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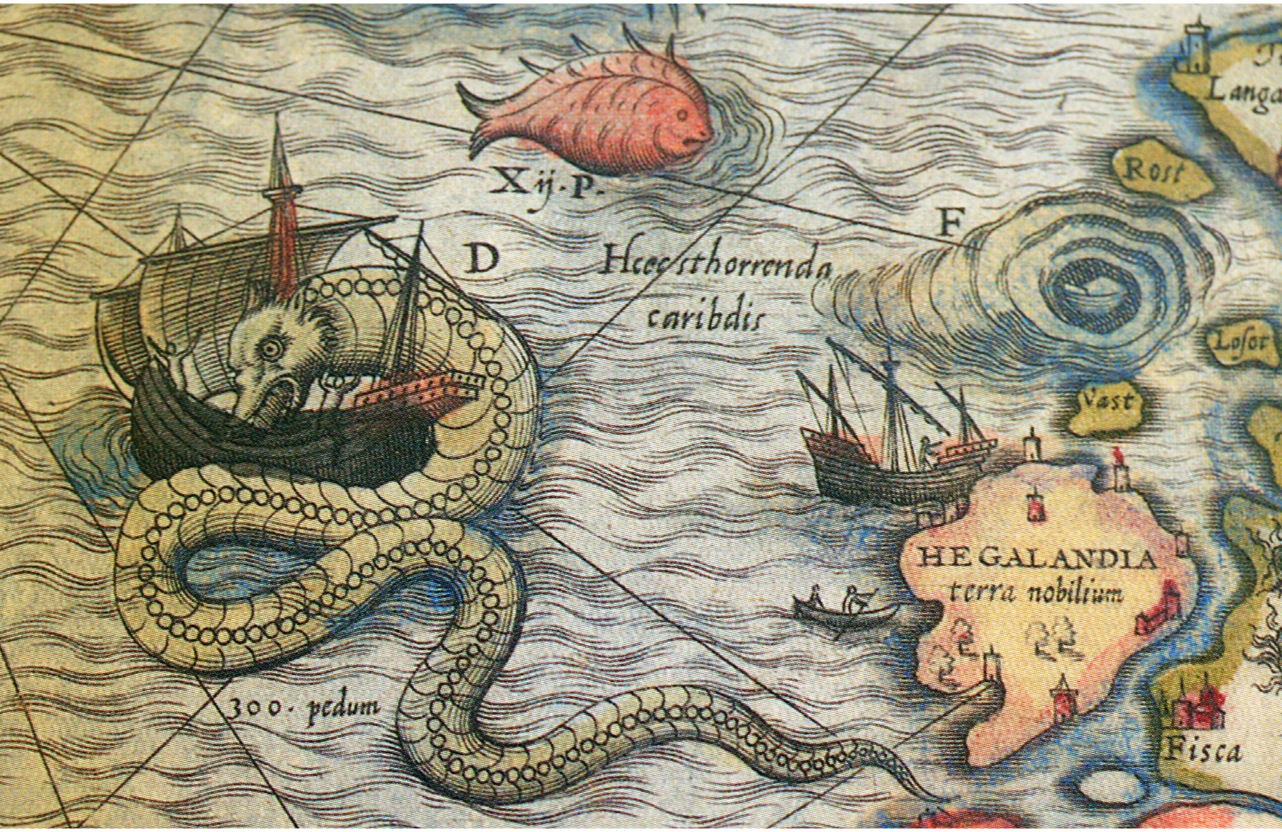

Here be monsters

Investigating sociotechnical interaction in safety-critical work in the maritime domain

LINDA DE VRIES

Department of Shipping and Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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Detail from *Carta marina, opus Olai Magni Gotti Lincopensis, ex typis Antonii Lafreri Sequani*, Rome, 1572, coloured copperplate, National Library of Sweden, KoB, Kartor, 1 ab

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ABSTRACT

Maritime Pilots and Vessel Traffic Services (VTS) operators work to improve the safety of navigation of seagoing vessels. As in many other safety-critical domains, work is increasingly characterised by the integration and dissemination of information between humans and technology, across disciplines and over multiple geographical locations. Technological advancements such as e-navigation facilitate increased monitoring and control from shore and create new possibilities to provide additional assistance on board vessels. E-navigation has thus a direct impact on navigational assistance as performed by pilots and VTS operators.

This thesis views navigational assistance as a case of sociotechnical work in a safety-critical domain. It attempts to understand how work is performed and how it contributes to maritime safety by starting from empirical observation and a Resilience Engineering focus on everyday operations. Interviews, focus groups and field observations on board vessels and in VTS centres were conducted and analysed using an iterative approach, inspired by the principles of grounded theory and the Functional Resonance Analysis Method (FRAM) and informed by the traditions of Workplace Studies, Science and Technology Studies and Activity Theory. A generic FRAM model of navigational assistance was developed to describe the practice of everyday work and how the conditions which affect its performance may vary. A scenario and case study were also analysed and modelled to illustrate how safety may manifest itself in typical and actual events.

Successful assistance was found to be dependent on: (i) the use of local knowledge, preparation and foresight to integrate information from a wide range of sources, and; (ii) communication and trust between the pilot, VTS operator, and the master and crew of the vessel, to provide timely assistance to vessels. FRAM was found to be a valuable tool for describing sociotechnical work, but was enriched by borrowing from the work studies traditions, with their strong grounding in empirical observations and themes of 'making work visible', symmetry between human/non-human, and work as activity. This approach indicated that bringing ideas from different traditions together to understand a real work practice may bring us closer to describing 'work as done', and its contribution to safe everyday operations.

This thesis concludes that safety is an emergent property of sociotechnical work, which manifests itself through the interaction between humans and other actors in the context in which work is performed. The configuration of a sociotechnical system is not necessarily pre-defined, but is dependent on the human, technological, organisational and natural factors which affect the performance of work. It is inherently uncertain, variable and must adapt to circumstances. In order to inform the design of new systems or evaluate the impact of new technologies, one should therefore take account of the factors which affect how work is normally performed, and also how it is actually performed in specific circumstances to enable safe operations.

Keywords: sociotechnical systems, safety, Resilience Engineering, Human Factors, Functional Resonance Analysis Method (FRAM), e-navigation, pilotage, Vessel Traffic Services (VTS)

ACKNOWLEDGEMENTS

2016 will be remembered for many things which should never have been allowed to happen, on both sides of the Atlantic. In such crazy times, the help we receive from those around us has even greater significance.

My heartfelt thanks therefore to everyone who has participated in, reviewed, funded, published, supported and otherwise encouraged my research, in particular to Lennart for creating a little order in chaos, to Barbara, Gesa, Lars-Ola and Torgeir for inspiring and challenging me, to Erik and Hannele for surprises, and to Per for keeping me sane.

'We are *all* monsters, outrageous and heterogeneous collages.'

- John Law (1990:18)

LIST OF PUBLICATIONS

Paper I - Success factors for navigational assistance: a complementary ship-shore perspective.

de Vries, L. (2015). Success factors for navigational assistance: a complementary ship-shore perspective. In D. de Waard, J. Sauer, S. Röttger, A. Kluge, D. Manzey, C. Weikert, A. Toffetti, R. Wiczorek, K. Brookhuis & H. Hoonhout (Eds.) *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2014 Annual Conference.*

Paper II - Work as done? Understanding the practice of sociotechnical work in the maritime domain.

de Vries, L. (2016, forthcoming). Work as done? Understanding the practice of sociotechnical work in the maritime domain. *Submitted for international publication.*

Paper III - The role of navigational assistance in managing uncertainty and improving safety at sea.

de Vries, L. (2016). The role of navigational assistance in managing uncertainty and improving safety at sea. In *Proceedings of the Royal Institution of Naval Architects (RINA) Human Factors in Ship Design and Operation Conference 2016.* 28-29 September 2016, London, UK.

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1.1 Maritime safety and the impact of e-navigation

Ensuring the 'safety and security of shipping and the prevention of marine pollution' (IMO, 2016a) is the main purpose of the International Maritime Organisation (IMO), the maritime domain's principal regulatory authority. Likewise classification societies (such as American Bureau of Shipping (ABS); Lloyd's Register; DNV GL), international non-governmental organisations which provide guidelines and standards on the design, construction and operation of vessels, all list safety as their highest priority. The maritime domain comprises a diverse set of industries (UNCTAD, 2014), including the transportation of goods and people, exploration and exploitation of natural resources, fisheries and aquaculture, leisure and tourism. In each of these sectors, international rules, regulations and guidelines translate into national, local and company-level rules, policies, training and certification, safety management systems, procedures, checklists ad infinitum, all with the aim of ensuring that maritime operations are carried out safely.

Nevertheless, certain areas are considered particularly hazardous, typically due to complicated geographical location, weather patterns or traffic density. Traditionally, areas containing both known and unknown dangers would be illustrated on sea charts with monsters, sea serpents and giant fish (see cover illustration), while land maps tended to show dragons (Elahi, 2011; Woods, 2016) or originally lions. Today, we have dispensed with monsters and dragons, although in some areas additional services are deemed necessary in order to help vessels navigate safely. These services - for which I will use the collective term *'navigational assistance'* - may be provided by either on board vessels or from shore by maritime pilots and Vessel Traffic Services (VTS) operators.

As with other safety-critical domains, such as aviation, nuclear, healthcare and offshore, new technologies are introduced into work systems with the aim of improving safety and efficiency of operations. One such ongoing development is *'e-navigation'* (IMO, 2008; 2014), which 'enables the transfer of data between and among ships and shore facilities, and that integrates and transforms that data into decision and action information' (US CMTS, 2012:4). E-navigation's two primary objectives (IMO, 2008:3) are to facilitate (1) 'safe and secure navigation of vessels having regard to hydrographic, meteorological and navigational information and risks' and (2) 'vessel traffic observation and management from shore/coastal facilities, where appropriate'. The IMO aims to 'facilitate a holistic approach to the interaction between shipboard and shore-based users, under an overarching e-navigation architecture' by 2019 (IMO, 2014:113)[1].

In other words, e-navigation has a direct impact upon the work of pilots and VTS operators, and will inevitably change how navigation and navigational assistance are performed. However, as Suchman (1995:58) states, 'the better work is done, the less visible it is to those who benefit from it.' In order to evaluate the impact of e-navigation, we must first understand the work of pilots and VTS operators, and their contribution to maritime safety.

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[1] The field studies described in this thesis were funded by one such e-navigation infrastructure project, the EU TEN-T project MonaLisa2.0.

1.2 Research questions

This thesis views navigational assistance as a case of sociotechnical work in a safety-critical domain. It aims to describe how the work of pilots and VTS operators is performed and how it contributes to safe maritime operations, and seeks to answer the following research questions:

1. How can safety be understood in the context of sociotechnical work?

2. How can studying work as a sociotechnical system assist in understanding the conditions which enable safe operations and how they vary?

3. How can knowledge of the practice of work be harnessed in order to inform the design of future work systems and provide a context for evaluating the impact of new technologies?

1.3 Appended papers

The content of this thesis is based upon three research papers which describe part of a larger body of work on navigational assistance, e-navigation and marine design. All papers attempt in part to answer the research questions, and should be seen as flowing more or less seamlessly into each other. The material presented in this thesis is a synthesis of the three papers.

- **Paper I** describes some initial qualitative studies and the beginnings of an empirical theory concerning the practice of navigational assistance from the on board and shore-side perspective.

- **Paper II** describes the practice of navigational assistance by complementing with further studies and continuing to develop the empirical theory. It also investigates the use of the Functional Resonance Analysis Method (FRAM) to develop a generic model of navigational assistance, and discusses a typical work scenario.

- **Paper III** considers how navigational assistance is performed in a specific situation by applying the FRAM model to a case of everyday work.

1.4 Structure of the thesis

The regulations, guidelines and scientific literature on navigational assistance will be introduced (Chapter 2) before establishing a theoretical and methodological framework with which to investigate the topic (Chapter 3). The research approach used here combines various themes associated with different theoretical perspectives or traditions; these will be introduced in Chapter 3. The methods used for data collection and analysis will then be described (Chapter 4), and the results summarised (Chapter 5). The reader is encouraged to read the attached papers (especially Papers II and III) in full, as these contain a richer description of navigational assistance than may be found in the results summary. The Discussion (Chapter 6) aims to show how the study of navigational assistance using the research approach introduced in Chapters 3 and 4 enables us to answer the research questions, and to contribute to the understanding of sociotechnical work and safety, and its application to design. Some short conclusions are presented in Chapter 7.

2 Introducing navigational assistance

2.1 Navigational assistance in regulations…

Navigational assistance encompasses several forms of service which aim to assist the ship's captain, known as the 'master', with the safe navigation of their vessel in areas where this is deemed necessary.

Pilotage has a long and well-established history, stretching back at least 4,000 years (IMPA, 2014), being first mentioned in the Babylonian Code of Hammurabi. It can be defined as 'to guide vessels into or out of port safely - or wherever navigation may be considered hazardous, particularly when a shipmaster is unfamiliar with the area' (IMO, 2016b). The pilot will generally board the vessel, become a member of the bridge team (Fig. 1, left), and perform 'activities related to navigation and ship handling in which the pilot acts as an advisor to the master of the ship' (IALA, 2012:10). Types of pilotage include local services such as coastal, harbour and river pilotage, in which the pilot performs a specific operation such as berthing or unberthing a vessel, as well as deep sea and transit pilotage, where the pilot stays on the vessel for a part of the voyage, e.g. for transit through the North Sea or entrances to the Baltic. In some areas and in certain, often weather-related, circumstances, remote or shore-based pilotage may also be conducted (IMPA, 2014; also Hadley, 1999).

Vessel Traffic Services (VTS) is a shore-based service, established in order to 'improve the safety and efficiency of vessel traffic and to protect the environment' (IMO, 1997:3). It was introduced after the Second World War, and facilitated by the development of shore-based radar and VHF (Very High Frequency) radio (IALA, 2016). A VTS area will usually (though not always) be situated within the territorial waters of a country. The VTS centre (Fig. 1, right) may offer one or more of three levels of service, usually provided over VHF radio to vessels: information service (INS), navigational assistance service (NAS) or traffic organisation service (TOS) (IMO, 1997; IALA, 2016). In practice, there is often no sharp distinction between INS, NAS and TOS, and all aim to 'aid the mariner in the safe use of navigable waterways' (IALA, 2016: 27). Whether or not a VTS Authority declares the service NAS in addition to INS or TOS, IALA states that, 'A VTS would normally be expected to respond to situations where a vessel is observed, or otherwise deemed, by the VTS to be in need of navigational assistance, using appropriate procedures. The VTS would also normally be expected to respond to requests from a vessel that is in need of navigational assistance' (IALA, 2016:35).

Figure 1. Pilot (left) and VTS operator (right) at work (source: empa-pilots.eu, sjofartsverket.se).

Please note that while both pilots and VTS operators may provide *advice* on navigational matters, *responsibility* for safety of navigation remains at all times with the master of the vessel (IMO, 1972). The master is not obligated to follow the advice, and the VTS operator or pilot does not relieve them of their responsibility (IMO, 1997; IMPA, 2014; IALA, 2016). (It should also be noted that questions of control versus responsibility are still largely unresolved in e-navigation.)

2.2 … and in literature

Given the inherent interaction between humans, technology, organisation etc., on board and between ship and shore, previous research has tended to view the maritime domain as a *sociotechnical system* (Perrow, 1984; National Research Council, 1994; Grech et al. 2008). More specifically, most current research into pilotage (e.g. van Westrenen, 1999, 2013; Mikkers et al., 2012) and VTS (van Westrenen & Praetorius, 2012; Praetorius & Hollnagel, 2014; Praetorius et al., 2015) is firmly based within the traditions of Cognitive Systems Engineering/Joint Cognitive Systems (Rasmussen, 1994; Hollnagel & Woods, 2005) and Resilience Engineering (Hollnagel et al., 2006), in which the human-technological-organisational elements of the system work together to keep the system operating within acceptable parameters and achieve a common goal. Much of the discourse revolves around control and the link between loss of control and unexpected events.

Issues raised are: whether safety is improved by centralised (shore-side) or decentralised (on board) control (van Westrenen & Praetorius, 2012; also Hadley, 1999); the role of both feedback control, i.e. input from the environment, and feedforward, the ability to pre-empt deviations, driven by local knowledge (van Westrenen, 1999; Bruno & Lützhöft, 2009; 2010). The importance of achieving both tactical (short-term, localised) and strategical (longer term, system-wide) control is emphasised (van Westrenen, 2013; Praetorius & Hollnagel, 2014; Praetorius et al., 2015), although this level of control is often not achieved in practice (Hollnagel & Woods, 2005). Other, wider issues which have been considered are: tacit knowledge and experience (Mikkers et al., 2012); and communication and trust between pilot and vessel crew (TSBC, 1995; Darbra et al., 2007; Bruno & Lützhöft, 2009, 2010) and ship-shore (Hadley, 1999; Bruno & Lützhöft, 2009, 2010; Brödje et al., 2012).

Previous research has also produced detailed system models of on board and shore-side assistance, both separately and as a single, distributed system, through the lens of Cognitive Systems Engineering/Joint Cognitive Systems (van Westrenen & Praetorius, 2012; van Westrenen, 2013; Praetorius & Hollnagel, 2014) and FRAM (Praetorius et al., 2015). However, beyond these invaluable contributions, scientific research into the work of pilots and VTS operators is relatively sparse. One may therefore argue that there is a risk of new technologies, such as e-navigation, being introduced without fully understanding the consequences. As Praetorius et al. (2015:20) state, 'Only if the complexity of everyday work is understood and properly analysed, one can estimate how changes will affect the overall system performance'.

3 Theoretical and methodological themes

Various traditions, perspectives, approaches, theories, methodologies, methods and models will be referred to throughout the thesis. Typically, these are not always well defined; they 'may appear more as a maze than as pathways to orderly research' (Crotty, 1998:1). To avoid confusion, I will attempt to delineate between them as follows (adapted from Crotty, 1998):

- Philosophical underpinnings: '*Epistemology:* the theory of knowledge embedded in the theoretical perspective and thereby in the methodology' (1998:3), and; '*Ontology* is the study of being' which 'sit[s] alongside epistemology informing the theoretical perspective' (1998:10).
- '*Theoretical perspective:* the philosophical stance informing the methodology and thus providing a context for the process and grounding its logic and criteria' (1998:3).
- '*Methodology:* the strategy, plan of action, process or design lying behind the choice and use of particular methods and linking the choice and use of methods to the desired outcomes' (1998:3).
- '*Methods:* the techniques or procedures used to gather and analyse data related to some research question or hypothesis' (1998:3).

