahl 2017, Kaber 2018). 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. These control issues will impact situation awareness, mental model development, decision-making and timely execution impacting overall safe use of automation (Creaser and Fitch 2015). These concerns are similar to the challenges predicted in the shipping context as various types and levels of automation are introduced into highly complex work environments.

Vagia et al. (2016) completed a review of the various LOA´s proposed since the 1950´s including the 12 most common taxonomies presented in the literature, including Sheridan and Verplank´s 10 level model (Sheridan and Verplank 1978), Endsley´s four level LOA model (Endsley 1987), and Parasuraman et al. four different classes of input functions (Sheridan and Verplank 1978, Endsley 1987, Parasuraman, Sheridan et al. 2000, Vagia, Transeth et al. 2016). 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. 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. The authors also indicate that the first two input functions, Level 1: "information acquisition" and Level 2: "information analysis" can be grouped together as "information automation", which aligns with the level and type of automation studied in the papers associated with this licentiate (described in Chapter 2) (Parasuraman, Sheridan et al. 2000). This approach is summarized in Table 1, which has been adapted from Vagia et al. (2016) to include navigation-related examples (*in italics*). This provides a framework to discuss the potential implications of low-level automation on human performance.

Table 1: Input functions and description as proposed by Parasuraman et al. (Parasuraman, Sheridan et al. 2000), and table adapted from (Vagia, Transeth et al. 2016).

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

1.2.1 Describing Levels of Automation in Ship Activities

The most recent initiative set by the IMO is the *Strategic Plan for the six-year period 2018-2023* (Resolution A.1110 (30)) which specifically lists a strategic direction (SD2) to "integrate new and advancing technologies in the regulatory framework" (IMO 2017). Part of this plan is a regulatory scoping exercise of Maritime Autonomous Surface Ships (MASS), with an anticipated completion date by 2020. The shipping industry has yet to agree on a unified definition and application of LOA. However, as part of the scoping exercise, the IMO has addressed autonomy of MASS with four degrees and definitions which are listed below: (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 is able to make decisions and determine actions by itself.

In order to align the MASS autonomy degrees with a more industry-independent, and well accepted framework, the scope of this licentiate is limited to low-level automation which would reflect the lowest level of autonomy defined by the IMO, Degree One and "information automation" as proposed by Parasuraman, et al. (2000) (Table 1) (Parasuraman, Sheridan et al. 2000, IMO 2018). This type of low-level human-automation relationship requires careful consideration as to how and which tasks are automated and how this will impact human performance outcomes.

1.3 RESEARCH GAP AND PROBLEM FORMULATION

Previous research in the maritime industry has described work practices and environments on board ships leading to improved theoretical and empirical developments in maritime human factors (Lützhöft and Dekker 2002, Lundh 2010, Praetorius 2014, Mallam and Lundh 2016, da Conceição, Dahlman et al. 2017, Costa 2018, Man 2019). Researchers have also attempted to predict the upcoming challenges of the future of shipping, including fully autonomous, unmanned ships (DNV GL 2014, Wahlström, Hakulinen et al. 2015, ABS 2018, MacKinnon and Lundh 2019, Mallam, Nazir et al. 2019, WMU 2019). However, the knowledge gap exists in the current to near future of the shipping industry as lower LOA are being adopted to support decision-making, without full consideration for human capabilities and limitations, or regulatory development. During this period, there will be unique combinations of humans and automation, and traditional ships/ports and smart ships/ports. These combinations will cause changes that will impact 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.

1.4 AIM OF THE THESIS

This thesis aims to study the impact of information automation (MASS level 1) on operator behavior. In this context an operator can be either ship based (Navigator) or shore based (Vessel Traffic Service Operator). Operator behavior can be defined as the *set of actions the operator performs to ensure the safety and efficiency of vessel traffic and compliance to traffic regulations*. A systems approach is adopted to provide insight into the opportunities and challenges surrounding the introduction of low-level automation within the maritime sociotechnical system.

1.5 RESEARCH QUESTIONS

The following research questions are considered in this licentiate:

RQ 1) What is the impact of information automation on operator behavior?
  a. What is the impact of information automation on the ship-to-ship subsystem?
  b. What is the impact of information automation on the ship-to-shore subsystem?
RQ 2) What are the system level implications associated with introducing low levels of automation in the maritime domain (i.e. regulatory, education and training, communication, etc.)?

1.6 APPENDED PAPERS

This licentiate thesis is based on three appended articles:

A. **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.**

This article discussed the impact of the STM functions on safety and efficiency from the bridge operator perspective. The data was collected using semi-structured post simulation group debriefs throughout the STM European Maritime Simulator Network (EMSN) testing. This paper provides insight into the user experience with each of the STM functions, and summarizes the common themes discovered using a grounded theory methodology for the analysis.

B. **Aylward, K., Johannesson, A., Weber, R., MacKinnon, S.N., Lundh, M. (2019),** ***Vessel Traffic Services: The impact of e-Navigation on work practices and operations.***
Paper submitted for review to World Maritime University (WMU) Journal of Maritime Affairs.

This article discussed the impact of the STM functions from the Vessel Traffic Services (VTS) perspective. The purpose of this paper was to understand how communication and interactions between ships and shore would impact VTS operations. 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. The results indicate that the frequency and method of interaction between the VTS and the ship will be affected by the integration of STM. The additional access to navigational information will allow the VTS operators to be more proactive and involved in traffic situations compared to traditional operations.

C. **Aylward, K., Weber, R., Man, Y., Lundh, M., MacKinnon, S.N. (2019).** ***"Are you planning to follow your route?": the effect of route exchange on decision-making, trust, and safety.***
Paper submitted for review to the World Maritime University (WMU) Journal of Maritime Affairs.

The purpose of this paper was to evaluate two functions developed during the STM project: a ship-to-ship route exchange (S2SREX) function and rendezvous (RDV) information layer, collectively referred to as S2SREX/RDV. Qualitative data were collected using post-test questionnaires to evaluate the participants' perception of S2SREX/RDV in the various traffic scenarios and quantitative data were collected to assess the ship distances and behavior in relation to the International Regulations for Preventing Collisions at Sea (COLREGs). The results revealed conflicting information between work as done and work as imagined, leading to unresolved questions about the potential impact of the functions on navigational safety.

1.7 STAKEHOLDERS

Increasing digitalization and automation will have an impact on all stakeholders within the maritime sociotechnical system. Those impacted include ship owners, international and national regulatory bodies, ship and shore-based operators, consumers, technology developers, and maritime academies. The findings and discussion in this thesis should provide relevant information to all of these stakeholder groups. However, three primary stakeholder groups are identified based on the appended papers A-C.

The first stakeholder group includes the operators at the sharp end of the technologies. Papers A-C 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.

1.8 DELIMITATIONS AND LIMITATIONS

Delimitations are characteristics that are defined by the researcher to limit the scope and define the boundaries of the study (Simon 2011). The field of human-automation interaction is multifaceted and can be studied from a variety of different perspectives. This thesis examines HAI from the operators perceived impact of low-level automation functions such as information automation on situation awareness, performance, decision support and safety. Further, the technologies tested within this thesis are limited to the navigation and communication functions developed and tested within the STM project. There are other types of e-Navigation functions or technologies, outside the scope of this thesis that could potentially render different results. Additionally, the majority of the participants, both ship and shore operators, were from European countries and therefore the results may not be generalizable beyond this population. Moreover, the discussions surrounding Vessel Traffic Service (VTS) are primarily based on the Swedish VTS legislation and procedures, recognizing that there are many national differences in levels of authority and service provisions. These differences should be taken into account when interpreting the results.

Limitations are potential weaknesses within a study that are outside of the researchers' control (Simon 2011). The data within this thesis were collected exclusively using high-fidelity simulators. 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, Dekker et al. 2009). Exploratory behavior 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) (Lee and Moray 1994, Inagaki, Takae et al. 1999). 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 (Lee and Moray 1994, Inagaki, Takae et al. 1999, Lee and See 2004). This is one of the limitations of simulation exercises and must be taken into account when interpreting the results of this work. However, given the novelty of the functions tested, simulation was the safest and most effective way to apply an empirical approach to answer the research questions.

2 The Context: Maritime Navigation and the Sea Traffic Management (STM) Validation Project

2.1 MARITIME NAVIGATION

Maritime Navigation involves planning, managing, and directing a vessel´s voyage. This is achieved through good seamanship, professional knowledge and judgement, and the application and use of various technologies (AMSA 2019). Navigation is known to be a complex activity involving distributed teams and knowledge, dynamic high risk situations, and a heavy reliance on effective communications and interactions between team members (Bailey, Housley et al. 2006). Modern ships use the following digital equipment to aid with navigation tasks: Automatic Identification System (AIS), Automatic Radar Plotting Aid (ARPA), Electronic Chart Display and Information System (ECDIS), Global Maritime Distress Safety System (GMDSS), and Very High Frequency (VHF) radio to communicate (International Maritime Organization 2014, International Maritime Organisation 2015). These technologies (Figure 1) have impacted the practice of navigation and altered the responsibility of the navigator to assume a predominantly planning and monitoring role as opposed to execution and surveillance (Conceição, Carmo et al. 2017).

