THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Vessel Traffic Service (VTS): a maritime information service or traffic control system?

Understanding everyday performance and resilience in a socio-technical system under change

GESA PRAETORIUS

Department of Shipping and Marine Technology

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2014

Vessel Traffic Service (VTS): a maritime information service or traffic control system?
Understanding everyday performance and resilience in a socio-technical system under change
GESA PRAETORIUS
ISBN 978-91-7597-048-6

gesa.praetorius@gmail.com

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 3729
ISSN 0346-718X

Department of Shipping and Marine Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers Reproservice
Gothenburg, Sweden 2014

Vessel Traffic Service (VTS): a maritime information service or traffic control system?
Understanding everyday performance and resilience in a socio-technical system under change

GESA PRAETORIUS
Department of Shipping and Marine Technology
Chalmers University of Technology

ABSTRACT

Vessel Traffic Service (VTS) is a shore-side maritime assistance service that supports bridge teams in their safe navigation of port approaches and other areas that present navigational difficulties. The VTS is implemented in national waters and provides vessels with information through transmissions and broadcasts on Very High Frequency (VHF) radio. With a continued growth in the number, size and cargo volumes of merchant vessels, the role of the VTS has recently become a matter of discussion, and it has been argued that changes, such as implementing an aviation-like control system, would be of an enormous benefit for stakeholders and guarantee safe and efficient traffic movements in the future.

The complexity of processes in safety-critical domains, such as maritime traffic management, is increasing due to continuing technical, organisational and environmental developments. The VTS is currently undergoing drastic changes, primarily driven by strategies and projects focusing on increasing the overall efficiency of the maritime transportation system through advanced technology. To reduce the risk of unforeseen consequences, it is important to study and understand the service and its contribution to traffic management before changes are implemented. The purpose of this thesis has been to increase the overall understanding of everyday performance of the VTS system and identify ways of modelling the performance of the service, as a contribution to the ongoing debate on the future needs of maritime traffic management.

The VTS is described as socio-technical system that controls and manages maritime traffic in port approaches and other areas that pose navigational difficulties for bridge teams. Field data collected through semi-structured interviews, observations and focus groups have been analysed with the aid of concepts derived from Cognitive Systems Engineering (CSE) and Resilience Engineering (RE) to understand how the VTS actively contributes to safety through monitoring, responding to and anticipating changes in traffic patterns in the VTS area. The data have also been used to model performance variability in everyday operation with the aid of the Functional Resonance Analysis Method (FRAM). Performance variability is necessary for a system to be adaptive, and is therefore essential for the system's functioning. By using the FRAM, a new angle of the VTS system has been explored to understand how variability in its functional units affects the overall system performance.

The thesis demonstrates the importance of understanding how performance in a socio-technical system can vary and the consequences this may have. The FRAM can be used to analyse the functional design of a socio-technical system, and therefore help to identify and assess ways in which performance variability can be monitored and managed. By understanding the functional design of the VTS system and the complexity of everyday operation, stakeholders will be able to identify advantages and disadvantages of current system design and use this to consider how future demands can best be met.

Keywords: Vessel Traffic Service, Traffic Management, Cognitive Systems Engineering, Resilience Engineering, Performance Variability, Functional Resonance Analysis Method (FRAM)

List of Publications

This thesis is based on the work contained in the following papers

I. Praetorius, G., van Westrenen, F.C., Mitchell, D., & Hollnagel, E. (2012). Learning lessons in resilient traffic management: A cross-domain study of Vessel Traffic Service and Air Traffic Control. In D. De Waard, K. Brookhuis, F. Dehais, C. C. Weikert, S. Röttger, D. Manzey, S. Biede, F. Reuzeau & P. Terrier (Eds.), Human Factors: a view from an integrative perspective. Proceedings of the HFES Europe Chapter Conference 2012.

The author of this thesis conducted the study visits with Mitchell and is the lead author of the manuscript.

II. van Westrenen, F.C., & Praetorius, G. (2012). *Maritime traffic management: a need for central coordination?* Cognition, Technology & Work. doi: 10.1007/s10111-012-0244-5

The author of this thesis has contributed VTS-related knowledge and wrote the article in collaboration with van Westrenen with a focus on the sections concerning the VTS.

III. Praetorius, G., & Hollnagel, E. (2014*). Control and resilience within the maritime traffic management domain.* Journal of Cognitive Engineering and Decision Making. (resubmitted pending minor revision)

The author of this thesis was responsible for the data collection and analysis, and is the lead author of the manuscript.

IV. Praetorius, G., Hollnagel, E., & Dahlman, J. (2014). *Modelling Vessel Traffic Service to understand resilience in everyday operations*. Reliability Engineering & System Safety (submitted)

The author of this thesis is the lead author of the manuscript responsible for data collection and analysis, as well as the modelling activities presented in manuscript

Additional publication focusing on the VTS

Praetorius, G., Bruno, K., & Lützhöft, M. (2010*). Enacting Reliability: First Steps To Define Safety in the VTS Domain.* Paper presented at the International Conference on Human Performance at Sea, HPAS 2010, Glasgow.

Praetorius, G., Lützhöft, M., & Bruno, K. (2010). *The context matters: Maritime safety in the Vessel Traffic Service (VTS) Domain.* Paper presented at the ESREL 2010. Reliability, Risk and Safety. Back to the Future, Rhodes.

van Westrenen, F.C., & Praetorius, G. (2012). *Situation awareness and maritime traffic: having awareness or being in control?* Theoretical Issues in Ergonomics Science, 15(2), 161-180. doi: 10.1080/1463922X.2012.698661

Praetorius, G., & Lützhöft, M. (2012). *Decision Support for Vessel Traffic Service (VTS): User needs for dynamic risk management in the VTS Domain.* Work: A Journal of Prevention, Assessment and Rehabilitation, 41 (Supplement 1/ 2012), 4866-4872.

Praetorius, G. (2012). Safety within the Vessel Traffic Service (VTS) Domain. Understanding the role of the VTS for safety within maritime traffic management. (Licentiate of Philosophy Licentiate thesis), Chalmers University of Technology, Reproservice.

Kataria, A., & Praetorius, G. (2014). *On common ground at sea: The proactive negotiation for channel navigation.* Paper presented at the Applied Human Factors and Ergonomics, Krakow.

Acknowledgements

An important aspect of doing a PhD is that it is a journey. You start an adventure that will last for at least four years and that will change you. Working on my PhD and writing on this thesis has changed me. It has been the most challenging, exhausting and amazing thing that I have so far attempted in my life, and I would like to express my gratitude for those who have been on this journey with me.

Foremost, I would like to thank my main supervisor Professor Erik Hollnagel. Erik, thank you for guiding and advising me, calming me down when I started to panic, putting me back on track when my focus started to drift, and encouraging me to aim high when I was about to give up. Thank you!

Secondly, I would like to thank my co-supervisor Joakim Dahlman. Joakim, I am thankful that you took on this task that has probably not always been the easiest. I appreciate your honesty and integrity, and I would therefore like to thank you especially for the times, where guidance was not only about research, but also about life.

I would further like to acknowledge my co-authors Fulko van Westrenen and Deborah Rushton. In addition to learning the basics of ATM from these two, the long discussions about research and life, as well as the trips to Middelfart, Stavanger and Vlissingen have been some of the highlights of my time as PhD student. I have learnt a lot from both of you and I really treasure the time we worked together and hope that our paths will cross again in the future.

Research can only be conducted if the right background is available; financiers, willing experts as research participants and a fruitful work environment, which encourages you to aim high. Firstly, I would therefore like to acknowledge the financial support of the Region of Vastra Gotaland (VGR) and the Fru Mary von Sydow, fodd Wijk, Donationsfond. Secondly, I would like to express my deepest gratitude to all experts that have been involved in this research. I know that it is not always easy to let an outsider - especially someone without any background in VTS - into your work environment, and I am grateful that all of you so willingly shared your thoughts and experiences with me. There would not be any results to present without your participation. Thirdly, I would like to thank my former colleagues in the Maritime Human Factors group and at the Department of Shipping and Marine Technology for the fruitful and inspiring work environment they provided me with.

Furthermore, what makes a person thrive, are the people that induce the spark of light into your daily life. In my case, I have been lucky enough to be surrounded by incredibly inspiring individuals that have shared my ups and downs with me. Some of these deserve to be acknowledged here.

Francesco Baldi and Erik Svensson; fellow PhD students, and probably my closest companions on this journey. Sharp minds, good friends and more than once the rocks that I could hold onto when times were rough. I would not have made it without you!

Kajsa Nalin, Joanna Paraiso, Antje Teda Niescken, and Kerstin Thomsen; close friends and truly strong women. I admire you for your honesty and the way that you overcome even the biggest obstacles without compromising your beliefs and values. You inspire me!

Lars-Ola Bligård, Eva Salomonsson, Johanna Larsson, Jörgen Frohm, Jonas Andersson, and Steven Mallam – my HFAW-seminar group – who challenged me with discussions and taught me more than once that there are many ways to achieve a good fit between human, technology, and environment. Thanks!

Clark Borst and Rolf Klomp, who have tried to teach me the details of ATM, experimental design, and of "engineering in the wild". The three months we worked closely together have helped me to identify new perspectives in my own research, and our common publications have been an inspiring distraction, whenever I got stuck in my thesis writing. Thank you and the other members of the Control and Simulation Division at the Department of Aerospace Engineering at TU Delft, especially Professor Max Mulder, for providing me with this opportunity.

Karl Bruno, Monica Lundh, Johannes Prison, Anders Brödje, Cecilia Österman, and Margareta Lützhöft, all of them colleagues at some point, and all of them people that I need to thank for the good and bad times we have had together, for tears and laughter. I wish you all the best on your paths and I hope that we will always stay in touch.

Doing a PhD abroad also means living in a country and a culture that is not your own and that might need some explaining from time to time. I had the opportunity to get to know Sweden and its culture through the eyes of an amazing family; Åsa & Sylve, Janne & Inger, Sandra & Magnus, and Sofie. Thank you so much for your patience and your kindness, for letting me be a part of your life without getting tired when I was barely speaking Swedish, and for accepting me the way that I am.

Lastly, I would like to thank my family Gesine, Klaus, Heike, Dirk and Tommy. Your love has encouraged me to pursue my dreams and has given me strength, when I was tempted to give up. Your belief in me is what has kept me going, and I will never find the right words to express how much your endless support means to me.

Gesa Praetorius

Malmö, 2nd August, 2014

Contents

Figures

Tables

Abbreviations

ATC	Air Traffic Control
ATCo	Air Traffic Controller
CSE	Cognitive Systems Engineering
CoCoM	Contextual Control Model
DSS	Decision Support System, referring to the technical support system at hand in an operational environment in the Vessel Traffic Service. It can incorporate several decision support tools, such as electronic charts
DTW	Deadweight tonnage
ECDIS	Electronic Chart and information System
FRAM	Functional Resonance Analysis Method
FSA	Formal Safety Analysis, the method recommended by the IMO to determine whether there is a need for a VTS
IALA	International Association of Lighthouse Authorities and Aids to Navigation
IMO	International Maritime Organization
INS	Information Service
JCS	Joint Cognitive System
NAS	Navigational Advice and Assistance Service
OJT	On-the-job training
RE	Resilience Engineering
SMCP	Standard Maritime Communication Phrases
SOP	Standard Operating Procedures
TOS	Traffic Organisation Service
VHF radio	Very High Frequency radio, the primary means of communication for VTS and vessels
VTS	Vessel Traffic Service, a shore-based support service for the mercantile fleet in constrained/confined waters
VTS area	Area in territorial waters in which VTS is provided to the merchant fleet
VTSM	VTS Manager

VTSO	Vessel Traffic Service Operator
VTSS	VTS Supervisor

1 Introduction

This chapter presents the domain of interest for this thesis, its objectives and research questions, and its limitations.

1.1 The shipping domain and Vessel Traffic Service (VTS)

Shipping has been one of the major means of transportation and commerce for the past 5000 years. From local trading along rivers in Mesopotamia and the Mediterranean in ancient times, shipping has developed into a global business in which cargo is transported between more than 3000 major commercial ports worldwide (Stopford, 2009). In Sweden alone, more than 95% of all goods are imported and exported through seaborne transport (Sjöfartsverket, 2013).

Driven by rapidly developing economies, such as China and India, the volumes of goods transported have steadily increased in recent decades. Over the past ten years, the world fleet has more than doubled to a collective size of 1.6 billion in deadweight tonnage (dtw) in January 2013 as depicted in Figure 1. Despite of the reduced pace of growth, seaborne trade increased by 4.3%, and overall, 9.2 billion tons of cargo were handled in ports worldwide (UNCTAD, 2013).

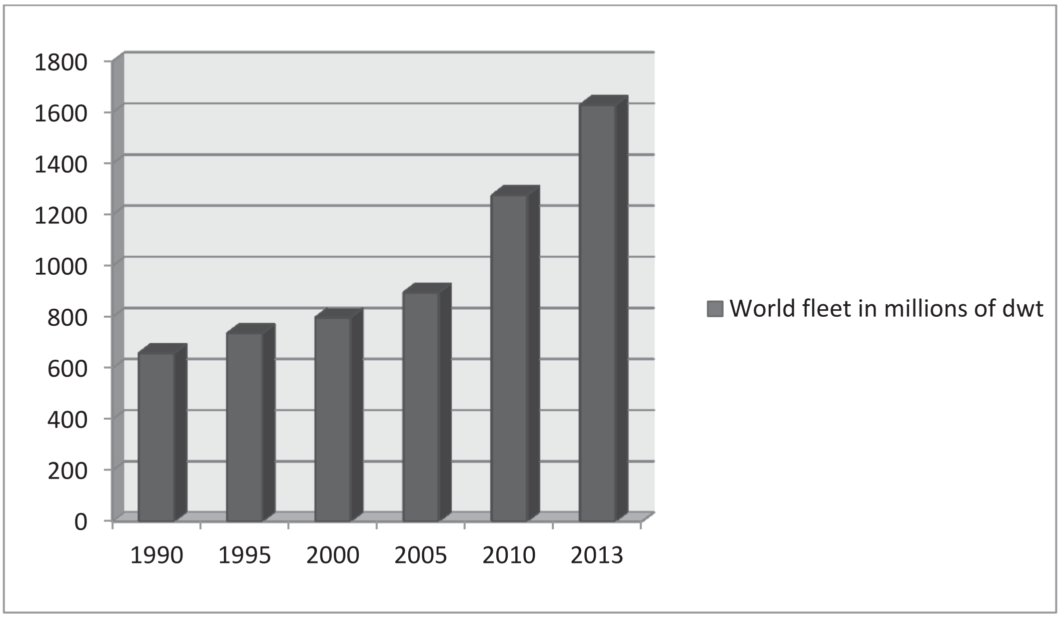

Figure 1: Increase of the world fleet's dwt between 1990 and 2013 (based on UNCTAD, 2013)

As a consequence of the steady growth in trade, an increase and change in the specialised type, size and volume of ships has occurred (UNCTAD, 2013). From the beginning of containerisation in the 1950s, the development of specialised vessels, such as car carriers, Liquefied Petroleum Gas (LPG) tankers, or bulk carriers, has continuously improved the safety and efficiency of vessel traffic. Contemporary container vessels, for example, can carry up to 18000 containers in a single voyage making shipping to the most efficient means of transporting the majority of goods.

With maritime traffic increasing in volume and size (fig. 1), structures in and surrounding ports have also changed worldwide. Traffic Separation Schemes (TSS), deep-water routes and specialised terminals have been introduced to facilitate cost-effective and safe seaborne trade (Stopford, 2009). As components of the maritime transport system in a port approach, there are several services to support the vessel traffic and to increase the safe and efficient flow of traffic into and out of port. One of these services is the Vessel Traffic Service (VTS).

The VTS is a maritime shore-based service to assist the vessel traffic in a specific area, a VTS area. The service is provided by VTS operators (VTSOs) using Very High Frequency (VHF) radio to provide information that is important for the safe navigation within the area. Following its introduction after World War II, VTS was no more than a radar chain. When vessels were delayed during periods of poor visibility, port operations came to a halt, spreading vessel delays throughout the transport chain to shore, regularly leading to disruptions and problems in the storage of goods. To minimise these disruptions, shore-based radar chains for traffic monitoring were implemented to ensure the traffic flowed efficiently in port areas even during periods of reduced visibility. The first radar chain was implemented at Douglas, Isle of Man, in 1948, but other major ports in northern Europe followed soon after, i.e., Amsterdam (IJmuiden) in 1952 and Rotterdam in 1956 (IALA, 2012a).

Due to several major oil spills in the 1970s, the public awareness of accidents in the maritime domain increased. This was followed by the need for harmonisation and cooperation among the radar chain operators and other actors, such as pilots. As a consequence, existing radar chains originally implemented to support the efficiency of traffic movements were changed to shore-based assistant services, VTSs, which, in addition to efficient operation, also sought to ensure that traffic flowed safely and decrease its environmental impact. In 1985, the International Maritime Organization (IMO) adopted Resolution A.857, *Guidelines for Vessel Traffic Services*. This resolution was superseded in 1997 by the IMO Assembly Resolution on VTS A.857 (20). Today there are more than 500 operational services worldwide offering VTS, with the primary goal of promoting efficient, safe and environmentally friendly maritime traffic movements in areas with high traffic density, such as the Hook of Holland, and sensitive sea areas, such as archipelagos or reefs (IALA, 2012a).

A Vessel Traffic Service (VTS) is normally implemented by a “Competent Authority”, i.e., a national maritime administration, *“to improve the safety and efficiency of vessel traffic and to protect the environment*” (IMO, 1997). Although defined and regulated at the international level by IMO guidelines and regulations, the VTS itself is implemented through national maritime administrations and realised at a local level by VTS managers (VTSM) and VTS supervisors (VTSS) (IALA, 2012a). There are three service levels, information service (INS), traffic organisation service (TOS), and navigational advice and assistance (NAS) (IALA, 2012a), that a VTS centre can offer in a specific area, a VTS area. While a VTS can offer all three service levels, depending on how the service is implemented locally, the service’s legal mandate does not provide sufficient means to actively manage the vessel traffic within the VTS area, as decision making authority always remains on board. As a consequence, the current role of the VTS in traffic management is often restricted to providing the “right” information at the “right” time (Praetorius, Bruno, & Lützhöft, 2010). Most traffic management, such as ensuring separation from other ships, is therefore conducted on board a vessel, only considering the immediate surroundings and pursuing highly individual goals, which can occasionally conflict with the overall safety and fluency of the overall traffic in the area. Although the VTS has the authority to enforce compliance, the operators are required to provide the service by transmitting information through the VHF, without knowing whether and how this information will be used on board.

The positive effect of the VTS on the overall safety of maritime traffic has been demonstrated in several administrative surveys and project reports. The Australian Maritime Safety Administration, for example, has reported that the average number of groundings decreased from 1 per year in 1997-2003, to 0.16 per year in 2004-2009 after a VTS was established (Australian Maritime Safety Authority, 2010). Similar results have been reported for Finnish VTS centres within the EfficienSea project (Westerlund, 2011) and by VTSOs at the Sound VTS in Malmö, Sweden (Gardebring, 2011). However, the way in which information from the VTS had been received and used on board was not included in these studies. The actual contribution of a VTS to the fluency and safety of maritime traffic therefore remains partly unknown.

1.2 Why study the VTS?

While the VTS system, as currently designed, can address minor local disturbances, e.g., two vessels in a conflict, the ability to promote the safety and efficiency of traffic as a whole is likely to be challenged in the future as a consequence of the anticipated growth in traffic volume (Allen, 2009). Incidents such as the grounding of Stena Danica in the approach to the port of Gothenburg, Sweden (SHK, 2010) reveal the vulnerability of the current configuration in the VTS domain.

> Three vessels were navigating within the southern fairway in slightly rough weather. Although the three vessels involved in the incident were aware of each other's presence and had been in contact with each other multiple times, two of them nearly collided as they met at the tightest spot of the fairway. In the investigation after the incident, both Masters highlighted that they had expected the VTSO, who was in responsible for the area and following the developments from the shore-based centre, to intervene and actively direct the vessels in case of danger. The VTSO, on the other hand, emphasised that he did not get involved into the situation as it was already complex enough, and he did not have the sufficient jurisdiction to steer the traffic more actively (SHK, 2010).

As traffic increases in volume and size, and the commercial pressure in the shipping domain is high (Stopford, 2009), new means of supporting a safe, and simultaneously efficient, flow of traffic into and out of ports need to be found. These means have typically been driven by technical developments, which have dramatically changed how ships navigate, e.g., GPS, ECDIS, AIS, internet, or through the introduction of centralised control including various forms of so-called chain planning within the VTS domain (Seignette, 2012).

A harmonisation of this development is the so-called e-Navigation strategy which is *"the harmonised collection, integration, exchange and presentation of maritime information on board and ashore by electronic means to enhance berth to berth navigation and related services"* (IMO, 2009). The aim of the e-Navigation strategy is to increase navigational and overall maritime safety, including environmental protection, by supporting the shore-based and ship-based operators in their daily work. Several organisations, including the Nautical Institute, have been developing the concept and attempted to capture stakeholders' and end-users' needs in light of e-Navigation (IMO, 2009; Nautical Institute, 2007). However, while the development of technical means on board has progressed rapidly, the distribution of the information gleaned through the enhancement of the shore-side centres "*has generally not kept pace, resulting in asymmetrical access to information" (Allen, 2009, p. 13).*

1.3 Objectives and research questions

The aim of this thesis is to shed light on what the VTS system does to promote safe and efficient traffic movements. Work at VTS centres has been studied with a focus on everyday performance to highlight the service's contribution to the safe navigation of vessel traffic within port approaches.