To these I will also add:

- *Tradition:* a particular school of thought or research community, often linked to a certain theoretical perspective (Haavik et al., 2016).
- *Approach:* a broader term for a way of investigating a topic, which may include a combination of methodologies, methods and so on, and is not limited to one specific tradition or perspective (Czarniawska, 2014).
- *Model:* generally used here to describe a (visual) representation of a phenomenon for the purposes of (retrospective) investigation, (prospective) prediction or communication, may also include textual and mixed text/graphic representations (Le Coze, 2013a,b).
- *Theory* may refer to:
    - The antonym of 'practice'.
    - A specific theoretical perspective (e.g. systems theory).
    - *Grounded theory*, a methodology according to Crotty (1998) but an approach according to Czarniawska (2014).
    - The results of a grounded theory-style analysis (e.g. my 'empirical theory' of navigational assistance), which may not be formal theory, but represents an iteration, approximation or 'interim struggle' towards understanding a phenomenon (Weick, 1995; Denscombe, 2010).

3.1 Establishing a theoretical and methodological framework

Before delving into theory, I will introduce my background and experience, as they shape the choice of theoretical framework, methodologies and methods used in my research. I am educated as a sea captain and hydrographer/oceanographer/meteorologist; I worked for several years in the North Sea/North Atlantic offshore oil and gas and renewable energy sectors on high precision environmental surveys, navigation and positioning of platforms and structures. I am an 'insider' from the maritime domain in which safety, as described earlier, is in principle omnipresent. My practical experience, however, is that while the vessels, platforms and equipment I've worked with have in most cases been designed and operated in accordance with safety rules and regulations, a considerable amount of gaffa tape, cable ties and other makeshift solutions (both physical, procedural and performative) have often been necessary to ensure that things didn't go horribly wrong!

I introduced this thesis by presenting a possible dichotomy between safety in principle and in practice, an initial assumption, not untypical of practitioners, that 'real' safety is created during operations; that the level of safety which is ensured by compliance with rules, regulations, safety management systems, and through design, is somehow incomplete and inferior. During the course of my research, I have come to challenge and refine this view, though not necessarily to refute it. It is though a fundamental assumption, based on observation and experience, that safety does not simply exist or come into being of itself; rather it *emerges through the interaction between humans and non-humans (technology, organisation, regulations etc.) in the environment in which they operate*. Consider the saying 'a ship in harbour is safe, but that's not what ships are for' (attributed J.A. Shedd, 1928); it is only in context that safety becomes meaningful, one may say that it is *constructed*.

This research therefore combines a Realist or Empirist ontology (in the tradition of Aristotle and Descartes) - there exists a world in which safety may be understood and observed - with a Constructivist epistemology - we may gain understanding of safety through observing how it emerges in the world. Indeed, ontology and epistemology are inherently intertwined in a constructivist worldview (Latour, 2005; Haavik, 2014a); to understand *what something is* is intimately linked to the understanding of *what it is to know that thing* (Crotty, 1998:10-11).

The research described here takes its starting point in empirical observation of navigational assistance, a Resilience Engineering focus on everyday operations, and a Human Factors-based desire to incorporate knowledge into design. However, themes borrowed from various traditions and theoretical perspectives will be utilised throughout to establish a conceptual framework to investigate the phenomenon. This framework emerged as a *result* of the research approach, rather than being an *a priori* lens through which the topic was viewed. One may say that both a 'bottom-up' approach (from observation of practice) *and* a 'top-down' approach (from theory) were utilised (see also Hale & Borys, 2013; Le Coze, 2013a,b; Grøtan, 2013). This transition between observation and theory and back again in an iterative process may be best described as abductive and pragmatic (Peirce, 1903; Magnani, 2001) - making the best possible explanation given the available data - or a hermeneutic circle (Heidegger, 1927; Gadamer, 1975) - attempting to understand the whole with reference to the parts and vice versa. Figure 2 visualises the research approach used.

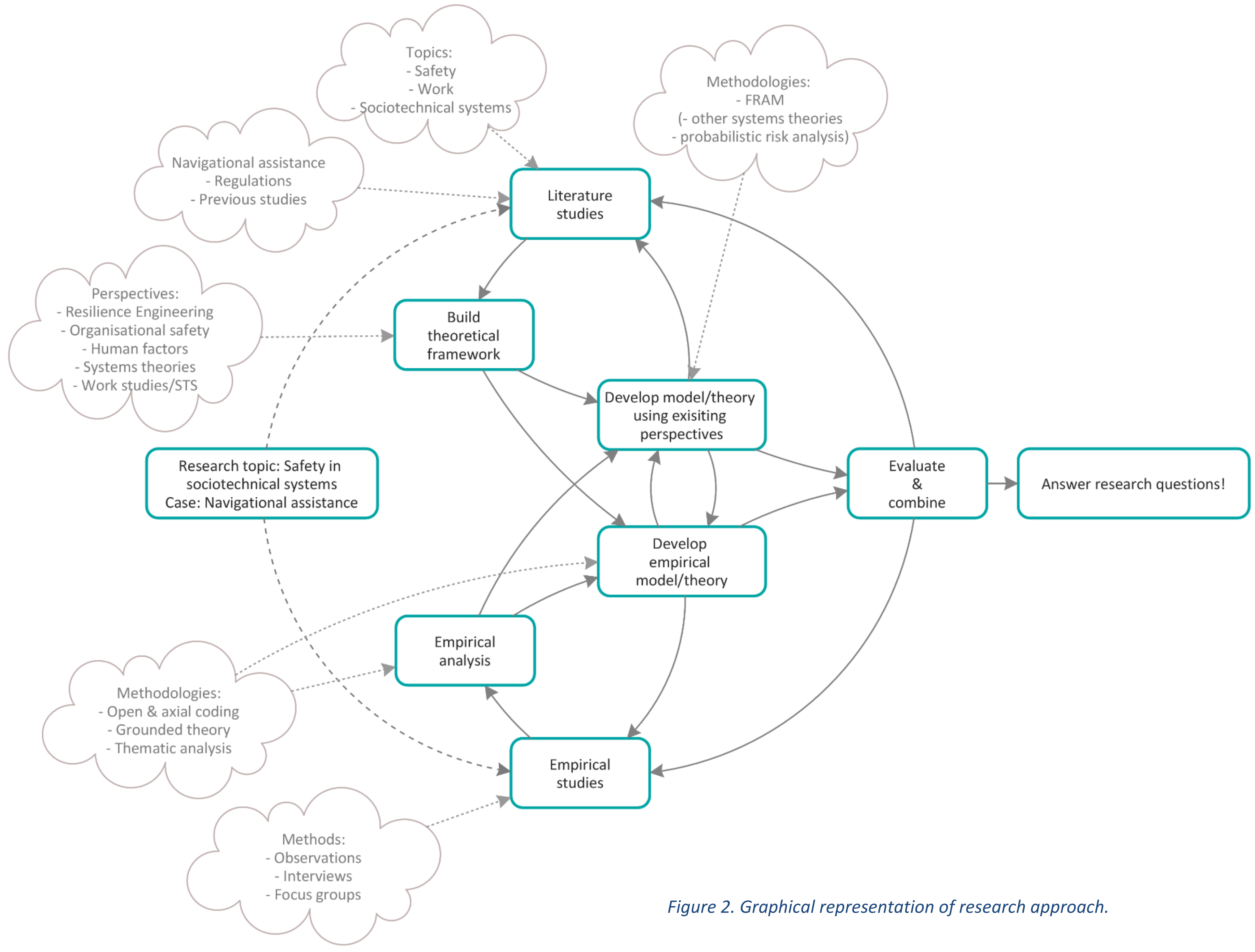


Figure 2. Graphical representation of research approach.

3.2 Resilience Engineering and Safety-II: studying safety in everyday operations

Traditionally, safety has been defined in terms of absence from harm or risk of harm. Various schools of organisational safety have developed over the last few decades in response to major disasters within high risk domains such as aviation, shipping, offshore oil and gas, and nuclear power (see Rosness et al., 2010; Le Coze, 2013a for a summary). They attempt in various ways to promote the idea that safety is about more than just avoiding accidents, but is also about understanding the mechanisms by which safety is or is not achieved in complex work systems and processes. Although originally referring to reliability, rather than safety in the strictest sense, Weick's 'dynamic non-event' (1987) has long been the accepted definition of safety in the research world. This implies that safety is not only the absence of incidents, but a continuous (dynamic) process of dealing with expected and unexpected circumstances to ensure their avoidance (i.e. resulting in a non-event) (Weick & Sutcliffe, 2001).

Organisational safety has, implicitly (e.g. La Porte & Consolini, 1987; Weick & Sutcliffe, 2001) and explicitly (e.g. Perrow, 1984; Rasmussen, 1997; Hollnagel, 2014a,b), been linked to studying *sociotechnical systems*, examining *how the interaction between components or actors (human and non-human) leads (or not) to safe operations*. Some prolific writers, such as Rasmussen and Hollnagel, have written extensively within the fields of both organisational safety and sociotechnical systems theory.

Normal Accident Theory (Perrow, 1984) postulates that work and work systems have become increasingly complex, being characterised by high interactive complexity (non-linear interactions between components) and tight coupling (disturbances in one part of the system propagate quickly to others), meaning that it is inevitable, or 'normal' that some accidents will occur. The theory of High Reliability Organisations (HRO) (La Porte & Consolini, 1987; Weick & Sutcliffe, 2001), considers that, despite high interactive complexity and tight coupling, some high risk industries actually have a very good safety record; HRO tries to understand why this is so, with emphasis on organisational redundancy and collective mindfulness. Collective mindfulness may be seen as promoting a good safety culture within a sociotechnical organisation or process (Nævestad, 2009). Rasmussen (1997) describes safe work as existing within a 'space of possibilities' bounded by potentially conflicting objectives: safety considerations, economic pressure and workload (see also Hollnagel's ETTO (efficiency-thoroughness trade-off) principle, 2009).

Resilience Engineering (e.g. Hollnagel et al., 2006, 2011; Woods, 2015, 2016) and Safety-II (Hollnagel, 2014b), which have grown out of the cybernetics and cognitive systems thread of systems theory (see Section 3.4 below), look at the ability of a system to adapt to its environment and create a successful outcome in everyday operations. The concept of resilience has become increasingly popular, and thereby risks becoming vague or watered-down (Woods, 2015) (ironically the same 'folk model' criticism made of e.g. situational awareness by Dekker and Hollnagel (2004)). There are however some core elements which characterise Resilience Engineering, and which may be useful in a scientific investigation of sociotechnical work and safety.

Systems are described in terms of their functions, and the connections between these, rather than their components. Variability is seen as an inherent property of a system, and is viewed as not only as the source of unwanted outcomes, but also successes (Hollnagel, 2012). The abilities to monitor, respond, anticipate and learn (Hollnagel, 2011) are essential characteristics of a resilient system which enable it to adapt to variability and thus deal with the unexpected. Woods (2015) identifies four 'senses of resilience' as the property of an adaptive system - rebound, robustness, graceful extensibility (i.e. the opposite of brittleness) and sustainable adaptability - the latter two being the potentially most fruitful for dealing with future challenges. However, 'the end story remains to be written' (Woods, 2015:5) regarding how to secure graceful extensibility and sustainable adaptability through engineering and design.

Though the various organisational safety perspectives employ distinct vocabularies and approach the subject from different angles (see e.g. Rosness et al., 2010; Le Coze, 2013a,b; Haavik, 2014a; Haavik et al., 2016 for a comparison), the idea that safety in principle does not necessarily ensure safety in practice is a common thread throughout (see also Hale & Borys, 2013a,b; Røyrvik, 2012). Resilience Engineering and Safety-II therefore propose that safety may be better understood by focusing on 'events' - i.e. *everyday work in sociotechnical systems* - rather than 'non-events' - or the absence of risk. One should consider 'work as done' - *as performed by practitioners* - rather than 'work as imagined' - as defined in rules and procedures. One should look at 'what goes right' - *successful work* - rather than 'what goes wrong' - i.e. accidents or incidents (Hollnagel, 2014b).

In addition to considering events or outcomes, one should also consider the process which leads to them, as Weick (1987) has previously indicated. Hollnagel (2012:9) states that 'safety is something a system *does* rather than something it *has*' [author's emphasis] and provides and an alternative definition of safety, as 'the ability to succeed under varying conditions, so that the number of intended and acceptable outcomes is as high as possible' (2014:back cover, also 134). Although it will not be explored further at this stage, it should be noted that while focus in the research community may be shifting from non-events to events, assessing risk to studying successful everyday operations, industry and regulatory bodies are still heavily reliant on a formal risk-based approach to safety (see e.g. Hale & Borys, 2013a,b; Grøtan, 2013; Hepsø, 2014).

3.3 Human Factors: understanding and designing for sociotechnical interaction

Bearing in mind that this thesis aims not only to understand safety in the context of navigational assistance, but also ultimately to influence design and evaluate the impact of change, if one were therefore to attempt to position the work contained herein within an overarching scientific discipline, it would conceivably be Human Factors or Ergonomics (HF for short). Kirwan (2000:678) emphasises the need for 'human factors integration in order to support safe design and operating practices', noting also that 'integration of HF into a system for safety purposes, is a practical result of the safety culture and safety technological awareness of an organisation' (2000:674). Hollnagel (2014a:43) claims that HF is an 'essential prerequisite for safe and productive work'.

The International Ergonomics Association (IEA) (2016) defines HF as:

> *'The scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory,*

principles, data and methods to design in order to optimize human well-being and overall system performance.'

Likewise, Wilson (2014:12) argues that, in order to understand and design for today's work, a systems approach to HF is necessary. This involves:

'Understanding the interactions between people and all other elements within a system, and design in light of this understanding, a system being a set of inter-related or coupled activities or entities (hardware, software, buildings, spaces, communities and people) with a joint purpose.'

Though one may easily become disoriented in the 'acronym soup' of systems approaches to design (Hoffman et al., 2002; also Wilson, 2014), a common element in all is that in order to design a system/process/artefact which fulfils its purpose or be *usable*, one must first understand the *context of use*. The International Standards Organisation (ISO, 2010:3) states that usability is 'the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use'. Understanding and specifying the context of use is thus a prerequisite for designing a system which achieves the goal for which it is intended, as illustrated by ISO's human-centred design cycle (2010:18).

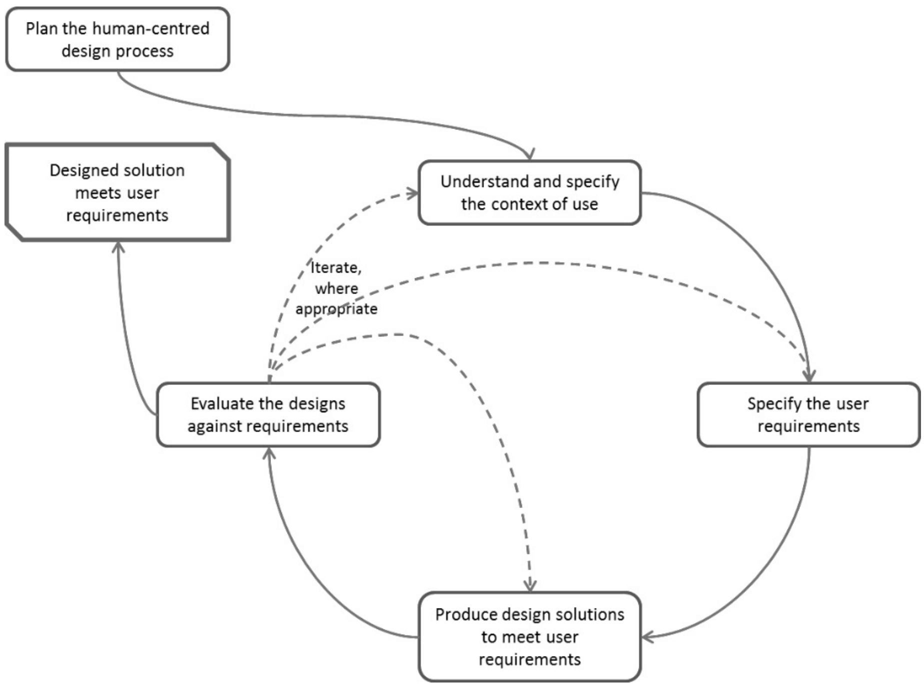


Figure 3. The principles of human-centred design for interactive systems, from ISO 9241-210:2010.

This thesis will therefore focus on discerning the context of use, by investigating *interaction between human and non-human actors in a sociotechnical system,* the *performance of work,* and *safety in practice.* While the research may be positioned roughly within the fields of Human Factors and Resilience Engineering/Safety-II, it will also incorporate some useful themes which are addressed by several related, but divergent, fields within modern science, such as Systems Theory and Work Studies, including Workplace Studies, Science and Technology Studies and Activity Theory. These will be introduced below, and the added value of such a combined approach will be discussed in Section 6.

3.4 Systems Theory: interaction and emergence, variability and control

Systems theory (von Bertanlanffy, 1968) is a holistic approach in which the human operator within their technological and organisational environment may be described as being part of a sociotechnical system (Hendrick & Kleiner, 2001; Rasmussen, 1997). Systems theory has grown out of an understanding that the reductionist approach of the 'scientific method', as developed by Bacon, Descartes and others - that a whole could be described by studying its constituent parts in isolation and assuming linear causality between them - could not sufficiently describe the *interaction* between humans and, for example, technology (Wiener, 1948; von Bertanlanffy, 1968; Skyttner, 2005). According to von Bertanlanffy (1968), a system is instead 'characterised by the interactions of its components and the nonlinearity of those interactions'.

A central tenet of systems theory is the idea that systems are *teleonomic* or *goal-seeking* (Wiener, 1948; von Bertanlanffy, 1968; Hendrick & Kleiner, 2001), with the components working *together* to achieve this goal. Systems theories provide models to describe *how* the goal is achieved through the interaction of the components. It also introduces the notion of *emergence* - that the whole is greater than the sum of the component parts (von Bertanlanffy, 1968, after Hagel), and that certain system properties, of which safety, efficiency, productivity are typical examples, emerge as a result of the interaction between the components (von Bertanlanffy, 1968). Systems theory is therefore very much in line with the constructivist worldview presented above.

Various 'threads' of systems theory have developed over the past century, aiming both to understand sociotechnical interaction, and to design for it. Some of the most influential are the cybernetics-based, or 'hard' (Checkland, 2000), systems engineering approaches, often referred to as *complex sociotechnical systems* theories, which express the goal of a system in terms of *control* of a process or situation based on feedback and feedforward from the system itself and its environment (e.g. Wiener, 1948; Skyttner, 2005). Another central theme is the idea of *variability* i.e. that performance of an individual, a component, a function or a system naturally varies, and may affect other parts of the system or lead unwanted outcomes. Control may be maintained by managing variability, and thus unwanted consequences may be avoided (Wiener, 1948; Skyttner, 2005).

Within this tradition, Cognitive Systems Engineering (Rasmussen, et al., 1994; Hollnagel & Woods, 2005) shifts focus from the *components* and their interactions, to the *functions* the system performs. A Joint Cognitive System (Hollnagel & Woods, 2005) aims to describe the ability of humans and technology working together to adapt and modify their actions in order to maintain control. Resilience Engineering (Section 3.2) and its associated Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) have evolved from this thread of systems theory. FRAM will be introduced in detail in Section 0. As noted in Section 2.2 above, Cognitive Systems Engineering/Joint Cognitive Systems and FRAM have been used successfully to investigate safety in maritime operations (e.g. van Westrenen & Praetorius, 2013; van Westrenen, 2013; Praetorius & Hollnagel, 2014; Praetorius et al., 2015).