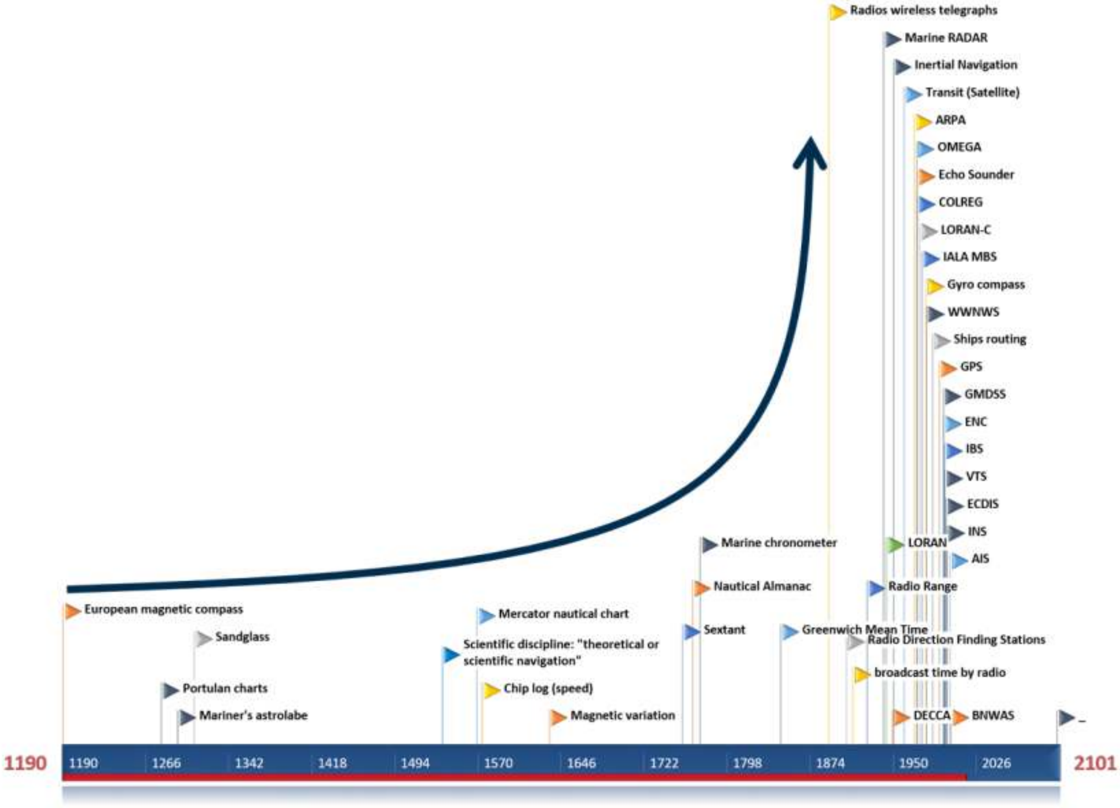

Figure 1: Timeline of maritime navigation technologies (reproduced with permission from (Conceição, Carmo et al. 2017))

2.1.1 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); (2) The Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREG); (3) The International Convention on Standards, Training, Certification and Watchkeeping for Seafarers, 1978 (STCW) (IMO 1972, IMO 1974, IMO 1978). In addition to the formal regulations set by the IMO, there are also rules and guidance provided by ship classification societies (e.g. ABS, Lloyds Register, DNV-GL) to further enhance safety at sea.

2.2 THE ROLE OF VESSEL TRAFFIC SERVICES IN NAVIGATIONAL ASSISTANCE

As defined by the IMO in Resolution A.857 (20), Vessel Traffic Services (VTS) is a “service implemented by a Competent Authority, designed to improve the safety and efficiency of vessel traffic and to protect the environment. The service should have the capability to interact with the traffic and to respond to traffic situations developing in a VTS area” (International Maritime Organization 1997). VTS are shore-based stations that provide a range of services to ships. This service extends from the provision of simple information related to traffic or meteorological hazard warnings to extensive management of traffic within a port or waterway (International Maritime Organization 1997). The three different levels of services offered by VTS are: (1) Information Navigational Service (INS) which supplies information to all participating vessels within the VTS area such as general traffic information; (2) Traffic Organisation Service (TOS) which is concerned with the traffic operations such as ship manoeuvres, access areas or speed limits; (3) Navigational Assistance Service (NAS) which provides information for the navigation task such as own position relative to obstacles (International Maritime Organization 1997, Praetorius, van Westrenen et al. 2012). 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 2008). A VTSO uses this information, in addition to their experience and knowledge, to generate an overview of the VTS area and traffic image. The VTSO can then contact the vessel via VHF radio to provide information or assistance to a vessel in the area, as deemed necessary. An example of this would be providing assistance 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 2014).

2.2.1 Regulation of VTS

In terms of governance, IMO Resolution A.857 (20) provides guidelines and criteria for VTS operations which are associated with SOLAS Regulation V/1/7/02; however, there is no international regulation governing the design and operation of a VTS leading to national differences in how VTSs are organized (IALA 2008, Brodje, Lundh et al. 2013). 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 2008).

2.3 SEA TRAFFIC MANAGEMENT (STM)

The Sea Traffic Management (STM) Project (2014-EU-TM-0206-S) is the most recent European Union (EU) funded project aimed at exploring concepts and applications that are described in the e-Navigation strategy (International Maritime Organization 2014, STM 2019). The STM project examines many aspects of digitalization within the shipping sector with aims to create a safer, more efficient and environmentally friendly maritime sector. More specifically, by 2030 the project goals are to reduce maritime accidents by 50%, obtain a 10% reduction in voyage costs, and reduce berthing waiting times by 30% (Sea Traffic Management 2018). The STM concept takes a holistic approach to services and connects and updates the maritime world (ships, ports, vessel traffic services, service providers, shipping companies) in real time through information exchange and sharing to offer a digital infrastructure for shipping. Although there are many activities and sub-activities of the STM project, this thesis focuses only on the STM Validation project.

The STM Validation project uses large-scale test beds to demonstrate the STM concept in both Baltic and Mediterranean Seas. The sub-activity that was assessed in this thesis is the European Maritime Simulator Network (EMSN). The EMSN was developed in a previous EU project, MONALISA2.0 and realized and tested in the STM project. It is a network of simulator centers enabling testing of STM concepts in complex traffic situations while using real operators. At the time of data collection there were 12 connected ship handling simulators based in several EU countries notably, Sweden, Norway, Finland, Spain, Germany, and the United Kingdom with the possibility to run scenarios with over 30 manned simulated vessels. The EMSN is a unique test bed that enables the introduction and testing of new technologies in complex and large-scale traffic situations, without exposing seafarers to any risks.

2.3.1 Description of the STM Functions

The technologies that have been developed and tested in the STM Project are called "STM Functions" and are intended to reduce administrative burden and accidents, and increase safety, situational awareness, operational efficiency, and transparency (STM 2019). Although the project developed many functions and services, this thesis is limited to an assessment of the following functions: Ship to Ship Route Exchange (S2SREX), Rendezvous (RDV), Shore-to-ship Route Exchange (receiving route suggestions from shore), receiving navigational warnings, chat function, enhanced monitoring and route cross check. The STM functions provide relevant information about the surrounding traffic situations and other vessels intentions. It is important to note that these functions do not replace the human action of decision selection and implementation. They are exclusively intended to be used for decision support at longer ranges (Parasuraman, Sheridan et al. 2000, Sheridan and Parasuraman 2005). The functions can be categorized as low-level automation, "information automation" or Degree 1 in the IMO MASS scale, which are intended to improve information sharing between ship and shore-based operators. Throughout this thesis, these low-level automation functions will be referred to as the "STM functions". Descriptions of the functions tested throughout this licentiate are provided below:[1]

Ship-to-ship route exchange (S2SREX): This function 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 Automatic Identification System (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 International Regulations for Preventing Collisions at Sea (COLREG).

Rendezvous Function: As an integral part of the S2SREX, this function allows the navigator to view where own ship will meet a target ship if both vessels continue on their monitored broadcasted route with the present speed over ground. This function provides route-based Closest Point of Arrival (CPA) and Time to Closest Point of Arrival (TCPA) based on AIS information.

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.

Receiving Navigational Warnings: This function provides a notification which overlays a Navigational Warning Message directly on the ECDIS. If the Navigational Warning involves a geographical area to avoid or be aware of, this will be automatically plotted onto the ECDIS, so it is visible to the bridge team.

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.

Enhanced Monitoring and Route Cross Check: After having received a ship's monitored route and schedule, the VTSO will be able to detect if planned schedule is not kept or if ship deviates from monitored route**.** The VTS has the ability to receive any planned route and cross check such route against any navigational dangers and if necessary, send a route suggestion back to the ship.

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[1] Paper A and B assessed all STM functions, and Paper C only assessed S2SREX and Rendezvous.

3 THEORETICAL FRAMEWORKS

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 (Von Bertalanffy 1968, Skyttner 2005, Dul, Bruder et al. 2012). 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 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, called a *system boundary* which is defined by the researcher (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, Challenger et al. 2014). Koester (2007) developed "The SEPTIGON Model" specifically for the maritime sociotechnical system (Koester 2007, Grech, Horberry et al. 2008). 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 (Koester 2007, Grech, Horberry et al. 2008). The purpose of this model is to advocate for a more holistic systematic approach to study the interaction and relationships between the individual elements or nodes. The individual studies within this thesis examine a micro-level (individual-technology) systems level, however the discussion within the thesis expands the system boundary 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 (Rasmussen 2000, Dul, Bruder et al. 2012).

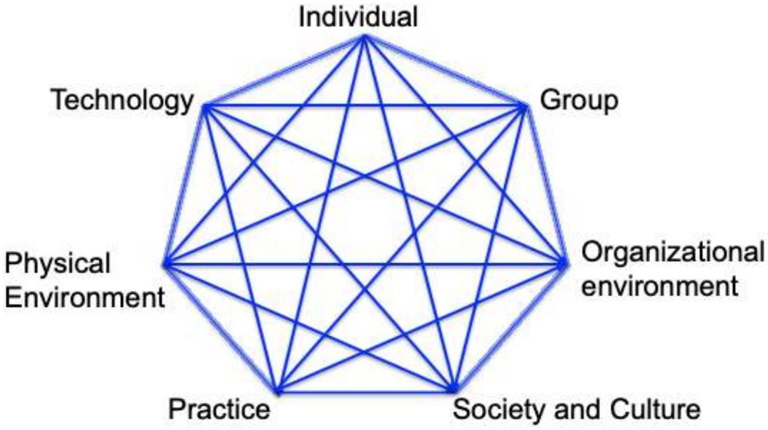


Figure 2: The SEPTIGON sociotechnical system model. Figure created by (Koester, 2007) and redrawn for this thesis.