The main objectives of the research have been to ***increase the overall understanding of everyday performance of the VTS system*** and ***identify a way of modelling the performance of the service*** to inform current and future developments with respect to anticipated change of demands within the maritime traffic management domain.

To achieve the objectives, following questions have guided the research activities.

1 **What are the preconditions for safe and efficient traffic movements within the VTS domain?**
  1a How is traffic management exercised at present?

2 **How does the VTS contribute to traffic management today?**

3 **How can the contribution of the VTS to safe traffic movement be identified and analysed to inform the design of future developments within the maritime traffic management domain?**
  3a Are there lessons to be learned from other domains, i.e., aviation, on how traffic management can be designed and realised?

1.4 Appended papers

This thesis presents research conducted over the past five years. The results presented here have partially been published through the four papers that at appended to the thesis. Each paper intends to explore a certain angle of the workings of the VTS system.

Praetorius, G., van Westrenen, F.C., Mitchell, D., & Hollnagel, E. (2012). Learning lessons in resilient traffic management: A cross-domain study of Vessel Traffic Service and Air Traffic Control. - ***main author***

Paper 1 compares the ATC domain to the VTS domain and discusses differences and similarities with respect to how traffic management is realised. The four resilience engineering corner stones (learn, monitor, respond, anticipate) are used to discuss the potential of each traffic management system for realising resilient operations.

van Westrenen, F.C., & Praetorius, G. (2012). Maritime traffic management: a need for central coordination? Cognition, Technology & Work. - ***co-author***

Paper 2 analyses and discusses how traffic management is currently conducted in the maritime domain. The paper focuses on the concept of control and reveals the vulnerabilities of the current control settings, as well as possible advantages and disadvantages of shifting towards a centralised control system.

Praetorius, G., & Hollnagel, E. (2014). Control and resilience within the maritime traffic management domain. Manuscript is under review pending minor revision (Journal of Cognitive Engineering and Decision Making) – ***main author***

Paper 3 presents findings from field research on how VTS operators strive to promote safe and efficient traffic movements. The VTS is identified as a Joint Cognitive System (JCS) with multiple layers of aggregation. The article discusses how control is maintained within VTS operations and how the VTS system's capabilities to monitor, anticipate, respond and learn could be strengthened.

Praetorius, G., Hollnagel, E., & Dahlman, J. (2014). Modelling Vessel Traffic Service to understand resilience in everyday operations. Manuscript submitted to Reliability Engineering & System Safety. –*main author*

Paper 4 presents how VTS is realised within two VTS centres. The article presents two functional models and discusses how the functional design of each system impacts its ability to manage, monitor and dampen potential performance variability. Further, based on the functional models, the systems' ability to cope with a variety of operational conditions is discussed through the lens of the four resilience abilities (monitor, respond, anticipate, learn).

1.5 Limitations

This thesis presents a new perspective on the VTS system and its contribution to safe traffic movements. It is acknowledged that maritime traffic management includes various stakeholders, e.g., maritime pilots, bridge teams, and that these may make a significant contribution to safe navigation within the VTS area. However, the focus of the thesis concerns the contribution of the VTS as a shore-based service and will not address maritime pilotage or navigation aboard merchant vessels in detail.

1.6 Structure of the thesis

Chapter 1 is an overall introduction to the research presented in this thesis. It is followed by an introduction to the VTS and prior research within this domain in Chapter 2. Chapter 3 presents the main theoretical concepts applied to study the VTS, while the methodological approach employed in the research is outlined in Chapter 4. The results of this research are presented in Chapter 5 and their implications for the role of the VTS in maritime traffic management and for current and future developments are discussed in Chapter 6. The thesis concludes by presenting findings and recommendations to the stakeholders in Chapter 7.

2 Background

The following paragraphs introduce the domain of study for this research, the VTS domain. The chapter begins with a brief description of the organisational frame of the VTS and then addresses how the VTS is currently operated.

2.1 The organisational frame of the VTS

The VTS is a service locally implemented by a Competent Authority to support the navigation of the merchant fleet in national waters. The service is legally defined by the International Maritime Organisation (IMO), the highest legislative body in the shipping domain, supported by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), which provides recommendations for the implementation and organisation of VTS systems, as well as training guidelines for personnel.

The IMO is a specialised United Nations agency responsible for developing and maintaining the regulatory framework within the maritime domain. The aim of the IMO's work is to promote and enhance maritime safety and to prevent marine pollution. The organisation was founded in the late 1950s as the Inter-Governmental Maritime Consultative Organisation, renamed the IMO in The organisation performs its workthrough committees and sub-committees, i.e., Maritime Safety Committee (MSC), Marine Environment Protection Committee (MEPC), Safety of Navigation (NAV) and Standards of Training and Watchkeeping (STW), that provide draft versions of codes, recommendations, protocols and conventions for their area of responsibility (IMO, 2013). At present approximately 50 conventions and protocols and about 1000 recommendations and codes have been adopted through the IMO. The International Convention of the Safety of Life at Sea (SOLAS, adopted in 1974), the International Convention for Prevention of Pollution from Ships (MARPOL, 1973/78), and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW, 1978) are among the most significant conventions for the promotion of maritime safety adopted by the IMO (Grech, Horberry, & Koester, 2008).

With respect to the VTS, the most relevant legal documents provided by the Organisation are SOLAS chapter V "Safety of Navigation", which includes regulation 11 and regulation 12 stating the goals of and differences between ship reporting systems (IMO, 2002a) and VTS (IMO, 2002b); STCW, which assigns the responsibility for the safety of navigation to the Master of a vessel (IMO, 1996); and the United Nations Convention on the Law of the Sea (UNCLOS, adopted in 1982) (United Nations, 1982) that poses minimal requirements for each member state to implement an information service within territorial waters.

In contrast to the IMO, a UN agency, IALA is a non-governmental and non-profit technical association seeking to harmonise Aids to Navigation (AtoNs). IALA strives to ensure safe and efficient vessel movements and the protection of the marine environment. It was founded in 1957, and its members represent AtoNs authorities, manufacturers and consultants, and other stakeholders in the maritime cluster (IALA, 2012b).

IALA publishes guidelines, handbooks and recommendations that are updated regularly. Within the VTS domain, IALA's primary influence is exercised through publishing the VTS Manual (IALA, 2012a), which includes guidelines for the education of VTS operators, supervisors and managers (IALA, 1998). The VTS Manual is updated every four years and establishes a standard for services offered at a VTS centres as well as basic requirements for the education and overall expertise that an operator should have.

Although the VTS is regulated o by the IMO at the international level, the responsibility for implementing a VTS service within national waters lies with the Competent Authority, often the national maritime administration. This authority is responsible for assessing whether there is a need for a VTS, determining the level of service that should be offered and implementing the international guidelines and regulations concerning the VTS within territorial waters.

2.2 VTS as service to the maritime community

Vessel Traffic Service (VTS) is the general term for navigational assistance services in a determined area, a VTS area. The VTS can offer three different service levels to merchant vessels within the area: Information Service (INS), Traffic Organisation Service (TOS), and Navigational Advice and Assistance Service (NAS) (fig. 2).

The information service (INS) provides information relevant to safe navigation, e.g., hydro-meteorological information, or upcoming vessel meetings, to the vessels in the VTS area. The VTS operator uses the VHF to transmit the information making it public to all participating vessels in the area. The traffic organisation service (TOS) is a service intended to support the efficient flow of traffic in the VTS area. Information transmitted as part of TOS might concern berth clearances, arrangements regarding lock times, speed limits, or other information that can be used to organise traffic. Navigational assistance (NAS), the third service level that can be offered by a VTS centre, concerns the active support of the decision making process of a bridge team. A VTSO can provide NAS through transmitting advices, including the positions of other traffic, a vessel's course and speed, or warnings to a specific vessel. In comparison to INS, NAS signifies active participation in a bridge team's navigation process. The VTSO does not only transmit information, but also closely monitors its effect (IALA, 2012a).

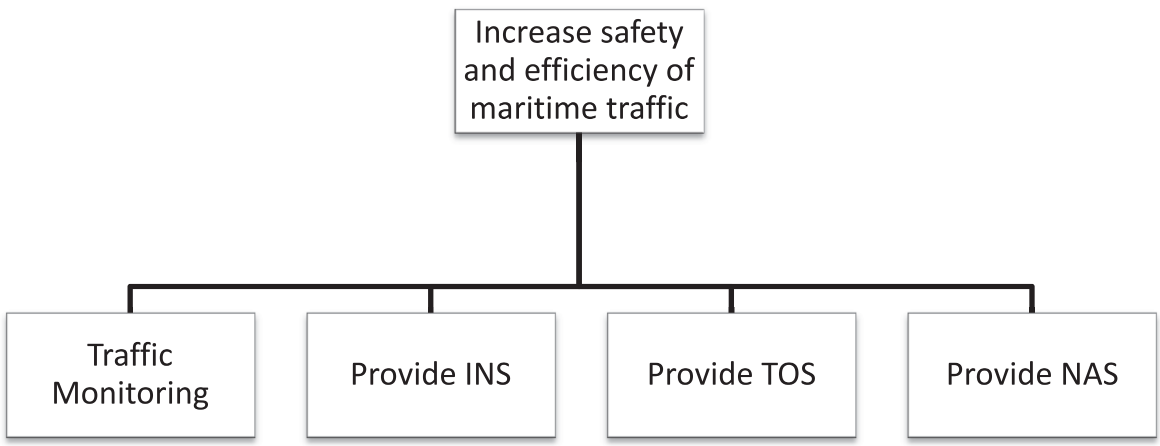

Figure 2: VTS as defined by the Organisation

The IMO defines each service level in conjunction with the recommendations issued by the IALA. The responsibility for defining the scope of a local VTS service lies with the national Competent Authority. This authority decides which service levels will be offered at a VTS centre. The service level of a VTS can, but need not differ among multiple VTS centres within the same country depending on the local geography, traffic density, and overall needs of the area. The IMO recommends that the Competent Authority adopts a risk assessment method called Formal Safety Assessment (FSA, Psaraftis, 2012) to determine which risk reducing measure, e.g., service level of VTS, is appropriate and cost efficient relative to possible hazards and their consequences within that specific area.

2.3 VTS, VTS area, VTS centre

VTS is primarily provided through technology-mediated communication on the Very High Frequency (VHF) radio from a service centre to all participating vessels within a VTS area.

A VTS area is an established area within national waters, in which all vessels above a certain length and breadth, e.g., above 300 GRT, or carrying a specific type of cargo, are obliged to report to and receive information from a shore-based service, the VTS. In addition to the services formally defined through the IMO, VTS can occasionally act as coordinator between merchant vessels and harbour services, such as pilot service or berth services.

In Figure 3 depicts the VTS area of VTS Gothenburg. It represents the area including the two fairways into port, the reporting line into the area and the reporting points (1,2, 3, 4, 5) at which all inbound and outbound vessels above a certain size need to report to the VTS.

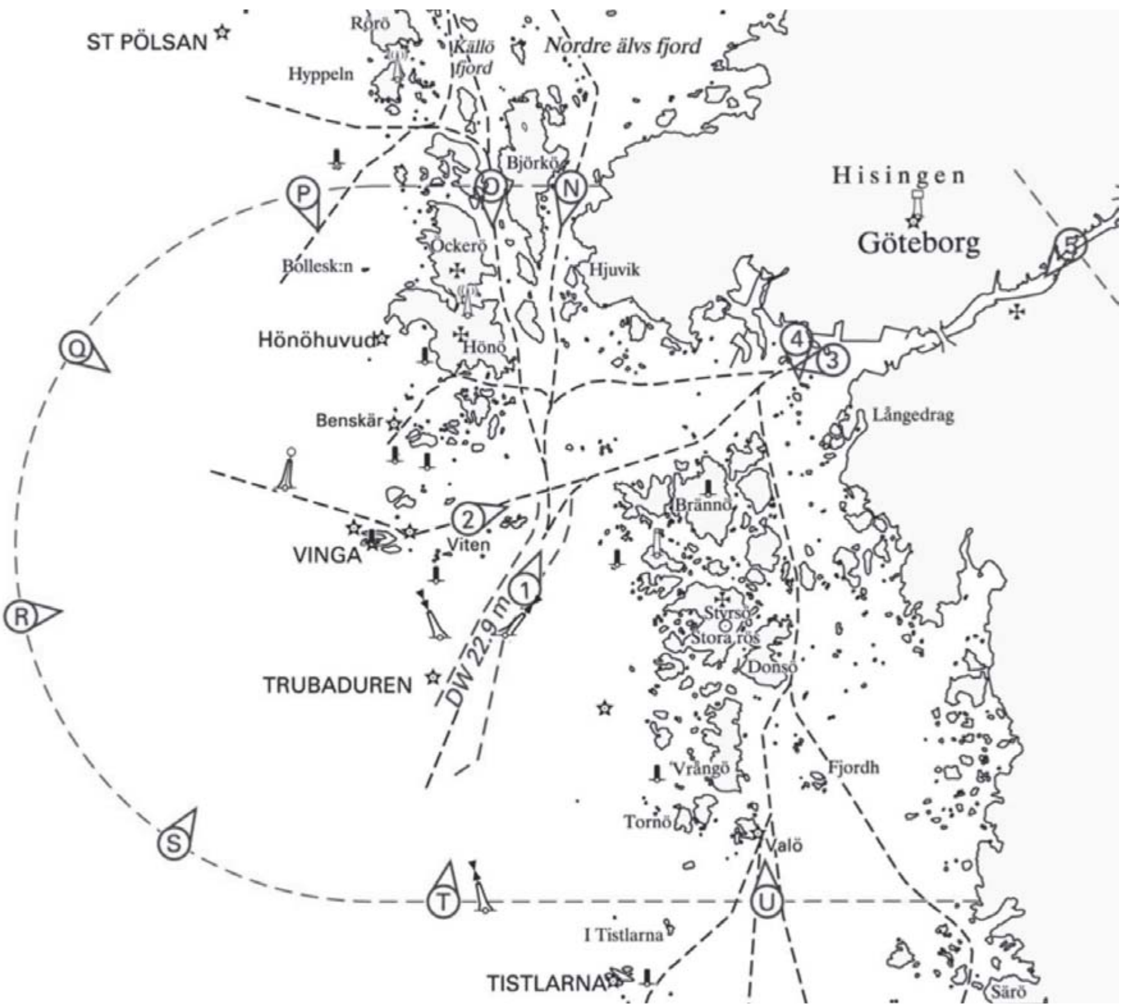

Figure 3: Gothenburg VTS area (Transportstyrelse, 2009)

Whenever a vessel passes a reporting point, the bridge team is required to report to the VTS. This report usually contains the vessel's name, callsign, destination and intention and her draught and is transmitted on the public VTS channel on the VHF. Depending on the current traffic situation and factors that might affect a vessel's ability to navigate safely, information is transmitted by a shore operator, the VTSO, to the vessel on the same channel.

The number of VTSOs assigned to an area depends on its size, volume and density of traffic and its geographic conditions. While smaller areas generally have one VTSO to provide the service, larger areas, especially those with major ports are often divided into several sectors. In Rotterdam, one of the world's largest ports, the VTS is split in no fewer than eleven sectors from the entrance to the port approach to the different berths within the port structure.

2.4 VTS manager, VTS supervisor, VTS operator

A VTS centre is typically manned with personnel classified into the following categories: VTS operator (VTSO), VTS supervisor (VTSS), and VTS manager (VTSM). Each of the categories has certain responsibilities and duties within the local organisation at the VTS centre.

The VTSO is the frontline operator that broadcasts messages to the vessels within the VTS area. Depending on the size of the monitored area, a VTSO is either assigned to the whole area or to a sector in which he/she informs vessels. Figure 4 depicts a VTSO at the HOC IJmuiden. The VTSO needs to monitor the area and decide on possible actions to take to improve the safety of navigation for the participating vessels. The activities of VTSOs include the use of various sensors (Brödje, Lützhöft, & Dahlman, 2010), e.g., VHF, radar, AIS information, for traffic monitoring and the use of information to maintain an awareness of possibly dangerous developments within the area. VTSOs can also establish communication links between traffic participants and other port services, such as pilotage or tug services.

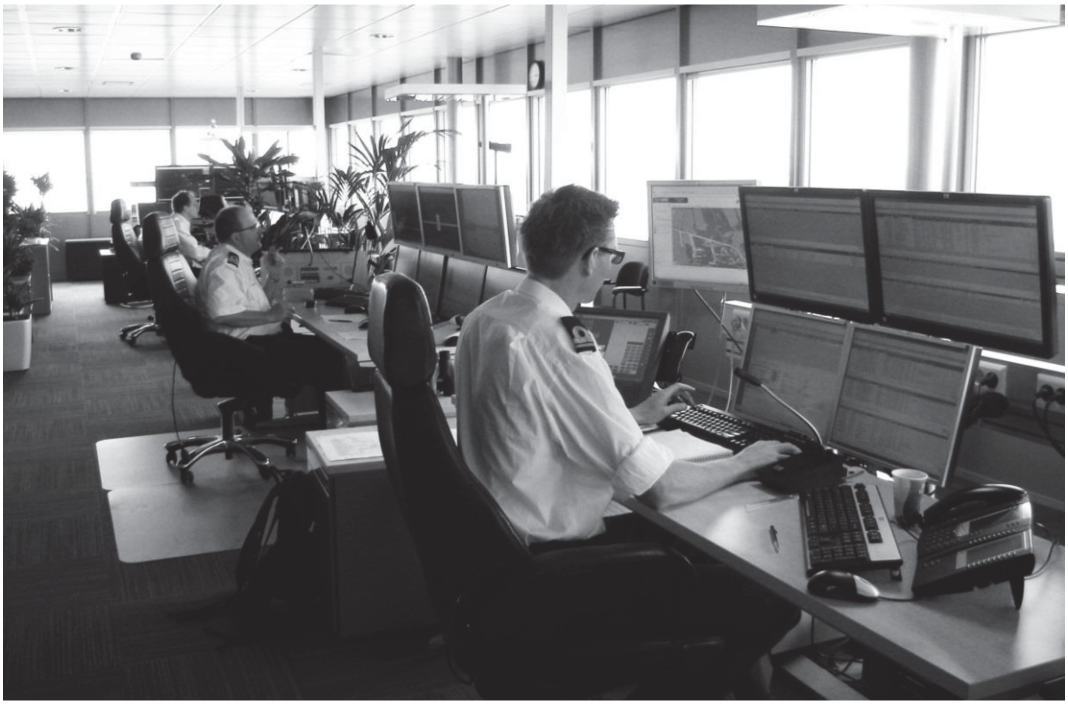

Figure 4: VTS operators working at the Harbour Operational Center (HOC) IJmuiden (April 2009)

VTSOs are responsible for ensuring traffic satisfies national waterways regulations, and have the authority to file reports to the authorities in the event of vessel non-compliance. Finally, in the case of an accident or incident, reporting and maintaining a log of the event, as well as taking appropriate actions, e.g. coordinating emergency operations, can be within the responsibility of a VTSO (IALA, 2012a).

The role of the VTS supervisor (VTSS) is to coordinate the tasks of the VTSOs, as well as allied[1] and emergency services. He/she oversees the efforts of the VTSOs and ensures that the service offered corresponds to the requirements of the Competent Authority and other stakeholders within the maritime domain. A VTSS can further assist in training and skill assessments of VTSOs. In the absence of the VTS manager (VTSM), the supervisor is responsible for ensuring that duties and activities are performed according to legislation and without any disruption (IALA, 2012a).

A VTSM is responsible for the coordination and management of VTS activities at a VTS centre on behalf of the Competent Authority. Ideally, a VTSM has a background in VTS and at least a basic understanding of tasks and responsibilities assigned to the VTSOs, as he/she is also the person responsible for ensuring an adequate level of training within a VTS centre (IALA, 2012a).

2.4.1 Training and certification

There are no formal training requirements at the international level, but IALA has published several guidelines for the accreditation and certification of VTS personnel and for VTS training institutes. In general, most VTSOs have a background in shipping and have previously sailed on merchant vessels. Nevertheless, whether a background as active seafarer is mandatory for becoming a VTSO or not, is at the discretion of the Competent Authority (IALA, 2012a).

After a basic course, VTSOs are trained locally through so-called On-The-Job (OTJ) Training. OTJ training is provided by another VTSO or VTSS to provide the VTS trainee with thorough knowledge on the area that he/she will be monitoring and to which he/she will be providing services to. This knowledge is primarily determined by the occupational circumstances at the specific centre and can contain local procedures. Besides OTJ training, VTSOs and VTSSs need to participate in refresher courses regularly to maintain their certification.

2.5 Research and on-going developments within the VTS domain

In general developments within the VTS domain have been highly localised, such as the introduction of chain planning within certain European ports (e.g. Seignette, 2012), and have been heavily guided by work conducted within projects funded by various organisations, including the European Union. The following paragraphs first briefly introduce on-going developments within the VTS domain, which indicate that the domain is undergoing drastic changes, and will then turn to earlier research to highlight the knowledge gap that this thesis attempts to fill.

2.5.1 Previous research within the VTS domain

Research on the VTS system, tasks, training, and organisation has up to now been very limited. Most research focussing on the VTS domain has been conducted within the area of equipment development with a strong focus on decision support tools for VTS operators.

One broad area of VTS-related research, for example, focuses on data sources and merging information for vessel detection and tracking. The studies (e.g. Chang, 2004; Høye, Eriksen, Meland,

[1] Services actively involved in the safe and efficient passage of the vessel through the VTS area, e.g. pilots, tug services (IALA, 2012a)

& Narheim, 2008; Kao, Lee, Chang, & Ko, 2007; Wawruch, 2004; Vespe, Sciotti, Burro, Battistello, & Sorge, 2008) generally focus on mathematical modelling to support human operator through information sources merged into the decision support system. However, only little attention is devoted to how VTSOs' efforts concerning everyday operation, and the human operator is treated as a source of failure, rather than a contributor to safety.