This thesis will however also explore an alternative, 'softer' thread of systems theory. Checkland (2000) argues that engineering approaches may not always be optimal for describing a complex object of study; rather it is the process of enquiry which should be treated as systemic (see Fig. 4). The reader will remember that human factors is concerned with the human as part of some form of system, usually a sociotechnical system (IEA, 2016; Hollnagel, 2014a; Wilson, 2014; Kirwan, 2000 etc.). It may be difficult to describe human factors itself as a system, but we may say that human factors employs a systemic approach to the work environment, and is a systemic discipline (Checkland, 2000; Hollnagel, 2014a). The IEA (2016), Hollnagel (2014a) and Wilson (2014) also emphasise the application of human factors to design, implying that the design process itself may be viewed from a sociotechnical perspective.

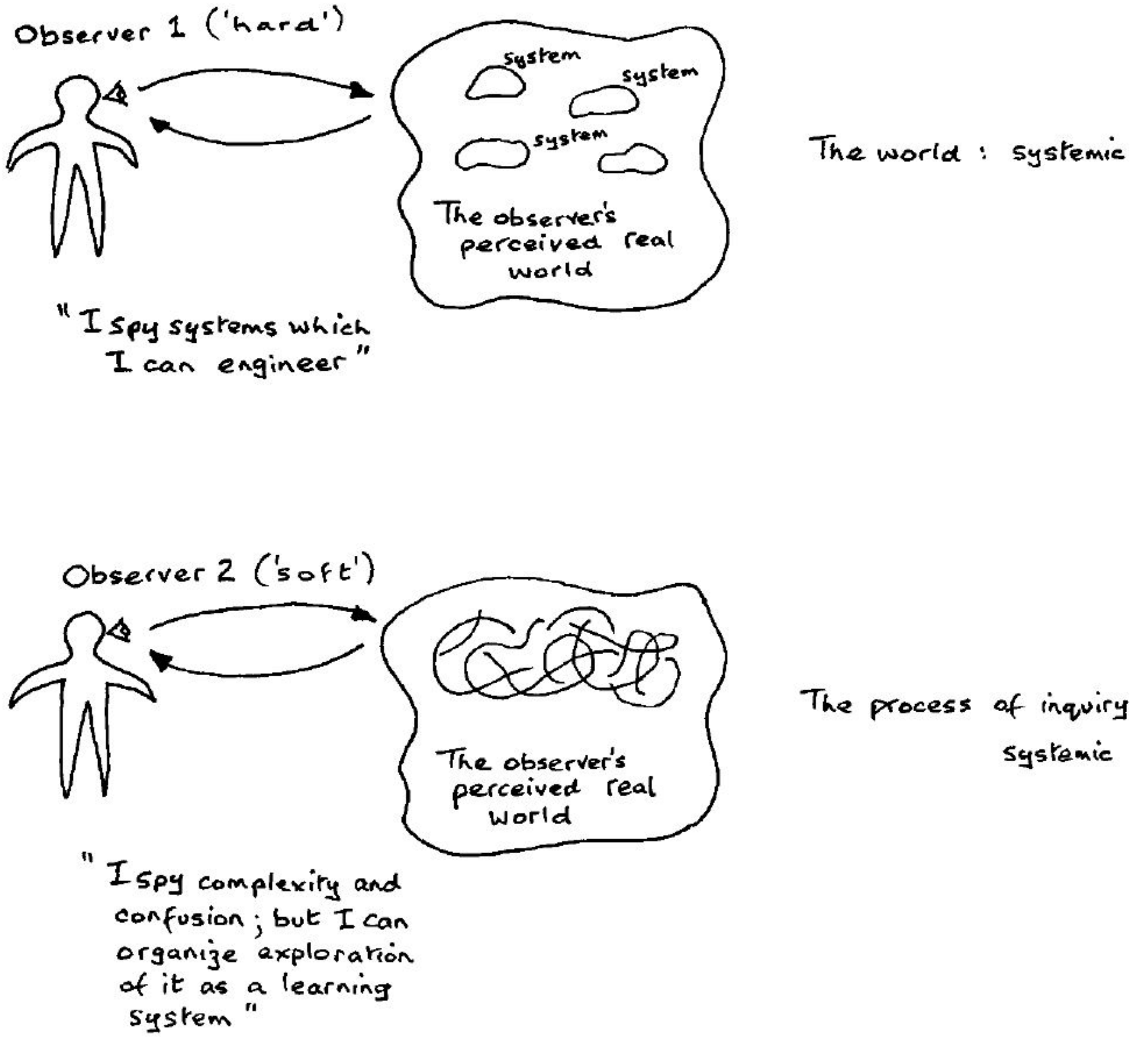


Figure 4. 'Hard' and 'soft' systems approaches to understanding a complex problem (source: Checkland, 2000:18).

Checkland (2000) also highlighted one of the main stumbling blocks with the application of systems theory to a complex problem, namely defining what constitutes the 'system' in question. One may begin by asking 'what constitutes *a* system?' It is generally agreed that a system is a construction; it may be defined in terms of its components and the interaction between them (von Bertanlanffy, 1968). However, if we aim to be truly holistic, then we face the impossible task of investigating the 'fundamental interconnectedness of all things' (Adams, 1987; Wiener, 1963). What is part of the system, what is not, and where the boundary should be drawn, depend rather on pragmatic grounds, such as the purpose of the analysis (see also Hollnagel, 2012). Once the boundary is drawn, the relationships between the components are established and their interaction may be studied. System theories often assume that these relationships between the components exists; the focus is not on how they came about.

3.5 Work Studies: describing everyday work

Wilson (2014) acknowledges the dynamic nature of sociotechnical work and argues that one should study sociotechnical systems 'in the wild' (a term originally coined by Hutchins, 1995a) to 'account for real variance in real practice' (Wilson, 2014:7). The notion of studying how work is performed in the workplace is a central theme of several ethnographically-inspired traditions such as Workplace Studies (Suchman, 1993, 1995, 2007), Science and Technology Studies (Latour & Woolgar, 1979/1986; Callon & Latour, 1981; Latour, 2005; Czarniawska, 2017) and Activity Theory (Leont'ev, 1981; Engeström, 1996) - or *Work Studies* for short (Haavik et al., 2016). Work Studies are not theories or methodologies per se, but are rather traditions or approaches which share many common themes (see e.g. Engeström & Middleton, 1996). Work studies are considered separately from systems theory (Kaghan & Bowker, 2001; Le Coze 2013a,b; Haavik et al., 2016), but some of their themes may be helpful when attempting to understand work in sociotechnical systems, and may complement 'harder' systems engineering approaches.

3.5.1 Workplace studies: 'making work visible', coordination, distribution and (re)configuration

Suchman (1995:56) quotes David Wellman in saying that 'how people work is one of the best kept secrets in America'. The practice of work is often invisible to everyone except those who perform it. Ethnographically-inspired workplace studies seek therefore to describe how everyday work is performed with the aim of *'making work visible'* to the outside world (Suchman, 1995). Of practical significance for e-navigation and HF integration is Suchman's statement that 'the goal of making work visible for system design is to develop more appropriate technologies from the point of view of those who will be using them' (1995:60). However we should be sensitive to the complexities of work, and wary of thinking that these can easily be 'revealed, "captured", analysed into constituent part and transformed into manipulable, objectified knowledge' or represented as 'rationalizable, abstract function/processes, enacted through specific behaviours/practices' (1995:60).

Within this tradition, a large body of studies describe how successful work depends on collaboration and coordination between human and non-human actors. The work 'system' is not pre-defined, but must dynamically respond and reconfigure in time and space to deal with emerging situations. Examples include studies from safety-critical domains such as aviation (Hutchins, 1995b), aircraft ground operations (Suchman, 1993; 1996), navigation (Hutchins, 1995a) and offshore (Haavik, 2011; 2013; 2014b). By observing and attempting to create faithful representations of *how work is actually done*, workplace studies show how decision-making and cognition in sociotechnical work is often found to be *distributed* between humans and other actors (Hutchins, 1995a,b), and actions are *situated* (Suchman, 2007) in the circumstances in which they take place. *Coordination* (Suchman, 1993) is thus required to configure the work system to provide the appropriate response to the situation.

3.5.2 Science and Technology Studies: symmetry, translation and the formation of networks

Another 'soft' constructivist approach to studying the interaction between humans and other stakeholders within the work environment, related to workplace studies, is Science and

Technology Studies (STS). *Actor-network theory* (ANT) is a branch of STS which looks at how a system, or *network*, *emerges* through the building and maintaining of associations between *human and non-humans actors* (Latour & Woolgar, 1979/1986; Callon & Latour, 1981; Callon, 1986; Law, 1990; Latour, 2005; Czarniawska, 2014, 2017). It is thus the creation of the system which is of interest; Callon (1986) describes this process as a series of *negotiations* between actors, which if successful, allow the actors to work together toward a common goal. A network is not necessarily goal-seeking, but its actors often are (e.g. Latour, 1996; Callon, 1986; Law, 1990), which may influence the formation of the resulting network.

STS also introduces the concept of *symmetry* - that one should not differentiate between humans and non-humans, or the social and the technical (e.g. Latour & Woolgar, 1979/1986; Callon, 1986; Law, 1990), or indeed the economic or political (Law, 1990, 1991; Latour, 2005). Anyone or anything may be or become an actor, so we should treat them as equal and trace the connections between them (Czarniawska, 2014, 2017; Sayes, 2014). Law (1990) claims that 'we are *all* monsters, outrageous and heterogeneous collages' (1990:18; also 1991:18), in which 'In practice nothing is purely technical. Neither is anything purely social. And the same may be said for the economic, the political, the scientific, and all the rest.' (1990:10; see also Latour, 2005).

Translation (Callon, 1980) is another central theme of STS - the idea that the actors are transformed through the process of interaction (Callon, 1986; Latour, 1996; Czarniawska, 2014, 2017), and that their properties, and by implication the properties of the network as a whole, are the *results* of the interactions between the actors (see also Haavik, 2011; Wilson, 2014).

The principles of symmetry and translation mean that, in addition to observing, interviewing, following humans when studying the formation of a network, one may also *follow objects* or *quasi-objects* (Czarniawska, 2014; exemplified in Latour, 1986, 1996, 1995/1999; Lindahl, 2005; also Røyrvik, 2012). In following an object, one may observe its transformation into an actor within the network. For example, Latour (1986) describes the role of visualisations of objects (maps, drawings, graphical representations etc.) in the translation of information from one form to another, thus becoming actors themselves, and enabling communication between other actors who are displaced in time and space, and who lack a common language (see also Suchman, 1995).

3.5.3 Activity Theory: work as activity, conscious and unconscious operations

Activity Theory is initially a sociohistorical behavioural theory (Leont'ev, 1981) but has been employed in studies of experts at work (Engeström, 1996), human-computer interaction (Karlsson, 1999) and industrial design (Andersson et al., 2011). It may be considered both a work studies approach (i.e. Engeström, 1996) or a soft systems theory (e.g. Karlsson, 1999; Andersson et al., 2011). It investigates the relationship between humans and their sociotechnical work environment, and the means by which actors achieve their goals. Work is described in terms of *activities*, which comprise an actor ('subject') using a 'tool' (a method or means such as technology, systems, procedures etc.) to achieve a 'goal' or 'object' (Fig. 5).

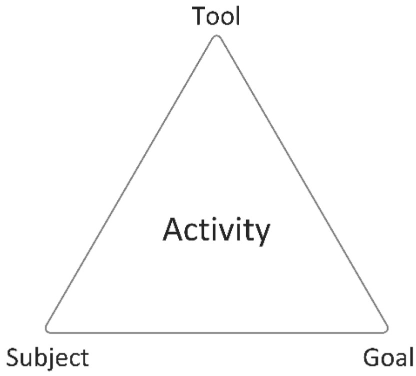


Figure 5. Activity triangle showing relationship between subject, tool and goal.

Activities may operate on several levels of abstraction or decomposition. On the highest level, activities relate to achieving the overarching goal e.g. to improve safety. Activities may also comprise concrete *actions* ('what must be done') and *operations* ('how it can be done') (Karlsson, 1999:381). Operations may be *conscious* or *unconscious*, conscious operations being similar to Heidegger's present-to-hand tools, and unconscious or internalised operations reflecting ready-to-hand tools (Heidegger, 1927). Parallels may also be drawn to Rasmussen's knowledge- or rule-based (i.e. conscious) and skill-based (unconscious) behaviour (Rasmussen, 1983).

3.6 Commonalities and controversies

While using different vocabularies, the notion that *safety emerges (or not) as the result of the interactions between human and non-human actors* is a common thread which can be traced through the various organisational safety theories, and which links organisational safety to both systems theory *and* work studies (see also Haavik, 2011; 2014a; Le Coze, 2013a,b; Haavik et al., 2016), and to the constructivist viewpoint proposed in Section 3.1.

Humans and other actors *interact* or *work together to achieve a goal*, whether this be safety (or efficiency, productivity etc.) or simply *work*. In the vocabulary of systems theory, the immediate purpose or goal of the interaction (e.g. work) is a first order *emergent property*, whereas safety (or the goal of work) is second order (Wiener, 1948; Skyttner, 2005). In other words, a system must first *work* in order to *work safely*. The factors affecting the performance of work, or the ability of a system to achieve its goals, are *dynamic* (Weick, 1987), *variable* (Hollnagel, 2012) and *situation-dependent* (Suchman, 2007), making *adaptation* an inherent element of sociotechnical work.

These common themes - *interaction, emergence, adaptation and variability (or uncertainty, see below)* - can be traced throughout the various theoretical perspectives described here and the methodologies which support them. As noted, there is some cross-fertilisation between organisational safety, human factors and systems theory, while, despite some obvious parallels, work studies are usually treated quite separately. There are certain points of contention or 'controversies' between them which the researcher may use to their advantage (Kaghan & Bowker, 2001; Le Coze, 2013a,b; Haavik et al., 2016). Haavik et al. (2016) suggest that, since different perspectives may employ 'different ways of seeing', by 'feeding off controversies' (Latour, 2005), the researcher may gain a richer understanding of the research topic. Kaghan and Bowker (2001) similarly suggest that by 'building bridges' between different perspectives, one may 'open black boxes', thus highlighting aspects of the phenomenon which remain invisible when viewing it through one theoretical lens.

3.6.1 Systems and networks

Systems theories and STS in particular may be viewed as conflicting in terms of their frameworks for viewing work as either a system or a network (Kaghan & Bowker, 2001). In the crudest terms, a system has boundaries (e.g. von Bertanlanffy, 1968) and a network does not (e.g. Latour, 2005). Alternatively one may say that a system is fixed whereas a network develops. Both consider the interaction between their human and non-human members, the difference being that in a system the members are defined at the start of the analysis and in a network this happens at the end. Rather than viewing these perspectives as irreconcilable, it is more interesting to consider how they may complement each other by starting with an empirical understanding of navigational assistance and investigating how the various theories help in highlighting different aspects of it. There are some indications that Resilience Engineering is in fact moving in this direction (e.g. Woods, 2015) by discussing resilience in the context of interconnected networks of adaptive systems.

3.6.2 Control and cooperation

Another facet of the 'harder' systems engineering approaches which may be complemented by a 'softer' approach is the role of non-humans in the system or network. Theories which focus on control as the means by which a goal is achieved (e.g. the cybernetics thread described above) tend to define membership of the system as *that which can be controlled* (Hollnagel & Woods, 2005). Thus technology and organisation are generally accepted as part of a sociotechnical system. Due to its unpredictability, the physical environment is usually seen as external to the system.

However, understanding the interaction with the sea itself is an essential component in ensuring maritime safety (see Section 5 and attached papers). Wilson (2014) contends, as does Le Coze (2013a,b), that in much sociotechnical work, interaction with the natural world is also part of the 'system', thereby advocating a 'socio-natural-technical' systems approach. Similar interaction with both natural actors - and technological representations of these - may also be seen in the work studies tradition (e.g. Callon, 1986; Latour 1986, 1996; Suchman, 1993, 1995; Røyrvik, 2012); Callon (1986) describes the importance of cooperation and negotiation with all actors in the creation of a network. The implications of this have not yet been fully investigated in the literature on systems and safety, although there is growing interest in understanding interactions with the natural world, for example in the context of building societal resilience to natural disasters (e.g. Wilson, 2014; Cabrera Aguilera et al., 2016).

3.6.3 Uncertainty and variability

Uncertainty pervades the literature on organisational safety; NAT (Perrow, 1984), HRO (La Porte & Consolini, 1991; Weick & Sutcliffe, 2001) and RE (Hollnagel et al., 2006, 2011) all agree that the increasing complexity of work systems means that our knowledge of and attempts to describe them will inescapably be incomplete or underspecified. Uncertainty or variability also appears in various different forms in several systems theories, from Wiener's 'sausage' (Wiener, 1948), to Rasmussen's Brownian motion (Rasmussen, 1997) to simple variability in the work of Hollnagel (2012) and others (Hollnagel et al., 2014). Within Resilience Engineering, and FRAM in particular, variability in and resonance between functions are illustrated by analogy to stochastic resonance between signals with varying amplitudes and frequencies (see Section 3.7.1 below).

Latour (2005) describes uncertainty in terms of: the formation and configuration of groups/ networks/systems of actors; who or what may be or become an actor; how actions or interactions take place; what is known and unknown; and ultimately how we describe our observation of these uncertainties. Kaghan and Bowker (2001) argue that uncertainty is an inevitable consequence of the open nature of networks; as such it is also inherent in the design process. In other words, uncertainty is everywhere, both in sociotechnical systems/networks and our attempts to describe them. However, that same uncertainty is precisely what allows the actors to adapt and manage the unexpected, a view also held by researchers within systems theory and organisational safety.

Given the prominence of variability in the vocabulary of Resilience Engineering and Safety-II, a potential controversy is whether variability, strictly speaking being only one form of uncertainty, is adequate to describe uncertainty within sociotechnical work. Borrowing from theories of probability and risk analysis (e.g. Bedford & Cooke, 2001; Grimmett & Stirzaker, 2001; Aven, 2012), variability (or aleatoric uncertainty) describes the natural variation present in all things, human, technological or otherwise. Another form of uncertainty, clearly seen in the writings of Latour and others in the work studies tradition, is that of epistemic uncertainty (or uncertainty due to lack of knowledge). Epistemic uncertainty is also implicit in the systems and safety perspectives, and may be linked to, for example, the adequacy of feedback and control mechanisms i.e. whether or not the operator receives correct and sufficient information to maintain control. Model uncertainty also describes the ability of a model to describe the phenomenon being investigated (Bedford & Cooke, 2001). As Le Coze (2013a,b) noted, a model of e.g. a sociotechnical system will inevitably be an approximation of reality, or as Hollnagel (2012) states, it will be underspecified.