As advocated by human factors researchers who have studied similar aspects of e-Navigation, a systemic approach towards new technology integration is imperative (Praetorius 2014, da Conceição, Dahlman et al. 2017, de Vries 2017, Costa 2018, Man 2019). 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. 2018). Introducing a change in the level or type of automation, or the number of actors within a subsystem (i.e. on a ships bridge) will cause changes in the entire system. transforming judgements, roles, relationships, and weightings on different goals (Woods and Dekker 2000). Therefore, 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 and Hollnagel 2006).

Sociotechnical system models are increasingly being applied within the field of human factors to describe work (Praetorius 2014, da Conceição, Dahlman et al. 2017, de Vries 2017, Costa, Lundh et al. 2018), improve safety and inform better design (Andersson, Bligård et al. 2011, de Vries and Bligård 2019). A recent study by de Vries & Bligård (2019) applied the following five STS models: Activity Theory, Cybernetics, Joint Cognitive Systems, Cognitive Systems Engineering (CSE), and Resilience Engineering to the case of navigational assistance with the aim of visualizing work through STS theories to further understand how work is performed (de Vries and Bligård 2019). This paper captured many elements of how *navigational assistance* is performed, identifying different but important elements of complex work practices in each of the models. 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). However, one of the benefits of these models is they provide a platform to discuss the existing challenges of a particular work practice(s) with various stakeholders. Further work must be completed to understand the most appropriate way to apply these models.

Cognitive Work Analysis (CWA) is a framework that exists within the CSE discipline which recognizes the complexity of STS and has been widely used as an approach for the analysis, design and evaluation of these systems (Rasmussen, Pejtersen et al. 1994, Vicente 1999). CWA is comprised of five phases according to Vicente (1999): work-domain analysis, control task analysis, strategies analysis, social organization and cooperation analysis and lastly worker competencies analysis. Each phase has certain types of boundaries or constraints (Vicente 1999). However, various phases and approaches using combinations of phases have been used to address different domain specific questions and research goals (Jenkins, Stanton et al. 2017). The purpose of the CWA approach is to recognize the unfamiliar situations which humans within a STS may have to deal with and overcome, as automation or more stable conditions are handled by automation (Vicente 1999). This framework requires significant effort for analysis and a detailed understanding of the subsystems within the STS of interest. Since the present work was an exploratory effort to highlight the potential issues with low LOA in a maritime context, it did not provide enough data to complete a CWA. However, a CWA framework is suggested for further assessment of the maritime sociotechnical system especially as higher levels of automation are introduced.

3.2 HUMAN-AUTOMATION INTERACTION

The field of human-automation interaction is extensive with much of its research focusing on higher levels of automation. This section does not intend to provide a comprehensive review of the HAI field. Instead this section provides insight into the aspects of HAI that were studied within the scope of this licentiate. It begins with definitions of automation and human-automation interaction, and then addresses the aspects of human performance and decision support studied in the context of low-level automation.

Automation has been defined in many different ways, incorporating diverse taxonomies, levels, applications, and functions depending on the contextual application. In this licentiate, with a focus on the human-automation relationship, 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, Sheridan et al. 2000). Further, as described in Chapter 1, this licentiate focuses on low-level automation, which aligns with Degree 1 of the IMO MASS scale, and "information automation" as proposed by Parasuraman et al. (2000) (Table 1). Higher levels of automation and human-automation interaction issues are outside the scope of this theoretical framework. *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 (Sheridan and Parasuraman 2005, Mattsson 2018).

Although the purpose of introducing automation into a workplace is generally to improve human performance and reduce human-related errors, the outcome has often caused more complex problems (Bainbridge 1983). The "ironies of automation" suggest that the more advanced a control or automated system is, the more important the role of the human operator (Bainbridge 1983). The two major ironies related to the removal of the human operator from the system are the following: (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 are still largely unresolved today as automation is becoming increasingly more complex and the role of the human operator is often diminished or not considered which jeopardizes system safety (Strauch 2017).

Another pivotal HAI paper was written by Parasuraman and Riley (1997) which discussed why automation often fails to perform as expected (Parasuraman and Riley 1997). The challenges identified related to automation use, misuse, and abuse, are more relevant than ever today in a technology-centred shipping industry (Parasuraman and Riley 1997, Lee 2008). Some of the human-automation challenges identified include: automation biases related to trust and overreliance, mental workload, and Situation Awareness (SA) (Parasuraman and Riley 1997, Parasuraman, Sheridan et al. 2000, Lee 2008). These are the concepts that will be discussed in this section.

3.2.1 Automation Biases, Trust, and Reliance

Information automation is intended to support human cognitive processes in decision-making, providing the most useful information to the operator. However, decision support aids are only useful if they are designed appropriately and used as intended. Altering the means of information retrieval for an operator will impact information processing, perception and decision-making (Endsley 1995). *Automation biases* stem from human interaction with automated systems and refer to a specific class of errors (omission and commission) when automation aids are imperfect (Parasuraman and Manzey 2010). These biases can lead to an inadequate assessment by the operator of all of the available information, leading to poor decisions. Automation bias is related to the "cognitive-miser hypothesis", which is the tendency for humans to exert the least amount of cognitive effort to solve a problem (Parasuraman and Manzey 2010). Automation bias has been studied extensively in aviation. One of the findings is that with lower LOA, where the decision and most of the planning was completed by the operator, there was less chance of automation bias as the operator was still directly in-the-loop and therefore better able to assess and evaluate different options of a flight path, compared to higher LOA (Parasuraman and Manzey 2010).

Another factor related to automation usage is trust. Perceived trust of automation strongly dictates automation usage (Parasuraman and Riley 1997). Trust is a construct in which a human considers the reliability, truth or ability of a system and is related to the concerns regarding the misuse and disuse of technology (Lee 2008). Over trust or complacency leads to misuse; specifically occurs when operators rely on automation when the automation performs poorly. Conversely, under trust leads to disuse occurring when operators fail to engage automation when it could enhance performance (Lee and Moray 1992, Lee and See 2004, Lee 2008). Within the transportation sector there are countless cases in which people have either misused, disused or abused automation leading to major accidents. Worth noting is the grounding of the 'smart' ship, The Royal Majesty cruise ship (Lee and Sanquist 2000, Lützhöft and Dekker 2002), and many aviation incidents (Parasuraman and Riley 1997, Gawron 2019). Interestingly, empirical results have shown that even a single automation failure (e.g. inaccurate navigational warning automatically plotted on an ECDIS) can significantly reduce trust in the automated system or function (Lee and Moray 1992).

Reliance is closely coupled with trust and can influence automation usage. Although trust is defined in many ways, most definitions include some level of vulnerability and an expected behaviour or outcome (Lee and See 2004). If someone has a high level of trust in a person (or automation) they tend to rely on that person (or function) without evaluating all the available information. It is also recognized that trust and reliance evolve in a complex way which include personal history, cultural and organisational factors (Lee and See 2004). This can lead to a certain level of scepticism in trusting automation, particularly in industries which have not traditionally been highly automated, namely shipping, and can undermine the benefits of automation (Lee and See 2004). Even though there have been major developments in onboard ship technology, the work practices and procedures reflect a more traditional workplace (MacKinnon and Lundh 2019, Mallam, Nazir et al. 2019).

3.2.2 Situation Awareness

A concept that is both highly applied and vigorously debated in cognitive science is situation awareness (SA). The definition of SA remains a topic of contention amongst academics, and even more disagreement surrounds how to accurately measure it (Salmon, Stanton et al. 2009). The debate hinges on how people view SA, as a product or a process (Stanton, Chambers et al. 2001). One of the most frequently cited definitions was proposed by Mica Endsley in 1995, 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 (Stanton, Salmon et al. 2010, Sorensen, Stanton et al. 2011). 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, Salmon 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, Stanton 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, Salmon et al. 2010). A systems approach to SA has been developed which originated from the distributed cognition movement of Hutchins (Hutchins 1995, Stanton, Stewart et al. 2006, Salmon, Stanton et al. 2009). 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 (Stanton, Stewart et al. 2006, Salmon, Walker et al. 2009, Stanton, Salmon et al. 2010). 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, Salmon 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. There are criticisms associated with each approach to SA. However, the more important questions related to 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, Salmon et al. 2010).

3.2.3 Mental Workload (MWL)

One of the primary reasons for introducing automation into a system is to reduce operator mental workload. MWL (also known as cognitive workload) can be defined as the amount of mental effort that is required by an operator to perform a task or tasks (Grech, Horberry et al. 2008). MWL also has many similarities to SA, including the fact that workload does not necessarily equate performance (Parasuraman, Sheridan et al. 2008). For example, two people completing the same task can have the same performance, yet one person may have additional attention to allocate to concurrent tasks, while the other is completely consumed with the task (Parasuraman, Sheridan et al. 2008). This concept is also known as *residual attention*. However, the evidence is unclear about task load and automation usage, which appears to vary significantly between individuals (Parasuraman and Riley 1997). One challenge specifically related to shipping is that workload is relatively low during long voyages. Most navigation tasks, apart from busy traffic scenarios, include monitoring and watchkeeping. The ideal situation is to find a productive balance between automation that will reduce workload, assist the operator, while still keeping operators in the loop.

3.2.5 Impact of Automation on SA and workload

Introducing a new type of technology of any LOA into a sociotechnical system will alter the relationship between system elements, influencing the task, the environment, and the team. The impact of different LOA on SA, workload on human performance has been studied extensively. The impact on human performance highly depends on the stage of task (i.e. information automation, action selection or action execution) that automation is applied (Parasuraman, Sheridan et al. 2000, Endsley 2017). Endsley (2017) summarized research related to the effect of autonomy applied to the stages of task performance. Given the scope of this licentiate, only the stages included in "information automation" are summarized below (Endsley 2017):

1) 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).
2) Information-cuing systems create good performance when correct but poor performance when incorrect
3) It is suggested that SA is generally higher with lower to intermediate LOA, as the operator is still in-the-loop, and exhibits an enhanced ability to respond to system failures, compared to higher LOA (Kaber, Onal et al. 2000).
4) Usability issues can mistakenly be attributed to a higher perceived MWL, when in fact it is the poor design of the function that is the issue and not the capacity and ability to handle the workload (Parasuraman, Sheridan et al. 2008).