In contrast, the importance of considering VTSOs, the end users, during the development of decision support systems has been highlighted by several studies focusing on the information displayed within the operators' decision support system. Wiersma, Jarvis, and Granholm (2000), and Wiersma and Mastenbroek (1998), for example, used focus groups and situation awareness assessment experiments to demonstrate that VTS operators acted over a larger time-frame than anticipated and therefore were only partially supported by the decision support system design. While the predictor was able to predict a vessel's path one minute ahead, the VTSOs demonstrated that their decision making was tactical, occuring in a time-frame of 5 to 15 minutes in experimental settings. Furthermore, VTSOs currently only use a fraction of the available decision support within their system to provide information service, traffic organisation, and navigational assistance. This emphasises the high degree of context-dependency of the efforts within the VTS domain and has also been discussed by Bruno and Lützhöft (2010) concerning the use of Standard Maritime Communication Phrases (SMCP). It is thus important to secure the end user's support for new technological measures if the technology is intended to support the VTS operator in his tasks (Brödje et al., 2010; Hadley, 1999).

Another line of research in the VTS domain has focused on identifying core tasks (the essential content of a particular work), work practices and expert identities within VTS (Nuutinen, 2005; Nuutinen, Savioja, & Sonninen, 2007) to understand how VTS can develop to meet future traffic demands. The authors (Nuutinen et al., 2007) identified the VTS as a socio-technical system under change and observed that other tasks, e.g., leading maritime rescue operations, beyond the three service levels (INS, TOS, NAS) were among the core tasks of some VTS centres. Additionally, practices and procedures differed across the centres as a result of local developments mainly to the demands of the VTS area. The result was that the provision of services can differ across VTS centres, in between VTSOs and even in how a service is provided by a single operator (Nuutinen, 2005; Nuutinen et al., 2007). The authors (Nuutinen et al., 2007) conclude that these differences can lead to ambiguity in the VTS domain resulting in difficulties for the service users, the vessels within a VTS area, in understanding what can be expected from the service provider, the VTSO, and the expected reaction of service users, i.e., the vessels.

2.5.2 Chain planning and sea traffic management

For the past 40 years advancements in technological and organisational design within the maritime domain have been highly influenced by developments in aviation. In particular, when discussing aspects of traffic management and traffic safety, the aviation domain is often cited as one of the predominant examples of safe and efficient traffic movements (e.g. National Research Council, 1994; van Erve & Bonnor, 2006; Österlund & Rosén, 2007).

Two of the ongoing European developments that are heavily influenced by how traffic management is conducted within the aviation domain, are the concepts of Chain Planning and Sea Traffic Management. Chain planning represents the centralisation of information and services provided to the mercantile merchant fleet. Harbours create vessel traffic management systems incorporating all services, e.g., VTS, pilot services, tugboats, and the harbourmaster, affecting the management of vessel traffic into, within and out of the harbour. The goal is to make the handling of traffic more predictable, and therefore also more efficient (Seignette, 2012). The core element of this chain planning is often an information sharing system, in which all traffic data are gathered and can be accessed by all parties, which connects to the overall IMO strategy of e-Navigation. At present, several of the major European ports, such as Antwerp and Rotterdam, have implemented chain planning within their port approaches.

Sea Traffic Management (STM) is a concept currently being developed by a European project called MonaLisa, Motorways and Electronic Navigation by Intelligence at Sea. The project focuses on how maritime traffic can become more efficient, safe and environmentally friendly. One of the core concepts is to introduce STM through a so-called Ship Traffic Coordination Centre (STCC), incorporating the notion of route exchange between ship and shore to de-conflict and optimise vessel movements with respect to safety and efficiency. Vessels share their routes with the STCC, which checks the route and may suggest changes to it that the vessels can either except or reject. As within the VTS domain, the decision making in navigational matters remains on the bridge (Porathe, de Vries, & Prison, 2013). The difference between STCC and VTS is that the STCC operates in open waters and is therefore not formally part of the regime of the national maritime administration (Mukherjee, 2013).

Both chain planning and Sea Traffic Management present ongoing developments inspired by the aviation domain to meet the increased demand for efficient and safe operations within the maritime traffic management domain. Further, both concepts are related to the strategy of e-Navigation and consider the necessary changes, primarily regarding how information can be shared among several stakeholders and what technical preconditions need to be fulfilled. Neither chain planning nor STM actually addresses how the change in system design will affect the operation of the VTS system, as one concept transforms maritime traffic management into a linear process, while the other adds a new system to the traffic management domain.

In summary, numerous current developments within the VTS domain are project-driven and highly related to the concept of e-Navigation and technical developments. Concepts such as STM and chain planning, as well as previous research, have primarily focused on how stakeholder information can be shared to improve traffic safety and efficiency. However, little attention is devoted to the current operation of the VTS system and how it contributes to traffic management and safety within a determined area. Furthermore, although there is a growing body of research that adopts a perspective rooted within human factors engineering, e.g., studies on situation awareness (Wiersma, 2010), interface design and sensor use (Brodje et al., 2010; Van Dam, Mulder, & Van Paassen, 2006), and communication (Bruno & Lützhöft, 2010; Froholdt, 2012; Kataria, 2011; M. Lützhöft & Bruno, 2009), little research has been conducted on the overall VTS as socio-technical system, and the way in which everyday operations are conducted.

3 Theoretical frame of reference

This chapter presents the theoretical background of this thesis. The chapter introduces the concepts that have been used to structure the observations and guide the study of everyday operations within the VTS domain.

3.1 Overall Approach

This thesis adopts a systems approach to study how safe and efficient traffic movements are accomplished within the VTS domain. The VTS is identified as socio-technical system actively seeking to promote safety and efficiency in a specific area, e.g., a port approach. The VTS is understood as a system that is *"a whole that is both greater than and different from its parts"* (Patton, 2002, p. 20). The focus is therefore on the VTS as control system and the complex interactions that occur within the system, e.g., among VTSO(s), VTSS, and DSS, and those of the system with the environment, such pilot services or vessel traffic within the VTS area. The theoretical frame of reference is based on concepts derived from Cognitive Systems Engineering (CSE) and Resilience Engineering (RE).

Cognitive Systems Engineering (CSE) is a discipline that emerged in the 1980s, when socio-technical systems, in which processes span across operators, organisations and technology (Hollnagel & Woods, 2005), and became increasingly complex as a consequence of the increasing degree of automation in safety-critical domains such as nuclear power and aviation. CSE is rooted in cybernetics, a theoretical field concerned with control and communication in animals and machines (Wiener, 1965). Cybernetics was formulated in the late 1940s and received its name from the Greek term kubernetes, steersman or rudder, to emphasise the focus on the concepts information, feedback and control for systems in general, not for a specific application (Skyttner, 2005).

CSE studies joint human-machine systems, so-called Joint Cognitive Systems (JCS), and the ways in which these maintain control in a dynamic environment. The focus is on the system's performance, i.e., on how its functioning manifests itself and is adjusted to the demands of a specific context, as well as on how the system accomplishes its goals within this context. CSE promotes a cyclical model (fig. 6) to depict how systems manage daily operations and cope with complexity in uncertain environments, in which tasks might be distributed across individuals, teams, technology and other artefacts (Hollnagel & Woods, 2005). It is a theoretical approach that can be applied to the design of technology, training and processes intended to cope with complexity (Militello, Dominguez, Lintern, & Klein 2010). As employed in this thesis, complexity emphasises how individuals make sense of the information available to them within the system and in their environment. CSE adopts an ecological approach to systems, meaning that they should be studied in context to ensure that the system's behaviour can be captured based on how practitioners, or operators, adapt and anticipate various conditions and constraints within the environment (Woods & Hollnagel, 2006). The concepts of JCS, complexity and control are central to the study of socio-technical systems based on the CSE framework and will therefore be introduced in greater detail later in this chapter.

Resilience Engineering (RE) is a relatively young body of research that emerged at the beginning of the 2000s. Resilience, which has its origin as a concept within ecology in the early 1970s, defines an ecological system's ability to arrive at an equilibrium, or stable state, over time in a dynamic and changing environment (Holling, 1973). In the context of socio-technical systems, resilience is the ability to sustain required functioning and achieve system goals under a variety of operational conditions. In resilience engineering, systems are analysed with the aid of four cornerstones, monitoring, response, anticipation, and learning, which characterise the features a system should have to be able to maintain its functioning before, during and after anticipated and unanticipated events have occurred. Furthermore, RE emphasises examples of the positive, meaning that it is concerned with how systems succeed by adapting their performance to the demands within the environment (Hollnagel, 2006). When adaption is successful, safety emerges as a property, as the system balances goals and demands in the current context (Woods, 2006). The four cornerstones and their importance to socio-technical systems will be described in greater detail later in this chapter.

3.2 Systems, objects, attributes and environment

As outlined above, this thesis is based on concepts derived from CSE, in which the notion of a system plays a crucial role. A system is commonly defined as *"a set of objects together with relationships between the objects and between their attributes"* (Hall & Fagan, 1968, p.82). The emphasis is on a system being an entity consisting of at least two elements, which are connected through relationships among the elements, or among their attributes. Objects in the definition refer to physical (e.g., a computer, cup, or book) and abstract components (e.g., a process, guideline, or mathematical variable) of the system. Attributes describe the properties of the objects within the system. Relationships, which unite the system as an entity, can exist directly or indirectly between objects and between their attributes (Ackoff, 1971). The relationship to consider depends on the purpose of the analysis and the system under study. In general, Hall and Fagan (1968) assert that relationships between elements and properties should always be considered in context. As there are uncountable interrelationships, both direct and indirect within the system, only those relationships that are important given the current problem in relation to the context of that the system should be considered.

Systems can be described as either closed or open (Skyttner, 2005; Von Bertalanffy, 1950). Closed systems have a clear boundary with the environment and do not interact with it. Therefore, changes within the environment do not affect the closed system's state. Open systems, on the contrary, are affected by changes in, impacts on, and interactions with the environment. The environment represents all relevant objects and their attributes which in case of an event are either affected by the system or affect the system's behaviour (Hall & Fagan, 1968). The system's behaviour changes in context, meaning that it is difficult, if not impossible, to map all possible system states. Therefore, it is essential to be pragmatic when defining the unit of analysis and its environment. As Ackoff (1971) notes, all systems are subjective in definition, as the interest of the researcher determines what will be defined as the unit of analysis.

Within the scope of this thesis, the type of system under study is a so-called socio-technical system. The notion of a socio-technical system emphasises the importance of recognising the interrelationships between humans and technology in a social context in which work occurs and originates from the 1940s, when production processes began to become increasingly complex due to a rapid pace of technical developments (Ropohl, 1999). Within the settings of today's socio-technical systems, most tasks are considered cognitive in a manner that requires the coordination and interaction of human and technology, which are directed based on social processes and shared goals and occur within and can therefore only be understood in context (Militello et al., 2010).

3.3 Complexity

Despite that the concept of complexity is widely used in numerous scientific fields, such as philosophy, political science, or biology, it is often not explicitly defined. Depending on the discipline in which a study is conducted, definitions and measures of complexity can differ substantially (Mitchell, 2009).

Within the settings of a socio-technical system, complexity can be described by the dimensionality of the problem space and the interdependence among system components and functions(Flach, 2012).

The dimensionality of the problem space characterises the variables that can affect the system and therefore generate possible system states. The higher the number of possible system states, the more uncertainty the system has to cope with, i.e., it is more difficult to predict future system states and the effects of system behaviour on the environment. As open systems affect and are affected by their environment, the number of variables to consider is uncountable (Flach, 2012). Open systems also exhibit a higher degree of interdependence, and system performance is based on the interactions among functions and components, making the system's behaviour less predictable and less foreseeable. In summary, the greater the dimensionality of the problem space and the interdependence within the system, the greater is the system's degree of complexity.

Another way to describe complexity in socio-technical systems is through the use of couplings and interactiveness. The two concepts stem from Normal Accident Theory (NAT), which was formulated in the 1980s (Perrow, 1999), and are used to characterise high-risk industries (fig. 5). Couplings are connections among subsystems and/or system components. They represent the dependencies within the system in a functional manner. Couplings can be either loose or tight. In the case of tight couplings, the system is characterised by dependencies among the system's components that constrain how a system can achieve its goals. There is little possibility for slack; resources in form of, e.g., personnel or time, are limited, and the sequence of processes becomes invariant. A consequence of tight couplings is that systems become difficult to control because of their limited flexibility. Interactiveness characterises how subsystems, components and units interact with one another. Interactions can either be linear, in a cause-effect relationship with one another, or non-linear. Linear interactions are those that are normally designed into the system, while non-linear ones are unanticipated and transpire between independent subsystems. They are often unnoticed, as they are not visible to and are more difficult to comprehend for the operators controlling the system. Over time, these unintended and unforeseen interactions can generate local failures in components that spread throughout the system and develop into a system accident (Leveson, Dulac, Marais, & Carroll, 2009).

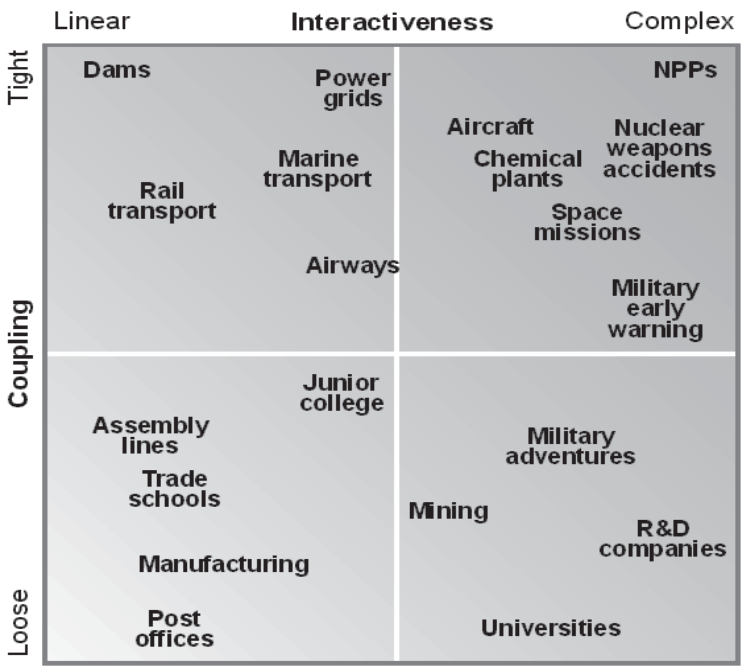

Figure 5: Interactiveness-coupling chart (Perrow, 1999)

As one can observe from Figure 5, systems are characterised by the interactiveness of their subsystems and components, as well as by the type of couplings present within the system. The more interactive complexity is and the tighter the couplings, the more difficult the system is to control.

In addition, barriers and other means introduced to prevent a system from failing tend to make it more complex (Hollnagel, 2004; Woods, Johannesen, Cook, & Sarter, 1994), as they introduce new sources of potential interactions and new types of couplings. Perrow (1999) notes that within marine transportation, for example, the RADAR that was once introduced to increase safety margins also enabled vessels to sail faster through crowded areas. RADAR as a safety measure was transformed into a productivity measure, enabling more and faster traffic movements and radar-assisted incidents (Grech, Horberry, & Koester, 2008; Lützhöft, Grech, & Porathe, 2011), such as that between the MS Stockholm and SS Andrea Doria. This type of behaviour has also been identified as pushing towards the boundaries of safety envelope or a *drift into failure* (Dekker, 2011).

3.4 Joint Cognitive Systems

CSE focuses on the study of regularities and irregularities in the performance of socio-technical systems, in which humans and technology embedded in an organisation achieve goals and maintain control over complex and dynamic environments (Hollnagel & Woods, 2005). The unit of analysis is a Joint Cognitive System (JCS), an ensemble of two or more systems, of which at least one is a cognitive system. A cognitive system is a system capable of anti-entropic behaviour, i.e., it can adapt its behaviour based on past experience to meet the current and anticipated demands of the environment. CSE studies JCSs to discover how joint systems perform in a controlled manner. This shifts the focus towards how humans and artefacts, whether physical (e.g., technology, tools) or social ones (e.g., rules, procedures, organisations), can effectively collaborate and be supported in their work, rather than concentrating on the interaction between operator and artefact. Examples of JCSs in the contemporary world are Air Traffic Control (ATC) and a bridge team on board a merchant vessel. In these settings, humans and machines are in control of complex situations with multiple goals, and the systems' functioning is generally non-trivial, meaning that more than a single action is necessary to achieve a desired result (Hollnagel & Woods, 2005).

A JCS can be represented as a system with multiple layers. Which layer an analysis emphasises is determined by the purpose of the study, i.e., the boundaries of the system relative to its environment, and therefore the units of analysis are defined pragmatically rather than in an absolute way.

> *"The boundary of a JCS can be defined pragmatically by considering two aspects. The first is whether the functioning of an object is important for the JCS, i.e., whether the object constitutes a significant source of variability for the JCS. The second is whether it is possible for the JCS effectively to control the performance of an object so that the variability of the object's output remains within a pre-defined range."* (Hollnagel & Woods, 2005, p. 116)

For the research presented in this thesis, this means that the JCS of interest comprises the VTSO(s) and/or VTSS and the decision support system at hand. As a joint ensemble, they provide a service to a dynamic and changing environment, the vessels within the area. While the service is provided, it also changes the environment, as one or more vessel might change its current actions to adapt to the information transmitted by the VTS. The VTS as JCS is presented in greater detail in the results in Chapter 5.

3.5 Control in JCSs

Within a CSE, control is defined as "*the ability to direct and manage the development of events, and especially to compensate for disturbances and disruptions in a timely and effective manner"* (Hollnagel & Woods, 2005, p.136). A JCS is in control when it produces a stable performance output by successfully anticipating future operating needs and responding to the demands of the current situation. To illustrate how the JCS maintains control, one can employ the Contextual Control Model (CoCoM). The CoCoM (fig. 6) depicts the relationship between the JCS's choice of action and the context. The model comprises three basic concepts: competence, control and construct. A construct is a system's current description of a situation, and it is used to determine what action the system should execute. When actions are executed, they affect the controlled system, or the process, which in turn produces events, both anticipated and unexpected, and feedback. The events and the feedback are used to modify the current construct and to choose a new action. In the model, competence represents the range of possible actions and responses in a JCS's repertoire to maintain control. It is based on the fact that the JCS recognises what needs to be done to meet the demands of the current situation and requires both feedback (compensatory) and feedforward (anticipatory) control (Hollnagel & Woods, 2005).

Feedback, or compensatory, control is based on a comparison between the actual and the intended state, and it helps the JCS to identify and interpret possible differences between the two. It provides information on how an action has influenced the context and the system's state. Feedback is essential for the JCS to be able to modify its construct if it demonstrates that a previous action has not had the intended effect on the controlled process or environment. Feedforward, or anticipatory, control means acting on expected changes within the controlled process or environment before they occur. The system successfully anticipates a disturbance or a deviation and prepares for it, such that adequate measures can be taken to satisfy future operating demands. To cope with complexity means to continuously employ both feedback and feedforward control so that the system can adapt its actions to the current context and possible future demands (Hollnagel & Woods, 2005).

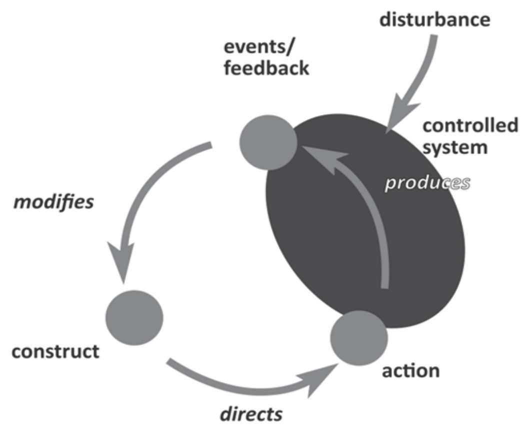

Figure 6: Contextual Control Model adapted from Hollnagel & Woods, 2005

Control in the CoCoM is defined by four different modes: scrambled, opportunistic, tactical and strategic control (Table 1). These four control modes express the degree of orderliness of performance and how the JCS applies its competency to select an action.

Table 1: Control modes

Control mode	Number of goals	Subjectively available time	Evaluation of outcome	Action choice
Scrambled	One	Inadequate	Rudimentary	Random, including complete loss of control
Opportunistic	One or two (competing)	Just adequate	Concrete	Based on habits/Associations
Tactical	Several (limited)	Adequate	Detailed	Based on plans/ rules/regulations
Strategic	Several	Abundant	Elaborate	Based on models/predictions

The four control modes in Table 1 describe performance characteristics, or the regularity of performance, of a JCS. The scrambled control mode represents situations in which the choice of action is essentially randomly determined. There is little or no reflection involved, and it is typically characterised by trial-and-error-type behaviour. In an opportunistic control mode, the system uses the salient features of a situation to determine an adequate action. The anticipation and planning of actions are limited, due to the lack of time, lack of understanding of the process, or both. The tactical control mode is characterised by a larger extent of planning than the opportunistic one. The time horizon stretches beyond the immediate present, and actions are performed according to a plan, rule or procedure. Even long-term effects are considered whenever an action's success is evaluated. The fourth control mode is strategic control. This control mode has the longest time horizon of the four and emphasises higher-level goals. In this control mode, planning occurs and multiple goals and dependencies between them and the task itself are considered. Most systems exhibit a combination of various control modes during normal operation. This is based on the dynamic context and the demands it imposes on the system's performance. According to Hollnagel and Woods (2005), most human performance, and therefore also the performance of JCSs, is a combination of opportunistic and tactical control modes with the goal maintaining equilibrium among the information gained by anticipation, feedforward control, and feedback.