3.6.4 Methods and models

Qualitative methods such as observations and interviews are invariably used to approach the field of enquiry in each of the traditions or perspectives described above, since, as Hollnagel et al. (2014:39) states, 'the best sources of information about activities of interest is [sic] the people who actually perform the work'. Data are typically analysed using techniques such as coding and categorisation and inspired to some degree by the principles of grounded theory (Glaser & Strauss, 1967; Corbin & Strauss, 2008; Charmaz, 2000, 2006/2014). Other human factors techniques such as task analysis (Stanton et al., 2013) are also common.

While not a 'controversy' as such, the results of research conducted within the various traditions are often presented in different ways. An investigation of sociotechnical work through the work studies lens will usually result in the production of narrative (Czarniawska, 2014), a textual account of the workplace or practice, often rich in detail and conveying a deep understanding of the situation. ANT-accounts such as Callon's scallops (1986), Latour's 'Aramis' (1996), Orr's 'Talking about Machines' (1996) and Lindahl's 'Little Engine' (2005) provided inspiration throughout my research. Such accounts may succeed in 'making work visible' (Suchman, 1995), but not necessarily in a format which is easily absorbed by managers or designers.

Systemic approaches, on the other hand, will often produce a model - primarily a visual representation - of the work system, highlighting the essential elements and interactions between them (see below). Latour (1986) argues that visualisations may transform objects, and knowledge of them, from being fixed in time and space to becoming mobile, and thereby transferrable between actors and contexts. They may function as a mediating tool (Karlsson, 1999) or boundary object (Star & Griesemer, 1989; Broberg et al., 2011), facilitating communication between stakeholders and thus enabling the integration of operational knowledge into design. Le Coze (2013a,b) and Hepsø (2014) therefore propose an "anti-dualist" or "double-level language" approach which emphasises the value of combining systemic representations with ideas and practices from sociology and 'softer' work studies traditions (above), particularly within safety-critical domains.

3.7 Modelling safety in sociotechnical systems

A multitude of tools exist for modelling safety in sociotechnical systems, and which are associated with the various threads of organisational safety and systems theories described above (see e.g. Rosness et al., 2010; Le Coze, 2013a,b, 2015). These models may be primarily intended for communication, (retrospective) investigation or (prospective) predictive purposes, but will to some extent inevitably achieve all three (Le Coze, 2013b:204)

Organisational safety perspectives have used various models to understand why safe or unsafe outcomes occur. Perrow's couplings/interactions matrix (1984), Turner and Pidgeon's man-made disaster model (1997), Reason's Swiss Cheese model (1997), Rasmussen's migration model and AcciMap (1997), and Weick's collective mindfulness model (Weick et al., 1999) are examples which have proved influential in understanding safety in complex systems and driving forward research in safety science (Le Coze, 2013a, 2015).

Likewise within systems theory, a host of models have been used to describe the interactions within sociotechnical systems in terms of maintaining control and achieving their goal, whether this be safety, efficiency, productivity or similar. Some examples are cybernetics-based feedback/feedforward control models such as the closed loop control system (Wiener, 1948; Skyttner, 2005), Hollnagel's Contextual Control Model (COCOM) and Extended Control Model (ECOM) (Hollnagel & Woods, 2005). Layers and nested hierarchies of a system may be visualised using models such as Rasmussen's sociotechnical system ladder (1997), sub-systems matrices (Hendrick & Kleiner, 2001), layers of abstraction in a Joint Cognitive System (Hollnagel & Woods, 2005) and Work Domain Analysis abstraction-decomposition matrix (Vicente, 1999; Lintern, 2009).

Choosing a suitable model from the 'model soup' (see Hoffman et al., 2002) may therefore not always be straightforward. Since we are interested in everyday operations and successful work, the model which was investigated in detail in this thesis was chosen for its explicit links to the Resilience Engineering and Safety-II perspectives, and its intention to model 'work as done' - namely the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012; Hollnagel et al., 2014). (Several models derived from alternative systems theories were also developed during this research. How these may be utilised to describe and communicate the practice of navigational assistance will be the subject of a forthcoming paper.)

3.7.1 Functional Resonance Analysis Method (FRAM)

The Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012; Hollnagel et al., 2014) is described as 'an analysis tool that reflects Resilience Engineering and Safety-II thinking' (Hollnagel et al., 2014:12). It models a sociotechnical system in terms of its functions, and the interactions between these, in order to analyse where variability may arise and 'resonate' throughout the system, leading to potentially unwanted outcomes. FRAM has mainly been used for retrospective analysis of single events or accidents (e.g. Herrera et al., 2010; Carvalho, 2011; Tian et al., 2016). It has also been used to produce general system descriptions for risk analysis purposes (Rosa et al., 2015), and to investigate work systems - such as VTS (Praetorius et al., 2015) and oil spill response (Cabrera Aguilera et al., 2016) - in terms of their capability for resilience, performing the analysis of variability at the system level, without reference to a specific event or situation. Hollnagel et al. (2014) also propose the use of FRAM in assessing variability in future system design.

Hollnagel (2012: 33) originally envisaged FRAM as a two-stage process: 'The first is using the FRAM to develop a model of the activity (process or performance) that is the focus of the analysis [steps 0-1]. The second is to use the model to create instantiations of the activity (or performance) and then to analyse these [steps 2-4].' It should be noted that the 'model' created consists not only of the visualisation of interconnected functions produced using e.g. the FRAM Model Visualiser (FMV)[2] (which is technically an instantiation), but also of the textual or tabular descriptions of functions, their aspects and their potential variability, upon which the visualisation is based.

The ability to describe work in terms of functions is central to performing a FRAM analysis. A function is the 'means that are necessary to achieve a goal' or the 'activities - or set of activities - which are required to produce a certain outcome' (Hollnagel, 2012: 40-41). However, the process of identifying and describing functions may not be straightforward (Praetorius et al., 2015). Analysis of qualitative data from e.g. interviews, field observations and document review is recommended (Hollnagel et al., 2014:39). Functions may be identified directly from transcribed records of the data (as in Hollnagel et al., 2014) or by first performing a hierarchical task analysis or goals-means analysis (Hollnagel, 2012) or grounded theory analysis (Praetorius et al., 2015). Performance Shaping Factors (PSFs) - 'conditions which influence the events being studied' - may also be identified and integrated directly as functions (Hollnagel, 2012: 57-58; Cabrera Aguilera et al., 2016).

Functions should be described in terms of six 'aspects' (Fig. 6): input; output; precondition (without which the function cannot be performed); resources (which are consumed during the performance of a function); control (which monitors or regulates the function), and; time (temporal aspects which affect the performance of the function) (Hollnagel, 2012; Hollnagel et al., 2014).

[2] FMV version 0.4.1 downloaded from http://functionalresonance.com/FMV/index.html

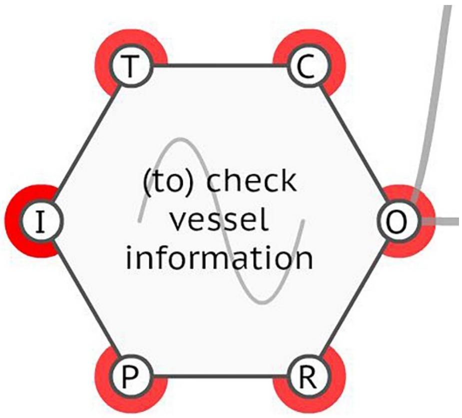


Figure 6. Example of a FRAM function, '(to) check vessel information'.

Functions, and their variability, should normally be classified as human, technological or organisational, and identified as *foreground* (those whose variability may affect the outcome of the analysis) and *background* (those which are relatively stable and thus have less impact upon the outcome). The interaction between functions is described as *upstream* coupling (occurring before another function) or *downstream* (occurring after). A function's performance may vary due to *endogenous* (i.e. internal), *exogenous* (external) or *upstream-downstream* variability. The effects of variability may be expressed as a change in the *timing* or *precision* of performance (Hollnagel, 2012; Hollnagel et al., 2014).

The FRAM method may be summarised as:

- **Step 0: Recognise the purpose of the analysis** i.e. to understand the practice of navigational assistance and describe this using a FRAM model.
- **Step 1: Identify and describe the functions** (see above).
- **Step 2: Identification of variability.** The functions should be examined separately to determine how each of them may vary, due to either endogenous, exogenous or upstream-downstream variability.
- **Step 3: Aggregation of variability.** Potential couplings between functions should be analysed to discover how variability in one function may affect others, and the outcome.
- **Step 4: Consequences of the analysis.** Potential ways to manage or control variability discovered during the previous steps should be analysed.

The reader will however not be surprised to learn that the application of FRAM in this thesis, in particular the identification and description of functions, was informed by the various work studies themes described above. How this was done will be introduced in Section 4.4 and discussed in Section 6.2 below.

4 Methods

4.1 Approaching the field - qualitative research

I mentioned earlier my background in the offshore industry, and the role of fieldwork in terms of observation and measurement of physical parameters such as waves, currents, water depths, position of structures etc. Knowledge of the world was obtained and converted using predominantly mathematical and statistical tools into numbers, tables, charts, maps and so on for communication to others (see also Latour, 1986). These tools and methods were largely unused in the studies described here, but are mentioned as they will conceivably return to play a larger part in my research post-Licentiate. (Two recurring themes which emerged during the empirical studies are those of pilots/VTS operators as skilled interpreters of quantifiable phenomena, and the use of subjective judgement in determining what is 'safe' in a given situation.) For the present task of studying safety in practice and interactions in sociotechnical systems, a new toolbox was required. Fieldwork and empirical data are still at the heart of my research, but were instead investigated using qualitative methods, derived primarily from Czarniawska (2014) and Stanton et al. (2013) and the work studies traditions described above.

As noted, work studies do not provide 'theories', 'methodologies' or 'methods' per se, but may function as a guide to the researcher when approaching the field (Czarniawska, 2014). The various themes mentioned in Section 3.5 - in particular those of 'making work visible' (Suchman, 1995), symmetry between human and non-humans (Latour & Woolgar, 1979/1986; Callon, 1986; Law, 1990), and following objects (Czarniawska, 2014; also Latour; 1986, 1996, 1995/1999) - help to maintain focus on observing *how work is actually done* and *how safety arises (or not)*, with reference to who is interacting with what; how, when, where and why it is done; and how it varies depending on the circumstances. These same themes, plus those of the formation of networks (Callon, 1986; Latour, 2005; Czarniawska, 2017), coordination and reconfiguration (Suchman, 1993, 1995, 2007), work as activity (Karlsson, 1999) and uncertainty (e.g. Bedford & Cooke, 2001) also provided valuable insights during the process of analysis.

4.2 Literature studies

A literature review (Galvan, 2006; Czarniawska, 2014) into the regulations and guidelines surrounding navigational assistance, and the scientific literature on the topic, was conducted near the beginning of the research. Starting with official documents and studies known to the author, a synthesis matrix was created to illustrate how different topics and themes were discussed in the source material. The search was expanded by reading works referenced in the original documents, conducting online blanket searches and searching the websites and databases of relevant international organisations, to form the body of literature summarised in Section 2. The literature on navigational assistance led me in turn to the study of complex sociotechnical systems and Resilience Engineering, while personal scepticism urged me to look beyond the first, rather neat, explanation I found there. This, and an excellent course on qualitative methods, introduced me to the initially incomprehensible world of Latour, and subsequently STS and workplace studies. Each of the diverse perspectives - summarised in Section 3 above - have been revisited iteratively during the course of the research (see Fig. 2) and their various themes utilised throughout the data collection and analysis, and in the writing process. (The irony in moving from the 'acronym soup' of complex sociotechnical systems

(Hoffman et al., 2002) to the 'theory soup' which is the above theoretical framework is not lost on me.)

4.3 Empirical studies

The empirical basis for this thesis is a series of qualitative studies which took place over a one-and-a-half year period from autumn 2013 to spring 2015. These studies aimed to understand the work of pilots and VTS operators, and its contribution towards maritime safety, as performed and described by practitioners. Although it was envisaged that the results of these studies would provide input to systems models such as FRAM, they were not expressly conducted with this intent. Rather, they were part of an iterative, explorative approach, using various qualitative methods derived primarily from Czarniawska (2014) and Stanton et al. (2013). The research moved backwards and forwards between data collection and analysis, field and office, in a process loosely inspired by grounded theory in the spirit of Glaser and Strauss (1967) and Charmaz (2000, 2006/2014). Similarities may also be seen with the principles of abduction (Peirce, 1903; Magnani, 2001) and the hermeneutic circle (Heidegger, 1927; Gadamer, 1975) (section 6 above). The data collection and analysis is described in detail in Papers I and II.

4.3.1 Observations, interviews and focus groups

The studies consisted of: a focus group with deep sea pilots; a workshop with VTS operators; a training session with a VTS trainer; a group interview with pilot trainers; and, interspersed throughout, field visits to a pilot station, two vessels and two VTS centres (Table 1). During each field visit, which lasted from two hours to a day, observations and semi-structured workplace interviews were conducted. The total number of participants were: five pilots, six VTS operators (one is also a VTS supervisor/ trainer), one VTS manager, two pilot trainers (ex-pilots), one VTS trainer (also an active VTS operator) and two pilot boat drivers. Participants were of five different nationalities and their level of experience ranged from trainee to over twenty years' experience in their current role. In total eight VTS and/or pilotage areas were covered, in four countries.

Table 1. Summary of empirical studies.

Study	Participant(s)	Area(s)	Methods
Deep Sea Pilots focus group	3 deep sea pilots	Areas 1, 2 and 3	Focus group
VTS Expert workshop	2 VTS operators	Areas 4 and 5	Workshop
Sea/harbour pilotage 1	1 sea/harbour pilot 2 pilot boat drivers	Area6	Observation /shadowing
VTS training session	1 VTS trainer/VTSO	Area 6	Observation
Pilot trainers interview	2 pilot trainers	Areas 7 and 8	Group interview
VTS observation 1	1 VTS operator	Area6	Observation, workplace interview
VTS observation 2	3 VTS operators 1 VTS manager	Area1	Observation, workplace interview
Sea/harbour pilotage 2	1 sea/harbour pilot	Area6	Observation /shadowing

Subsequent to the studies described in this thesis, further field observations on vessels and in VTS centres, as well as interviews with pilots, VTS operators and pilot/VTS trainers, have been conducted in four of the areas covered here. Although the data are not incorporated in the current studies, they confirm the results achieved.

4.3.2 Grounded theory-inspired thematic analysis

Data were analysed continuously throughout the studies, inspired by the principles of grounded theory (Glaser & Strauss, 1967; Charmaz, 2000, 2006/2014; Czarniawska, 2014). The aim of this analysis was to describe the common elements found in the work of pilots and VTS operators, and regarded by them as essential for successful performance (*success factors*, or *factors* for short). With the exception of the field visits on board vessels and interview with pilot trainers, all studies were audio recorded and verbatim transcriptions made of each recording. Images, photographs and participants' sketches and drawings were collected throughout. Written notes were taken either during each data collection or as soon as possible thereafter.

After the first study, textual data were systematically sorted using a form of thematic analysis (Charmaz, 2000, 2006/2014; Vaismoradi et al., 2013). Open coding (Charmaz, 2006/2014) was used to generate codes and categories, which were interlinked and consolidated using axial coding (Corbin & Strauss, 2008), first into themes, then again to form a central concept. Categories tended to describe lower level, or more concrete factors (e.g. to check weather forecast), while themes described higher level, or more abstract, factors (e.g. to use local knowledge) (see Table 2 below for a summary). Images were compared to and analysed together with the written data.

An empirical theory (Denscombe, 2010) - effectively a summary of the emergent success factors - was formulated after analysing data from the first study. The same process was repeated after every data collection, reusing codes, categories and themes from previous studies where appropriate, and refining or adding new codes as necessary. Targeted coding and cross-referencing between different texts was also done as the studies progressed. The empirical theory was refined throughout, the resultant empirical model thus summarising the success factors for navigational assistance, and the relationships between them (Fig. 8 below). It should be emphasised that the version presented here (at least the tenth iteration!) represents an approximation or 'interim struggle' towards understanding the phenomenon (Weick, 1995; Denscombe, 2010), rather than a definitive, formal theory.

4.4 Functional Resonance Analysis Method (FRAM)

The data were (post-coding and -categorisation) analysed using the FRAM, following the procedure described in Section 0 above, and inspired by the applications of FRAM by Praetorius et al. (2015) and Cabrera et al. (2016). The primary **purpose of the FRAM analysis (Step 0)**, as previously stated, was to (investigate FRAM as a tool to) describe the work performed by pilots and VTS operators and to understand their contribution to safe maritime operations. This was done in three stages.

1. Generic FRAM model of navigational assistance

The first stage aimed to describe the practice of navigational assistance on a system level by developing a generic description of the common elements of the work of pilots and VTS operators, and regarded by them as essential for successful assistance, whether provided on board or from ashore. The thematic analysis described above had (similar to Praetorius et al., 2015), revealed an interconnected network of factors which are integral to and affect the performance of navigational assistance. These success factors were treated as Performance

Shaping Factors, translated into activities and incorporated directly into the model as functions (as described in Hollnagel, 2012:57-58; also Cabrera Aguilera et al., 2016). This is equivalent to **Steps 1 and 2** of the FRAM method (identify functions and potential variability) and is described in detail in Paper II.

2. Instantiation of a scenario

In order to investigate how everyday work may vary in a typical scenario, the event of reduced visibility caused by fog, a FRAM instantiation was created. This used the functions described in the generic FRAM model to discuss how the performance of work is affected in this scenario, thereby demonstrating how potential variability may be identified (**Step 2**), then how it may propagate (**Step 3**) and be managed (**Step 4**). Details may be found in Paper II.

3. Instantiation of a case study

Similarly, a FRAM instantiation was created to explore a case study (Paper III), aiming to show work is actually performed, and how pilots and VTS operators deal with uncertainty in their work. The instantiation once again showed how variability manifested itself (**Step 2**), spread through the ship-shore system (**Step 3**) and was managed (**Step 4**), this time in an actual event.

In applying the FRAM method in this way, added value was found in borrowing inspiration from the various themes of the work studies tradition discussed in Section 3.5. For example, the notion of work as activity and conscious/unconscious operations aided in identifying and describing functions, particularly those associated with tacit knowledge. Following objects (vessels) and the formation or (re)configuration of a network (pilot-VTS-vessels…) were central to developing instantiations of the scenario and case study. Making work visible, symmetry between humans and non-humans and a broader concept of uncertainty were guiding principles throughout. Figure 7 shows how the empirical studies (top left) were used throughout the FRAM method (centre) to produce the various analyses and models (left centre, bottom), and how FRAM was informed by the various themes 'borrowed' from the work studies traditions (right). This will be discussed further in Section 6.2.