There also 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 situation awareness and therefore reduced ability to take over a system in a failure (Endsley 2017). 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 (Kaber, Onal et al. 2000, Endsley 2017).

4 METHODOLOGY

4.1 METHODOLOGY APPROACH

The work included in this licentiate thesis was carried out during 2017-2019 within the Sea Traffic Management (STM) Validation project. These data were collected at Chalmers University of Technology in Gothenburg, Sweden, and several other European Universities involved in the EMSN (see Chapter 2 and full description in Papers A-C). A pragmatic mixed-methods approach was used to address the research problems (Creswell and Clark 2017). The development of this work follows an *exploratory sequential design* which prioritizes qualitative data analysis in the first phase, which then informs the next phase of quantitative measure/intervention, followed by quantitative data collection and analysis (Creswell and 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 (Silverman 2011, Corbin and Strauss 2015).

The qualitative data collected in Paper A generated themes for further exploration, which were grounded in the views of the participants. These findings led to the need for further investigation that inspired Paper B and Paper C using both quantitative and qualitative methods. Typically, in exploratory sequential design, the researcher only uses quantitative measures and analysis to finalize the study and interpret the data. However, to deepen the understanding of the research questions it was decided to collect and analyze additional qualitative data. Therefore, the results from the three papers are assessed together to form a holistic view representing a *convergent design*. This is when a researcher combines both qualitative and quantitative data to obtain a more complete understanding of the research questions or problem (Creswell and Clark 2017). A summary of the methodological approach for the appended papers is provided in Table 2.

Table 2: A summary of the methodological approach

Paper	Aim	Approach	Methodological Tools	Analysis Method	Number/ Role of Participants
A	To understand bridge operator's perception of STM functions on navigation practices and define additional research questions for further studies.	Qualitative	Post-simulation debriefing	Grounded Theory	227 Bridge Officers
B	To measure and analyze the use of STM functions and the user experience from the VTS operator perspective	Qualitative Quantitative	Post-simulation questionnaires Observations SME review	Descriptive Statistics Comparative analysis related to the frequency if interaction Frequency of use of STM functions	16 VTS Operators
C	To compare navigational traffic situations with and without STM functions to further understand the implications of two specific functions on safety and decision-making	Qualitative Quantitative	Post-scenario Questionnaires (per scenario and per day) Video playback of scenarios SME consultation	Descriptive statistics Numerical analysis of ship distances	24 Bridge Officers

4.2 EXPERIMENTAL DESIGN

Simulation is increasingly being used for research, training, and continuing education in a wide range of disciplines; medicine, transportation, and military to name a few. Since its origin in the 1950´s, simulation technologies have continuously developed both hardware and software systems to be able to create highly realistic, and immersive experiences, also known as high-fidelity simulation (Massoth, Röder et al. 2019). High-fidelity simulators are commonly used for training officers, maritime pilots, VTS operators and for practicing safety critical operations (Sellberg 2017, Sellberg 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 this thesis were collected exclusively using high-fidelity simulators (Figure 3).

Figure 3: High-fidelity ship´s bridge simulator at Chalmers University of Technology

4.2.1 Papers A & B

Subject Matter Experts (SMEs) developed two simulator scenarios; one located in the South Western Baltic and another in the English Channel/Southampton. The scenarios were designed to test the different functionalities of the STM functions. The Baltic Scenario tested dense, close quarters traffic situations whereas the English Channel scenario was generally less busy. Each geographical area also had a respective shore center (VTS); one located in Southampton, UK and the other in Gothenburg, Sweden. The shore center functioned as a typical VTS center with additional access to the STM functions. A simple factorial design was used in Papers A and B in which two levels of two different independent variables were combined, as shown in Table 3 (Wickens, Lee et al. 2003).

Table 3: Simple factorial (2X2) design used in Papers A and B

	Light traffic (English Channel)	**Dense traffic (Baltic)**
Baseline	No STM functions while navigating in light traffic situations	No STM functions while navigating in dense traffic
STM Functions	STM functions while navigating in light traffic	STM functions while navigating in dense traffic

4.2.2 Paper C

SMEs developed six different traffic scenarios lasting approximately 15-20 minutes respectively. The purpose of these scenarios was to test the impact of the S2SREX/RDV functions on decision-making and navigational safety. The scenarios (S1-S6) can be grouped into two types of traffic situations: (1) Meeting/overtaking (S1, S2, S4) and (2) Crossing and general traffic situations (S3, S5, S6). The scenarios are fully described in appended paper C. A simple factorial design was used in Paper C as shown in Table 4.

Table 4: Simple factorial (2x2) design used in paper C

	Meeting/Overtaking Scenarios (S1, S2, S4)	Crossing and general traffic scenarios (S3, S5, S6)
Baseline	No STM functions while navigating in meeting/overtaking scenarios	No STM functions while navigating in dense traffic
STM Functions	STM functions available while navigating in meeting/overtaking scenarios	STM functions available while navigating in crossing/general traffic scenarios

4.3 METHODOLOGICAL TOOLS

To increase reliability and validity 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 (Olsen 2004, Denzin 2012). The following methodological tools were used to study the research questions.

Post simulation debriefing is known as the "heart and soul" of simulation experiences (Rall, Manser 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 (Rall, Manser et al. 2000, Fanning and Gaba 2007, Sellberg 2017). The purpose of the group debriefs was for the test participants to provide an account of their experiences with the STM functions, both positive and negative in a non-bias environment (Patton 2002). Two types of post simulation debriefings were used throughout this thesis. Paper A used an *intermediate* level of facilitation throughout the debriefing. To clarify, the participants were generally able to keep up the discussion, but the facilitator followed up on certain questions, and probed participants to provide input when necessary (Fanning and Gaba 2007). Paper A also had a pre-defined list of open-ended questions designed to guide the discussions in the same direction for all participating simulator centers. Paper C used an *intermediate* level of facilitation paired with video playback to jog the participant's memory to recall specific traffic scenarios with which the STM functions were useful or not (Fanning and Gaba 2007).

Observations are one of the most valuable data collection methods in trying to understand what users actually do compared to what they say or think they do (Wickens, Lee et al. 2003). Observations were completed throughout data collection reported in papers A, B and C by SMEs, human factors specialists and sometimes supplemented with video and audio recordings. In Paper B, the observer used pre-determined taxonomies (i.e. name of STM function, names of vessels, time, etc.) to populate an excel spreadsheet in order to capture all the data 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, Lee et al. 2003). However, observations as a standalone method is generally not sufficient to understand the observed phenomenon (primarily cognitive tasks) and therefore were always complemented with other methodological tools.

Questionnaires

Questionnaires were used to measure the participant's subjective rating and perception of the STM functions. The questionnaires included questions related to safety, situation awareness, trust, risk, reliance on information, workload, and usefulness of the functions. They were primarily closed-ended questions using Likert Scales with endpoints ranging from either 1-5 or

1-7 (SAGE 2008). All questionnaires were developed using online survey software Qualtrics (Qualtrics^{XM}, © 2019, Provo, Utah, USA, https://www.qualtrics.com).

Grounded theory is a systematic methodology used in qualitative research which begins with raw data (i.e. interviews, debriefs, focus groups, etc.) and raises it to a conceptual level (Corbin and Strauss 2008). It is the analytic process of continuously comparing different pieces of data for similarities and differences to generate codes, concepts and eventually theory (Corbin and Strauss 2008). A grounded theory approach was used to collect and analyse the qualitative data from the debrief sessions in Paper A. MAXQDA12 (Release 12.3.5, distribution by VERBI Software GmbH, Berlin Germany), a mixed methods software program, was used to organize, visualize and analyse the open-ended debrief responses. The coding process, also known as axial coding, was continuous as new categories and relationships emerged between data. Memos explaining the phenomena were recorded continuously throughout the data analysis to refine and keep track of ideas and how they relate to each other. Once it was established that the data were saturated, the memos were sorted and written up to help understand and finalize the theory development (Corbin and Strauss 2015).

Subject Matter Expert Consultation

In papers A-C, SMEs were continuously consulted from the initial development of the questionnaires, throughout the analysis, including 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 for Papers A-C.

4.4 PROCEDURES

4.4.1 Research Ethics

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.

4.4.2 Participant recruitment and sampling

Purposive sampling, also known as judgment sampling, is a nonrandom 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) as test participants. Participants were recruited through various social media platforms, professional maritime organizations, maritime academies, and word of mouth.

4.4.3 Paper A

4.4.3.1 Participant Demographics

A total of 227 professional mariners, 33 women and 194 men participated in this study. The participants were between 20 and 69 years of age. In terms of navigational experience, one participant had less than one year of experience. The rest of the participants had between 3 to 31 years. The majority of participants had between 11-20 years of sea-going experience. The current role of participants varied. Among the participants, there were 68 Captains, 18 Pilots, 29 Chief Officers, 57 Deck Officers, 7 VTS Operators, 16 working in Educational Services, 14 working in the Maritime field, and 18 who did not report in the demographic survey.

4.4.3.2 Procedures

Data were collected over eight days during two non-consecutive weeks in 2018 in the EMSN test bed. The participants were assigned to a two-person bridge team, one Master and one Officer of the Watch (OOW). The participants completed two 1.5-hour simulator exercises, one in the English Channel, and one in the Baltic (see Chapter 2 for scenario description). The test day concluded with a post-simulation group debriefing at all simulation centers. The purpose of the group debriefs was for the test participants to provide an account of their experiences with the STM functions, both positive and negative in a non-bias environment (Patton 2002). The structure and process were consistent at all simulation centers involving an intermediate level of facilitation from the project member leading the debrief. The participants were encouraged to explain the motivation of their responses. The guiding list of questions included:

1. In general, do you think the STM functions affect safety in Navigation?
2. In general, do you think the STM functions affect efficiency in Navigation?
3. Do you think that the STM functions will change today's way of working/navigation/management procedures?
4. What training (technical/pedagogical) would be necessary in order to use the STM functions?
5. Do you think Shipping Companies will adopt these tools for their fleet?