Control modes are essential to understanding the orderliness of a JCS's performance in various operating conditions. The modes and the cyclic model will be applied to the settings of the VTS to demonstrate how a systems perspective can increase understandings of everyday operations and how VTSOs adapt to and cope with complexity.

3.6 Resilience – to monitor, respond, anticipate and learn

As VTS is a system with the goal of promoting both safety and efficiency, Resilience Engineering (RE), has been adopted as a theoretical frame to analyse and evaluate the ways in which the VTS system balances system goals during everyday operations. The concept of resilience originally stems from ecology and is concerned with how a system maintains a stable state over time. Within the settings of a JCS, resilience describes how a system is able to maintain or regain a dynamically stable – meaning producing stable performance output based on a dynamic input- state to be able to continue functioning in the presence of continuous stress in daily operations (Weick & Sutcliffe, 2007). As within the VTS domain, system goals, such as efficiency and safety, often conflict and require trade-offs because both goals cannot be achieved simultaneously. As a consequence, human operators in high-risk industries are often forced to improvise and discover workarounds to be able to cope with limited resources (Hollnagel, 2009).

Within RE, resilience is the intrinsic ability of the system to maintain its functioning in a vast variety of operational conditions. As mentioned above, there are four cornerstones within resilience engineering; monitor, respond, anticipate and learn. These four abilities are essential for a system to be able to recognise challenging conditions, respond to them, evaluate the response and prepare for future events. The four abilities are mutually dependent, and each represents one facet of a system's functioning. By analysing everyday operations with the aid of the abilities, the analyst is able to identify ways in which the system's capacity for knowing what to do (respond), what to look for (monitor), what to expect (anticipate) and what has occurred (learn) can be strengthened (Hollnagel, 2011a).

There are several methods that are currently used to analyse a system's ability to resilience, such as the Resilience Engineering Analysis Grid (RAG) (Hollnagel, 2011b), resilience marker framework (Back, Furniss, Hildebrandt, & Blandford, 2008; Furniss, Back, & Blandford, 2011), and the Inventory to assess Behaviour towards Organisational Resilience in Aviation (I-BORA) (Heese, Kallus, & Kolodej, 2013). In this thesis, the Functional Resonance Analysis Method (FRAM) has been applied to study everyday operations within the VTS domain. The FRAM is a method that can be used to model complex socio-technical systems and has been applied in multiple domains to gain a deeper understanding of a system's behaviour and its intrinsic ability to resilience (de Carvalho, 2011; Macchi, Hollnagel, & Leonhardt, 2009).

4 Methodological frame of reference

This chapter presents an overview of the methodological frame of reference of this thesis. It introduces the overall approach, the methods used during the data collection process, and how the data have been analysed to model the everyday performance of the VTS system.

4.1 Overall approach

The thesis presents the findings from four papers that focused on understanding the VTS from a systems perspective. The focus of this thesis is the VTS system. It is identified as a JCS that actively adapts to a dynamic environment to cope with the complexity of its everyday work. To be able to understand a complex socio-technical system, such as the VTS, it is not enough to study a system by decomposing it into its parts, as a structural representation cannot account for how the system interacts with and adapts to its environment. What is needed is a functional account (Dekker, 2004, Woods & Hollnagel, 2006) of the system at work; what is its purpose, what are its goals, what means are needed to achieve system goals, and what trade-offs, i.e., efficiency and safety, does the system face to be able to operate in various conditions?

In the research presented in this thesis, the VTS was first studied through interviews and observations and then been modelled using the Functional Resonance Analysis Method (FRAM) to gain a better understanding of everyday operations within the settings of the VTS domain. Multiple data collection methods (focus group, semi-structured interviews, and observations) have been applied to collect field data with the aim of portraying the complexity of everyday work within the VTS system. Figure 7 presents an overview of data collection and data analysis methods used in the appended papers.

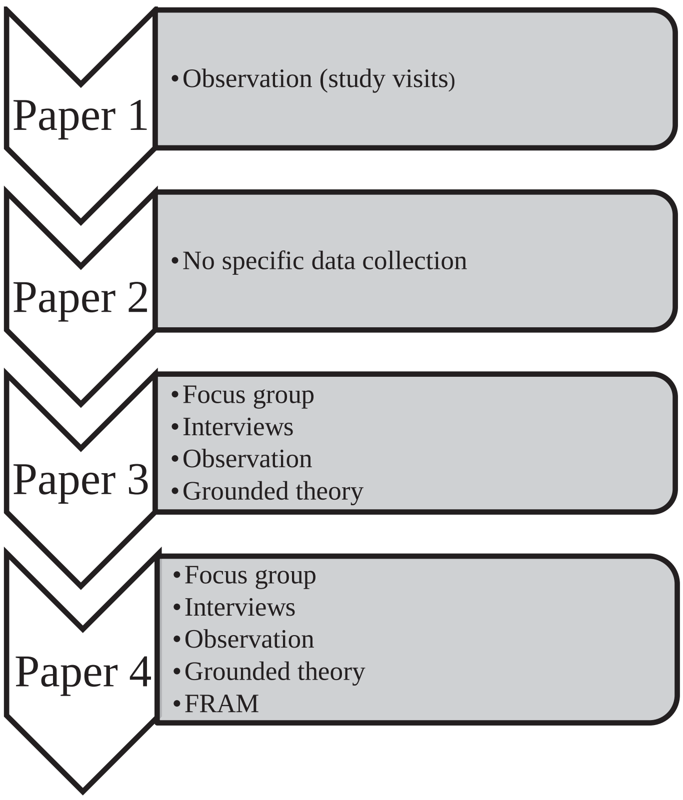

Figure 7: Overview of the data collection and data analysis methods

Paper 1 employed study visits coupled with observations to identify differences and similarities between the VTS and ATC. Paper 3 studied the VTS from a CSE perspective and presents results based on data collected through interviews, observations and a focus group. In Paper 4, the FRAM was applied to model everyday operations at two VTS centres. To construct the model, semi-structured interviews, an observation and two focus groups were conducted.

4.2 Methods for data collection

The following paragraphs will introduce the methods used to collect data during the course of the research presented within this thesis.

4.3 Opportunistic sampling

This research employed opportunistic sampling (Patton, 2002) during the data collection process. Opportunistic or emergent sampling is based on the notion that field research is unpredictable; not everything that a researcher will experience during a field study can be anticipated, as the researcher him-/herself is one of the central research instruments. During data collections in the field, he/she will constantly have to decide what to focus on, which questions to ask, or to which degree the phenomenon under study is influenced by the researcher's presence. The data collection in the field evolves with the phenomenon studied, as real-world settings reveal various facets of a complex reality. Using opportunistic sampling therefore essentially entails being flexible in designing the study to be able to follow the changes in the environment. As not everything is predictable, one must be open to adjusting to one's methodology during the course of the study. In addition, sampling makes it possible to data collected accidently (Patton, 2002).

4.4 Interviews

The qualitative interview is one of the foremost methods employed in qualitative research approaches, as it allows the researcher to explore and enter the interviewees' perspective (Patton, 2002) concerning what is occurring in their "world", how they relate to it, and how they interpret it.

4.4.1 Focus group

A focus group interview is a moderated group interview in which several participants are asked a certain number of questions, which are then discussed (often) openly in the group. The group discussion features one or two moderators who guide and steer the informants during their discussions (Kuniavsky, 2003). Focus groups are generally good for understanding the fundamental issues and perceptions and the attitudes, thoughts and feelings of the informants. They can are also highly useful for brainstorming. However, the moderator has few opportunities to control the outcome of the interview, as it is difficult to steer interactions among the participants (Bryman, 2002).

4.4.2 Informal conversational interview

Informal conversational interviews are essentially spontaneous interviews based on questions that emerge from the context in which the informant currently resides (Patton, 2002). Observations are typically coupled with this type of interview, as it permits the researcher to explore an informant's actions in relation to why and how the informant achieves his or her goals. Interview questions arise from the immediate context, allowing the researcher to obtain knowledge on, e.g., why specific actions are performed, providing the researcher with a high degree of flexibility and spontaneity (Patton, 2002) to explore various aspects of a situation.

All observations and study visits were accompanied by informal conversational interviews. The purpose was to provide a better understanding of the actions performed by the informants and the meanings attached to them.

4.4.3 Semi-structured interview

Semi-structured interviews provide the researcher with systematic information on the phenomenon under study. They involve an interview guide, a list or set of questions and topics to discuss, to structure the interview; they simultaneously provide the flexibility to ask follow-up questions or change the order of questions. This provides the potential for clarifications of the respondents' answers, and in-depth information can be obtained (Patton, 2002).

4.5 Observations

In addition to interviews, observations were conducted to gain insights into the workings of the VTS system. Observations and interviews are mutually reinforcing techniques capable of providing rich data that can be transformed into detailed descriptions of the context and the phenomenon under study. According to Patton (2002), the main purpose of observations is to describe the observed settings, the actions conducted by the community under study, and the meanings of those actions for those studied. Observations can either be direct, in the field, or indirect, e.g., observing participants through recordings. Direct observations will allow the researcher to be participate in the world that is studied but limit the extent to which preparations can be made beforehand (Patton, 2002).

Two types of observations were employed during the data collection, open-ended naturalistic observation and participant observation.

4.5.1 Open-ended naturalistic observation

An open-ended naturalistic observation is an observation conducted in the field that does not build on a hypothesis make prior to the data collection process. This type of observation is often used to observe *what is out there* without being limited by preconceptions or hypotheses (Patton, 2002).

Although this type of observation is occasionally considered ideal (Morrison, 1999, as cited by Patton, 2002), as the researcher is not limited by any preconceptions, it also poses the problem that the real world is highly complex and dynamic. Even if it were desired, it is essentially impossible to actually capture all aspects of the context within a single observation. If only one researcher is in the field, he or she will ultimately need to choose a focus that will highlight certain aspects at the expense of others.

The study visits conducted at the beginning of this research can be characterised as open-ended naturalistic observations. They were intended to gain a deeper understanding for the VTS system and the operators providing the service.

4.5.2 Participant observation

When entering the field as an observer, one of the most important matters is to carefully consider the degree of participation during the observation process. According to Repstad (1999), the degree of participation ranges from actively participating in the settings, e.g., completing the same training programme and participating in the same training units as the individuals under study, to a rather passive participation, being openly in the field but only participating in a limited manner, e.g., participate in shift changes but not becoming involved in the actual work of an operator.

4.6 Methods for data analysis

All collected data were entered in MaxQDA (VERBI Software Consult SozialforschungGmbH, 2013) and then systematically organised with the aid of grounded theory (Corbin & Strauss, 2008). In a second step, the collected data informed the modelling of everyday operations as presented in Paper 4.

4.6.1 Grounded theory

Grounded theory is a methodology to systematically organise, categorise and analyse the data collected. During the analysis, all data derived from fieldnotes, interviews, and documents were jointly analysed with an emphasis on how the VTS personnel related their work to the service's goals (safe and efficient traffic movements) and what opportunities and challenges they identified within the settings of their daily operations.

In an analysis guided by grounded theory using micro-coding, the data are collected and the analysis iteratively guided towards a macro-analysis level, at which larger pieces of data are compiled under a more abstract concept (Corbin & Strauss, 2008). For example, while micro-coding might have identified individual actions such as hammering, forging, and screwing, the macro-coding might frame this under the label "tool use". Micro- and macro-coding helps to identify multiple complex relationships within the phenomenon under study and can be an essential input to understanding the development of this phenomenon in context and over time (Corbin & Strauss, 2008).

4.6.2 Functional Resonance Analysis Method (FRAM)

FRAM is a method to model complex socio-technical systems. The method focuses on the concept of performance variability and ways in which systems manage and monitor potential and actual variability. The FRAM is based on four basic principles*: the Principle of Equivalence of Successes and Failures, the Principle of Approximate Adjustments, the Principle of Emergence*, and *the Principle of Functional Resonance* (Herrera & Woltjer, 2010; Hollnagel, 2012, 2014):

- *Principle of Equivalence of Successes and Failures*
  Failures and successes stem from the same source. The only difference between the two is the assessment of the outcome, as failures are often attributed to the malfunctioning of a certain part or component of a system, e.g., human error. However, when outcomes differ, this does not imply that the underlying process is different.

- *Principle of Approximate Adjustment*
  Today's socio-technical systems operate in uncertain and dynamic environments. They are therefore partially underspecified to allow them to adjust their performance to the wide variety of operating conditions that they might encounter. However, as resources, such as time, manpower, money, are often limited, adjustments are always approximate, leading to performance variability.

- *Principle of Emergence*
  As systems adjust their performance to the current operational conditions, this everyday performance is variable. While variability within one function can be managed or monitored, variability in multiple functions can combine in unanticipated ways and cause disproportional and non-linear effects. While performance variability can cause negative outcomes, it is also a necessary feature of a system's resilience, the ability to function under a vast variety of conditions, including the capacity to recover from system disturbances (Woods, 2006).

- *Principle of Functional Resonance*
  Performance variability in multiple functions may resonate, i.e., reinforce and amplify itself, and hence the variability in one or more functions is unusually high. The consequences of this may spread to other functions through their couplings, which can lead to unexpected and adverse events.

FRAM consists of four steps that are used to model the system. In *Step 1,* all necessary system functions are defined. The aim is to afford a consistent description as a basis for the analysis. All functions are described with respect to their six aspects (Input, Output, Time, Control, Precondition, Resources/Executing conditions, Table 1). These aspects describe the basic characteristics of an activity and help to understand the relationships among the functional units within a system.

Table 2: Aspects of a function

Aspect	Description
Input (I)	A signal that activates the function, is used or transformed by the function (requires a change of state for the function to begin)
Output (O)	A result of what the function does, represents a change in the system's state or output parameters
Precondition (P)	Conditions that need to be fulfilled before the function can be performed
Resource (R)/ executing condition	The material or matter consumed, or executive conditions, that need to be present while the function is active
Control (C)	Supervises or regulates the function such that it derives the desired output
Time (T)	Aspects of time that affect how the function is performed

Foreground functions are the focus of the analysis, while background functions are those affect them. Upstream functions are performed before downstream functions in the instantiation of the model and can therefore affect their variability (Hollnagel, 2012).

Step 2 contributes to determining variability. As the model has yet to be instantiated, this step helps to characterise the variability of the functions in the model. While functions involving humans tend to vary substantially, technical functions typically exhibit stable performance over time. There are three types of variability that can be characterised in a function: endogenous, exogenous, and upstream-downstream coupling variability. Endogenous variability arises due to the nature of the function and is therefore internal, while exogenous variability is due to the variability of external factors, such as the work environment. Most interesting for an event analysis is the upstream-downstream coupling variability, as it is the basis of functional resonance (Hollnagel, 2012).

In *Step 3* of the analysis, an instantiation is created to determine the potential for the propagation and accumulation of performance variability. The model is instantiated and the system's performance is studied given a specified operating condition. This enables an analysis of how likely a function is to exhibit variability and whether this variability is likely to accumulate or be amplified into a situation in which functional resonance may occur. Within the area of risk assessment and system design, this step can be employed to simulate the functions' performance within a specific operating condition to identify the strengths and vulnerabilities of the system at work. *Step 3* can be used to visualise the connections among the functions. Functions are represented as "snowflakes" (fig. 8), and couplings between the functions are depicted within the instantiation.

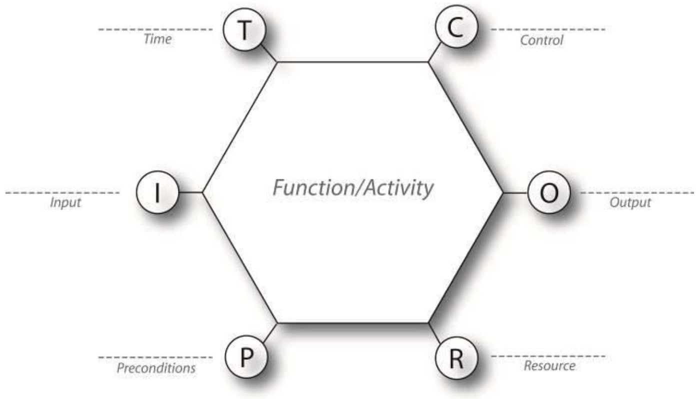

Figure 8 FRAM "snowflake" (adapted from Hollnagel, 2012)

After identifying potential and actual variability and instantiating the model, *Step 4* of the method focuses on suggesting how the system's performance variability can be monitored, managed or eliminated.

4.7 Procedure

The following paragraphs describe the methods applied for data collection and analysis for each of the appended articles (Paper 1 - Paper 4).

4.7.1 Paper 1

Study visits to two full-mission VTS centres and one ATC Approach centre were conducted to gain a basic understanding of the working conditions and system operations within the two domains. Both VTS centres are part of the infrastructure surrounding a medium-sized European port and offer all three service levels (INS, TOS, NAS). The ATC Approach centre visited is responsible for the Terminal Manoeuvring Area surrounding a medium-sized European airport. The centre offers full ATC services for commercial and general aircraft operating between 3000ft and Flight Level 095. The airspace is used by aircraft arriving at and departing from the airport and aircraft transiting its airspace.

The aim of these visits was to enhance the domain knowledge and obtain information on how the operators in the centres address a variety of situations encountered during normal operations for the arrival phase of a mission. During the visits, the researcher(s) were given tours of the centre and had the opportunity to make contextual inquiries to obtain data on how the services offered by the centres are realised in varying environments, as well as on how the operators relate their actions to the operational short-term and long-term goals of the organisation. Each study visit was conducted by at least one researcher during the day.

4.7.2 Paper 2

Paper 2 presents a theoretical discussion of the possible need for centralised control. The paper's arguments were informed by the findings of prior research.

4.7.3 Paper 3

A total of 20 maritime professionals participated in this study, fifteen VTSOs, two VTS supervisors, and three pilots (Table 3). All participants had at least two years of work experience in the VTS domain and previously worked as active seafarers.

Table 3 Overview of participants, VTS centres and research activities

No. of Participants & position	VTS – Centre (service level)	Research activity
1 shore-based pilot **1 VTS supervisor**	Harbour Operation Centre (HOC) IJmuiden (INS, TOS, Shore-based pilotage)	Study visit (approx. 4 h)
3 VTSOs	Sound VTS (INS)	Study visit (approx. 4 h) Semi-structured interviews
2 shore-based pilots/VTSOs	Traffic Centre Hook of Holland (INS, TOS, Shore-based pilotage)	Study visit (approx. 4 h)
4 VTSOs **1 VTS supervisor**	VTS West Coast (INS)	Observation (approx. 8-10 h) Semi-structured interviews
8 VTSOs	Education at maritime academy (Information on specific VTS-centre not available)	Focus group (2 h)

4.7.3.1 Data collection and analysis

Three open-ended naturalistic observations at VTS centres were conducted to obtain insight into the working environment and actual operations of the VTS service. The Harbour Operation Centre (HOC) IJmuiden, Traffic Centre Hook of Holland, and Sound VTS were visited. Each study visit was coupled with informal conversational interviews (Patton, 2002).

Furthermore, a focus group interview with eight VTS operators training to become on-the-job instructors was conducted on the premises of the Swedish Maritime Institute in Turku, Finland.

To further explore everyday operations within the VTS domain, eight interviews were conducted with VTSOs (7) and a VTS manager (1) from two different VTS centres. The interviews were semi-structured and followed an interview guide focusing on the definition and promotion of maritime safety in relation to the daily work conducted at a VTS centre. Finally, to complement the data obtained through the various types of interviews, an observation at a VTS centre was conducted. The observation was performed on two days during the daytime with the aim of observing the typical working procedures and routines of a VTS operator at work.

The data analysis was interactively conducted with the aid of grounded theory. Grounded theory is a methodological framework to link theory and methodology (Corbin & Strauss, 2008). In the present work, grounded theory has been used as a guide to link concepts derived from CSE and RE to the collected data.

4.7.4 Paper 4

Eight informants participated in the data collection. An overview of the activities each informant participated in is displayed in table 4. The informants stem from four different VTS centres (VTS 1, VTS 2, VTS 3, VTS 4) in Northern Europe and currently work as a VTSO (5), VTS supervisor (VTSS, 1), VTS manager (1) or Traffic Planner (1). All participants previously worked as navigating officers for at least two years, and their work experience in the VTS domain ranged from 6 to 26 years.

4.7.4.1 Data collection and analysis

Three separate interviews with one VTS manager, one supervisor and one traffic planner were conducted as part of this data collection process. All interviews were conducted at a VTS centre, due to the availability of participants, and were electronically recorded.

Table 4: Overview of the research activities and informants

Participant's position	VTS centre	Participated in
VTSO	VTS 4	Focus group 1
VTSO	VTS 4	Focus group 1
VTSO	VTS 1	Focus group 1
VTSO	VTS 1	Focus group 1, focus group 2
VTSS	VTS 2	Interview, focus group 2
VTSO	VTS 3	Observation, focus group 2
Traffic Planner	VTS 3	Observation, interview
VTS manager	No specific centre	Interview

The data collected through the interviews were complemented by open-ended naturalistic observation. The observation was held at a VTS centre offering all three service levels during a VTSO shift. The observation followed that operator through the various stages of work during a shift. The aim of the observation was to obtain a better understanding of how VTS operators monitor, adapt to, and respond to variations in the dynamic environment. The observation was accompanied by an informal conversational interview (Patton, 2002).

In addition, two focus groups were conducted during the course of this study. The first focus group sought to explore VTS operators' considerations regarding the balance of efficiency and safety when providing a service to the vessels under their control. Four VTSOs from two different VTS centres participated. The subjects were asked to sign a consent form after receiving both written and verbal information. The first focus group lasted approximately 120 minutes in total and focused on three questions.

- What are the preconditions for safe traffic movements?
- What are the preconditions for efficient traffic movements?
- What is the role of the VTS in a Vessel Traffic Management setting?