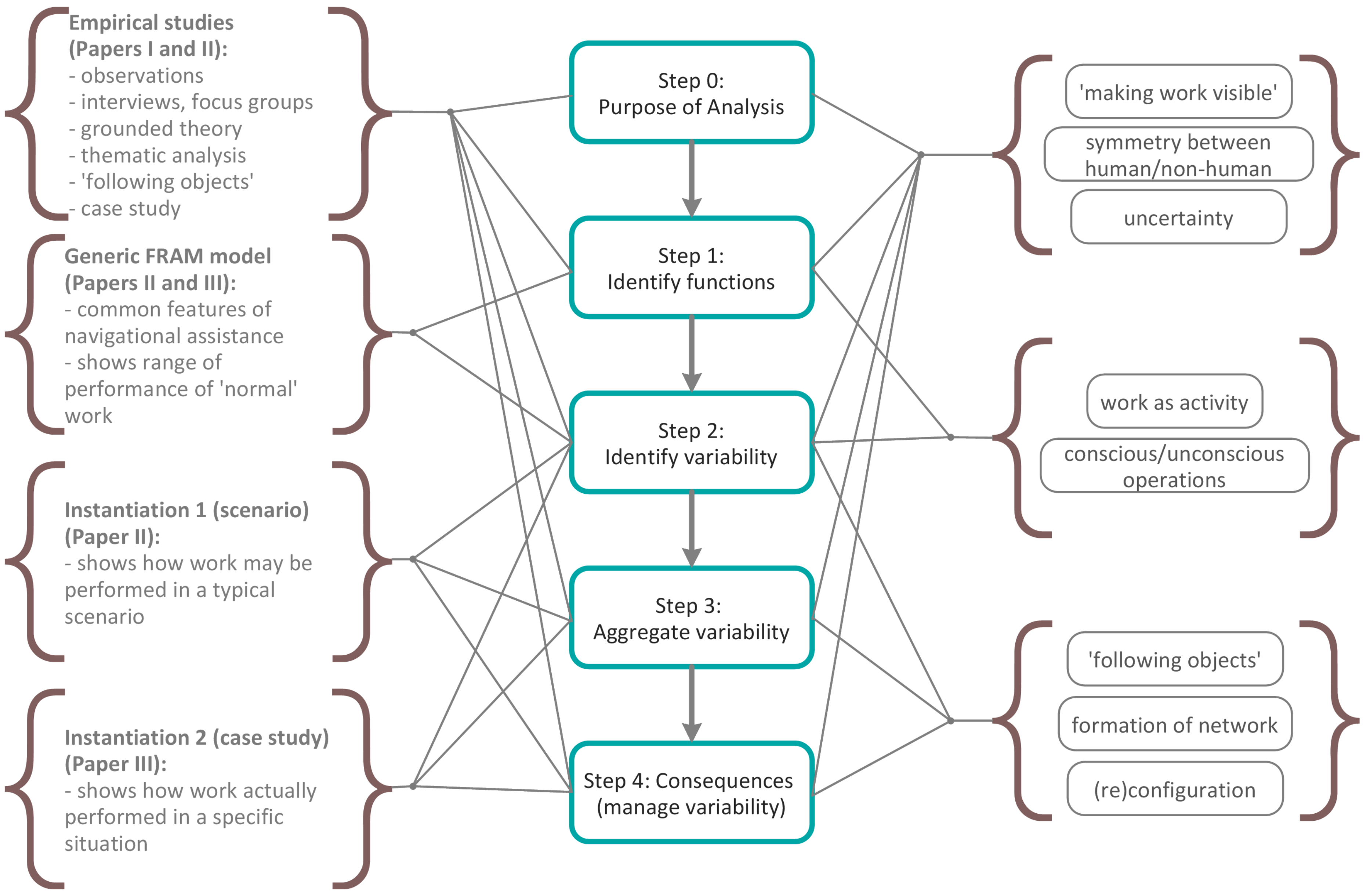


Figure 7. Diagram showing application of FRAM method.

5 Results: describing and modelling navigational assistance

This section aims to simply present the results of the thematic analysis (the 'empirical theory') and models of navigational assistance which were developed throughout the course of the research. How these assist in answering the research questions will be discussed in Section 6. For the remainder of the thesis, quotes from participants will be shown using *'single quotation marks and italics'*. Icons for pilot (red), VTS operator (green), vessel/crew (blue) and other vessels (grey) will be used to assist in interpreting models and visualisations.

5.1 Empirical theory and model (Papers I and II)

The empirical theory of navigational assistance which emerged from the thematic analysis (see Section 4.3 above) may be summarised as:

> *The work performed by pilots and VTS operators (whether on board or shore-based) is dependent on:*
>
> *(i) the use of local knowledge, preparation and foresight to integrate information about vessels/traffic, the physical environment and human/organisational factors from a wide range of sources, and;*
>
> *(ii) communication and trust between the pilot, VTS operator, and the master and crew of the vessel;*
>
> *to provide timely assistance to vessels.*

Successful assistance - of which the main indicator is *'no incidents'* - depends on the pilot or VTS operator having an understanding of how all the factors above vary, how they are interlinked and how to handle them in a given situation. These factors *shape how work is performed* - they may be described as the Performance Shaping Factors (Hollnagel, 2012:57-58) or *success factors* for navigational assistance. Table 2 shows a summary of the results of the thematic analysis (organised into themes, sub-themes and categories), from which the empirical theory is derived.

Table 2. Themes and categories of success factors.

Themes	Sub-themes	Categories (selected examples)
Local knowledge		
	vessel/traffic patterns	- vessels: types, numbers, sizes, (crew) nationalities - traffic: routes, schedules, seasonal variations
	environmental factors	- geographical location: narrow channels, shallow waters, locks - navigational aids: buoys, lighthouses - weather patterns: tides, currents, fog
	experience	- shiphandling: vessels, seatime, navigational systems - pilotage/VTS experience: work systems, communication with crews, procedures

Preparation		
	vessel/traffic information	- pre-information: draught, size, cargo, destination, planned route - expected traffic situation: traffic density, number/type of vessels, expected times
	environmental information	- weather forecasts: tides, wind, water level, forecasting software - measurements: local/remote sensors - navigational information: diving operations, military exercises
	organisation	- handover: vessel/traffic/ environmental/organisational info - scheduling: work/rest hours, rest period - pilotage plan: ETA pilot boarding point
Foresight		
	vessel/traffic movements	actual traffic situation: traffic density, number/type of vessels, keeping to routes/ETAs vessel motion: proximity to other vessels, shallow water
	environmental conditions	- weather observations: visual, sensors, measurements - update forecasts
	ability to adapt	- interpreting information - effects of weather on vessels/traffic - time to take action
Communication		
	vessel-VTS, VTS-vessel(s), vessel-other vessels, vessel-tugs/fishing vessels, pilot-vessel crew	- VHF radio - navigation/VTS displays - voice, visual
Trust		
	successful communication	- voice: tone, readiness/hesitation, language skills - small talk, body language - gut feeling
	role, status	- local expert
Success = 'no incidents'		
	'no incidents'	- incidents, accidents, collisions, groundings, near misses… - proactive intervention, mitigation - incident reporting - formal/informal discussions, storytelling

Navigational assistance may also be visualised using an empirical model (Fig. 8). It should be noted that Figure 8 shows a later iteration than Papers II and III, and emphasises that navigational assistance is not a linear process, but involves continuously integrating and updating information, and building and maintaining a relationship of communication and trust, between pilot, VTS and vessels.

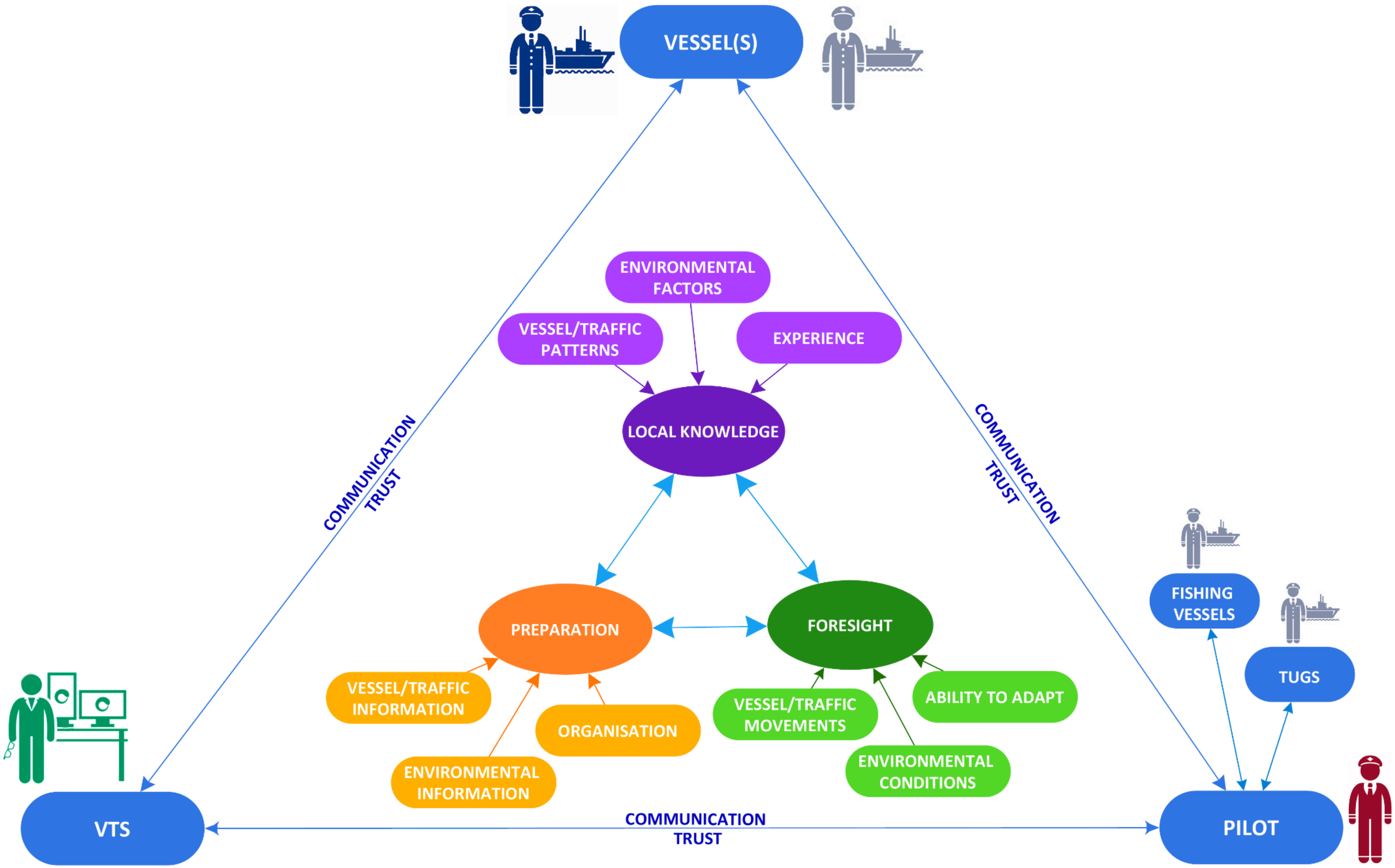


Figure 8. Empirical model of success factors for navigational assistance.

One may also view navigational assistance on a time continuum. Knowledge about vessels and traffic, the environment and human and organisational aspects of the ship-shore system, are built up on three time scales - long-term local knowledge, short-term preparation, and foresight about the present and near future. Local knowledge provides the pilot or VTS operator with the range of factors which should be taken into account, or the normal variation in everyday work. Preparation indicates which factors can be expected to play a part in their upcoming shift. Foresight enables them to act on the information available to them, interpreting this in the light of their knowledge and preparation. These factors are continuously communicated and distributed throughout the ship-shore system and brought to bear on the situation at hand (Fig. 9).

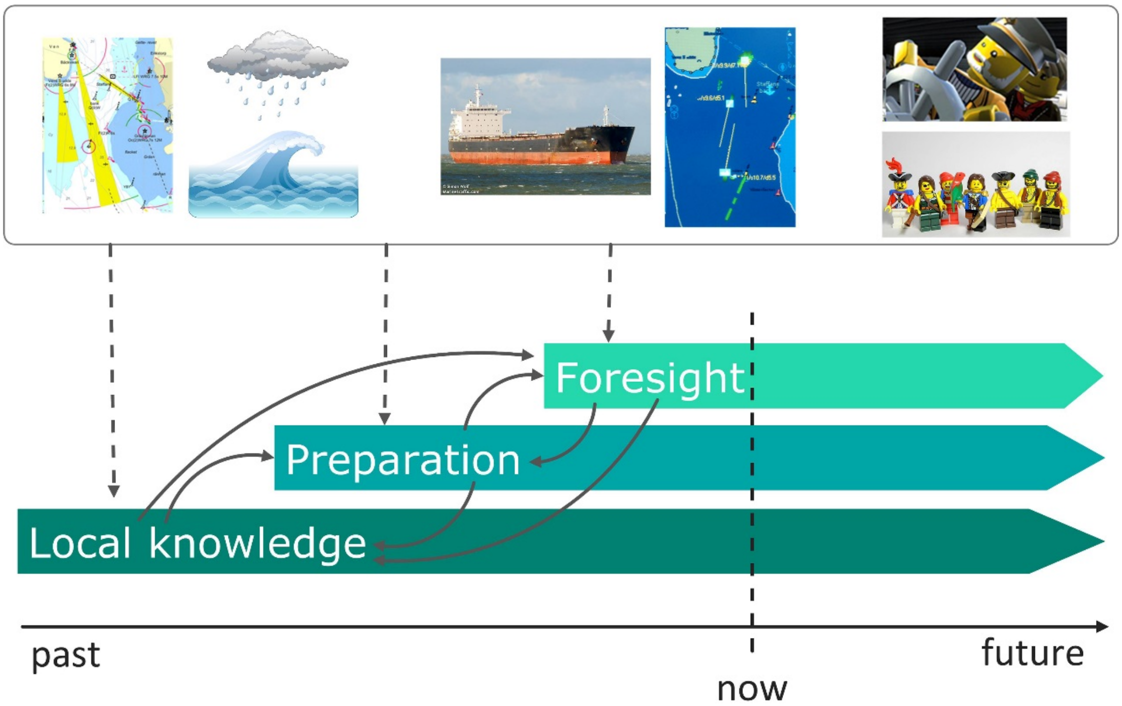


Figure 9. Navigational assistance on a time axis.

An in-depth description of the various success factors, and full details of how the empirical theory and model were derived from the data, may be found in Papers I and II. The work of pilots and VTS operators is complex and varied, and while it may be summarised in theories and models, the reader is strongly recommended to read the narrative exposition in Section 5 of Paper II in order to gain a richer understanding of the scope of normal or everyday operations. It was also a main finding of Paper II that thorough groundwork - by which I mean extensive empirical studies and preliminary data analysis such as coding/categorisation/thematic analysis or similar - is a prerequisite for enabling systems modelling approaches such as FRAM to reflect 'work as done' (see Section 6.2.2 below).

5.2 Generic FRAM model (Papers II and III)

The generic FRAM model shows the common features of navigational assistance, independent of location, situation or whether provided from vessel or from shore. It shows how navigation assistance is usually performed in everyday operations, with work being described in terms of the functions which reflect the activities necessary to perform successful assistance (Table 3).

Table 3. FRAM functions and corresponding success factors.

Function name	Success factor/Performance shaping factor
(to) use local knowledge	**local knowledge**
cluster functions:	
(to) know local traffic patterns	vessel/traffic patterns (vessels, traffic)
(to) know local geography	environmental factors (geographical location)
(to) know local navigational aids	environmental factors (navigational aids)
(to) know local weather patterns	environmental factors (weather patterns)
(to) have shiphandling experience	experience (shiphandling)
(to) have pilotage/VTS experience	experience (pilotage, VTS)
(to) prepare	**preparation**
(to) check in/outgoing vessels	vessel/traffic information (pre-information)
(to) check vessel information	vessel/traffic information (pre-information)
(to) check traffic situation	vessel/traffic information (expected traffic situation)
(to) check weather forecasts	environmental information (weather forecasts, measurements)
(to) receive handover	organisation (handover)
(to) receive pilot booking	organisation (scheduling)
(to) make pilotage plan (pilot function)	organisation (pilotage plan)
(to) use foresight	**foresight, ability to adapt**
(to) monitor traffic situation	vessel/traffic movements (actual traffic situation)
(to) monitor vessel motion	vessel/traffic movements (vessel motion)
(to) monitor vessel instruments (pilot function)	vessel/traffic movements (vessel motion)
(to) monitor radio communication	vessel/traffic movements (traffic information)
(to) monitor weather conditions	environmental conditions (weather observations, measurements, forecasts)
(to) communicate vessel-VTS	communication, trust
(to) communicate VTS vessel(s)	communication, trust
(to) communicate vessel-other vessels	communication, trust
(to) give navigational instructions pilot-vessel (pilot function)	communication, trust
(to) communicate vessel-tugs/fishing vessels (pilot function)	communication, trust

Figure 10 shows typical interactions between the functions, illustrating how information obtained through local knowledge (top left), preparation (middle left) and the use of foresight (bottom left) are integrated and communicated (right) between the actors. A detailed exposition, which synthesises the empirical data and analysis and the generic FRAM model, may be found in Paper II.

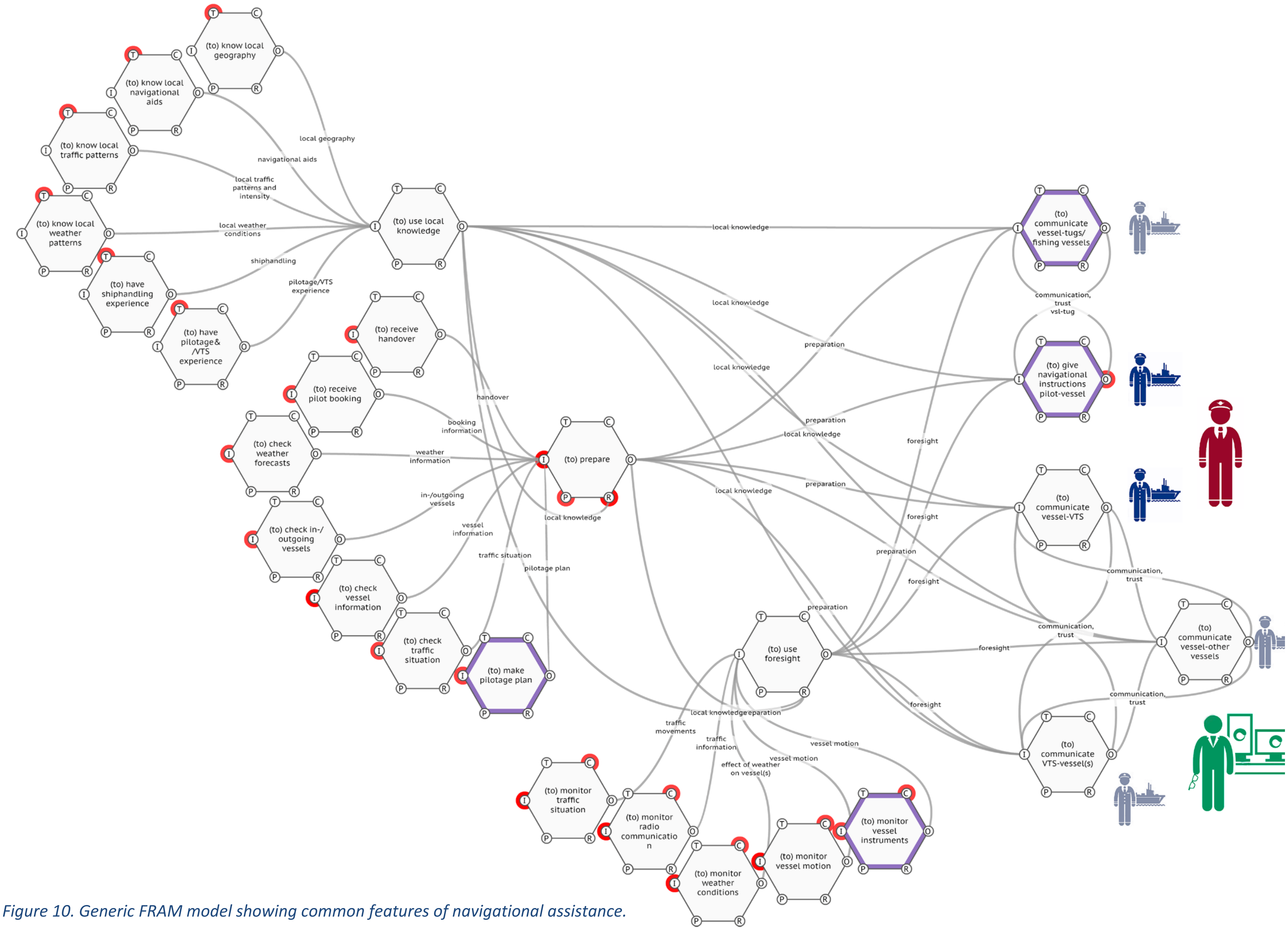


Figure 10. Generic FRAM model showing common features of navigational assistance.