The transcripts from the debriefings at all the simulation centers were gathered together and analyzed using grounded theory as described in section 4.3.

4.4.4 Paper B

4.4.4.1 Participant Demographics:

A total of 16 different VTS operators participated with a gender breakdown of 13 men and 3 women. Eight VTSOs were from Sweden, six from the UK and two from Norway. The participants were between 20 and 69 years of age. Years of experience as a VTSO ranged from <1 year to 11-20 years, with most VTSOs having between three to five years of experience. The current role of the VTSOs varied. At the time of the study, nine participants worked as VTS Managers, Operators, or Supervisors, three worked as pilots, two as instructors, one participant worked as a project leader, and one as a captain.

4.4.4.2 Procedures

The data from Paper B was collected during the same data collection effort as Paper A and the experimental deign is described in Table 3. Data were collected over 16 days during four non-consecutive weeks in 2017 and 2018 in the EMSN test bed. The participants were VTS operators situated at either the simulated VTS station at Chalmers University, Sweden or Warsash Maritime Academy, UK. The VTSOs participated in two, 1.5-hour simulator exercises; one in the English Channel, and one in the Baltic (see Chapter 2 for scenario description). The VTSOs were not given any specific instructions related to the use of the STM functions versus traditional communication means, such as VHF. This approach was selected to represent a more realistic situation so that the VTSOs were not forced to use the services, and instead would use the services based on their time, ability, and interest.

An experienced VTS instructor and paper 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 more channels to actively interact with ships including VHF, chat, and route suggestion from shore to ship. The use of these three functions is considered *direct interactions with ships*. The observer used pre-determined taxonomies (i.e. name of STM function, names of vessels, etc.) to populate an excel spreadsheet in order to capture all the data as efficiently as possible. 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.

4.4.4.3 Data Analysis

The post-scenario questionnaires were analyzed using descriptive statistics. The observational data were analyzed using a comparative analysis of the frequency and type of interactions between ship and shore (direct or indirect) between the baseline and the STM data. Two independent researchers analyzed the data to improve the validity of the results and provide more than one viewpoint to interpret the data, also known as *Investigator triangulation* (Creswell and Clark 2017).

4.4.5 Paper C

4.4.5.1 Participant Demographics

A total of 24 test participants made up of three females and twenty-one males were included in this study; 12 at CTH and 12 at WMA. Nineteen participants were from either Sweden or the United Kingdom, and the others were from Latvia and Nigeria. The majority of the participants were between 30-49 years old. The rest of the participants were either between 20-29 or 50-59. There were ten deck officers, six chief officers, three captains and one VTS operator among the test participants and the remainder selected "other" in the questionnaire. In terms of computer literacy, approximately 50% of the participants started using computers between 6 to 11 years old, and approximately 20% of participants between 12 to 15 years old. The majority of participants (75%) indicate that they spend more than 31 hours per week on a computer.

4.4.5.2 Procedures

A one-day pilot study was completed at CTH and WMA prior to the official data collection with three in-house highly experienced mariners. Data were collected over four days in October 2018 at each simulation center and the same protocol was followed by CTH and WMA for all aspects of experimental set-up and data collection. Each scenario (S1-S6) (Table 4) was run every day as either a control/base line condition or an experimental condition (S2SREX/RDV). The order of the scenarios was randomized to avoid any learning effect (Rosenthal and Rosnow 1991). Twelve different test participants tested each scenario, baseline and S2SREX/RDV as the OOW for their individual vessel involved in the scenario. The only difference between baseline and the experimental condition was that the test participants had access to an ECDIS with S2SREX and RDV functionality. In all scenarios, the routes were pre-planned by the instructor and set on monitoring on the ECDIS before the start of the exercise.

A simulator instructor and a human factors specialist observed the trials from the control room of the simulation centre. After each simulation scenario (S1-S6), the participants filled in a brief post-scenario questionnaire regarding their perceived performance and opinions about the scenario and STM functions. At the end of each day, there was also a common open-ended debrief which included semi-structured interviews to obtain information related to the participants overall perceived performance and opinions about S2SREX/RDV (Preece, Sharp et al. 2015). 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 S2SREX/RDV influenced their decision-making processes and how it could impact safe navigation practices.

4.4.5.3 Data Analysis

The post-scenario questionnaires were analyzed using descriptive statistics. A lightweight qualitative data analysis approach was used to analyze the debrief sessions (Goodman, Kuniavsky et al. 2012). This data analysis consisted of reviewing the field notes taken during the debriefing sessions, accompanied by parallel discussions with SME´s & simulator instructors to understand the data. The videos were mainly used for clarification purposes (instead of for transcription). The numerical analysis was completed by replaying the log files of each simulation run on a simulator instructor station; ship distances and Closest Point of Approach (CPA) values were recorded.

5 RESULTS

This section summarizes the results from Papers A-C. It is highly recommended to review the individual papers for a full understanding of the results.

5.1 PAPER A

The results from paper A are from the perspective of bridge officers. Throughout the analysis the comments were tagged as either positive or negative. A visual representation of the attitudes towards the STM functions are provided in Figure 4.

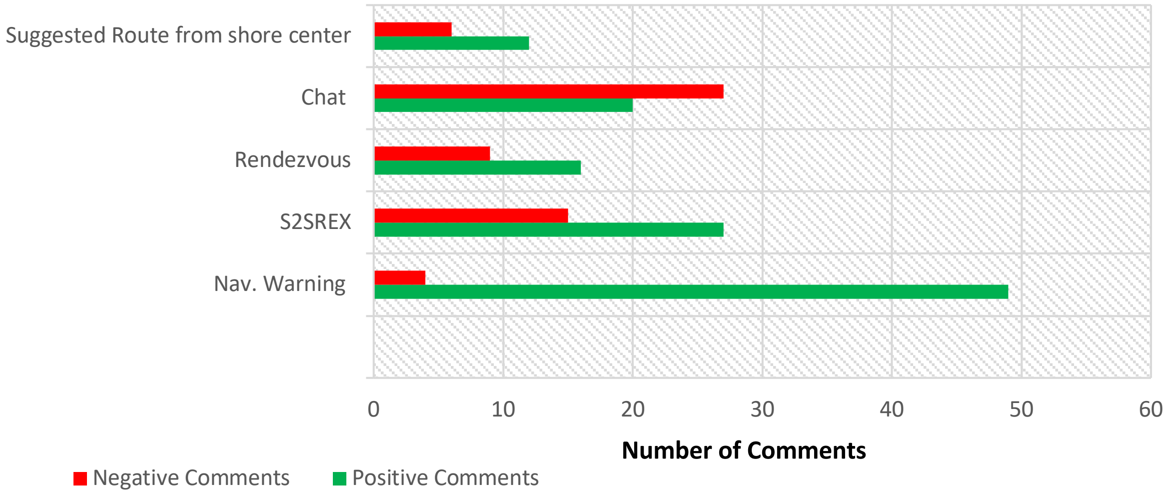


Figure 4: Summary of positive and negative comments from each STM Function

To further expand on the type of comments analyzed, Table 5 provides a summary of the most frequent positive and negative comments associated with each STM function.

Table 5: Summary of positive and negative comments related to each STM Function

STM Function		**Comments**
Navigational Warning	Positive	- Automatic plotting could reduce workload and increase situational awareness - Could reduce "noise in communications" on the VHF radio - Could reduce human errors with manual plotting coordinates
	Negative	- Usability (unable to see notification of Navigational Warning message on the ECDIS)
S2SREX and RDV	Positive	- Informative tool that can help with planning and decision-making - Allowed ships to identify other ships intentions and act accordingly - Visualization of CPA
	Negative	- Over reliability: concerns that ships were not following their broadcasted route - Usability - Not useful in dense traffic situations
Chat	Positive	- Potentially decrease miss-communications over VHF and promote clearer information exchange - Could increase efficiency
	Negative	- Distraction to operator and could decrease situational awareness - Information exchange limited between ships or shore and ship - Usability
Suggested Route from Shore Centre	Positive	- In a hectic traffic situation (e.g. notification of an oil spill) this function was highly appreciated - The VTS could have more accurate information about an upcoming area which could improve the route
	Negative	- Workload shift from ship to VTS - Captain still has to confirm new route which could increase workload for bridge team - Liability concerns

The main categories that emerged from the analysis of the coded segments include planning ahead, situational awareness, trust, workload, cost, decision-making, and communication. Within these categories, two common themes emerged. First, the STM functions provided seafarers with additional time to plan and respond to emerging navigational situations. This category encompasses both safety and efficiency, which were difficult to separate from one another. The results indicate that the STM functions automate previously manual tasks, freeing up time for watchkeeping or other important navigational tasks. The participants appreciated the benefit of the STM functions and if used properly believe that they could lead to a decreased workload, improved situational awareness, and increased safety.

The second category emerged from the negative comments about the STM functions. Participants generally agreed that the usability of the functions caused frustration, which negatively impacted their overall opinion of the experience. Many of the comments related to poor usability cannot be resolved given current ECDIS regulations. Examples of usability related comments are provided below:

- The color (green) of the routes is all the same. If you have multiple routes showing on the ECDIS this becomes very confusing (Figure 5).
- There are too many “clicks” required to access certain functions (i.e. chat).
- It wasn´t obvious when there was new information. One must search for the information provided by the STM functions.