Each question was posed to the participants separately, and they were asked to first respond individually in writing (5 min) and then discuss the same question in a group session for approximately 25 to 30 minutes.

The second focus group was held after all semi-structured interviews and the observation were completed and the data had been analysed through grounded theory. The aim of focus group 2 was to seek confirmation and calibrate the results obtained from the first period of data collection. The original intent was to hold focus group 2 with all subjects who had previously participated in this study, but due to the availability of informants, only two VTSOs and one VTSS could attend. After a brief summary of the study's results to date, the participants were asked to describe their everyday work in the form of the activities that they perform to increase predictability and foresight for themselves and the traffic participants.

All collected data were analysed using two different methods. First, a grounded theory analysis was conducted (Corbin & Strauss, 2008). All data recorded during the interviews were transcribed for the analysis, and all fieldnotes and transcriptions were entered into MaxQDA (VERBI Software Consult SozialforschungGmbH, 2013) to identify the core concepts of how VTS contributes to safe and efficient traffic movements. In a second step, the collected data were used as basis for modelling the everyday operations of two VTS systems using FRAM. The aim of this analysis was to obtain more in-depth information on how VTS is realised in various settings and how that affects the ability to monitor, respond, anticipate and learn.

5 Results

This chapter summarises the most important findings from each appended paper. The results of the four papers all present a specific perspective on the VTS system and how the service operates. Figure 9 reports the main focus of each paper.

Paper 1 presents findings from a cross-domain study of VTS and ATC and reveals the similarities and differences in how traffic management is realised in each domain. Paper 2 discusses the overall control settings within the maritime traffic management domain and highlights the advantages and disadvantages of how traffic is currently managed. Paper 3 presents findings from studying the VTS as JCS and discusses the relationship between the system's ability to maintain control and its ability to be resilient. Finally, paper 4 reports the results of modelling the everyday operations of two VTS systems and highlights the effects of a system's functional design on its capability to monitor, anticipate and respond.

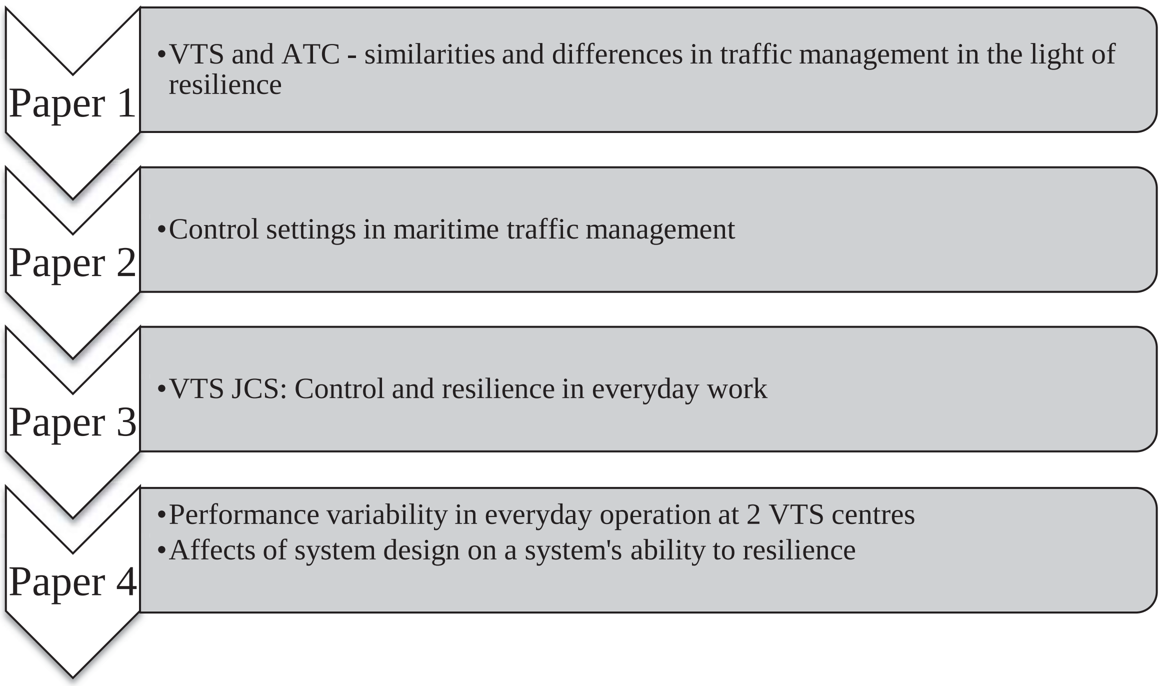

Figure 9: Main topic of each appended article

5.1 Learning lessons in resilient traffic management: A cross-domain study of the Vessel Traffic Service and Air Traffic Control

Paper 1 presents results of a cross-domain study on ATC and the VTS. The aim of the study was to identify the differences and similarities in how traffic management is realised in each domain to be able to understand instances in which each system could learn valuable lessons to become more resilient.

Table 5 presents the four main functions required to ensure safe and efficient traffic movements: monitoring the state of traffic, ensuring separation between aircraft/vessels, routing participants, and capacity planning. In the ATC system, the ATCo performs all four functions, while responsibility in the VTS system is shared by the VTS, traffic participants and other services, such as pilotage. In a VTS, control is distributed, with the primary responsibility remaining on board the individual vessel, in contrast to the centralised control assigned to the ATCo in ATC. As a consequence, the VTS is forced into a primarily reactive role focusing on the monitoring task, with only limited potential to influence how traffic is separated, routed and planned.

Table 5: Main functions of traffic safety and fluency

Function	ATC	VTS
Monitoring state	ATCo	VTSO & participants
Ensuring separation	ATCo	Traffic participant(s)
Routing participants	ATCo	Traffic participant(s)
Capacity planning	ATCo	VTSO (limited degree), mostly pilots & participants

To learn, monitor, respond to and anticipate are the essential abilities a system requires to adjust its functioning to a variety of operational conditions without experiencing any disruptions. The analysis revealed that learning is largely reactive in both domains and often driven by examples of the negative, e.g., training to avoid error. Furthermore, a VTS is dependent on experienced-based learning. In addition to area-specific knowledge that is acquired by inter-personal learning during OTJ training, a VTSO also needs to have an understanding of how a vessel is operated and manoeuvres to be able to provide information at the right time. This requires experience in the merchant fleet. Monitoring is a core ability for both of the services, as it is a precondition for providing support for the crews, but in contrast to ATC, VTS does not offer objective measures, such as a minimum separation, to support the operator during the monitoring task.

The VTS and ATC differ to the greatest extent with respect to their ability to anticipate and respond (Table 6). VTSOs only have limited access to information regarding future traffic movements in the VTS area. In conjunction with the limited legal mandate, this restricts the VTS's capacity to respond to events, as there is no possibility to steer the traffic, irrespective of whether a dangerous situation might be developing. Navigational decision making always remains with a vessel's master. Anticipation is also limited in the VTS, as capacity planning is primarily executed through other services, such as pilot or tug services. The VTS does not influence the planning of those services, despite that their planning will eventually affect how much traffic a VTSO will need to service.

The presence of procedures and a high degree of standardisation support the capacity to anticipate and respond within the ATC domain. Clear performance margins provide guidance for standardised responses that leave fewer details that depend on the expertise and the experience of the operator. Furthermore, as all four main functions are the responsibility of the ATCo, the operator can actively influence traffic movements through routing and clearances.

Table 6: Resilience abilities within each domain

	ATC	VTS
Learn	Reactive	Seamanship/experience from both sides
	Proceduralised	Local needs
	Centralised	Interpersonal learning amongst operators
Monitor	Hierarchical	Individual
	Objective measures	Objective/subjective measures
	Expertise	Experience & expertise
Respond	Procedures	Experience
	Upward delegation	
	Discretion of ATCo (to some extent)	
Anticipate	Capacity planning	Berth planning
	Weather planning	Pilot service cooperation

The paper demonstrates that the ATC and VTS systems, while sharing a common goal, have little in common. How each system is designed affects its ability to learn, anticipate, monitor and respond. The important finding concerning a VTS was that VTS is very limited in its ability to respond relative to ATC due to how control is delegated in the two domains.

5.2 Maritime traffic management: a need for centralised coordination?

Paper 2 presents the VTS as a part of a distributed traffic management system, in which each vessel is responsible for its individual safe and efficient conduct. The paper discusses the consequences of how maritime traffic is currently managed. The role of the VTS within the contemporary traffic management structure is highlighted to emphasise the advantages and disadvantages of decentralised and centralised control.

Maritime traffic management is distributed with respect to its control settings, as the responsibility for safe navigation is assigned to the master aboard a vessel. However, as most VTS systems are responsible for areas characterised by confined waters and limited space for larger vessels to manoeuvre, such as port approaches or rivers, it is essential for every part of the system to cooperate.

Figure 10 depicts the Ship-VTS system, which has the system goal of providing safe and efficient traffic movements for all traffic in the area. The overall system can be understood as a JCS with four layers:

1. the ship with the bridge team in question
2. the ships within the sector/VTS area
3. the traffic with the VTSO in one sector/area
4. the VTS including all VTSOs in the sector/area, including all traffic

The vessels are autonomous in their decision making but must cooperate with other traffic and the VTS to achieve maximum efficiency and safety in the area. Information is shared among all vessels, the VTS and other services through the public exchange of messages on predetermined VHF channels. Cooperation between the vessels is achieved through regulations, i.e., traffic separation schemes, mandatory reporting points within the VTS area, and negotiations via VHF radio (mutual adjustment) amongst the vessels. However, following regulation and negotiating on the VHF alone cannot entirely prevent problems in situations in which resources, such as space to navigate in, are limited.

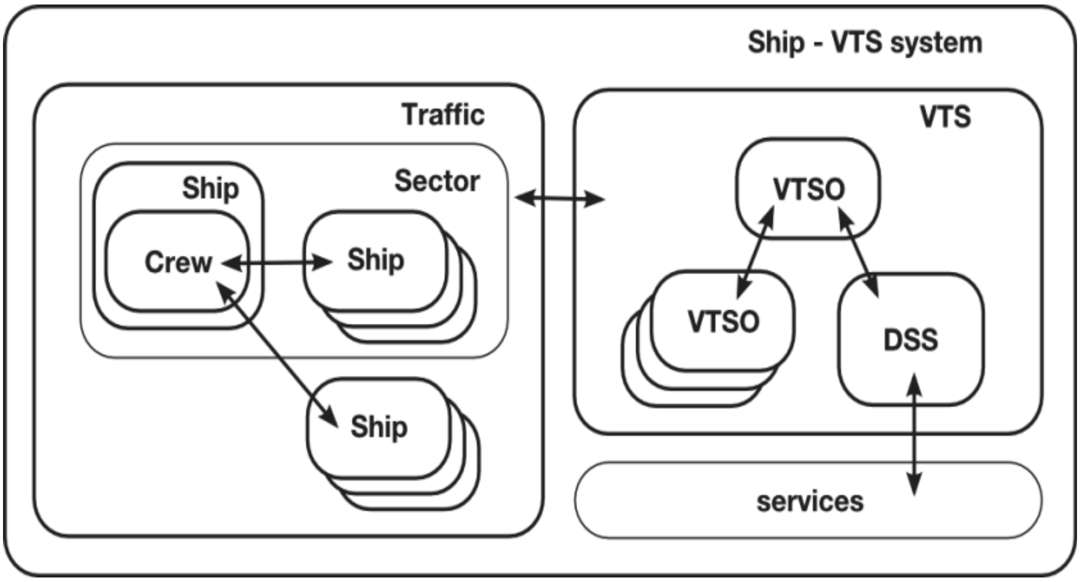

Figure 10: Ship-VTS system depicting four layers of the distributed traffic management system (van Westrenen & Praetorius, 2012)

In the maritime traffic management system, the VTS serves as a monitoring entity and contributes to the safe conduct of the vessels within the area by transmitting information on the overall state of the system. However, as the VTS has a restricted legal mandate, there is currently a risk of system disturbances, as all vessels might be tempted to pursue their own goals and prioritise these over the safety of the overall system. As the VTS is the only entity monitoring the state of the overall system and pursuing the goal of safe movement for all traffic in the area, the service has the potential to play a crucial role in the distributed traffic system.

5.3 Control and resilience within the maritime traffic management domain

Paper 3 presents the results of an analysis of everyday operations within the VTS domain. The VTS is identified as a human-machine control system, a VTS JCS, that is in control of a dynamic environment, maritime traffic. Everyday operations are analysed to depict how control modes and resilience capacities manifest themselves in the behaviour of the VTS system.

The results reveal how resilience and control are interrelated and describe how the system decreases uncertainty and maintains control.

5.3.1 Control in everyday VTS operations

The VTS JCS is a system with several layers, and the activities in each layer affect the system's behaviour at a lower level. The system under study in paper 3 consists of the VTSO and the DSS at hand. The process, or environment, to be controlled is the safe and efficient flow of traffic in the VTS area. The interaction between traffic and VTS is primarily mediated via the VHF component of the decision support system (DSS).

“The work and conditions are controlling you. There is no possibility to prepare” (VTSO)

The results of paper 3 reveal that the VTS JCS encounters a wide variety of situations during everyday operations. Traffic density, hydro-meteorological conditions and traffic type can vary considerably, meaning that it is difficult to develop expectations of and prepare for a day of VTS operations, as the quote above emphasises. The situations encountered are also often complex, combining various constant, i.e., legal framework, fairway design, and dynamic, e.g., weather, traffic density and type (ferries, cargo vessels, fishing boats, leisure craft), factors, which the VTS JCS must account for but that an operator cannot prepare for in advance.

Figure 11 illustrates the basic cyclic control model adapted to the everyday operations of the VTS JCS and depicts how the system copes with the complexity of daily operations. The VTSO and the decision support available at the centre constitute a level of system aggregation of a JCS, the VTS JCS. The goal of the system is to promote traffic fluency and safety within the VTS area. The VTS JCS includes a construct that incorporates knowledge on the current state of the system and its history, as well as the experience and expertise of the human operator, the VTSO. The construct of traffic behaviour is developed based on the system’s competencies, which consist of the operator’s experience, both on board and as VTSO, the enabling technology, and rules and regulations, which frame the cooperation between the VTS and the traffic. The DSS enables the VTSO to observe and monitor the traffic within the area. The operator can choose to interact with a certain vessel or the traffic as a whole based on the anticipated change in the process or environment to be controlled, namely the traffic within the VTS area. The traffic’s movement, both individual ships and traffic as whole, provide sensor input to the DSS and the information is displayed in the system, which is in turn the feedback for the operator regarding the effects of a recently executed action.

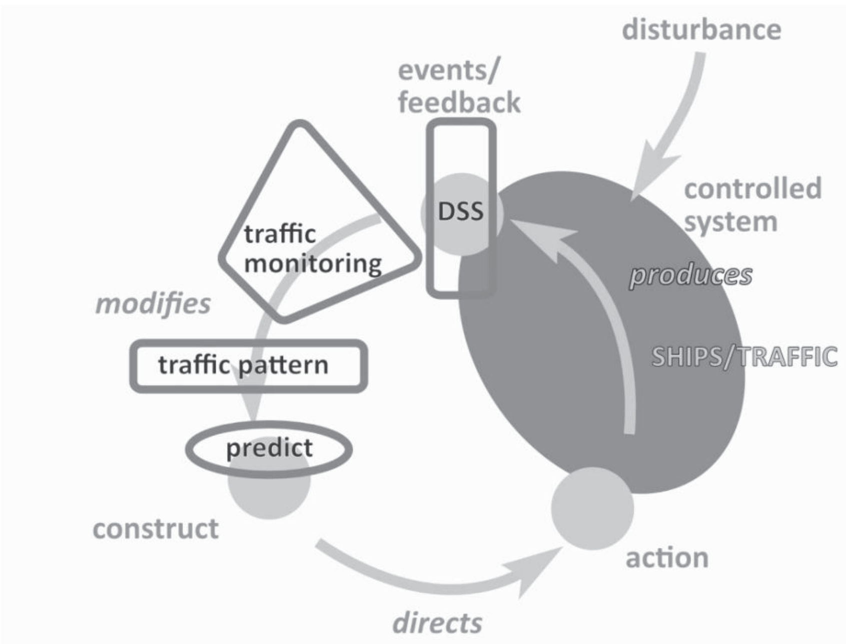

Figure 11: Cyclic control model for the VTS JCS

Most of the control exercised by the VTS JCS is characterised by an opportunistic control mode, in which the salient features of the present situation are used to determine the next action. The VTS JCS closely monitors the traffic and uses several sources of information (voice communication, data in the electronic chart system and other databases) to identify patterns in the traffic's behaviour. These patterns are identified based on experience from working as a VTSO in an area, as well as from his/her prior experience as a mariner to decrease the uncertainty over how a vessel is likely to manoeuvre. The identified patterns inform and help to update the system's construct, which is in turn used to select the best and most efficient action in a given situation.

In the context of maritime traffic management, opportunistic control manifests itself in how the VTS JCS adapts to the current demands of the situation over a short- to medium-term time horizon. Experience guides operators in their choice of action, and little support is provided through the legal framework. Concerning how the VTS JCS determines a course of action, this means that the system and its construct are heavily based on traffic patterns, which are identified as safe or unsafe.

The construct is updated through feedback obtained from the DSS, and it is essential that it be provided in a timely manner. As the results of paper 3 indicate, sensor input can occasionally be somewhat slow (several minutes may be required before all vessel information is updated), and as a consequence, the information that the VTS JCS employs to modify its construct is already *"old"*. However, this also implies that the VTS JCS attempts to act based on a context that has already passed and is therefore limited by possessing information on the *"situation-as-it-was*" when determining future actions. While delays in information presentation can partially be compensated for through the experience of the VTSO, the use of the opportunistic mode allows for several possibilities for losing control and falling back to a scrambled mode. In the face of disturbances, e.g., a drifting vessel within a fairway, the VTS JCS lacks the ability to actively organise the traffic, meaning that there is little to no opportunity to regain control when it is lost. When control is lost, the system returns to a scrambled control mode in which the choice of action is based on trial-and-error strategies and might even be random.

Within the VTS domain, tactical control is realised foremost through standardised reporting and communication between vessels and the VTS JCS. There are stated procedures for what to report when passing a reporting point. The VTS JCS essentially provides the information necessary for vessels to comply with the national rules and regulations and is supported in this task by local procedures stated at a higher level of system aggregation. Nevertheless, there are few situations in the VTS domain that are sufficiently clear that the use of procedures and rules alone is adequate. In addition, as vessels are only obliged to report 30 minutes prior to entry, the system design of the VTS provides little support for tactical control. The time horizon is rather short, and while safety and efficiency are defined as overall goals, it has little to no jurisdiction to actively guide traffic.

Finally, as the VTS JCS is currently designed, there is little opportunity for strategic control. The time horizon of the VTS JCS is typically limited to when traffic is within the designated area, resulting in a situation in which little planning is conducted for a longer time horizon than the immediate present. For overall traffic management, this means that no long-term goals are pursued and that the evaluation of the VTS is primarily based on the current situation, not on the overall functioning of the VTS as a service to the maritime community. Traffic management is primarily reactive, and there are limits to the proactive measures that the VTS JCS can take.

In summary, most of the actions the VTS JCS performs to control the maritime traffic are opportunistic. While there are seldom situations in which control is entirely lost, there are moments in which the VTS JCS is essentially forced into a scrambled control mode due to unforeseen changes in the environment. Consequently, actions are no longer evaluated, and last-minute actions might occur solely to mitigate the consequences of an adverse event that could not be responded to in time. In these situations, it is often the case that an incident or accident occurs, and substantial consequences for the environment, the traffic system as such, e.g., congestions in a fairway, and the general public are possible results. Therefore, it is desirable to apply the results obtained from this study to discuss potential avenues for improving the capacity to operate in a resilient manner within the VTS domain.

5.3.2 From control modes in the VTS towards resilient traffic management

The maritime traffic management domain is experiencing changes, and the pressure for more efficient and safer operations has already driven the VTS system towards the edge of its performance envelope through a heavy focus on technological development without recognising the need to understand everyday operations. For the VTS JCS to be able to sustain operations in the presence of changes in the environment, i.e., increasing traffic and cargo volumes and decreased vessel manoeuvrability, and to successfully cope with the complexity of future traffic scenarios, it is important to strengthen the system's ability to resilient operations. New means and methods to understand the VTS need to be found. In this context, becoming resilient entails emphasising and reinforcing activities that improve a system's possibility to respond to, monitor, anticipate and learn from events that occur/might occur to be able to maintain constant performance output under a variety of operating conditions. In the context of the VTS, this means successfully coping with the demands of everyday operations, regardless of the density, size, type and cargo of a vessel or weather conditions.

Monitor

Monitoring is the foundation of all of the system's action choices and contributes to updating the state of the system. Monitoring occurs simultaneously with a developing situation, and it is an important input for responding to and anticipating what actions might be needed now and in the near future. To increase the system's capacity to monitor its own state and provide for the possibility to anticipate and respond in good time, the VTS JCS must have access to all relevant information concerning traffic movements in the VTS area. It is important to note that while a picture of current traffic can be obtained, despite suffering from delays, this is not sufficient to estimate how the traffic flow will develop over a longer time horizon, i.e., beyond the vessels in the area and the immediate surroundings of the reporting line. Furthermore, the results indicate that local VTS systems adopt strategies, such as the use of "*hot spots*" (areas that are monitored more closely because they are where most incidents occur), to increase the system's monitoring capacity. However, these strategies appear to be highly individualised and more based on several operators' experience than reflecting official monitoring procedures. To support the monitoring capacity of the VTS JCS, the paper suggests that these adaptive strategies should be more explicitly integrated into local standard operating procedures. This might also reduce the currently held perception that the organisational framework is not closely associated with everyday operation.