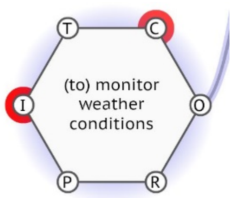
5.3 FRAM instantiations (Papers II and III)

To understand how the performance of work varies, and how the work system adapts to deal with emerging circumstances, two FRAM instantiations (Steps 2, 3 and 4 of the FRAM method) were created. The first scenario (Paper II) shows how pilots and VTS operators typically manage the effects of reduced visibility. The second involves a case study (Paper III) of a potential close quarters situation between three vessels.

5.3.1 Scenario: reduced visibility (Paper II)

The presence of fog, which reduces visibility, was identified by both pilots and VTS operators as a typical, but problematic, occurrence with potential consequences for the safety and efficiency of navigation. As one VTS operator said regarding the impact on workload, *'the worst is bad visibility - fog'.* In a worst-case scenario it may lead to collision or grounding. A FRAM instantiation was created around the function 'monitor weather conditions' (Table 4) to investigate, and is shown in Figure 11.

Table 4. Function '(to) monitor weather conditions'.

Function	**(to) monitor weather conditions**
Description  	Pilot/VTSO monitors observations and measurements of wind, waves, current, water depth, visibility etc., to determine their effect on vessel and traffic movements. Pilot/VTSO also compares observations with forecasts to make updated assessment of reliability of forecasts.
Aspect	
Input	Observations and measurements from visual estimates, buoys, cameras etc. Relayed information from vessels, lighthouses, VTS etc. Weather forecasts
Output	Assessment of current weather conditions Updated interpretation of forecasts
Precondition	Communication with sources of info (buoys, vessels, VTS etc.) Sources working properly
Resource	Local knowledge (local weather patterns, experience) Preparation (weather forecasts)
Control	Local knowledge (local weather patterns, experience) Preparation (weather forecasts) Multiple inputs may be control on each other's reliability
Time	Ongoing

The presence of fog was found to affect the performance of navigational assistance in several ways. How visibility is monitored depends on the pilotage/VTS area, the location within the area and sensors available to the pilot, VTS operator and vessels. Local knowledge and experience of weather and traffic patterns indicate what to expect in reduced visibility conditions, but as the location and intensity of fog change rapidly, it may be difficult to predict its effects in a specific situation. Vessels are more reliant on instruments and information from land, thus what is considered a 'safe distance' between them increases, as does workload and volume of communication on and between vessels and shore. Vessels *'want much more information, much more information… You notice that people, that the vessels, are more nervous too'.* For more detail, see Paper II.

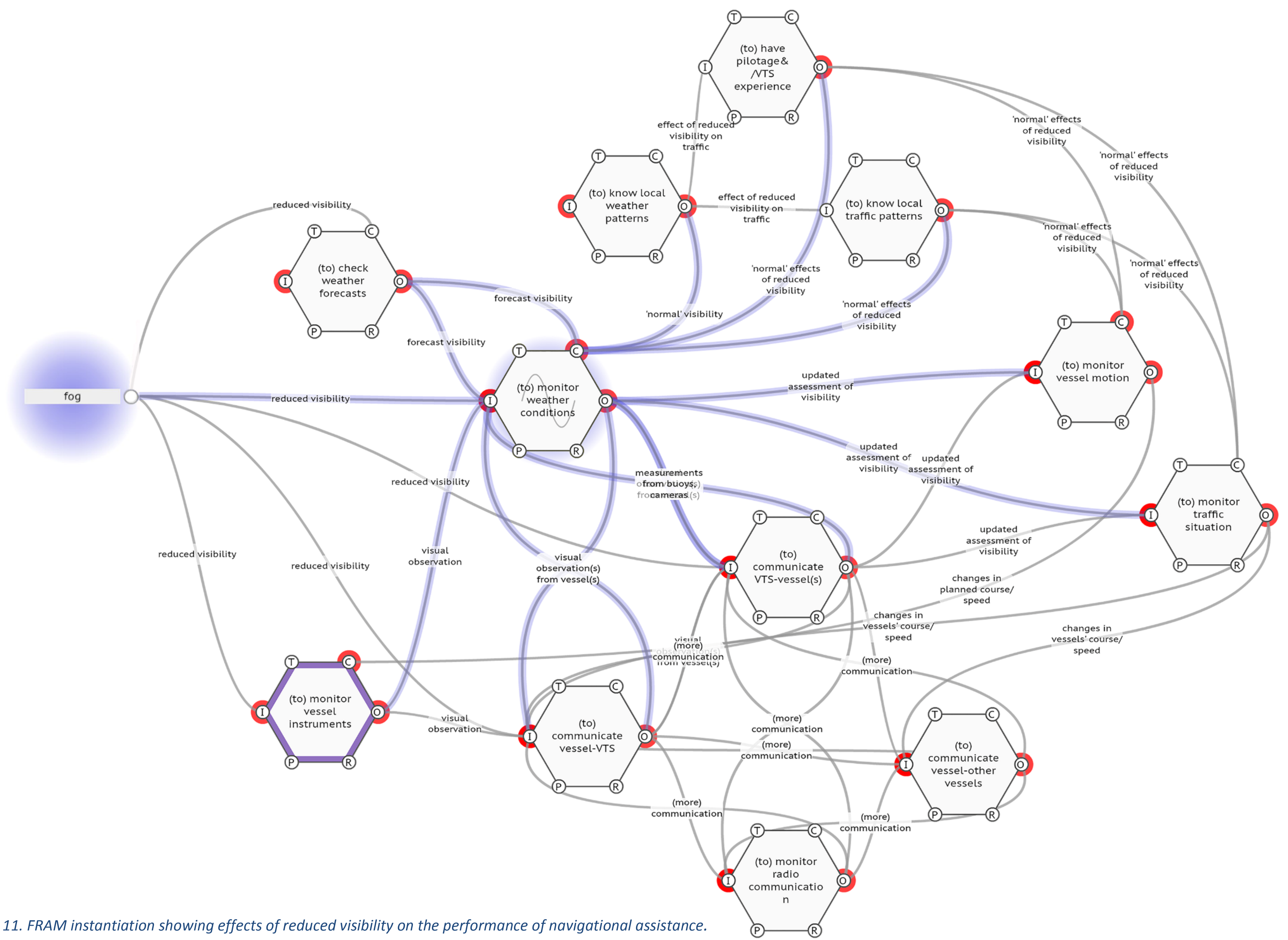


Figure 11. FRAM instantiation showing effects of reduced visibility on the performance of navigational assistance.

5.3.2 Case study: close quarters situation (Paper III)

While Paper II described how navigational assistance *may be* performed normally in a typical scenario, Paper III examined how it *was actually* performed in a specific case which was witnessed by the author when conducting field observations at a VTS centre (Fig. 12). A large bulk carrier, CHARLIE (Fig. 12, top right), found itself in a potential close quarters situation with two other vessels (ALPHA, FIg. 12 top left, and BETA, bottom left) near the entrance to a deep water route. Uncertainty regarding the vessel's draught restricted its manoeuvrability, increasing the risk of collision and grounding.

Figure 12. VTS screen (centre) showing close quarters situation between vessels (vessel images: MarineTraffic.com).

Due to conflicting sources of information, CHARLIE's draught was uncertain when entering the VTS/pilotage area; it was on or near the limits for safe passage through the area. This was discussed but not resolved by radio communication between VTS and pilot/vessel. CHARLIE was treated as a deep draught vessel, meaning that it should take the deep water route. When approaching the entrance to this route, it became clear that CHARLIE would find itself in close proximity to vessels ALPHA and BETA, and shallow water, unless one or more vessels deviated from their present course. The situation was resolved by negotiations between the vessels, which were monitored by the VTS operator.

Starting with the function 'check vessel information', a FRAM instantiation was created in three parts to discuss the case study, showing how the effects of uncertainty or variability regarding the draught of vessel CHARLIE spread through the ship-shore system and affected the performance of work (summarised in Figure 13). A complete account of the case study and discussion of the FRAM instantiations is found in Paper III.

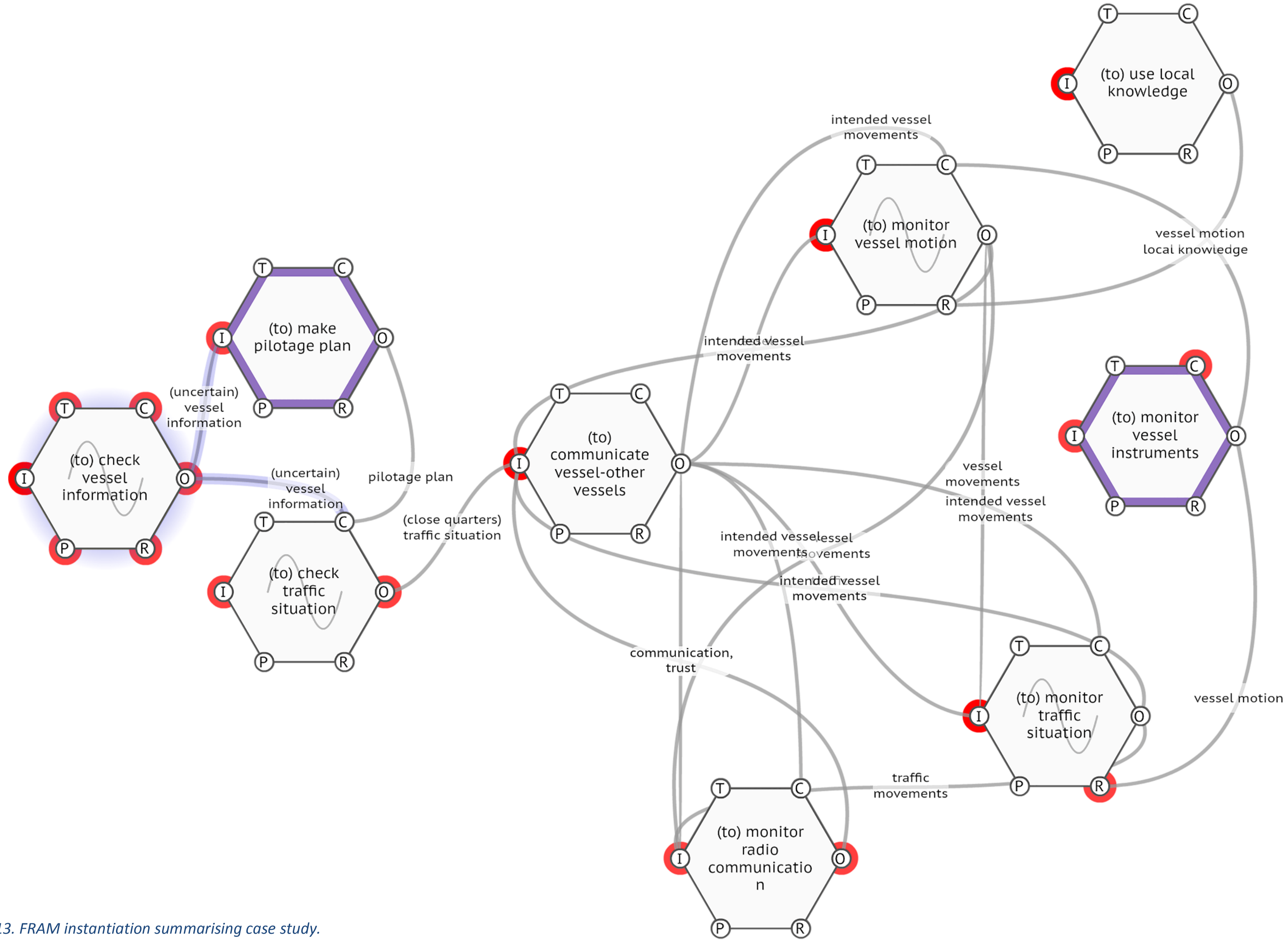


Figure 13. FRAM instantiation summarising case study.

6 Discussion

6.1 Understanding safety in the context of sociotechnical work (Research question 1)

6.1.1 Defining safety

Defining safety or 'what is safe', as we noted in Section 3.2, has occupied researchers, regulators, industry and practitioners for decades, and will undoubtedly continue to do so in the foreseeable future. As the pilots in the first focus group emphatically expressed, *'What is safety? We can't measure it, but what we can see is that nothing went wrong.'* In subsequent studies, questions regarding 'what is safety?' - both on an abstract level and in concrete situations e.g. 'what is a safe visibility limit for entering this harbour?' or 'what would be a safe distance between these vessels?' - invariably elicited the response *'it depends on…'* followed by a list of factors such as those found in Table 2 above. This was commonly followed by animated discussion between colleagues and stories of situations or incidents.

We can with some degree of certainty say what safety is *not* i.e. easily defined or quantified. One may in fact surmise that the abundance of safety science literature and research into the tension between safety in principle and in practice, and conceivably the volume and complexity of safety rules and regulations themselves, are a consequence of the challenges of understanding what safety is and how we may know it. This is somewhat of a conundrum, given that much safety-critical sociotechnical work, such as navigational assistance, is governed by rules, guidelines and procedures stating that its express purpose is to *improve safety* and safe operating limits defining *what is safe and what is not* (see Sections 1.1 and 3.2).

For example, Røyrvik (2012) describes the use of the weather window, a typical safe operating limit in the offshore industry, as a 'technologically articulated entity in the oil industry's conquest of nature'; a representation of what is 'safe', which does not accurately capture the reality of the operation. Rules governing safe operation may be 'work as imagined' (Hollnagel, 2012; see also Hale & Borys, 2013), they may define safety in principle and not necessarily in practice. However, the studies undertaken in this thesis showed them to be still part of the context of work; rather than viewing 'work as imagined' and 'work as done' as a dichotomy (as was my inclination before embarking on these studies), one may achieve a greater understanding of safety by investigating the dialogue between them, as suggested by Grøtan (2013) and Hepsø (2014).

Visibility and draught limits for entering/leaving harbour or transiting channels are typical examples of safe operating limits within navigational assistance (see Papers II and III); these may either be set internationally (e.g. recommended under keel clearance in international waters), nationally (e.g. characteristics of vessels which must take a pilot or report to the VTS) or locally (e.g. visibility limits in harbour).

For example, in the area discussed in Paper III, there are two channels with guaranteed depth 8 metres. Recommended maximum draught in the channels is 7.2m and 7.7m respectively - interestingly, the difference being due to political and economic considerations (e.g. who owns the waters, and thus provides the pilotage services), rather than safety issues. The pilot or VTS operator may *'only inform them that the channel is eight meters, and what the actual water* *level is, and it's up to the Captain'*, but *'most of the cruise ships, you know, can be quite deep and there are not a lot of gaps… they take chances, go through with 7.95… so they must own that risk'.*

In the reduced visibility scenario in Paper II, we noted sight restrictions in one pilotage/VTS area (two nm in loaded condition and one nm in unloaded condition). Compliance will not necessarily guarantee safe passage: indeed, whether visibility is within limits, whether a vessel has complied, or whether the limit is appropriate in the circumstances, are dependent on, and consequently affect, a variety of factors, including traffic situation, available sensors, familiarity with the area, if a pilot is on board, communication with the VTS and other vessels, and so on. Thus the sight restrictions do not by themselves define what is safe or not, but are one of many factors which should be taken into account, and which shape how work is performed (see Section 5.3.1, Fig. 10)

In the case study in Paper III, the VTS operator was largely unconcerned by the prospect of a small distance or CPA (closest point of approach) between the vessels, saying *'if the vessels, on the bridge, are not worried, why should I sit here and be worried?'* Despite shallow water, restricted manoeuvrability and uncertainty about one vessel's draught, he considered the situation 'safe' since the vessels *'have been talking so they know what is going on'*. Shortly before, his colleague had described a similar situation resulting in a CPA of 0.2 nm as *'a little bit too close'*, since contact with the vessel capable of taking avoiding action was only established at the last minute. The lack of communication between the parties and time to take appropriate action therefore made this situation 'unsafe'.

Thus 'safety' or 'what is safe' cannot be easily defined or quantified, but always *'depends on…'*

6.1.2 Success vs safety

Despite the challenges of defining and measuring safety, the pilots and VTS operators in the empirical studies unanimously and unhesitatingly described *successful assistance* as *'no incidents'*, or *'No incidents - no groundings and no collisions… No incident report written. That means we have done our jobs.'* Taking action to avoid incidents is seen as a measure of success, for example *'when we have done something proactive to prevent something from happening… there are several people each year who have prevented vessels from going aground. That's a great indicator'.* Mitigating action is also seen as successful work, even in cases where *'sure, there was an incident but it could be much worse'.* Even if the action has no effect, it may be seen as a success: *'if I have an incident and it went aground, but I have tried to do anything, that's a success as well, I think, because you have tried. But maybe they're sleeping or… What could we do? But we have tried.'*

The reader should also note that, since the role of navigational assistance is *advisory* (IMO, 1972, 1997; IALA, 2016), the pilot or VTS operator cannot enforce compliance with their recommendations, although, as one VTS operator said, *'we are recording [radio and data traffic] and if there would be an incident, and they didn't follow the advice, it would not look good'*.

Safety is the ultimate goal of both pilotage and VTS - as clearly stated both at the operational level and at the highest level of organisation by IMO (2016a,b) and IALA (2016). It is measured on a national and local level of organisation by the number of incidents, accidents, reports and so on. But for the practitioners, a *successful outcome* is not necessarily a safe one. Success is described superficially as a 'non-event' (Weick, 1987), but we may also consider this a 'black box' (Kaghan & Bowker, 2001), which once opened reveals both 'non-events' (absence of incidents) but also 'events', including actions taken to avoid or mitigate incidents, *whether or not* these actually lead to a safe outcome. Therefore navigational assistance may be seen as a practice in which success is related primarily to the performance of work but safety to its outcome (see also Hollnagel, 2012, 2014b; Haavik et al., 2016). This point is definitely worthy of further investigation, as it has implications for the ability of approaches such as Resilience Engineering and Safety-II to investigate safety through studying everyday operations and events.