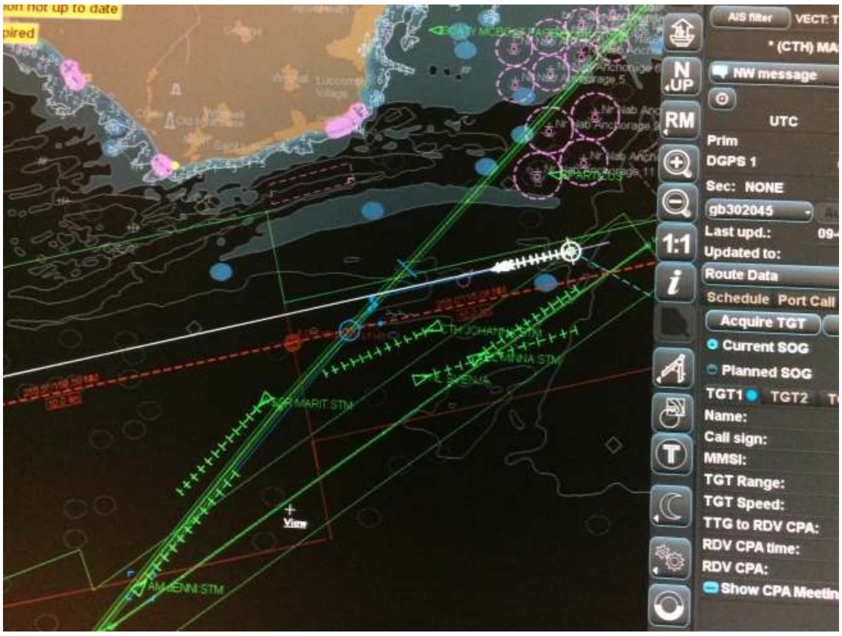


Figure 5: An ECDIS screen capture of several ships and their broadcasted routes.

5.2 PAPER B

The results from paper B are from the VTS perspective. The data were obtained from questionnaires and an analysis of the observations including the frequency of use of the STM functions. To review all of the results from the questionnaires please see appended Paper B. The most interesting findings are related to how communication or interaction will change between ships and VTS with the introduction of STM functions.

A comparison of the number of direct interactions between ship and VTS in the baseline (VHF only), and the STM trials (VHF, chat, and route suggestions from shore) was completed. In both the English Channel and Baltic scenarios, the total number of interactions increased (Figure 6). A larger increase is observed in the English Channel, which is to be expected because the traffic situation was less intense offering additional time to test the STM services. 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 (can be visualized by comparing the striped blue bar with the solid blue bar).

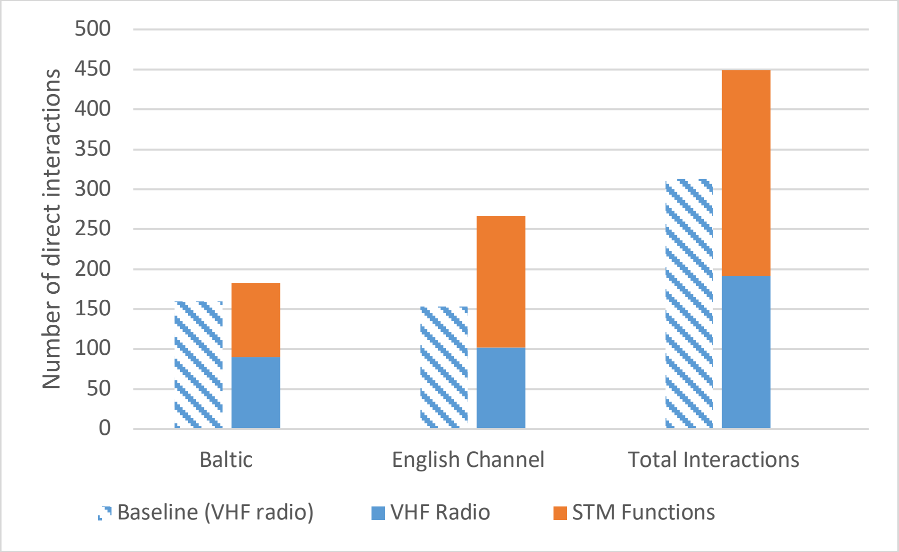


Figure 6: The number of direct interactions between ship and shore in both baseline (VHF only) and STM conditions (VHF and STM)

In terms of workload, it was interesting to further analyze the direct interactions as presented in Figure 6. Further investigation revealed that when STM functionality was available, the VTS operators initiated the interaction approximately 50% more than they did in the baseline. This finding warrants a discussion about workload, and the potential shift of tasks from the bridge officers to the VTS operators (Table 5).

Table 5: Initiation of interaction from ship or VTS operator

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

Table 6 presents the total number of times each STM function was used in the English Channel (port approach) and Baltic (dense traffic) scenarios. The table is divided into "functions for direct interaction between ship and shore" and "tools used for planning and predicting traffic". The chat function and route cross check were the most frequently used services in the English Channel. In the Baltic, the chat function and the route suggestion from shore to ship were used the most frequently, but to a lesser extent. In both scenarios, route-based prediction tool and enhanced monitoring were used the least frequently.

Table 6: Total Usage of STM Functions

STM Function	**English Channel**	**Baltic**	**Total**
Functions for direct interaction between ship and shore			
Route Suggestion from shore to ship	65	45	110
Chat Function	99	48	147
Tools used for planning and predicting traffic			
Route Cross Check	81	15	96
Route Based Prediction Tool	18	11	29
Enhanced Monitoring	3	1	4

5.3 PAPER C

The results from paper C are from the bridge operator perspective and consist of two sets of questionnaires (see appended Paper C for complete questionnaire results), end of the day post-simulation debrief, and a numerical analysis to assess ship behavior and distances.

5.3.1 Post-scenario Questionnaires

The post scenario questionnaires yielded 143 valid responses and one corrupted response (3 responses per scenario x 6 scenarios per day x 8 days). 72 questionnaires were from the baseline scenarios and 71 from the S2SREX simulations. All (100%) of participants chose to use S2SREX when it was available. The top three reasons selected by the participants to use S2SREX were: "to enhance Situational Awareness", "to supplement information from other means (ARPA, AIS etc.)", and "to help in assessing if a close-quarters situation was developing". The S2SREX/RDV function combination was used less than the standalone S2SREX function, 74.7% of participants reported using this function and the primary reasons cited by participants for not using RDV were: it was not considered helpful (76.2%), or unnecessary (14.3%) in that particular situation (e.g., "*CPA through radar was enough in this situation*", "*no need*", and "*in this situation it made no difference. Seeing the routes of the other vessels was enough both to make decisions and to understand the other vessels' intentions*."). The RDV information layer was used primarily in the assessment of a developing close-quarters situation. The results related to situation awareness, decision-making, and the clarity of information are provided in Table 7.

Table 7: Frequency distribution of S2SREX and S2SREX/RDV on SA, decision-making and clarity of information

S2SREX	**N**	**Yes**	**No**
Did S2SREX improve your SA?	71	68 (95.8%)	3 (4.2%)
Did you make a decision based on S2SREX information?	71	48 (67.6%)	23 (32.4%)
Were you confused about the information displayed?	71	7 (9.9%)	64 (90.1%)
S2SRX/RDV			
Did S2SREX/RDV improve your SA?	53	45 (84.9%)	8 (15.1%)
Did you make a decision based on S2SREX/RDV information?	53	28 (52.8%)	25 (47.2%)
Were you confused about the information displayed?	53	6 (11.3%)	47 (88.7%)

5.3.2 End of the day questionnaires and post-simulation group debrief

The end of the day questionnaire asked more generic questions about navigation practices, trust, overreliance and risk. These results include 24 responses from all 24 participants from both CTH and WMA simulation centers (Table 8).

Table 8: 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 and RDV 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 and RDV?	24	0 (0%)	3 (12.5%)	**12 (50%)**	8 (33.3%)	1 (4.2%)

The post-simulation group debrief with video playback provided further insight into the questionnaires results. The findings are summarized as below:

- Positive impact on navigational safety: the participants shared a positive attitude towards the usefulness of the functions and perceived that S2SREX/RDV will improve SA. They also believe that the functions will increase the available time to respond to potentially dangerous situations, and they placed a high level of trust in the information.
- Purpose of STM functions: There was discussion surrounding the purpose of the functions, i.e. when should they be used (strategic long-term planning) and when they should not be used (tactical tool for collision avoidance). The participants claimed to be aware of the potential risks and challenges associated with the functions (i.e. violation of COLREGs, information overload, decisions made based on assumptions, etc.).
- Usability: This was the only result that did not directly align with the questionnaire results. The participants mentioned several issues related to usability including: the overlapping routes of other vessels on the ECDIS, all the routes are the same color, and some difficulty with the RDV information layer. However, the participants discussed that usability would be more of an issue in traffic scenarios with more than three vessels.

5.3.3 Numerical Analysis:

In addition to the questionnaires, a numerical analysis was completed to assess the positions of the ships in relation to closest point of approach (CPA) and COLREGS. This was completed by re-playing the videos of each simulation. The results from the numerical assessment are provided in Table 9.

Table 9: Numerical Analysis of baseline and experimental conditions

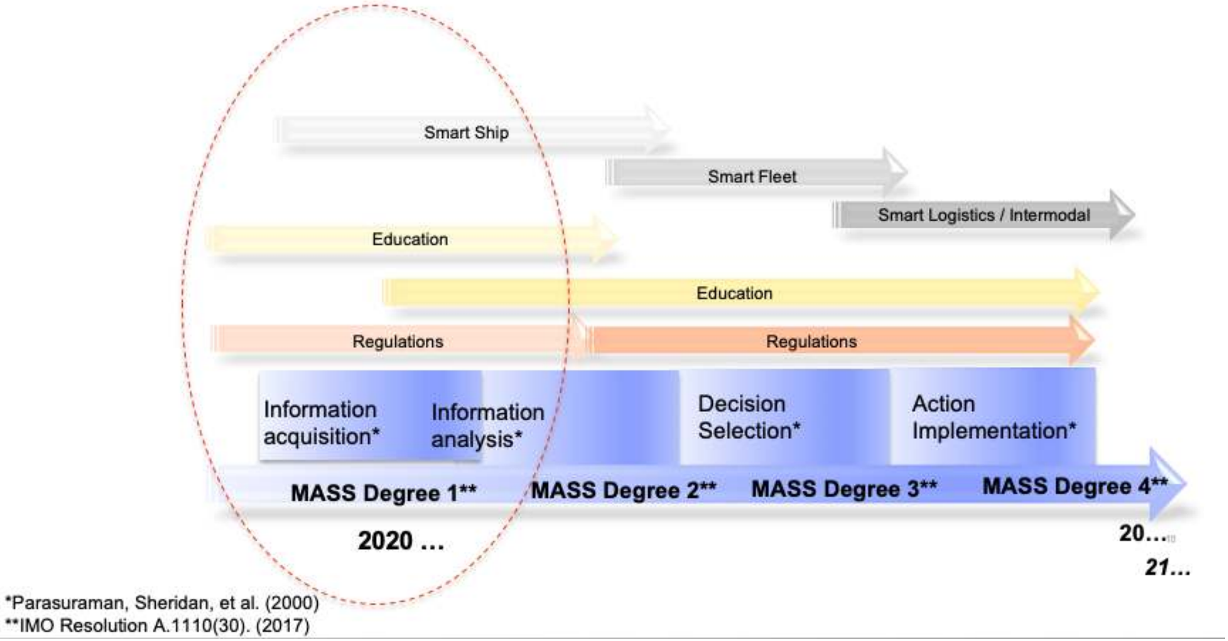
All scenarios	**Distance when taking action (NM)***	**Resulting CPA (NM)***	**Breach of COLREG**
No S2SREX	3,6	0,9	2
with S2SREX	4,1	1,1	11
Means in meeting/overtaking scenarios 1, 2 and 4			
No S2SREX	2,4	0,7	0
with S2SREX	2,6	0,9	3
Means in crossing scenarios 3,5 and 6			
No S2SREX	4,4	1,1	2
with S2SREX	5,2	1,3	8