Respond and anticipate

The capacities to respond and anticipate are highly dependent on the control mode in which the VTS JCS operates. Tactical control, which provides a longer time horizon and the opportunity to evaluate previous actions, is only partially supported by the way that the VTS JCS is organised. That challenges and limits the system's ability to respond to and anticipate over a longer time horizon. Furthermore, there is no legal mandate for a VTS JCS to actively control and guide traffic, meaning that monitoring and anticipating are both crucial for the system to be prepared, and to respond, when an adverse event occurs.

To increase the capacity of the VTS JCS to respond and anticipate, it is crucial to introduce a longer time horizon into VTS operations and support the system by delineating a clearly stated role for the system within the maritime traffic management domain. As port infrastructures worldwide are increasingly operated with an emphasis on efficient cargo movements, it should be recognised that the VTS JCS is the only entity providing state information to the maritime traffic system during approach. Therefore, the role of the VTS JCS in the port infrastructure should be acknowledged at both higher levels of the system and by the marine traffic within the VTS area.

Learn

The abilities to learn is not fully developed within the VTS JCS. While individual operators learn through OTJ training and other certifications, it appears that there is a lack of organisational learning with respect to examples of the positive. Although work practices, such as the use of hot spots, demonstrate that operators learn coping strategies, no indication was found concerning how these strategies are incorporated into working procedures and operator certification. As outlined above, the recommendation is to thoroughly analyse and understand how everyday operations are conducted, such that learning in general, and learning regarding specific events, can address both positive examples, i.e., successful coping strategies, and adverse events, i.e., training based on previous accidents to understand why the event occurred.

In summary, each of the four abilities highlights an area in which minor changes, such as training using examples of successful coping strategies, can increase the system’s overall capacity for resilience in its operations. While respond, monitor and anticipate are characterised by actions conducted synchronously, i.e., in real-time, there is a need to acknowledge that the ability to learn is both synchronous, as every experience increases the VTS JCS’s understanding of its own operations, but also diachronic, i.e., developing over time as strategies are tested and reinforced through success.

5.4 Performance variability and resilience in the Vessel Traffic Service (VTS) domain through the lens of FRAM

Paper 4 presents results from analysing the VTS system’s overall role in traffic management and how VTS manifests itself within specific conditions. The aim was to explore the complexity of everyday work and highlight differences and similarities in how a VTS contributes to safe and efficient traffic movements. Therefore, the everyday operations of two VTS systems were modelled through FRAM.

5.4.1 The functional models of VTS 1 and VTS 3

The FRAM analysis revealed that the two systems share few characteristics when a VTS is implemented as a service to the mercantile fleet. Both systems provide information to the vessels within the area. In addition to the functions “provide information service” and “monitor traffic”, each system exhibits a unique set of functions that is required to realise everyday operations. The two models (fig 11, fig 12) depict each system’s functional design and the initial dependencies among functions.

VTS 1

VTS 1 is a part of the local port infrastructure in one of Northern Europe’s largest ports. The service is provided by a single VTSO on duty. The operator is located in next to the pilot dispatch and the harbour master in a joint operation centre at the port. In this area, the VTS provides an information service (INS), as well as the service is responsible for issuing berth clearances and clearances to leave anchorage.

VTS 1's core activities are to monitor and inform the traffic. Information on traffic participants must be obtained through other services, and due to the limitations of its legal mandate, the VTS system is largely characterised by feedback control. The VTSO cannot actively organise the traffic and needs to rely on support from other services, such as the pilot service.

> *We can delay vessel from anchorage and berth. The harbour office or the port control can support, if it's in or within the harbour limit, because they are sitting next to us […] They can say "No you are not going to come to that berth". I can't say it because I don't have the jurisdiction. (VTSO)*

A VTSO therefore actively collects information on the vessels (ETA, destination, draught, speed), ordered services (booked tugs and/or pilots), and harbour operations (terminals, loading schedules, etc.) from other organisations in the port infrastructure. The VTS itself receives no notice of incoming traffic until a vessel crosses the reporting line into the VTS area.

> *Yeah, they got it before us, because they got 24h notice, I have, the pilot, they got 24h, the port authority, pilot order got 5 h notice, and we actually is when entering the VTS area. (VTSO)*

The functional model of VTS 1 (fig.12) consists of four foreground functions (provide traffic information, give/deny berth clearance, give/deny clearance to leave anchorage, traffic monitoring) and four background functions (collect traffic information, collect hydro-meteorological information, receive vessel reports, establish VHF contact). Seven other functions that represent aspects of the environment (i.e., "request berth clearance" is necessary to activate give/deny berth clearance, but it is executed by a vessel, not by the VTS system) have been added to complete the model. These functions are performed by vessel traffic or other services and are thus background functions.

The connections between the functions represent the dependencies among them. For example, the function "(to) give/deny berth clearance" is activated by "(to) request to leave berth"; therefore, the latter is an input to the former. The analysis revealed that the VTSO is an essential control measure for all functions of VTS 1. For example, the VTSO determines the content of what is transmitted as an aspect of the function "(to) provide traffic information". The model of VTS 1 also reveals a dependency on information that must be actively collected from other services (e.g., "(to) collect traffic information", "(to) provide forecast to VTS"). As a consequence, there is a risk of coupling variability that might affect several functions simultaneously once the traffic information cannot be collected from the other service, e.g., due to missing information, acting too late.

In certain cases, the adjacent services do not serve as informational resources but additional control. VTS 1 has only a limited mandate regarding traffic organisation. Therefore, even if the VTS denies berth clearance, or clearance to leave anchorage, the vessel can nevertheless take action in contravention of this decision. In those cases, pilot services and/or the harbour master are required as additional control. This dependency on support from other services can introduce variability into the couplings among the functions.

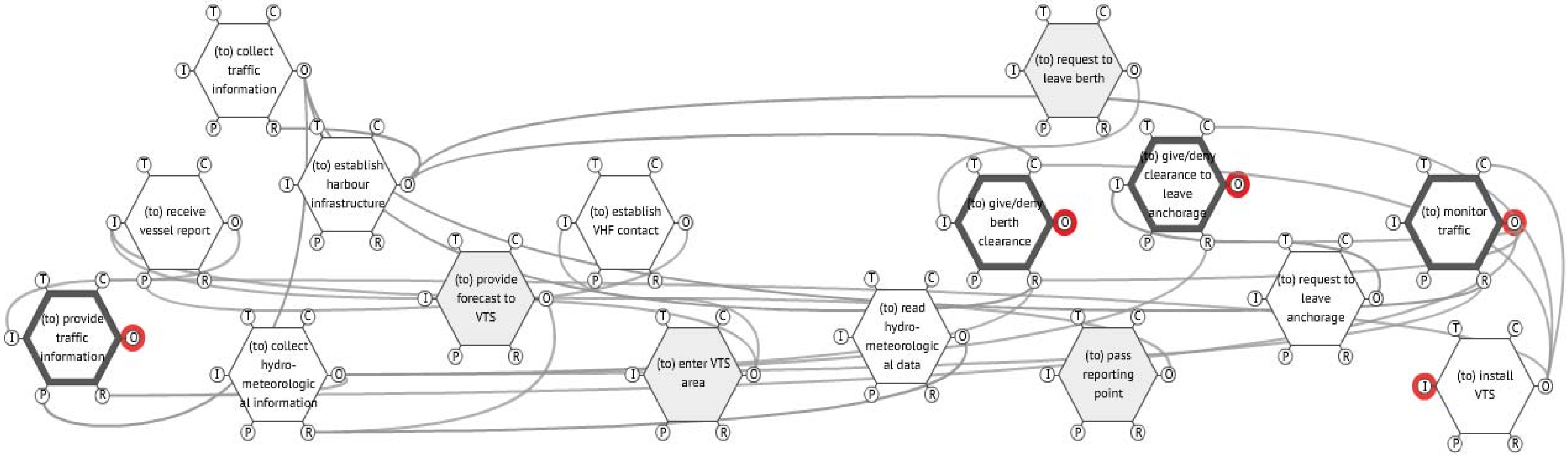

Figure 12: VTS 1 and its functional units (foreground functions are white with a grey border, background functions grey). The harbour infrastructure is an important resource for many of the VTS-related functions. The dependencies among the functions demonstrate the complexity of daily work. The outputs marked in red are directed towards the vessel(s) that are navigating within the VTS area

VTS 3

VTS 3 is located at the entrance to a river in Europe. The VTS centre incorporates staff from two countries that jointly operate the VTS system. The VTS offers all three service levels and closely collaborates with other services, such as a pilot service, lock service and tug service, to supervise and assist traffic along the river that serves several major ports with complex lock systems, which constrain the capacity of the nautical services. In combination with tidal waters, strong currents, and limited manoeuvring space along the river, supporting maritime traffic is a complex task requiring activities conducted at various time horizons to respond rapidly to upcoming problems.

The functional model of VTS 3 (fig. 13) consists of 18 functions; eleven foreground functions (translate messages, provide shipping broadcast, organise traffic on river, provide information services, provide navigational assistance, monitor traffic, queue vessels for pilotage, decide on pilotage method, request information for pilotage, calculate tidal windows, make sailing plan), three background functions (establish contact, supervise staff, obtain vessel information) and four functions included to complete the model, e.g., establish VTS organisation, which provides the VTS staff and local operational procedures.

In comparison to VTS 1, VTS 3's model exhibits functions, such as translate messages, that have been permanently introduced to manage the performance variability that could stem from the environment, i.e., vessels that need to make a traffic arrangement for a meeting but lack the means to communicate because the two bridge teams do not share a common language. Within the area of VTS 3, a substantial amount of traffic is inland traffic that does not typically report in English. Therefore, local operating procedures dictate that both English and Dutch be used within this system. This places an additional burden on the VTSO, who represents the control aspect of multiple foreground functions.

In addition to the three service levels offered at the centre, the VTS system also provides the intake for the pilotage of a vessel. It results in three additional functions, namely, queuing vessels for pilotage, determining the pilotage method and requesting information for pilotage, which must be performed in addition to the functions connected to the service levels. During the data collection, the informant also recognised that the conditions under which these functions are performed often lead to substantial performance variability in output, which could easily accumulate and lead to functional resonance.

> *So that gives very confusing traffic patterns and even for us, and even given our cooperation with the pilot, it sometimes like, we think, "oh, we had a guardian angel today", so we are still waiting for the day when we don't have a guardian angel because it's very messy for us but also for the ships too. Sometimes they are like, "ahh, what do I have to do", and we have to get used to this new situation. (VTSO)*

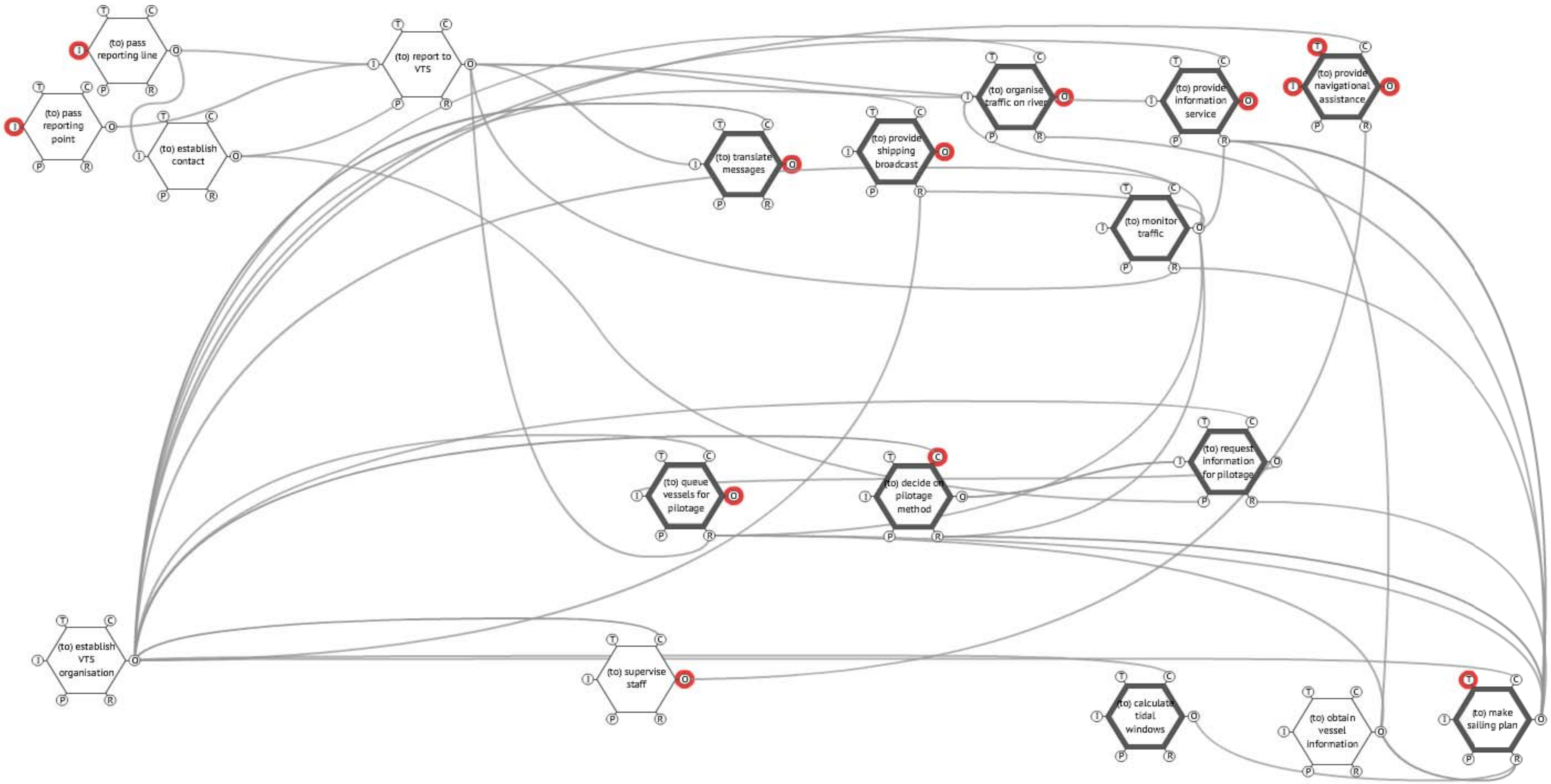

Figure 13: VTS 3 and its functional units. The VTS 3 includes additional functional units such as pilotage intake that are integrated with the other services offered. This generates additional functions and couplings with other units within the system. The outputs marked in red, time aspects and control aspects, represent interactions with functional units beyond the scope of the analysis

In VTS 3, the traffic planner develops advance sailing plans to reduce conflict in traffic movements and compensate for the natural constraints placed on the navigation of vessels within the area. The traffic planner is primarily responsible for planning for deep draught vessels, as these are the most restricted ships and can only meet other traffic at a limited number of locations along the river. The planner-related functions, (to) develop a sailing plan and (to) calculate tidal windows, provide another measure of the extent to which performance variability is managed within the system, as they provide a traffic plan that increases the predictability of traffic movements within the area. This, in turn, supports the tasks of traffic monitoring and providing an information service.

5.4.2 Creating foresight and shaping preconditions- but very differently

Creating foresight and *shaping preconditions* were identified in the grounded theory analysis as the two common functions regarding how the VTS system contributes to the safe and efficient movement of maritime traffic. Furthermore, the FRAM analysis revealed that the two systems perform different activities during their daily operations, as they must respond to different constraints, some of which are products of the natural environment, e.g., tidal waters, while others are due to how the specific VTS is organised and integrated into the overall port structure.

While VTS 3 is a system that must cope with high traffic loads in tidal waters, requiring more thoroughly planned traffic patterns to avoid congestion resulting from the presence of lock structures at port entrances, VTS 1 is responsible for an area where the surrounding geography restricts navigation and water levels do not differ to the extent that traffic is heavily affected. The greatest challenge faced by VTS 1 is that the traffic is unevenly distributed in the fairways and the system lacks a legal mandate to support traffic organisation, meaning that the system is unable to restrict traffic movements by directing vessels into one of the two fairways depending on the current traffic density.

In addition to the geographical conditions, the local organisations of the VTS systems differ substantially. A single operator operates VTS 1, while VTS 3 has a more complex organisation, in which operators are responsible for a certain set of activities and there are multiple operators working during a given shift. Due to the need for more detailed traffic planning in accordance with tidal windows, the system requires a division between VTSOs to provide information and monitor traffic in real time and VTSS or traffic planners that plan and de-conflict traffic movements to decrease the risks of congestion and incidents.

The difference between the two systems is reflected in their functional designs. The two systems exhibit a unique functional design through which VTS is realised in everyday operations, which in turn affects their ability to respond, monitor and anticipate. Furthermore, the findings also reveal how VTS 3 effectively uses natural constraints, such as tidal waters, to support tasks that provide more certainty regarding what to expect. This behaviour indicates a greater potential to detect and address situations beforehand through, e.g., de-conflicting vessel traffic over a longer time horizon. However, considering the preconditions that the two systems face, it also indicates that VTS 1, as it is loosely organised and not as dependent on the performance of functions controlled by other parts of the system, has the most flexible design and exhibits the least potential for brittleness in the event that the systems were to operate near its system boundaries. This should be considered when making changes to local operating procedures or adding new functions to the responsibilities of the VTS system. As indicated by the results regarding VTS 3, a highly coupled and somewhat aviation-like traffic planning system, new functions affect how the other functions in the system are performed. If changes, e.g., a change in the pilot intake procedure, are implemented, they will affect other parts of the system and could lead to non-linear outputs. As emphasised by the quote above, the system is already operating near capacity, and the multiple dependencies between functions create a highly complex web of interconnected activities, rendering the system rather vulnerable and brittle. As the functions are so dependent on one another, there is a high risk that performance variability could be reinforced and amplified and one of functional resonance, which can, in the worst-case scenario, lead to an incident or accident, in the event that the system is unable to respond to changes in favourable periods.

Everyday operations within the VTS domain are highly complex, and each of the modelled VTS systems has developed its own means and measures to cope with the natural constraints and uncertainty encountered in the environment. Before any changes to a VTS system are made, regardless of whether these are organisational, technical or legal, a thorough analysis of the current system and the dependencies between its functions should be conducted. Only if the complexity of everyday work is understood and properly analysed can one estimate how changes will affect the system's overall performance. One approach to this would be to employ FRAM in conjunction with expert calibrations to ensure that work, as currently conducted, is properly understood before new measures are introduced.

6 Discussion

The purpose of this thesis has been to increase the general understanding of the everyday performance of the VTS system and model this performance to inform current and future developments within the VTS domain.

The following sections will discuss the results presented in this thesis relative to its objectives. The first half of the chapter will synthesise the results, while the latter half will discuss the broader implications of the findings for the maritime domain and highlight the advantages of understanding socio-technical systems and their performance before changes are pursued. The chapter concludes by presenting suggestion for future research based on this thesis' results.

6.1 How is traffic management currently performed?

As paper 1 and paper 2 highlight, maritime traffic management is currently performed through distributed control. The system is loosely coupled (Perrow, 1999), with the primary responsibility for efficient and safe movements remaining with each vessel. Four main activities have been identified that guarantee safe and efficient traffic flows: monitoring traffic status, ensuring separation, routing traffic and capacity planning. Within the VTS domain, monitoring traffic status is the responsibility of VTSO, while routing and ensuring separation remains the responsibility of the vessels in accordance with STCW (IMO, 1996). Control is therefore distributed within the maritime transport system, and each vessel has the right to prioritise individual goals over system goals, e.g., being first at the pilot station, and selecting the fastest route into port, over overall traffic safety and fluency. This introduces a risk of system disturbances in form of congestion or even incidents that can have consequences for the maritime domain and the general public.

Paper 2 further reveals that maritime traffic management can be understood as a large, socio-technical system, the Ship-VTS system (fig. 9), incorporating the VTS organisation offering a service, all vessels navigating within the area and the services offered through the port infrastructure, e.g., the pilot service, tug service. STCW (IMO, 1996) assigns the responsibility for safe navigation to the masters on board the vessels, meaning that the decision making remains on board, resulting in distributed control within the system. The VTS has the crucial task of facilitating safe and efficient navigation and striving for the safety of the traffic as a whole, while each vessel is only responsible for its own safe conduct. Furthermore, regarding the overall system goal, the VTS is the only entity that is not pursuing individual goals. Therefore, there is tremendous potential to increase and strengthen the overall role of the VTS within the distributed system. One example of a means of realising this would be to assign the VTS the role of allocating resources among the participating vessels, e.g., divide the traffic among multiple fairways, to be more actively involved in the actual management of traffic.

6.2 What is VTS' contribution to safe and efficient traffic movements?

This thesis has identified the VTS as a socio-technical system that actively strives to shape the preconditions of and create foresight for the traffic participants within its area of responsibility (paper 4). Table 7 summarises the key features of the VTS system that were addressed in the four papers.

The VTS is one component of a large socio-technical system featuring interactions among shore services, vessels and allied services. Within the distributed Ship-VTS system, the VTS is the only part that is responsible for overseeing the overall system goal. Information is used to guide and assist the traffic in its safe passage, but ultimately the VTS remains a consultancy service with VHF broadcasts as its only means of influencing vessels' navigation. Even if a VTS is assigned TOS and NAS as service levels, the VTSOs are bound by guidelines not to intervene unless requested by a vessel (IMO, 1997). It can therefore be difficult for the VTSO to persuade vessels to abandon individual benefits for the sake of the overall traffic flow and safety within the VTS area.