6.1.3 To understand safety, we must first understand work

A common thread, which can be drawn through the literature on organisational safety, human factors, systems theory and work studies, and through the empirical research described in this thesis; namely that *safety emerges (or not) as the result of the interactions between human and non-human actors in the context in which work is performed.* Whether one starts from the Resilience Engineering/Safety-II focus on 'events' instead of 'non-events' (Hollnagel et al., 2006; 2011; Hollnagel, 2014b), the cybernetics view of safety as a second order emergent property of a complex system (Wiener, 1948; von Bertanlanffy, 1968; Skyttner, 2005), or the stories of pilots and VTS operators, it becomes clear that, in order to understand safety in the context of sociotechnical work, we must first understand *work*. As one VTS operator said, *'That's why I'm sitting here, to improve safety, and I do that by doing my job. […] But you don't say that a fireman is good at fighting fires. "It's my job", he'll say. "It's great, but it's my job".'*

6.2 Understanding and describing sociotechnical work (Research question 2)

6.2.1 Reviewing the research approach

As described in Section 3, there are as many different approaches to understanding work as there are to understanding safety. The approach taken in this thesis was thus iterative and abductive, taking its starting point 'in the wild' (Hutchins, 1995a; Wilson, 2014) - in the practice of navigational assistance - but also complementing this empirical understanding with an intellectual investigation into the commonalities and controversies of various theoretical and methodological approaches to work and safety, and integrating these themes together with the empirical studies and FRAM analyses. The result thus aiming to achieve an understanding of navigational assistance and its contribution to maritime safety with a thorough grounding in both theory and practice.

Previous research into pilotage (e.g. van Westrenen, 1999; Mikkers et al., 2012) and VTS (van Westrenen & Praetorius, 2012; Praetorius & Hollnagel, 2014; Praetorius et al., 2015) (see Section 2) has shown the value of viewing navigational assistance in its various forms as a complex sociotechnical system: it has highlighted the interaction between pilots, VTS operators and their work systems and environment; it has shown how they work to improve maritime safety. These studies have also shown the importance of eliciting the knowledge of practitioners - through qualitative methods such as observations, interviews and focus groups - when attempting to understand and describe the practice of work.

The research undertaken within this thesis is inspired by, and a continuation of, these previous studies. However, by starting 'in the wild', it became apparent that, although a 'harder' systems engineering approach such as FRAM may provide many valuable insights, it may not fully address certain important aspects of navigational assistance. Haavik et al. (2016) contend that, by employing different perspectives or 'ways of seeing', one can increase the 'knowledge of how organisations and sociotechnical systems work, and how they work safely' (2016: 9). Since understanding work and safety is the primary aim of this thesis, this was done here by complementing a Resilience/Safety-II perspective with insights from the work studies tradition. Several authors (e.g. Checkland, 2000; Le Coze, 2013a,b; Grøtan, 2013; Hepsø, 2014; Haavik et al., 2016) have suggested that this type of 'double level' approach may in fact benefit systems engineering approaches to work and safety.

I have been asked on several occasions whether I would have achieved the same results had I approached the field with the express purpose of conducting a FRAM analysis, or if I had started by asking participants to describe safe navigational assistance, rather than successful. The answer is probably 'no'. I cannot say if the approach taken was better or worse; it was certainly time-consuming, not least in terms of writing and trying to draw the various threads together to form a coherent account. This however is true of any approach which depends upon a thorough understanding of how work is performed (see also Praetorius et al., 2015; Hoffman & Lintern, 2006; Kirwan, 2000). But hopefully the following sections will demonstrate the added value of using such a multi-disciplinary approach to understanding safety in the context of sociotechnical work.

6.2.2 Making groundwork visible

Empirical studies using qualitative methods are the foundation for the majority of research done within each of the fields or traditions described in the theoretical framework (Section 3). Since 'the best sources of information about activities of interest is [sic] the people who actually perform the work' (Hollnagel et al., 2014:39), qualitative methods are recommended to aid in 'making work visible' (Suchman, 1995). Data collection using observations, interviews, focus groups etc. and data analysis using coding and categorisation, often inspired by grounded theory, are as central to creating an ANT-account as a FRAM model. As Czarniawska (2014:25) contends, such methods are 'the commonsense of fieldwork'. Or as one VTS operator said of 'good' research, *'maybe for the people who did that research it was like 'wow', but for me it was very clear. I think me and [another VTSO], we could have come to the same results when thinking logically'.*

Such studies require extensive, time-consuming groundwork on the part of the researcher and the participants; the studies are reliant on both the knowledge of practitioners and their ability to communicate this, and on the role of the researcher as an observer, but also a translator or interpreter of the observed. This is immediately apparent in the work studies tradition (e.g. Suchman, 1993; Hutchins, 1995a,b; Latour, 1996; Orr, 1996; Lindahl, 2005; Haavik, 2013), where accounts of work practices are presented in detail; the study of work results in the production and reproduction of narrative (Czarniawska, 2014). The importance of thorough groundwork is also implicit in, and a necessary part of, systemic approaches such as FRAM (see e.g. Praetorius et al., 2015; Cabrera Aguilera et al., 2016).

However, I contend in Paper II that, while aiming to present a holistic systems view of work, the focus on the method and resultant models (e.g. describing work in terms of functions) may ironically oversimplify the work practice being studied. It may mask its detail (see also Le Coze, 2013a,b) and reduce the results of the groundwork to simply input to the method or model. One should explicitly recognise the value of the time and effort spent in the field, and in the subsequent analysis of empirical data, and present the results as being of value in their own right. Often details may seem extraneous, but they bring us closer to understanding daily work. For example, when asked the most important characteristics of a VTS operator, three participants replied: *'caffeine tolerance', 'yeah, chocolate', 'cake… well patience, because sometimes the ships can be a bit annoying'*. This seemingly superfluous information reveals a very important aspect of work - the ability to stay alert during periods of inactivity and boredom - which may be difficult to capture in a systemic representation, and thus remain invisible to other stakeholders such as designers and managers.

Seeking to present a balance between what was learned about navigational assistance through empirical studies and through the FRAM analysis, and show the added value each has brought to the other, has not been easy, and I am unsure whether I have achieved this. However, the point I wish to make here is that by complementing a systems model with a richer narrative description (see e.g. Hepsø, 2014), a systemic approach such as FRAM, one may increase the sense of ecological validity, and one may provide weightier evidence that the resulting model does actually portray 'work as done', rather than 'work as imagined' (Hollnagel, 2012). (Once again, the reader is encouraged to read Papers II and III in addition to the results summary in Section 5.)

6.2.3 Making knowledge visible

Hoffman and Lintern (2006:203) claim that, as work systems become more complex, the 'elicitation and representation of expert knowledge (and the subsequent use of the representations, in design)' becomes a pressing issue for research. In other words, how do practitioners make sense of the information available to them, and how can we design to support them?

Mikkers et al. (2013) have previously emphasised the role of tacit knowledge and experience in the work of pilots (see also van Westrenen, 1999 etc.), as have Praetorius et al. (2015) with VTS operators. The empirical studies conducted here also showed the importance of *local knowledge, preparation and foresight* in the performance of navigational assistance. Obtaining local knowledge is a core element in the training of both pilots and VTS operators. Being the *'local expert'* is fundamental to the pilot or VTS operator's ability to instil trust and confidence in vessel crews: *'I have "status" as soon as I step on board, they see me as the local navigation expert'* (see also Darbra et al., 2007; Bruno & Lützhöft, 2009). Although several pilots considered this 'status' undeserved (the author respectfully disagrees), it is undoubtedly an important element of navigational assistance, and one which means the advice of pilots and VTS operators is usually followed by vessels.

Monitoring of screens, instruments, vessel motion etc. is also central to the performance of navigational assistance (see also van Westrenen, 1999; Praetorius et al., 2015). By monitoring the information available to them, the pilot and VTS operator can assess how a situation is developing and use *foresight* to enable vessels to take timely and appropriate action, as exemplified in the discussion of function 'monitor weather conditions' in Paper II. Monitoring is also a cornerstone of resilience (Hollnagel, 2011), a prerequisite for a system to adapt to both expected and unexpected events. As such it has generally been accepted in systems models, despite being an internal process, and hence difficult to observe in practice.

The use of tacit knowledge and internal processes, though potentially unmeasurable and unfalsifiable (see Dekker & Hollnagel, 2004), are paramount in providing successful navigational assistance, and must be included in a work system description if we are also to succeed in 'making work visible' and describing 'work as done'. Resilience Engineering/Safety-II promotes looking at successful everyday work; FRAM allows us to investigate success (and indeed failure) through defining the Performance Shaping Factors which affect the performance of work and using these as functions within the FRAM method (Section 0, Hollnagel, 2012:57-58). Since functions are, according to Hollnagel (2012:40-41) the 'activities - or set of activities - which are required to produce a certain outcome', Activity Theory proved helpful in translating Performance Shaping Factors into functions.

We have seen in Section 3.5.3 that activities may operate on several levels of abstraction (Karlsson, 1999). The *activity* of navigational assistance (Fig. 14) is performed by pilots or VTS operators (actors) using local knowledge, preparation, foresight (tools) to integrate and communicate information to vessels in order to improve maritime safety (goal). In order to achieve its goal, navigational assistance comprises a set of activities, including concrete actions (e.g. 'check weather information'), conscious operations (e.g. 'monitor weather conditions') and unconscious operations (e.g. 'use local knowledge') (see Table 3 and Paper II for further examples). By allowing these various levels of activities which shape the performance of work to enter as functions into a FRAM model, we can thereby include tacit knowledge and internal processes into a description of work as a sociotechnical system.

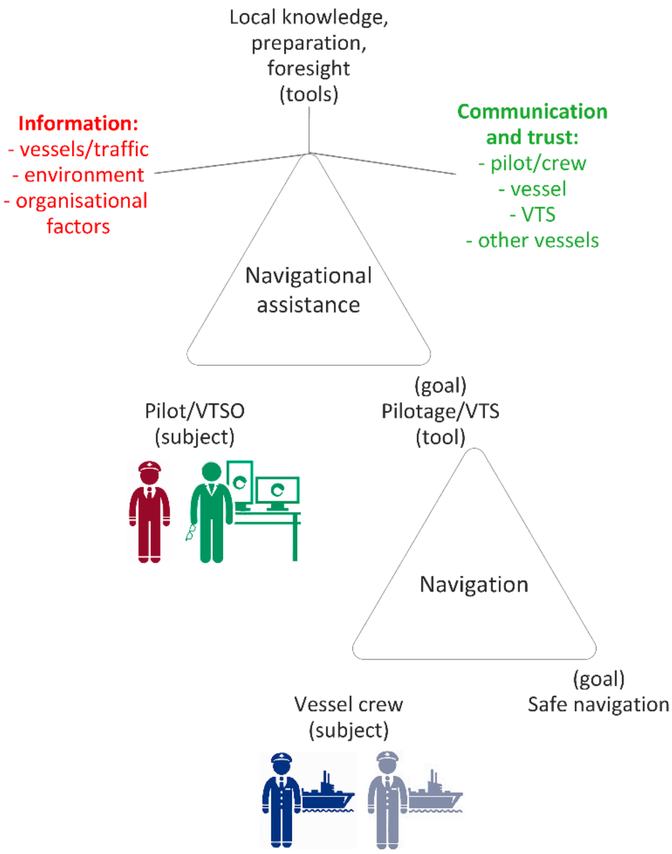


Figure 14. Navigational assistance as activity triangles (author, forthcoming; inspired by Andersson et al., 2011).

6.2.4 Sociotechnical work is… *sociotechnical!*

In addition to 'making work visible', one of the core themes of this thesis is the sociotechnical nature of work; that by invoking the notion of *symmetry* - by not distinguishing between human/non-human or social/technical, as in the STS tradition (Section 3.5.2 above) - we may better investigate how humans and other actors *work together* to perform work and improve safety. As Law (1990) stated, 'we are *all* monsters, outrageous and heterogeneous collages' (1990:18), in which 'In practice nothing is purely technical. Neither is anything purely social. And the same may be said for the economic, the political, the scientific, and all the rest.' (Law, 1990:10; also Latour, 2005). As with 'making work visible', symmetry may influence how we approach the field, choice of methods, observational strategy, how we describe and ultimately how we visualise the topic of interest.

i. Actors are sociotechnical

As an observational strategy (Czarniawska, 2014), for example *'following the vessel'*, it may aid in understanding how human operators relate to their workplace. Throughout the empirical studies, it became clear that pilots and VTS operators themselves do not distinguish between human and non-humans in their work. The vessel is a normal unit of interaction, as can be seen in the various quotes used throughout Papers I, II and III, in particular the case study in Paper III, e.g. *'we had two vessels coming southbound'; 'if the vessels, on the bridge, are not worried…'; 'this is BETA'; 'BETA is local'*. Clear parallels may be drawn to Woods' concept of adaptive units in Resilience Engineering (2015), as well as the notion of levels of abstraction in Joint Cognitive Systems (Hollnagel & Woods, 2005; exemplified by van Westrenen &

Praetorius, 2012), or (confusingly) levels of decomposition in Cognitive Systems Engineering (Rasmussen, 1997; Vicente, 1999; Hoffman & Lintern, 2006; Lintern, 2009). Visualising navigational assistance as a Joint Cognitive System (Fig. 15) clearly illustrates this point.

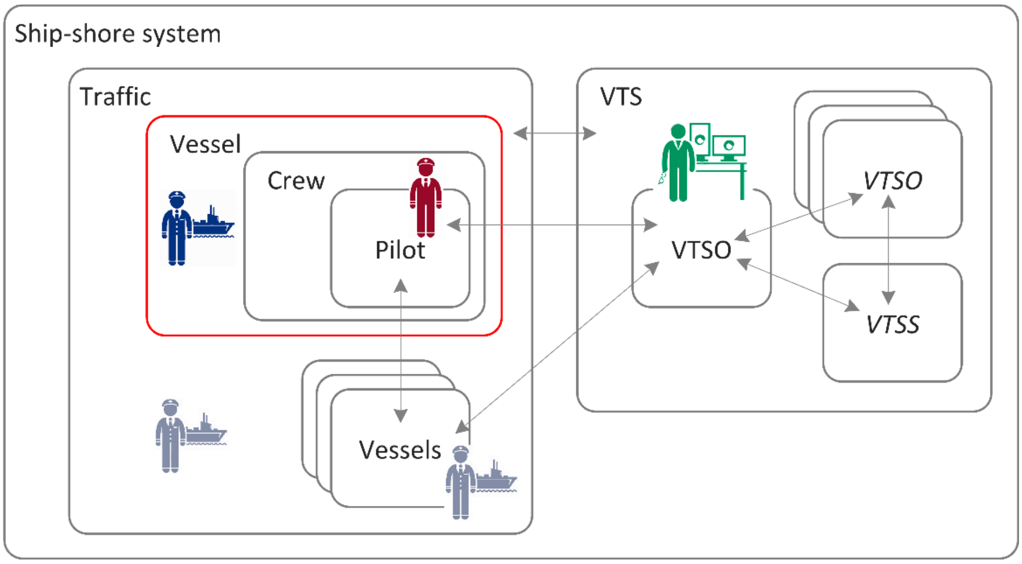


Figure 15. Navigational assistance as a Joint Cognitive System (author, forthcoming; inspired by van Westrenen & Praetorius, 2012).

In discussing interaction in the context of navigational assistance, it thus makes sense to refer to vessels as actors. This is mainly uncontroversial both within systems and work studies perspectives. The studies in this thesis have however described navigational assistance as a cooperative practice not only between pilots, VTS operators, vessels and their crews, but also various sensors, instruments, geographical location, weather, international regulations, local rules and many other factors.

One consequence of a symmetric view of sociotechnical work is that *who or what may be or become an actor* is not pre-defined (Latour, 2005; Sayes 2014; Czarniawska, 2017). One may legitimately consider that in the reduced visibility scenario, the fog, cameras, forecasts, visibility limits etc. are actors, as are the vessel draught, email, navigation marks and so on in the case study. Being more precise, they *become* actors as events unfold, and as the scenario/case are analysed. For example, fog is one of many environmental conditions which may affect the performance of work; only when it is actually present or predicted does it come to the foreground as an actor (similar to 'foreground' functions in FRAM (Hollnagel, 2012)). Likewise actors may not be one 'thing' but a synthesis of socio-technical-etc. elements: the draught measurement is a combination of the physical draught, together with the reading from sensors/visual estimates, communicated measurements and interpretation of the pilot/VTS operator.

To clarify, this does not mean that non-human actors, such as the fog or the vessel draught, consciously or intentionally act or create uncertainty which must be dealt with by the system, but by their interaction with other parts of the system, they may affect, impact upon and be a part of how work is performed (see also Latour, 2005; Sayes, 2014).

ii. Systems are sociotechnical

In order to describe actors, and consequently systems, as sociotechnical in the sense described above, one must depart from the traditional view of systems as made up of human-technological-organisational components, and see them rather as Law's monsters or heterogeneous collages (1990). The reduced visibility scenario and the case study illustrate how pilots and VTS operators interact both with socio-technical-organisational and natural phenomena, and representations of them in various forms (see also Latour, 1986, 1995/1999), as shown in Figure 16 (also Fig. 1 above). In order to describe this work as a sociotechnical system, one should accept, as Wilson (2014) and Le Coze (2013a,b) suggest, that systems theories and models should be also able to account for interaction with natural and other phenomena.

Figure 16. VTSO at work, showing VHF radio (left), chart displays (centre), email/ship reporting (right) and weather (top).

This however raises questions about the role of control in sociotechnical systems. Feedback/feedforward and control (Wiener, 1948; Skyttner, 2005) are clearly useful concepts for expressing the interaction between humans and technology, in particular how information is processed and communicated (as illustrated by viewing navigational assistance as a closed loop control system, Fig. 17). Feedback/feedforward may enable the foresight necessary to provide timely assistance to vessels. Strategic and tactical control enable planning of e.g. pilot transfers and intake of vessels, thus allowing traffic to flow efficiently. As such, control is an important part of both on board and shore-based navigational assistance (also van Westrenen, 1999, 2013; van Westrenen & Praetorius, 2012; Praetorius & Hollnagel, 2014).