*NM is Nautical Miles

6 DISCUSSION

The rapid development of higher LOA, artificial intelligence (AI), big data and fully autonomous ships have the potential to transform the maritime industry. This transformation will cause changes slightly altering the role and tasks of seafarers, VTSOs and the relationship between them. During this time humans will remain highly involved in the system, making it critical to have a better understanding of the upcoming mixed human-automation levels and types. Investigating the current to near future of the shipping industry will allow for a safer, more systematic progression towards the future.

An exploratory mixed-methods approach was adopted to investigate the research questions, RQ1 and RQ2. The aim was to study the impact of information automation functions on navigator behavior from a systems perspective. Figure 7 (adapted from MacKinnon & Lundh 2019) shows the sociotechnical elements that are impacted by digitalization and automation and the red circle defines the framework of this thesis. The beginning of the discussion will focus on RQ1 and discuss the findings specific to operator behavior in the STM context. The second part of the discussion will address RQ2 and the system level implications related to technology development, smart ships/fleets, and logistics, education, training and regulatory considerations (MacKinnon and Lundh 2019).



*Parasuraman, Sheridan, et al. (2000)
**IMO Resolution A.1110(30). (2017)

Figure 7: Framework for this licentiate and future research areas (adapted from MacKinnon, & Lundh, 2019)

6.1 ZOOMING IN: LESSONS LEARNED FROM STM

The STM Validation project provided the context for the three papers included in this licentiate. These papers primarily addressed the interaction between the individual-technology nodes within the sociotechnical system model. Each paper assessed operator behavior and an assessment of the STM functions including participant perceived safety, efficiency, SA, workload, trust and usability. The five STM functions tested throughout these experiments yielded some interesting and potentially complex findings relating to the "work as done" for both bridge and VTS operators.

6.1.1 Ship-ship Subsystem

One of the goals of the fully deployed STM concept is to improve safety through a 50% reduction in accidents by 2030 (STM 2019). Safety is considered based on the results from Papers A-C. The aim of Paper A was to understand the impact of the STM functions on safety and efficiency from the bridge operator's perspective. Throughout the analysis it became difficult to dissociate safety from efficiency, as participants believed that most of the functions would positively impact both. The automated plotting of navigation information on the ECDIS, and the ability for VTSOs to send digitized route information was highly praised by the participants in the post-simulation debriefings. One of the themes that emerged from the qualitative analysis of Paper A is that the STM functions will "free up time" to perform other tasks (i.e. improve efficiency), including watchkeeping of surrounding traffic, ultimately leading to improved perceived SA (i.e. increased safety). Ideally, having access to another ship's monitored route and the ability to predict the rendezvous point would lead to earlier actions and reduce the risk of creating a close quarters situation.

The research objectives described in Paper C were motivated by concerns raised by the International Chamber of Shipping (ICS) related to the S2SREX/RDV functions. The concerns relate to navigators' potential assumptions in decision-making if the traffic situation and risk of collision is assessed based on the broadcasted routes (as presented on an ECDIS with S2SREX/RDV functionality) rather than by current navigation practices such as visual and radar assessment of the range, relative bearing, movement and aspect, and VHF radio confirmation. The STM functions may have the potential to cause confusion and possibly create dangerous situations between vessels unless navigators are fully aware of the data sources for S2SREX, the basis of the RDV calculations, and use them as intended (longer-range strategical navigation). These two functions have the greatest ability to influence decision-making and impact navigational safety. The qualitative findings in Paper A were supported by the quantitative results in Paper C (Table 9) showing that on average, ships took action at a slightly further distance, and the resulting distances between ships were numerically larger when the S2SREX/RDV functions were used compared to the baseline. These results would appear to refute the concerns presented by the ICS, indicating safer navigation behavior.

In general, the perception from bridge operators (Masters, OOW) is that the STM functions will improve navigational safety and efficiency. The questionnaire results indicate that participants placed a relatively high level of perceived trust and reliance in the information and approximately 67% of participants made a decision based on the S2SREX/RDV information (Table 7-8). The participants responded that they were aware of the risks of relying on the STM information and acknowledge its limitations on decision-making. However, given the controlled simulated environment it is difficult to fully assess risk perception as the participants most likely exhibited exploratory behavior (Lee and Moray 1994). This is when 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 (Lee and Moray 1994, Inagaki, Takae et al. 1999, Lee and See 2004). The participants may not have responded in the same way if the STM functions were being assessed in real life (i.e. not within a simulated environment). Further research is needed to evaluate the perception of risk, reliance, and trust in information automation as it has the potential to contribute to automation biases.

It is crucial to acknowledge that introducing new technology into a STS will impact other aspects of the system (Woods and Dekker 2000, Grech, Horberry et al. 2008). An interesting discussion about the formal and informal rules of navigation is provided by Chauvin and Lardjane (2008). The COLREGs, or collision regulations, define the “rules of the road” for vessels at sea, and the informal rules can be characterized by deviations from the formal rules given situation-dependent interactions between vessels (Chauvin and Lardjane 2008). Research looking at the cause of maritime accidents found that the existence of these two rule systems could cause misunderstanding, uncertainty, and potentially lead to accidents (Chauvin, Lardjane et al. 2013). The quantitative results from Paper C found that COLREGs were breached more often when S2SREX was used compared to baseline trials, although never leading to unsafe or close call situations (Table 9). These findings were the most concerning in relation to navigation behavior. The introduction of more information, and automated functions on some vessels and not others may further exploit the differences between the two-rule systems. The functions could complicate the decision-making process and lead to potentially false assumptions about other vessels intentions. These findings support the concerns put forward by the ICS and lead to an interesting discussion about the future introduction and deployment of low LOA.

6.1.2 Ship-shore Subsystem

Papers A and C provided insight into the individual-technology interactions for ship-based operators (Masters, OOW). Paper B assessed the STM functions from the perspective of VTS operators and studied the ship-shore subsystem. It is interesting to note that the formal and informal rule systems are not exclusive in ship-to-ship interactions; they also exist in ship-to-shore interactions. Brödje (2012) studied VTS operators with a major focus on communication and miscommunication and found that the existence of informal hierarchies between ships and VTSO´s can have a negative impact on navigational safety (Brödje 2012). These studies provide evidence towards a discrepancy between the system task description (work-as-imagined) and the everyday work and cognitive tasks (work-as-done) (Hollnagel 2017). The formal rules and procedures indicate how work should be done; yet work studies in the maritime context continuously show that mariners and VTSO´s succeed at their goal (i.e. safe navigation) but achieve it in different ways than formally prescribed by procedures and rules (Brödje 2012, Praetorius 2014, Costa, Lundh et al. 2018, Man 2019).

Similar to the ship-ship subsystem, the STM functions provide an alternative means to share information, monitor traffic, and chat with vessels. These alternative solutions can change the way ship and shore operators interact with one another. These findings were reported in Paper B (Figure 6) (Tables 5-6) in which the interactions between ship-shore increased when STM was available compared to the baseline. The increase was attributed to the VTS operators initiating contact with vessels (Table 5), leading to a discussion about workload and task distribution. The STM functions are intended to improve safety and efficiency. However, adding information to operators´ task can lead to information overload and can consequently negatively impact situation awareness (Endsley 1999). Workload was not quantified in Paper B as the experimental protocol would not allow for this, and it is therefore impossible to determine the influence of the STM functions on this metric. However, the results point towards a potential shift in number and type of tasks, which could impact mental workload, suggesting the need for a more detailed workload analysis.

While the total frequency of ship-shore interactions increased using STM functions, the VHF interactions decreased (Figure 5). 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. The term ¨disruption¨ in this sense in not necessarily intended to have a negative connotation. An alternative means of communication between ship-shore could positively impact the ship-shore relationship and existing challenges associated with busy VHF radio communications. The results in Paper B reported that the frequency of miscommunication decreased with the use of STM functions compared to the baseline. However, all existing research studying work practices of VTSO´s, bridge officers (or both) focus on VHF radio as the foundation of maritime communications as it was the only available means of communication (Lützhöft and Dekker 2002, Lützhöft 2004, Brödje, Lützhöft et al. 2010, Brödje 2012, Brodje, Lundh et al. 2013, Praetorius 2014, Praetorius, Hollnagel et al. 2015). VHF radio conversations are used by VTSOs and surrounding traffic to obtain important traffic information, the status onboard other vessels, and a general shared awareness of the surrounding traffic (Brödje 2012). The chat function, for example, would isolate the conversation between two parties (i.e. two ships or ship and VTS). This isolation of information could change or *disrupt* the existing subsystem communication practices. Whether the disruptions are positive or negative, it is important to better understand how new technologies (STM or similar) will affect the actors, teams and organization within the sociotechnical system(s). Without further research and consideration of standardization, regulation and education to accompany these changes, the technologies have the potential to negatively influence current work practices.