Table 7 Characteristics of a socio-technical system (adopted from Vicente, 1999) applied to the VTS

Characteristic	VTS
Interactions of various layers	VTS interactions with vessels, allied services, agents
Large problem space	Complexity of everyday work based on a large number of variables (ship-related, environmental, geographical, etc.) creates difficulty in articulating general procedures
Dependence on communication and coordination	VHF as the primary means of coordination through communication between vessels and shore services
Distributed	Ship-side and shore-side services are important, as vessels are autonomous in their navigation
Dynamic	VTS is developing and changing (e-Navigation, chain-planning, spatial planning)
Mediated communication	VHF, mobile phones, email
Couplings	Complex net of technical, human and organisational functions
Automation	Increased automation based on strategies encouraging technical innovation, i.e., e-Navigation
Uncertainty	Limited time horizon to prepare for upcoming events
Potential hazard of operation	Oil spills, wrecks, etc. with consequences for the general public

Furthermore, prior research (Nuutinen, 2005; Nuutinen, Savioja, & Sonninen, 2007; Praetorius, 2012; Praetorius & Lützhöft, 2012) has identified a certain ambiguity within VTS operations because VTS is realised locally, meaning that there can be differences across countries, VTS centres in one country, and as highlighted by Nuutinen (2005), even in how VTSOs at one centre provide a service level. Furthermore, as emphasised by paper 4, there are many ways in which VTS operations are adapted to specific local conditions. This leads to differences in service provision and even in the services offered by a VTS system, ultimately making it difficult for bridge teams to understand what type of service to expect (Praetorius & Lützhöft, 2012). As a consequence, it can be difficult to realise a complete distributed system, in which there is a need for all actors to cooperate to ensure that traffic moves safely and fluently. While the decentralised control system is effective at addressing situations in which resources are abundant, maritime traffic management becomes tightly coupled once resources, such as navigational space or the availability of tugs or pilots, become limited.

Whereas paper 2 analysed the role of the VTS within the Ship-VTS system, paper 3 focused on how the VTS contributes to fluent and safe traffic movements in greater detail. By applying concepts from CSE, the VTS has been described as a VTS JCS that is in control of the maritime traffic within the VTS area. Here, control is not meant in an absolute sense, but it is rather understood as the ways in which the system manages to produce constant performance. In the VTS domain, this means that traffic moves fluently and without any safety breaches, congestion, or delays. The VTS JCS provides information to the maritime traffic and evaluates actions taken based on the traffic patterns displayed in the DSS. The VTS JCS is responsible for ensuring the overall system goal and seeks to provide guidance on a "*field of safe travel*" for a vessel based on the state of traffic in the system and the expected events occurring along the path of each vessel. The concept of "*field of safe travel*" (Gibson & Crooks, 1938) stems from the automobile domain and defines the area, at any given moment, that represents the field of possible paths that a car may take without any hindrance. In maritime settings, the field of safe travel is the area that represents the possible paths for a vessel in which it can be manoeuvred without hindrance from other traffic or any geographical circumstance. As VTS systems are only introduced in high-risk areas, e.g., areas with high traffic density, conflicting and complex navigational patterns, shifting shoals and local hazards, etc., the system represents essential support for each vessel in identifying the safest and most efficient route for its voyage within the VTS area. The VTS is aware of the status of the traffic as a whole and can assist a bridge team in anticipating future events.

It was further found that the VTS JCS often operates within the opportunistic control mode and only exercises limited strategic and tactical control. This affects the system's ability to respond to and anticipate changes in the operating environment. At present, the VTS JCS relies heavily on the experience of the human operator when determining how and when to interact with traffic, which may influence the quality and consistency of the service. Operating under opportunistic control carries the risk of returning to a scrambled mode (Hollnagel & Woods, 2005). This is characterised by trial-and-error behaviour and can lead to a complete loss of control. It is therefore essential to gain a greater understanding of when and how the system is on the verge of transitioning into a lower mode of control. As Amalberti (2001) notes, control modes can be essential to complement traditional risk assessment methods with a more ecological perspective on how safety is maintained within a system. Furthermore, control modes can indicate whether there are insufficient resources to be able to maintain control and recovery in real time. Within the VTS domain, it is therefore particularly important to identify means and measures to support operations in the tactical and strategic modes to prevent situations in which the system's control degrades.

Paper 2 and paper 3 argue that the limited legal support in the form of defining a clear role for the VTS within the Ship-VTS system has a negative effect on the VTS' ability to contribute to safe and efficient traffic movements. While vessels, the pilot service, tug service, and other port services all primarily pursue individual economic goals, the VTS is the only system responsible for overseeing efficient and primarily safe traffic movements. As such, its ability to maintain control at a tactical and strategic level should be improved to prevent the VTS JCS from degrading to a scrambled mode of control. As strategic and tactical control require a longer time horizon and include the system's ability to evaluate and balance long-term and short-term goals, the VTS JCS requires organisational support, locally at the centre, from the vessels within the area and from legal stakeholders, to achieve those modes of operations.

Further, the results of the paper 3 reveal that operations of the VTS system emphasise monitoring and responding to real-time developments. The system exhibits a limited capacity to anticipate and learn, which in turn affects its ability to plan and prepare the system to adapt its operations when conditions change. To counterbalance this effect, it is essential to discover ways to strengthen the system's ability to learn and to anticipate. Potential remedies include efforts to identify ways in which the VTS organisation, including the staff and legal stakeholders, can learn from examples of operations in which the VTS JCS has successfully coped with both extreme conditions, e.g., high stress and incidents, but also everyday operations.

Furthermore, to strengthen the system's ability to operate on a tactical and strategic level, clear definitions of both service levels and the service's objectives are necessary. At present, considerable efforts are being devoted to increasing the technological level in the maritime domain, but substantial ambiguity remains concerning the goal of the VTS system and how it is provided. Only a clear mission statement and a unified realisation of VTS systems worldwide will lead to a greater recognition of the importance of the service's contribution to safe and efficient traffic movements. However, as Nuutinen et al. (2007) have noted, a definition of VTS and its services, as well as its increased role in maritime traffic management, will have to be combined with bottom-up activities that can help the system to adapt to local circumstances, e.g., lock systems, fairway design, or traffic density.

6.3 How can everyday operations of the VTS system be modelled?

While paper 1, paper 2 and paper 3 discussed the VTS system and its contribution to safe and efficient traffic movements in general, paper 4 presented results from modelling two VTS systems through the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012). The aim was to gain insights into how the VTS system serves to promote safe and fluent traffic movements during everyday operations. The results indicate that while the two VTS systems considered in the paper share a common purpose (shaping preconditions, creating predictions) and two foreground functions (provide information service, monitoring traffic), there are substantial differences in how the systems operate. Both VTS systems are well adapted to local circumstances, and one of the models demonstrated that hard constraints, e.g., tidal waters or a lock system, can be effectively used to provide increased predictability for possible changes in operational conditions. Instead of becoming a hindrance, natural constraints are used to justify the planning of traffic movements at a longer time scale to mitigate the risk of future congestion, close traffic encounters and generally dangerous situations to the greatest extent possible.

The modelling further revealed that the most important means of controlling the VTS systems' operations is the VTSO. In nearly all functions in the two FRAM models, the VTSO was identified as the control aspect responsible for supervising and adapting the systems' performance to the current situation. While this provides the system with substantial flexibility, i.e., humans can rapidly adapt their performance to changing conditions, it also drives the system further towards the boundaries of its performance envelope. The more functions a VTSO must supervise, the more the operator is forced to make trade-offs between efficiency and thoroughness, as resources such as time and manpower are limited. As discussed above, the VTS system primarily operates in an opportunistic control mode, meaning that if the system is driven towards efficiency, there is a risk of it degrading into a scrambled mode that can lead to multiple negative and unanticipated consequences, such as congestion, close encounter situations, and so forth.

Furthermore, the results of papers 3 and 4 highlight the importance of considering the complexity of everyday operations whenever new procedures or technologies are added. This is in accord with the findings of Johansson and Hollnagel (2007), who demonstrate that coordination in large-scale systems requires understanding what means are needed and when to best support operators in coordination tasks. Control in socio-technical systems is highly dependent on gaining insights into how to facilitate coordination and communication due to distributed nature of tasks in contemporary systems. The means and measures to best support the VTSOs can only be identified if one understands how the VTS and vessels coordinate activities in the Ship-VTS system.

The functional models of both VTS systems portrayed functional units and their relationships as currently designed. Thus, by identifying the relationships among several units, the analysis revealed potential ways in which performance variability might accumulate or be amplified resulting in functional resonance. In addition, the two models also revealed how the VTS systems adapted their functional units to manage performance variability during daily operations. One of the systems, for example, introduced the function “translate messages” to control variability in situations in which vessels regularly experienced communication problems.

Although well adapted to local constraints and common performance variations, both systems exhibited signs of operating at near capacity. This was particularly salient in the case of VTS 3, where the functional model illustrated how a small change in the pilotage procedure meant that there were four additional functions for the VTS system to perform and the VTSO to supervise. Additional functions, also mentioned by one of the informants, drive the system further towards the boundaries of its performance envelope (Dekker, 2011), into states in which control can be easily lost.

By understanding the complexity of everyday operations and how the VTS system adapts to changes in the environment, it is possible to identify challenges and opportunities that arise from the system’s design. In paper 4, the models of everyday operation proved to be a powerful tool to analyse dependencies among the functional units, how the units’ performance is affected by performance variability, and how the system, in turn, manages this variability.

6.4 VTS – a maritime information service or traffic control system?

The question posed in the heading of this section is also on the title of this thesis. Ultimately, as presently constituted, the VTS is on the verge of change and several simultaneous developments, such as e- Navigation (IMO, 2009), chain planning (Seignette, 2012), extended ship-shore route planning (Porathe, 2012; Porathe, de Vries, & Prison, 2013), and a drive for advances in the organisation and technology of the VTS system. Originally introduced as a RADAR chain system to assist in safe port entry during periods of poor visibility (IALA, 2012), the VTS system is now a complex socio-technical system that is realised in different ways around the world. Depending on local conditions, a VTS can offer services ranging from information services, containing important information for safe conduct, to complex traffic organisation systems, such as that demonstrated by VTS 3 in paper 4, in which traffic is planned and de-conflicted prior to its arrival in the area. Although certain VTS systems might appear similar to Air Traffic Control (ATC) systems, it must be acknowledged that the two systems are significantly different. The results of this thesis are in line those of prior studies (i.e. Anderson, 1991; National Research Council, 1994; van Erve & Bonnor, 2006; Österlund & Rosén, 2007) demonstrating that comparisons between the maritime and aviation domains are often not particularly fruitful because the two domains are organised in entirely different ways.

While ATC is a centralised control system responsible for the safe separation of aircraft and supported by a mandate to guide and provide clearances to traffic, the VTS is a distributed control system, in which the VTS is solely a support system for maritime traffic that lacks the means to guide traffic directly. Furthermore, as mentioned above, the VTS was designed as a support system for an existing structure, while ATC was implemented in conjunction with designing the overall air traffic structure. As a consequence, the preconditions to contribute to safe and efficient traffic movements in the two domains differ substantially.

With this in mind, attempts to adopt traffic management solutions from the aviation domain and directly implement them within the maritime domain amounts to implementing means and measures developed for an entirely different context. The papers included in this thesis revealed that everyday operations are a complex interplay between a VTS system and its environment. Therefore, adapting concepts from air traffic management may pose numerous undesirable and unanticipated consequences that cannot be predicted when measures and means are de-contextualised and transferred.

Furthermore, many suggestions currently being pursued concerning the future of the VTS and maritime traffic management in general advocate a more centralised system design in which traffic is planned using predicted traffic flows and de-conflicted over a longer time horizon through advanced technology (Porathe, 2012; Porathe et al., 2013). Many of these suggestions appear to ignore the fact that technical and/or organisational changes are typically accompanied by changes in how work is conducted, or as Wiener (1988) states, *"Progress imposes not only new possibilities for the future but new restrictions."*(p.46). While new technology and more centralised traffic management appear appealing, one should bear in mind that new demands will arise from these changes. Centralised systems, for example, are considered robust. However, while they typically feature a high degree of predictability, the ability of such systems to adapt to varying operational conditions is rather limited, and they are often somewhat brittle in the face of surprises or disturbances. As a consequence, adopting centralised control in maritime traffic management might improve the system's ability to plan and de-conflict vessel movements, but it will make the overall system more vulnerable to disturbances, as disrupting the traffic flow at one point is sufficient to affect the system's performance as a whole.

Thus, what can be said concerning future developments in the VTS domain? Should the VTS be reformed in pursuit of a more centralised control system, or should it remain an information service that is primarily concerned with supporting, but not organising, maritime traffic? The findings of this thesis have demonstrated that distributed traffic management, as currently implemented, has created a situation in which the VTS is the only means of ensuring the achievement of overall system goals (traffic safety and efficiency), while vessels within the VTS area remain free to prioritise individual goals. As a consequence of the contemporary system design, VTS systems are operating near their performance limits and offer a wide variety of different services, leading to ambiguity regarding what such a system can actually provide for vessel traffic (Praetorius, 2012).

In summary, work processes, components of work systems and procedures surrounding work are never value free, as they are interpreted and placed into context by the frontline operators. Changes to the system, whether technical or organisational, will always therefore be accompanied by changes in how work is conducted. It is only possible to predict the challenges and opportunities that the system will face when a change is introduced if the system and its daily operations are properly studied and modelled. The decision of whether to implement an information service or traffic control system should be made based on a thorough modelling of daily operations to ensure that current and possible future needs within a specific area are satisfied.

6.5 What are the wider implications for the maritime domain?

This thesis has focused on the VTS domain and the VTS system in particular. However, while the findings are rooted in this domain, broader implications can be drawn.

Although the IMO acknowledges the importance of integrating the human element into the design of maritime equipment and operations (IMO, 2003), a large body of research (e.g. Chauvin, 2011; Hetherington, Flin, & Mearns, 2006; Schröder-Hinrichs, Hollnagel, Baldauf, Hofmann, & Kataria, 2013; Schröder-Hinrichs, Hollnagel, & Baldauf, 2012) indicates that the maritime domain continues to reflect a perspective on safety associated with Safety-I (Hollnagel, 2014). Within Safety-I, efforts to increase the overall safety of the system emphasise eliminating the causes of vulnerabilities. This is perspective can be identified in the following principle stated in Resolution A.947 Human element vision, principles and goals for the Organization.

h) Consideration of human element matters should aim at decreasing the possibility of human and organizational error as far as possible. (IMO, 2003)

However, while Safety-I has been a fruitful approach during periods when systems where tractable and their components had limited interaction, contemporary systems are far too complex to identify and eliminate individual causes. A failure to acknowledge this implies a gap in the stakeholders' understanding of the system and of how it actually operates. Design is always based on assumptions, but as socio-technical systems develop in interaction with their environment, design assumptions must be checked and frequently evaluated. Eliminating the reasons for failure does not help to understand how systems adapt to continue operating in a changing environment. Therefore, the maritime domain and its legal stakeholders must shift their perspective to a more positive account of the human contribution to safe operations.

This thesis has identified one approach for achieving this. By shifting from identifying failures and instead emphasising what the system does to maintain control highlights the importance of the human operator in responding to, monitoring and anticipating change. The VTSOs make the VTS system effective, and they are the essential aspect of the system that provides the flexibility to adapt the performance of one or more functions to a specific condition.

Furthermore, as extensively discussed above, understanding daily operations is essential for anticipating the consequences of changes to a system's design, organisation or technology. Many researchers (e.g. Amalberti, 2001; Dekker, 2011; Vicente, 2006; Woods, Johannesen, Cook, & Sarter, 1994) have emphasised that understandings of contemporary socio-technical systems cannot be simply based on a structural account of the system and its components. While structural accounts can identify components, socio-technical systems are complex entities that change constantly in response to the demands of their environments. Acknowledging the maritime domain as a complex socio-technical system demands not only a focus on the human element but also the realisation that new ways to conceive of and work for safety are needed at all levels of the organisation. Both the results of this thesis and findings from research conducted in other areas of the maritime domain (Lützhöft, Sherwood Jones, Earthy, & Bergquist, 2006; Morel, Amalberti, & Chauvin, 2008) and other high risk systems, e.g., healthcare (Furniss, Back, & Blandford, 2011) and aviation (de Carvalho, 2011; Heese, Kallus, & Kolodej, 2013), demonstrate that resilience engineering has the potential to aid stakeholders, operators and researchers in understanding the positive contribution the human operator makes to successful operations.

6.5.1 Understanding everyday operations

As argued above, it is essential for the maritime domain to shift its perspective on safety towards Safety-II and efforts with the potential to understand, analyse and strengthen the role of the human operator in contemporary socio-technical systems. It is necessary to understand the interior operations of system (what it is) and its behaviour (what it does) to allow stakeholders to be certain that the maritime transport system will not further drift towards its safety limits. While there are currently many different developments (Porathe & Shaw, 2012) that address the future of maritime transportation and the human element in particular, it is important to acknowledge that these need to be based on a thorough understanding of the current system and the possible consequences of future changes. In doing so, it is insufficient to conduct quantitative risk assessments. The IMO generally suggests using a Formal Safety Assessment (Psaraftis, 2012), a quantitative method to assess the benefits of and need for risk-reducing measures, which can contribute to decisions concerning a general need, but is silent on the actual contribution to maritime safety make when a measure is implemented.

Furthermore, as the findings in this thesis reveal, FSA is often only used before a system is implemented. Once in place, the effect of safety measures are seldom evaluated over time, meaning that initial assumptions concerning the demands of the maritime transport system are neither changed, nor assessed with respect to whether they still correspond to the initial prediction.

This thesis presented a method that could be applied if stakeholders wish to increase the overall understanding of the daily operations, needs, demands, challenges and opportunities that operators face during their daily work. As demonstrated by paper 4, the FRAM can be used to analyse a system's capacity for resilience by understanding the potential for performance variability in the system's functional units and the potential for functional resonance based on the dependencies designed into the system. As the method models work-as-done, in comparison to work-as-imagined (Hollnagel, 2014b), it can assist stakeholders in understanding the complexity of work and the trade-offs, e.g., efficiency-thoroughness, safety-efficiency, individual goals-system goals, that frontline operators must address to ensure that the system remains within its performance margins. Based on the increased understanding, improved procedures, guidelines and training on how to increase a system's capacity for resilience could be developed. Furthermore, as models reflect work as actually conducted, they can also serve as mediating tools between the blunt and sharp ends of the system, as operators are able to demonstrate activities that might otherwise go unnoticed by management.

6.6 Methodological considerations

This thesis studied the VTS system and its contributions to maritime traffic management using a naturalistic study, or inquiry. Naturalistic inquiry is a qualitative approach in which the researcher attempts to minimise the manipulation of the settings within which the research is performed (Patton, 2002). In general, naturalistic inquiries are non-manipulative, non-controlling, and conducted in real-life settings (Patton, 2002). As one of the objectives of this thesis has been to increase the overall understanding of everyday performance within the VTS domain, the VTS system was studied in its natural settings. While VTS-related research in controlled environments, such as in E. Wiersma and Mastenbroek (1998) and in Brodje, Lundh, Jenvald, and Dahlman (2013), has proven useful in increasing understandings of an individual operator's performance, it is not suitable for studying how VTS systems cope with complexity and maintain their functions in the dynamic conditions that constitute everyday operations. Thus, this thesis analysed the VTS through interviews, observations and functional modelling to understand the complexity of work conducted at VTS centres under various operating conditions.

6.6.1 Data collection

The research presented in this thesis was primarily guided by opportunistic sampling (Patton, 2002). Opportunistic sampling emphasises that qualitative studies can only be partially planned. As a phenomenon is studied in context, it might require the researcher to adapt the study design (i.e., the number of interviews, focus of observation). For the research presented in this thesis, opportunistic sampling provided a means of exploring the VTS from various perspectives. Study visits were conducted to gain a basic understanding, which were then followed by interviews, observations and focus groups with VTS personnel in various positions. The data collection was discovery-oriented, non-controlling and non-manipulative (Patton, 2002), in an attempt to exploit several data collection methods to achieve triangulation.

Triangulation denotes studying a phenomenon from different angles. Studying a phenomenon using a method reveals certain aspects of the phenomenon but leaves others unobserved, thus only providing partial information on the subject. To achieve triangulation, multiple methodological tools can be combined to complement one another (Fishman, 1999). In studies in naturalistic settings, such as the research presented in the thesis, interviews and observations are often used as mutually reinforcing techniques to obtain a deeper understanding of the phenomenon under investigation. In the area of qualitative research, triangulation is employed to provide a higher degree of credibility (Stenbacka, 2001).

This notion of credibility (Fishman, 1999) describes the degree to which the results are credible from the respondents' perspective. In the research presented in this thesis, various data collection methods, as well as research auditors, have been used to increase credibility. The participants in the various studies constituted the research auditors. These auditors were frequently consulted during the analysis to allow the respondents to comment on and examine the findings.

6.6.2 Data analysis

The data analysis was conducted through the application of two techniques: grounded theory (Corbin & Strauss, 2008) and the FRAM (Hollnagel, 2012). Grounded theory was used to categorise and systematically organise the data collected from the interviews and observations. The aim was to identify core concepts in how the VTS contributes to maritime traffic management based on the collected field data. The findings of this first analysis were also used to inform the FRAM modelling.

The grounded theory analysis rendered general VTS functions (i.e., create foresight, shape preconditions) more salient, but it could not provide detailed information on how these are achieved. Furthermore, as is often criticised (e.g. Thomas & James, 2006), while useful for categorising larger data sets, the analysis itself primarily highlighted apparent and observable behaviour, presumably leaving numerous aspects of the how the system constantly adapts to the changing environment undiscovered. However, the relationships identified and the concepts developed through the grounded theory analysis proved to be crucial to the communication between researchers and participants throughout the modelling activity. The findings were visualised and used as input to extract detailed data on everyday work, as the FRAM requires extensive data on the preconditions, controls, resources, inputs, outputs and time aspects of each function of the socio-technical system under study.

Modelling everyday operations with FRAM was also been essential to understanding how the VTS system adapts its functioning to cope with the demands and constraints at hand. It provided deep insight into the functional design of two VTS systems, and the findings can inform future VTS system design with respect to resilience. However, the FRAM requires extensive cooperation with domain experts to depict work-as-done (Hollnagel, 2014), as well as to obtain knowledge on external, internal, and coupling variability, and how functional resonance can accumulate.

6.7 Future Research

This thesis presented a new perspective on socio-technical systems under change and demonstrated how resilience engineering, control and functional modelling can provide insights into how a socio-technical system maintains its required operations under a variety of conditions.

However, the findings presented in this thesis only present the beginning of the exploration of resilience engineering and functional modelling as approaches to understanding the complexity of everyday operations within the maritime domain. Thus far, the focus of study has exclusively been on the VTS and the system's contribution to fluent and safe traffic movements. It would be interesting to expand the model and incorporate the functional units of the individual vessels within a VTS area. Once identified, a model incorporating VTS and vessel functions could be used as a basis for understanding the consequences of changes in both shore services and vessels within the maritime domain.

Furthermore, if used by stakeholders or management, a functional account of everyday operation can help the sharp end of a system to express and explain how blunt-end decisions affect the variability that the human operators need to manage and monitor in the context of their daily work. Using models, such as those presented in paper 4, has the potential to increase stakeholder awareness of double binds that result from the system's design.

7 Conclusions

7.1 Findings

- VTS is a socio-technical system to control and manage maritime traffic in port approaches and other areas that pose navigational difficulties to bridge teams in national waters to increase the safety and efficiency of seaborne traffic.

- To re-design the VTS into a system that can cope with a wide variety of operation conditions, everyday performance must be understood to allow the researcher or practitioner to identify ways to monitor and manage the system's variability in the future.

- Performance variability makes a system adaptive and resilient and is therefore essential to the system's functioning. FRAM is a method that allows the researcher to capture performance variability in everyday operations. With the aid of FRAM, a new facet of the VTS system can be explored, which can help to understand how the system will affected by variability in certain functions and how this affects the system's ability to maintain control.

- VTS is realised in vastly different ways across countries. Control modes and functional modelling can help to make the differences in realisation salient and offer an approach to understand how VTS systems cope with the complexity of everyday operations. This in turn can help to identify opportunities and challenges in current and future operations.

7.2 Recommendations to the stakeholders

- New methods that can account for how variability can be monitored and managed within everyday operations need to be employed to evaluate current and future system design. While traditional risk assessment will help to identify certain risks, it cannot provide information of possible consequences to a system's ability to operate safely and in a resilient manner.

- Before re-modelling the VTS or augmenting the existent system, thorough analyses of the VTS system beyond what is presented here should be conducted to make an inventory of what types of services are currently offered under the umbrella of the VTS.

- To create a traffic management system, it is not sufficient to copy the aviation domain, as ATC and VTS are two different systems that need to respond to different demands in different environments. Solely copying external developments increases the risk of unforeseen and possibly catastrophic consequences.

- Technology should never be at the centre of changes in socio-technical systems, as technology per se will not be sufficient to promote safe and efficient traffic movements.

References

Ackoff, R.L. (1971). Towards a System of Systems Concepts. *Management Science, 17*(11).

Allen, C. H. (2009). Hiding Behind "Tradition"? - Should U.S. Vessel Traffic Centers Exercise Greater Direction and Control over Vessels in Their Areas. *Tulane Maritime Law Journal, 34*(1), 1-61.

Amalberti, R. (2001). The paradoxes of almost totally safe transportation systems. *Safety Science, 37*, 109-126.

Anderson, D.H. (1991). Review of David Freestone, and Tone Distra 'The North Sea: Perspectives on Regional Environmental Cooperation'. *International and Comparative Law Quarterly*(40), pp 742-743

Australian Maritime Safety Authority. (2010). Improving safe navigation in the great barrier reef.

Back, J., Furniss, D., Hildebrandt, M., & Blandford, A. (2008). Resilience markers for safer systems and organisations *Computer Safety, Reliability, and Security* (pp. 99-112).

Brodje, A., Lundh, M., Jenvald, J., & Dahlman, J. (2013). Exploring non-technical miscommunication in vessel traffic service operation. *Cognition, Technology & Work, 15*(3), 347-357. doi: 10.1007/s10111-012-0236-5

Brodje, A., Lützhöft, M., & Dahlman, J. (2010). *The whats, whens, whys and hows of VTS operator use of sensor information*. Paper presented at the International Conference on Human Performance at Sea, HPAS 2010, Glasgow.

Bruno, K, & Lützhöft, M. (2010). Virtually Being There: Human Aspects of Shore-based Ship Assistance. *WMU Journal of Maritime Affairs, 9*(1), 81-92.

Bryman, A. (2002). *Samhällsvetenskapliga metoder*.

Chang, S. J. (2004). *Development and Analysis of AIS Applications as an Efficient Tool for Vessel Traffic Service*. Paper presented at the OCEANS '04.

Chauvin, C. (2011). Human Factors and Maritime Safety. *The Journal of Navigation* (64), 625-632.

Corbin, J., & Strauss, A. (2008). *Basics of qualitative research 3e* (3rd edition ed.). London: Sage Publication, inc.

de Carvalho, P. V. R. (2011). The use of Functional Resonance Analysis Method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience. *Reliability Engineering & System Safety, 96*(11), 1482-1498. doi: http://dx.doi.org/10.1016/j.ress.2011.05.009

Dekker, S. (2004). Why we need new accident models. *Journal of Human Factors and Aerospace Safety, 2*.

Dekker, S. (2011). *Drift into Failure. From Hunting Broken Components to Complex Systems*. Surrey: Ashgate Publishing Limited.

Fishman, D. B. (1999). *The Case for Pragmatic Psychology*. New York: New York University Press.

Flach, J. M. (2012). Complexity: learning to muddle through. *Cognition, Technology & Work, 14*(3), 187-197. doi: 10.1007/s10111-011-0201-8

Froholdt, L.L. (2012). Getting closer to context: a case study of communication between ship and shore in an emergency situation. *Text & Talk - An Interdisciplinary Journal of Language, Discourse & Communication Studies, 30*(4), 385–402.

Furniss, D., Back, J., & Blandford, A. (2011). *Unwritten Rules For Safety And Performance In An Oncology Day Care Unit: Testing The Resilience Markers Framework*. Paper presented at the Resilience Engineering IV, Sophia Antipolis, France.

Gardebring, T. (2011). Passagen som aldrig sover. Ständig kontroll, *Sjörapporten*, pp. 10-11.

Gibson, James Jerome, & Crooks, L E. (1938). A Theoretical Field-Analysis of Automobile Driving. *American Journal of Psychology, LI*, 453-471.

VERBI Software Consult Sozialforschung GmbH (2013). MAXQDA. The Art of Data Analysis.

Grech, M., Horberry, T., & Koester, T. (2008). *Human Factors in the Maritime Domain*. Boca Raton: CRC Press

Hadley, M. (1999). Issues in Remote Pilotage. *The Journal of Navigation 52*(1), 1-10.

Hall, A.D., & Fagan, R.E. (1968). Definition of System. In W. F. Buckley (Ed.), *Modern systems research for the behavioral scientist: a sourcebook* (pp. 81-99). Chicago, IL: Aldine Pub. Co.

Heese, M., Kallus, W., & Kolodej, C. (2013, 25 – 27 June 2013). *Assessing Behaviour towards Organizational Resilience in Aviation.* Paper presented at the 5th Resilience Engineering International Symposium, Soesterberg, The Netherlands.
Herrera, I.A., & Woltjer, R. (2010). Comparing a multi-linear (STEP) and systemic (FRAM) method for accident investigation. *Reliability Engineering and System Safety (RESS), 95*(12), 1269-1275.
Hetherington, C., Flin, R., & Mearns, K. (2006). Safety in shipping: The human element. *Journal of Safety Research, 37*(4), 401-411.
Holling, C.S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics 1973, 4*, 1-23.
Hollnagel, E. (2004). *Barriers and Accident Prevention*. Aldershot, UK: Ashgate.
Hollnagel, E. (2009). *The ETTO Principle: Efficiency-Thoroughness Trade-Off. Why Things That Go Right Sometimes Go Wrong*. Burlington: Ashgate Publishing Company.
Hollnagel, E. (2011a). Prologue: The Scope of Resilience Engineering. In E. Hollnagel, J. Pariès, D. Woods & J. Wreathall (Eds.), *Resilience Engineering in Practice. A Guidebook*. Farnham, Surrey, UK.: Ashgate Publishing.
Hollnagel, E. (2011b). The Resilience Analysis Grid In E. Hollnagel, J. Pariès, D. Woods & J. Wreathall (Eds.), *Resilience Engineering in Practice. A Guidebook*. Farnham, Surrey, UK: Ashgate Publishing.
Hollnagel, E. (2012). *FRAM: The Functional Resonance Analysis Method - Modelling Complex Socio-Technical Systems*: Ashgate Publishing Company.
Hollnagel, E. (2014a). The Four Basic Principles of the FRAM. Retrieved 20140312, from http://functionalresonance.com/basic-principles.html
Hollnagel, E. (2014b). *Safety-I and Safety-II: The Past and Future of Safety Management*: Ashgate Publishing, Limited.
Hollnagel, E., & Woods, D. (2005). *Joint Cognitive Systems: An Introduction to Cognitive Systems Engineering*. London: CRC Press.
Hollnagel, E., & Woods, D. D. (2005). *Joint Cognitive Systems. Foundations of Cognitive Systems Engineering*. Boca Raton, FL: CRC Press.
Hollnagel, E., Woods, D.D., & Leveson, N. (2006). *Resilience Engineering: Concepts And Precepts*: Ashgate.
Høye, G. K., Eriksen, T., Meland, B. J., & Narheim, B. T. (2008). Space-based AIS for global maritime traffic monitoring *Acta Astronautica, 62*, 240-245.
IALA. (1998). IALA Recommendation V-103 on Standards for Training and Certification of VTS Personnel *IALA Recommendation V-103*: International Association of Marine Aids to Navigation and Lighthouse Authorities.
IALA. (2012a). *IALA Vessel Traffic Manual 2012* (5 ed.): International Association of Marine Aids to Navigation and Lighthouse Authorities.
IALA. (2012b). What is IALA. Retrieved 20140727, from http://www.iala-aism.org/iala/aboutiala/about.php
IMO. (1996). STCW 95. London: International Maritime Organization.
IMO. (1997). Guidelines for Vessel Traffic Services. *Resolution A.857 (20)* International Maritime Organization.
SOLAS Regulation V/11 Ship reporting systems (2002a).
SOLAS Regulation V/12 Vessel traffic services (2002b).
IMO. (2003). Resolution A.947(23) Human Element Vision, Principles and Goals for the Organization. In I. M. Organisation (Ed.).
IMO. (2009). Strategy for the development and implementation of e-Navigation *Report of the Maritime Safety Committee on its eighty-fifth session* (Vol. MSC 85/26/add.1).
IMO. (2013). IMO What it is. Retrieved 20140727 from http://www.imo.org/About/Documents/What%20it%20is%20Oct%202013_Web.pdf
Johansson, B., & Hollnagel, E.. (2007). Pre-requisites for large scale coordination. *Cognition, Technology & Work, 9*(1), 5-13. doi: 10.1007/s10111-006-0050-z
Kao, S.-L., Lee, K.-T., Chang, K.-Y., & Ko, M.-D. (2007). A Fuzzy Logic Method for Collision Avoidance in Vessel Traffic Service. *The Journal of Navigation* (60), 17-31.

Kataria, A. (2011). *Maritime English and the VTS.* Paper presented at the International Maritime English Conference, Constanta, Romania.

Kuniavsky, M. (2003). *Observing the user experience. A practitioner's guide to user research*. San Francisco: Elsevier Science.

Leveson, N., Dulac, N., Marais, K., & Carroll, J. (2009). Moving Beyond Normal Accidents and High Reliability Organizations: A Systems Approach to Safety in Complex Systems. *Organization Studies, 30*(02 & 03), 227-249.

Lützhöft, M, Sherwood Jones, B, Earthy, J.V, & Bergquist, C. (2006). Making Safety by Tying the Knot: Examining Resilience in Shipping. Proceedings of The 2nd Symposium on Resilience Engineering. Juan-les-Pins, France, November 8-10.

Lützhöft, M., & Bruno, K. (2009). *Talk and trust before technology: First steps toward shore-based pilotage.* Paper presented at the RINA Human Factors in Ship Design and Operation Conference, 25-26 February 2009, London, U.K.

Lützhöft, M., Grech, M., & Porathe, T. (2011). Information Environment, Fatigue, and Culture in the Maritime Domain *Reviews of Human Factors and Ergonomics* (Vol. 7, pp. 280-322): Human Factors and Ergonomics Society.

Macchi, L., Hollnagel, E. , & Leonhardt, J. (2009). A White Paper on Resilience Engineering, Retrieved 20140727 from http://www.eurocontrol.int/sites/default/files/article/content/documents/nm/safety/safety-a-white-paper-resilience-engineering-for-atm.pdf

Militello, L. G., Dominguez, C. O., Lintern, G., & Klein , G. (2010). The role of cognitive systems engineering in the systems engineering design process. *Systems Engineering, 13*(3), 261-273.

Mitchell, M. (2009). *Complexity: A guided tour*: Oxford University Press.

Morel, G., Amalberti, R., & Chauvin, C. (2008). Articulating the Differences Between Safety and Resilience: The Decision-Making Process of Professional Sea-Fishing Skippers. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 50*(1), 1-16. doi: 10.1518/001872008x250683

Mukherjee, P.K. (2013). Impact of the MonaLisa project on the international legal framework for navigation at sea: Swedish Maritime Administration.

National Research Council. (1994). *Minding the Helm: Marine Navigation and Piloting*. Washington, DC: National Academy Press.

Nuutinen, M. (2005). Contextual assessment of working practices in changing work. *International Journal of Industrial Ergonomics, 35*, 905-930.

Nuutinen, M., Savioja, P., & Sonninen, S. (2007). Challenges of developing the complex socio-technical system: Realising the present, acknowledging the past, and envisaging the future of vessel traffic services. *Applied Ergonomics, 28*, 513-524. doi: http://dx.doi.org/10.1016/j.apergo.2006.10.004

Patton, M.Q. (2002). *Qualitative research & evaluation methods*: Sage Publication.

Perrow, C. (1999). *Normal Accidents. Living with High-Risk Technologies* Princeton, New Jersey: Princeton University Press.

Porathe, T. (2012). Transmitting intended and suggested routes in ship operations: cognitive off-loading by placing knowledge in the world. *Work, 41*, 4873-4878.

Porathe, T., de Vries, L., & Prison, J. (2013). *Ship voyage plan coordination in the MONALISA project: user tests of a prototype ship traffic management system.* Paper presented at the Human Factors and Ergonomics Society Europe Chapter 2013 Annual Conference, Torino.

Porathe, T., & Shaw, G. (2012). *Working with the human element: Human Factors and technical innovation from EfficienSea*. Paper presented at the International Symposium. Information on Ships, ISIS 2012.

Praetorius, G. (2012). *Safety within the Vessel Traffic Service (VTS) Domain. Understanding the role of the VTS for safety within maritime traffic management.* (Licentiate of Philosophy Licentiate thesis), Chalmers University of Technology, Reproservice.

Praetorius, G., Bruno, K., & Lützhöft, M. (2010). *Enacting Reliability: First Steps To Define Safety in the VTS Domain*. Paper presented at the International Conference on Human Performance at Sea, HPAS 2010, Glasgow.

Praetorius, G., & Lützhöft, M. (2012). Decision Support for Vessel Traffic Service (VTS): User needs for dynamic risk management in the VTS Domain. *Work: A Journal of Prevention, Assessment and Rehabilitation, 41*(Supplement 1/ 2012), 4866-4872.

Psaraftis, H. N. (2012). Formal Safety Assessment: an updated review. *Journal of Marine Science and Technology, 17*(3), 390-402. doi: http://dx.doi.org/10.1007/s00773-012-0175-0

Repstad, P. (1999). *Närhet och distans. Kvalitativa metoder i samhällsvetenskap*. Lund: Studentlitteratur.

Ropohl, G. (1999). Philosophy of Socio-Technical Systems. *Research in Philosophy and Technology, 4*(3), 186-194. doi: DOI: 10.5840/techne19994311

Schröder-Hinrichs, J., Hollnagel, E., & Baldauf, M. (2012). From Titanic to Costa Concordia—a century of lessons not learned. *WMU Journal of Maritime Affairs, 11*(2), 151-167. doi: 10.1007/s13437-012-0032-3

Schröder-Hinrichs, J., Hollnagel, E., Baldauf, M., Hofmann, S., & Kataria, A. (2013). Maritime human factors and IMO policy. *Maritime Policy & Management, 40*(3), 243-260. doi: 10.1080/03088839.2013.782974

Seignette, R. (2012). Vessel traffic management in the Port of Rotterdam. *Port Technology International*, 105- 107.

SHK. (2010). Grundstötning av fartyget Stena Danica efter närsituation med Tor Magnolia vid Gäveskär, O län, den 10 januari 2008, Dnr S-13/08.

Sjöfartsverket. (2013). Vad gör Sjöfartsverket? Retrieved 20140220, from http://www.sjofartsverket.se/sv/Om-oss/Vad-gor-Sjofartsverket

Skyttner, L. (2005). *General Systems Theory: Problems, Perspectives, Practice* (2nd edition ed.). Hackensack, NJ: World Scientific Publishing Co. Pre. Ltd.

Stenbacka, C. (2001). Qualitative research requires quality concepts of its own. *Management Decision, 39*(7), 551-555.

Stopford, M. (2009). *Maritime Economics*. New York: Routledge.

Thomas, G., & James, D.. (2006). Reinventing grounded theory: some questions about theory, ground and discovery. *British Educational Research Journal, 32*(6), 767-795. doi: 10.1080/01411920600989412

Transportstyrelsens föreskrifter och allmänna råd om sjötrafikinformationstjänst (VTS) och sjötrafikrapporteringssystem (SRS), TSFS 2009:56 C.F.R. (2009).

UNCTAD. (2013). Review of Maritime Transport 2013. In United Nations Conference on Trade and Development (UNCTAD) (Ed.), *Review of Maritime Transport*. New York and Genua: United Nations.

UN General Assembly, Convention on the Law of the Sea (UNCLOS), 10 December 1982.

von Bertalanffy, L. (1950). The theory of open systems in physics and biology. Science, 111(2872), 23-29.

van Dam, S., Mulder, M., & Van Paassen, M.M. (2006). *Ecological interface design for vessel traffic management: A theoretical overview*. Paper presented at the 11th IFAC Symposium on Control in Transportation Systems (2006).

van Erve, P., & Bonnor, N. (2006). Can the Shipping-Aviation Analogy be used as an Argument to decrease the need for Maritime Pilotage? *Journal of Navigation, 52*(2), 359-363.

van Westrenen, F.C., & Praetorius, G. (2012). Maritime traffic management: a need for central coordination? *Cognition, Technology & Work*. doi: 10.1007/s10111-012-0244-5

Wawruch, R. (2004). *Quality of information about tracked vessel in VTS centre*. Paper presented at the 461h International Symposium Electronics in Marine, ELMAR-2004., Zadar. Croatia.

Weick, K. E., & Sutcliffe, K. M. (2007). *Managing the Unexpected: Resilient Performance in an Age of Uncertainty*. San Francisco: Jossey-Bass.

Vespe, M., Sciotti, M., Burro, F., Battistello, G., & Sorge, S. (2008). *Decision Support Platforms for Satellite-Extended Vessel Traffic Services*. Paper presented at the RADAR.

Westerlund, K. (2011). The Risk Reducing Effect of VTS in Finnish Waters. Finnish Transport Agency

Vicente, K.J. (1999). *Cognitive Work Analysis.Toward Safe, Productive, and Healthy Computer-Based Work*. Mahwah, NJ: Lawrence Erlbaum Associates Inc.

Vicente, K.J. (2006). *The Human Factor*. New York: Taylor & Francis Group.

Wiener, N. (1965). *Cybernetics Or Control and Communication in the Animal and the Machine* (2nd edition ed.). Cambridge: MIT Press.

Wiener, N. (1988). *The Human Use of Human Beings: Cybernetics and Society*: Da Capo Press, Incorporated.

Wiersma, E., Jarvis, D., & Granholm, G. (2000). *VTS Operator performance and acceptance of a short-term path prediction display in a low density traffic area.* Paper presented at the IEA/HFES 2000 Congress.

Wiersma, J.W.F. , & Mastenbroek, N. (1998). Measurement of Vessel Traffic Service Operator Performance. *AI & Society, 12*, 78-86.

Wiersma, J.W.F. (2010). *Assessing Vessel Traffic Service Operator Situation Awareness.* (PhD), Technische Universiteit Delft, Delft. (978-90-8891-148-4)

Woods, D.D. (2006). Essential Characteristics fo Resilience. In E. Hollnagel, D. Woods & N. Leveson (Eds.), *Resilience Engineering: Precepts And Concepts* (pp. 21-34). Abingdon: Ashgate Publishing Group.

Woods, D.D., & Hollnagel, E. (2006). *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: CRC Press / Taylor & Francis.

Woods, D.D., Johannesen, L.J., Cook, R.I., & Sarter, N.B. (1994). *Behind Human Error: Cognitive Systems, Computers, and Hindsight*. CSERIAC SOAR 94-01. Ohio, USA: Wright-Patterson Air Force Base.

Österlund, A., & Rosén, C-G. (2007). Jämförande studie av luftfart och sjöfart. In Statens Offentliga Utredningar, *SOU 2007:106*.