6.1.3 User-centered Design and Technology Acceptance

A common finding from Papers A-C which could potentially threaten safety and negatively impact user acceptance is user interface design and usability. It presented one of the greatest barriers to user acceptance and perceived usefulness towards the usage of the STM functions. Most of the negative comments were directed towards the chat function, and the S2SREX/RDV functions. The bridge operators generally agreed that the chat function interface was not intuitive and required too many clicks to type and send a message, then the participants felt it was more efficient to do via VHF radio. The VTSOs had the opposite view of the chat function, rating it higher than others and expressing little frustration with the usability. This function is designed differently for compatibility with an ECDIS and with the VTS operating systems. The S2SREX/RDV functions caused frustration if multiple vessel routes were selected as this quickly cluttered ECDIS screens which was further distracting as all the routes are bright green (Figure 5). However, this is a limitation of the ECDIS manufacturers and not the fault of the STM functions. It was discussed that the poor usability issues were much more prevalent in busy traffic scenarios.

The content, format, interface and usability of technology have shown to have a powerful impact on trust, even if this is not associated with the true capabilities of the system (Corritore, Kracher et al. 2003, Lee and See 2004). The results indicate that the functions were not adequately user tested prior to implementation, which can present a major barrier to technology use and acceptance (Grech and Lutzhoft 2016). User-centered design has been advocated for years in the maritime domain, and was specifically identified in the e-Navigation plan as a priority in the development and implementation of new technology (International Maritime Organization 2014, Mallam, Lundh et al. 2017, Costa 2018). The findings from Papers A-C indicate that the maritime industry must do a better job of involving users in all stages of technology development from inception to implementation.

6.2 ZOOMING OUT: LOW LOA ON THE MARITIME SOCIOTECHNICAL SYSTEM

Papers A-C assessed specific functions (STM) in a simulated setting, with all actors equipped with the same technology, training, vocational experience and level of familiarization. Although this provided important insight into the STM functions, it represents a small component of the larger maritime sociotechnical system. In reality, the system will be made up of complex combinations of humans, technologies, harsh operating environments, rules and legislation, etc. New technology solutions comprised of other types and degrees of LOA can and may replace the STM functions. In the near future the traffic ecosystem will include some ships that have adopted various automated solutions, and others that have not and maintain traditional work procedures and tasks. The idea that new technologies can simply be a substitute for a person while expecting improved results, also known as the *substitution myth* remains a prevailing attitude in the shipping industry (Woods and Dekker 2000). If the industry continues to adopt a reductionist or technology-focused approach, the gap in understanding the interactions between other elements of the sociotechnical system will increase. This includes challenges related to regulations, training and skills, culture, organization, and teamwork. It is therefore important to zoom out (from the STM project context) and “think big” towards the potential impact of low LOA on the maritime sociotechnical system (Hollnagel 2011).

6.2.1 Regulatory Considerations

The post-simulation debriefings in Papers A and C sparked interesting discussions related to the regulatory aspects of new technology in a sociotechnical system. The IMO and other regulatory bodies are currently undergoing a scoping exercise to define autonomous systems, find methodologies to assess them, and define a clear path of work (IMO 2018). As of now, STM or similar functions arising from the e-Navigation concept are not fully addressed by existing regulations. The maritime industry is struggling to keep up with the pace of technology development on board and ashore creating both regulatory and liability challenges (Mallam, Nazir et al. 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 and Lundh 2019). Although the barriers described by Carey are related to autonomous ship(s) operations, the results of this licentiate, particularly Paper C, indicate that these barriers are also relevant for lower-intermediate LOA. On traditionally operated vessels, these technologies can serve as problem-patching solutions that will change *work as done.* As observed in Paper C there might be an impact on COLREG compliance with only minimal changes to available information. Without proper assessment of these individual solutions on the entire system these challenges have the opportunity to contribute to the barriers identified by Carey (2017).

A question discussed with participants in post-simulation debriefings in Paper A was the following: *If a VTSO sent a route to a vessel, the vessel accepted the route and then has an accident…who is responsible*? In terms of existing regulations, the captain is responsible as they must review or accept the route, accepting responsibility for the final decision. However, as automation becomes more accepted, trusted and reliable in the maritime domain the chance of automation biases and the corresponding HAI challenges from higher LOA will likely increase (Hancock, Jagacinski et al. 2013). Further, as the automation function shifts towards decision-making and response selection generated by non-human agents (i.e. algorithms and AI), the liability and responsibility situations will become increasingly more complex. It is important to continually assess the regulatory regime, particularly in an era of rapid technology development, integration and implementation, and try to understand how it either supports and protects or threatens and risks the sustainability of the shipping industry.

6.2.2 Training and Education of the Future Mariner

As digitalization and automation are continuously introduced into the maritime sociotechnical system, training and organizational factors will have to be evaluated. One of the post-simulations debrief discussion points in Paper A was related to the necessary training for the STM functions. Participants generally agreed that because the functions were not highly complex, they could be added elements to an existing ECDIS model course and should not require stand-alone training or certification. However, this integrated training does not exist today while the services are already being implemented on board ships. The training in place today for the STM functions was created by project members and would not be classified as approved instructional materials by regulating authorities. If other STM-like solutions (similar to STM) are being independently adopted, the existing challenges related to the lack of standardization in the maritime industry will be further exacerbated. This situation would be applicable for both ship and shore-based systems.

As a personal anecdote, while teaching fourth year Master Mariner students about Ergonomics and Human Factors, we discussed automation in relation to a different EU project, called SEDNA. This project disregards current regulatory frameworks and technology capabilities to encourage researchers to think outside the box for future solutions in maritime navigation in Arctic environments. While discussing this project with the students (and potentially seeking volunteers for prototype testing), one of the comments was: "*...this technology is interesting, but it will take our jobs away. Why would we want to be involved*?" This attitude represents a valid concern and one that resonates strongly with workers in industries that are introduced to increasingly automated systems (Brynjolfsson and McAfee 2014). Today there is a feeling of uncertainty and insecurity for workers in the maritime industry. This situation is driven by the demand for cost savings and efficiency and fueled by an outdated attitude that the human element is the root cause of all accidents and incidents(Grech, Horberry et al. 2008). This situation was discussed and sometimes debated in the post-simulation debriefs while collecting data for Papers A and C. It seems that people usually fall somewhere on a spectrum of either accepting digitalization and automation or rejecting it. It is no secret that the role of the seafarer has already changed and will continue to evolve. The IMarEST Maritime Autonomous Surface Ship 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 (Meadow, Ridgwell et al. 2018). There is also the Human Maritime Autonomy Enable (HUMANE) project in Norway, which is trying to understand the needs of future seafarers and provide a set of methods to industry stakeholders to better prepare them for the future. These efforts adopt a human-centered approach and are highly essential throughout the transition towards the future shipping industry.

6.3 FUTURE DIRECTIONS FOR SHIPPING

"Seafaring in 2050 will bear scant resemblance to the occupation today" (Meadow, Ridgwell et al. 2018). The exponential rate of technology development presents difficulties in anticipating the future of maritime operations. The promise of artificial intelligence, big data, and autonomous ships will completely change the maritime sociotechnical system. The investigation into these future challenges is already well underway (Wahlström, Hakulinen et al. 2015, MacKinnon and Lundh 2019, Mallam, Nazir et al. 2019, WMU 2019). This evolution period towards autonomous shipping has an unspecified timeline (Figure 7). Therefore, in the current to near future, the STM functions or similar technological solutions must be better understood. This licentiate contributes to the limited body of research focused on low LOA in the maritime STS. It provides empirical results based on the STM Validation project that describe and explore the impact of information automation on operator behaviors. Throughout this investigation, major gaps have been identified in existing knowledge about the near future of a mixed human-automation shipping system. These gaps motivate questions that should provide direction for future research. Although by no means exhaustive, some of these questions include:

- Will automated functions increase navigational safety?
- Will these functions cause mariners to break more formal rules (COLREGs) and rely more heavily on the informal rules?
- 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?
- How will changing communication between ship-shore impact navigational behaviors?
- What are the optimal manning requirements as automation levels increase?
- Who is the future mariner? Will there even be a future mariner?

Zooming out to study these questions will allow for a deeper understanding of low-intermediate LOA functions within complex sociotechnical systems. The STM Validation project simulates an "ideal" situation of all vessels 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). Further investigation is needed to determine the transferability of the results to reality. Similar to the automotive industry, future research should focus on the upcoming mixed human-automation types and levels, working together in the same system. A mixed methods approach to these questions would provide valuable insight into the future of the maritime sociotechnical system and contribute to a safer and more efficient shipping industry.

7 CONCLUSIONS

Automated functions will have a disruptive impact upon the maritime sociotechnical system. Automation, artificial intelligence, and big data will be the catalysts that drive the transformation of the shipping industry. This work foretells of how low-level information automation, in itself, will influence how navigation safety might evolve. The results point towards changes in both the ship-ship and the ship-shore subsystems. The operators´ *perceived* that the STM functions will “free up time” to plan, respond or tend to other tasks compared to traditional navigation practices, leading to an improvement in situation awareness, safety and efficiency. There is also a positive attitude from the operators; both bridge and VTSO, towards incorporating STM (or similar) automated functions into the work practices. The value of low LOA in the maritime sociotechnical system is recognized through enhanced access to relevant information and improved information exchange between ship and shore. If used as intended, the STM functions have the potential to assist and improve navigation and navigational assistance tasks. They have the potential to change the tasks, the role of the operator(s) and how work is done.

Operational changes will correspondingly introduce gaps and barriers to overcome as the industry adopts these new technologies. 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. Challenges related to communication, informal and formal rules, and human-automation interactions have been identified in this licentiate. Understanding the problems must include; qualitative and quantitative assessments of human performance, an assessment of current and future regulations, training needs and skill development, formal (COLREGs) and informal rules, and work practices for both ship and shore operators. As the industry evolves towards 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 human and automation interactions.

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