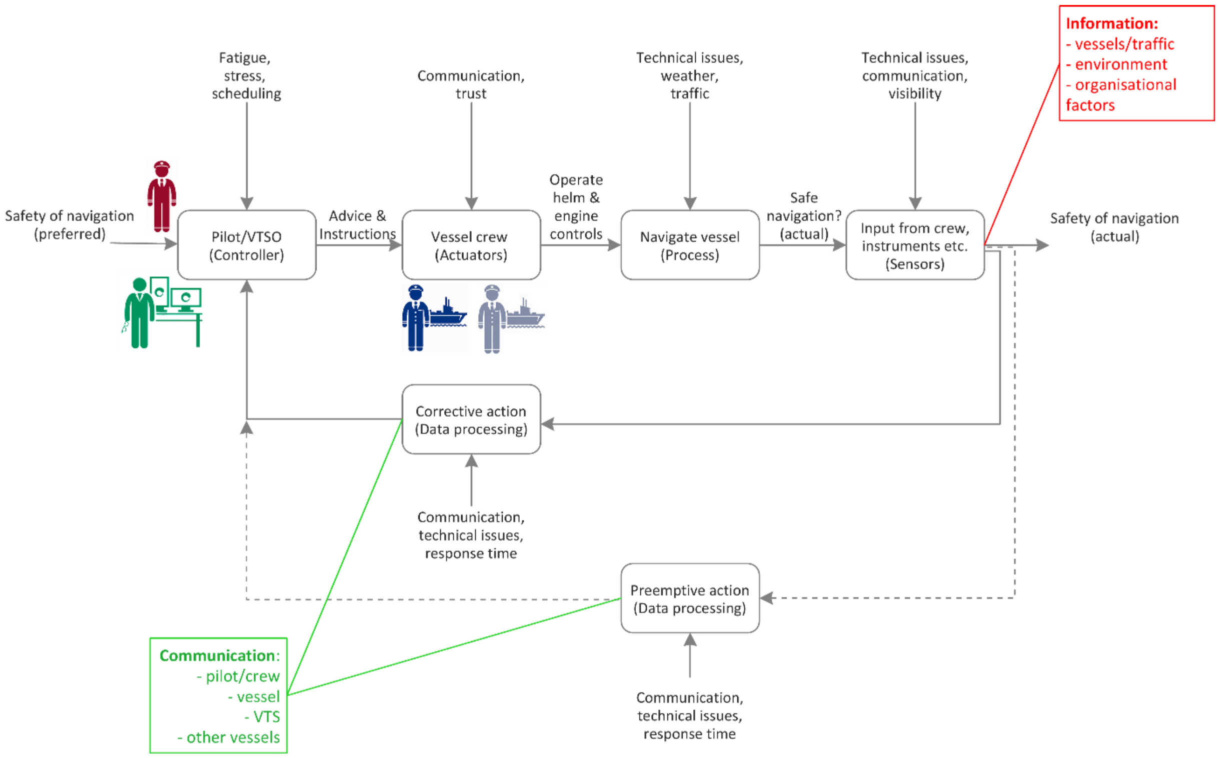


Figure 17. Navigational assistance as a closed loop control system (author, forthcoming; inspired by Skyttner, 2005).

However, a symmetric view discourages the notion of control as a defining feature of sociotechnical work. Rather than defining membership of a system as that which can be controlled, with that which cannot being external to the system (e.g. Hollnagel & Woods, 2005), symmetry enables the inclusion of human or non-human actors, social, technical or otherwise (Law, 1990; Latour, 2005), but also controllable and uncontrollable. As the empirical theory/model, and the generic FRAM model and instantiations show, nature and interaction with it may be seen as an integral part of the work system.

Acknowledging this also enables us to describe work in terms of cooperation and negotiation between actors (similar to Callon, 1986; also Suchman, 1993), rather than control over them, e.g. in the way fog changes the determination of safe distance and volume of communication between vessels (Paper II), or the way the water depth limits the manoeuvrability of the vessels in the case study (Paper III). (See Røyrvik (2012) for a discussion of the tendencies of industry nevertheless to transform that which cannot be controlled into that which can, thereby creating safety in principle but not in practice.)

iii. Functions are sociotechnical

Similarly, in describing a work system in terms of functions or activities (e.g. Hollnagel, 2012: Hollnagel et al., 2014; also Karlsson, 1999), we shift focus from *who or what is performing the function* to *what is to be done*, and *how it is achieved*. We see once again how humans and non-humans work together to achieve a goal. By not classifying functions, or their consequent variability, as human, technical or organisational as suggested in the FRAM method (Hollnagel, 2012: Hollnagel et al., 2014), but allowing them to remain sociotechnical[3] (as in Papers II and III), a more accurate description of how work is performed may be achieved.

For example, on a generic level, the function '(to) use foresight' includes the monitoring of various sources of information (from vessels, sensors, environmental data and forecasts, communication tools etc.), interpretation in the light of local knowledge and preparation, and communication of the relevant information between pilots, VTS operators and vessels. Performance of 'monitor weather conditions' in foggy conditions entails the pilot or VTS operator interacting with humans (vessel crew, lighthouse personnel), but also local geography, vessels, sensors, cameras, measurements and forecasts (electronic, textual or graphical), procedures, and indeed the fog itself. 'Check vessel information' in the case study describes the pilot or VTS operator acting together with some or all of the vessel crew, vessels, draught sensors, chart display, emails, VHF radio, navigation marks, water depth and so on.

When investigating the uncertainty or variability in functions, it is therefore more helpful to consider the variability of both the actors and their interactions, than to predefine or categorise variability as human, technological or organisational. To exemplify, 'monitor weather conditions' varies not only due to the pilot/VTS operator's ability to interpret the information available to them, but also the inherent variability in the fog itself, the accuracy of weather predictions, the ability of sensors to measure visibility and so on. One cannot say that variability in this function is, or will be, predominantly human, technical or organisational, but is inevitably a combination of both aleatoric uncertainty in and epistemic uncertainty about each of the actors involved, and consequently in the performance of the function and its output.

iv. Sociotechnical actors, functions and systems all emerge, adapt and reconfigure, or, uncertainty is everywhere

By investigating a work system on a generic level (Sections 5.1 and 5.2, Papers I and II), and producing either a narrative description or a functional model, we may explore the scope of work as normally done and the factors which affect its performance. This may show the variability or uncertainty in the actors themselves and the functions they perform, from e.g. seasonal variations in traffic density or weather patterns to the *'gut feeling'* of a pilot or VTS operator when interpreting a forecast or making first contact with a vessel. It may also show the possible interactions between the actors/functions, and follow the ways in which uncertainty may potentially affect the ability of the system to achieve its goal. A work system such as navigational assistance can be described in a manner which is independent of location, situation or whether it is provided from ship or shore, potentially making knowledge of it transferrable between contexts.

However, when investigating how sociotechnical work is actually performed in a particular event or scenario, it becomes clear that both what is being done, how it is being done, and its effects are situation-dependent or *situated* (Suchman, 2007), and decision-making is often *distributed* between actors (Hutchins, 1995a,b). In the reduced visibility scenario, the determination of visibility is dependent on the means available for estimation (windows, sensors, cameras, forecasts etc.), and the ability to communicate this between vessels and

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[3] By which I of course mean *socio-technical-organisational-natural-political-economic…* (above, also Law, 1990; Latour, 2005).

shore, and significant, rapidly changing variations in each of these elements are seen both locally within each pilotage/VTS area and in time. Consequently the determination of a safe distance between vessels and to shallow water changes as the situation evolves. Likewise in the case study, the safe navigational space available to vessel CHARLIE is affected by multiple and conflicting sources of information about the vessel draught, and uncertainty about the accuracy of the usual control measures. This is not resolved, but negotiations with the other vessels and the VTS enable CHARLIE to navigate safely.

These examples show how outcomes (safe or otherwise) emerge from the performance of work, as discussed in the literature of both work studies and sociotechnical systems. Note, however that uncertainty is not necessarily actually reduced or resolved, it may simply be accepted by the actors as one of the conditions which shape performance in the particular situation; it may influence the choice of actions taken, as in the scenario and case study (see also Latour, 2005).

As mentioned in Section 3.6.3 above, uncertainty is everywhere. While a list of *'depends on…'* (see Section 6.1) may aid in understanding a work practice, both a richer description of how work is performed and a visual model may be more helpful for communication purposes. By tracing the connections or interactions within a work system in scenarios or events - denoted within STS (by e.g. Callon, 1986; Latour, 2005; Czarniawska, 2014, 2017) as the *formation of a network* - we can describe *and* visualise the uncertainties in the practice of work, how they are understood by the actors, how they spread throughout the system, and also how they are managed. We can show how the configuration of the system/network is not actually fixed (see e.g. Kaghan & Bowker, 2001; Checkland, 2000), but *reconfigures* to adapt to the circumstances (see also Suchman, 1993; 2007).

'Work as done' in any particular situation may be seen as one of all possible configurations of the work system, or by analogy as somewhere within Rasmussen's 'space of possibilities' (1997). FRAM proved to be very effective to demonstrate this point, but other models may prove equally helpful. A system model - e.g FRAM, but also others such as Le Coze's 'sensitising model' or 'socio-natural-technical systems model' (2013a,b) or Hoffman & Lintern's Work Domain Analysis 'activity overlay' (2006) - which may be reconfigured to show both a generic practice and specific situations, is a valuable tool in visualising the actions, interactions and uncertainties within sociotechnical work. It brings added value by literally 'making work visible'.

6.2.5 Managing the expected and unexpected

Although we have demonstrated that there is inherent uncertainty in many aspects of work, and adaptation to circumstances is inevitable, both pilots and VTS operators describe this as within the normal scope of their work. A common cause for concern throughout the organisational safety literature is the ability to deal with both the expected and the unexpected (e.g. Weick & Sutcliffe, 2001; Hollnagel et al., 2011; Hollnagel, 2014b). Or as Woods evocatively expresses it, the 'dragons of surprise' (Woods, 2016), lurking outside the boundaries of the system's ability to deal with emerging situations, similar to the monsters and dragons on old navigation charts and maps.

It will not be discussed in detail here, but a point worthy of further investigation is that what is 'expected' and 'unexpected' within navigational assistance is, like safety, not clearly defined. Uncertainty and variability are 'expected', though sometimes certain outcomes are considered unlikely or improbable. Most incidents are not 'unexpected' (at least from the practitioners' point of view), but are rather a consequence of the combination of factors at play in that situation. As the principle of 'equivalence of successes and failures' in Resilience Engineering states, whether a set of circumstances leads to success or failure can only be judged by the outcome (Hollnagel, 2012). Outcomes may be *foreseeable*, but this does not necessarily mean that they will be *foreseen*.

Defining what is 'unexpected' or 'unknown' before the event is inherently problematic (Elahi, 2011; Woods, 2016). Even with hindsight it may not be straightforward. When asked the last unexpected event which they remember, few participants were able to reply. (One exception being a pilot who answered, *'It was when you [i.e. the author] changed the settings on my pad [portable pilot unit] and it actually looked better. So now I will keep it like this'.*) Only occasionally do truly unexpected events occur, such as this example told by two VTS operators. The VTS centre in question is located on a partially protruding platform on the top floor of an office block (Fig. 18).

Figure 18. VTS centre (source: Google maps 2016).

VTSO1:	*When it's blowing, and the building is falling… You see, under here [gestures under workstation], the house ends and we are sticking out in the air. We had a big storm, when was this?*
VTSO2:	*About 2011, 2012… first of December, I think…*
VTSO1:	*When the dry dock in […] got loose, it was a big storm. [VTSO2] was sitting there [workstation furthest out], and the house was standing like this… [hand gestures, shows building leaning and swaying]*
VTSO2:	*You couldn't hear anything, because everything was just… [makes roaring noise]*
VTSO1:	*We had to put her in a harness so she was attached…*
VTSO2:	*I was attached onto the chair…*
VTSO1:	*To stop her from falling out.*
VTSO2:	*But that only happened once.*

6.3 From knowledge to design? (Research question 3)

The final research question brings us to one of the main challenges of systems approaches to design (e.g. Wilson, 2014; IEA, 2016), and indeed qualitative research in general: how best to capture operational knowledge in a way which may be integrated into the design of future workplaces and systems (Hoffman & Lintern, 2006). We must consider how to translate knowledge from one setting to another (e.g. Latour, 1986, 1995/1999), how to move between the generic and the specific and vice versa (Le Coze, 2013a,b; Hepsø, 2014), and how to communicate between practitioner, management, designers and other stakeholders (Karlsson, 1999; Broberg et al, 2011). For example, we have seen the potential effects of reduced visibility on the safety of navigation, but how do we assess the ability of a work system to manage it? How do we evaluate the impact of change, e.g. placing a new camera or sensor in a strategic location, or introducing an overarching e-navigation infrastructure (IMO, 2014)?

As discussed in Section 3.3, understanding and specifying the context of use is a prerequisite for a design which will enable the system to fulfil its goal. Le Coze describes four requirements for a model which may be used in this way (2013b:194). He describes a 'sensitising' sociotechnical systems model which brings together elements of systems thinking with insights from sociology and 'softer' work studies traditions (also advocated by e.g. Haavik et al., 2016; Wilson, 2014; Hepsø, 2014; Checkland, 2000). It also seeks to reconcile the top-down safety management approach typical within industry (Hale & Borys, 2013; Grøtan, 2013) with bottom-up (or 'dark side') practitioner experience, in order to design a system which can proactively address safety challenges. The four requirements are (Le Coze, 2013b:194):

> 1. first, one needs a generic model, not specific to one case but with a potential for relevance across a variety of technological and social configurations, a model that is generic enough to sensitise without destroying the distinctiveness of real cases (a 'sensitising model');
>
> 2. second, one needs to strike a balance between a descriptive and a normative posture, between what 'is' and what 'should be'; one cannot only rely on a descriptive and neutral approach as this would mean that no assessment could be provided;
>
> 3. third, one needs to grasp several nested layers of analysis to capture the patterns identified retrospectively in accidents by social scientists, and this requires the introduction of the micro–meso–macro-systemic and dynamic link;
>
> 4. fourth, one needs to produce a model that is not too simple, to capture phenomena that are multidimensional, but not too complex either, in order to serve its purpose of being useful for safety assessment, e.g. not to be rejected by people without a strong social sciences background.

An approach such as the one taken in this thesis - which describes work using a sociotechnical systems model (in this case FRAM) but complementing with insights from the work studies traditions - may conceivably fulfil the first three criteria. The configurable generic/specific FRAM model is capable of showing how work is *normally done* and also how it is *actually done* in a specific scenario or situation (step 1 above). Since rules and regulations may be actors, the model may maintain a dialogue between principle ('work as imagined') and practice ('work as done') (step 2). The generic model may conceivably be transferable to other instances of navigational assistance; one could produce further instantiations to discuss other scenarios, or to analyse a specific situation (e.g. an event or incident), or to discuss the impact of proposed changes to the work system (e.g. the introduction of cameras in the VTS area or a new e-navigation infrastructure) (step 3).

However, in order to go beyond understanding and describing work, to *influencing design*, a model must also be capable of communicating between multi-disciplinary stakeholders such as designers and managers (step 4). I believe that the approach taken in this thesis has this potential, and should be investigated further. Building on previous work in the context of marine design (de Vries et al., 2015; 2016) on the use of boundary objects (Star & Griesemer, 1989; Broberg et al, 2011) and mediating tools (Karlsson, 1999), I would argue that if a system model were successful in this respect, the potential advantages (as illustrated by activity triangles in Fig. 19) would be to:

(i) enable the system designer (and other stakeholders) to gain a greater understanding of the context of use, the task and requirements of the user (pilot, VTS operator or vessel navigator) (green arrows), and simultaneously;

(ii) enable the users to bring their knowledge of the context of use, task and requirements to evaluate the design and provide feedback to the designer (and others) (red arrows).

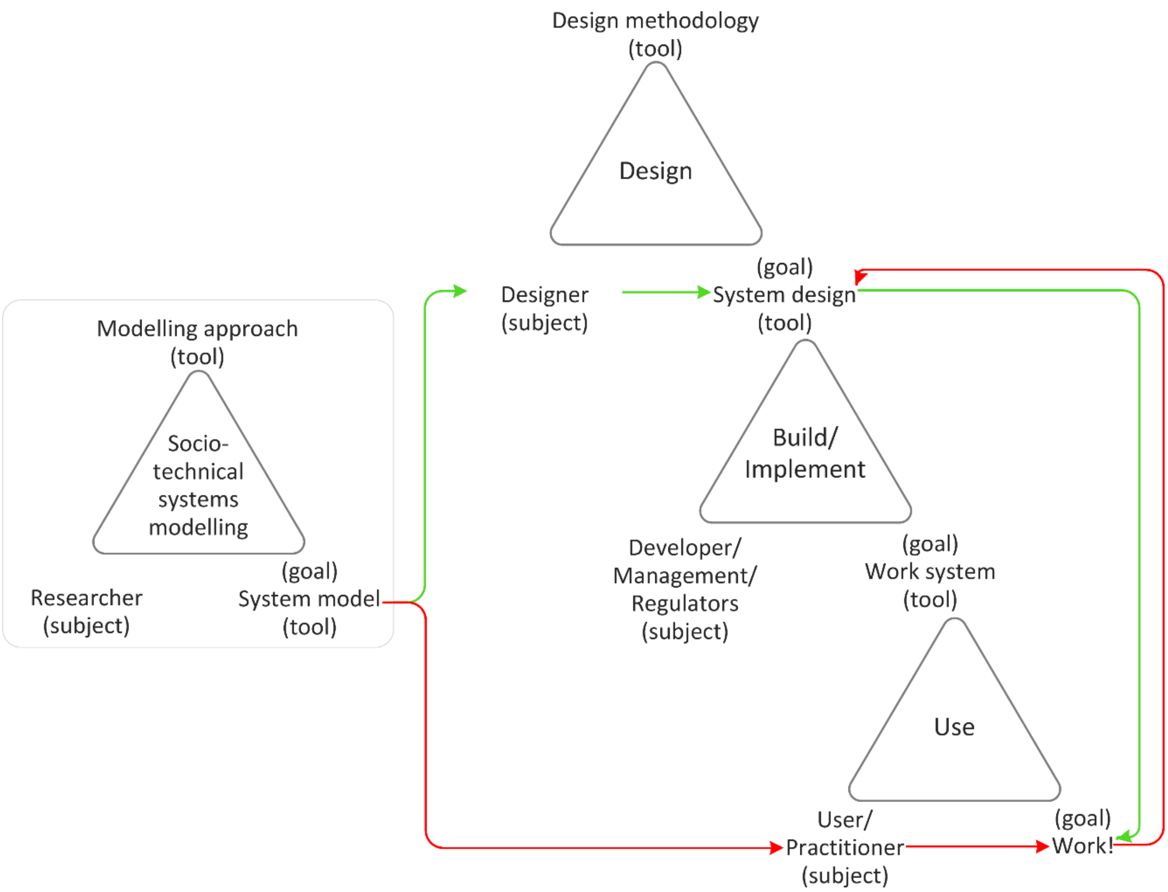

Figure 19. The potential use of system models in design and operation (author, forthcoming, adapted from Andersson et al., 2011).

7 Conclusions

This thesis aimed to investigate sociotechnical work and safety within the context of navigational assistance. It attempted to understand how the work of pilots and VTS operators is performed and how it contributes to safe maritime operations, and sought to answer the following research questions:

1. How can safety be understood in the context of sociotechnical work?

2. How can studying work as a sociotechnical system assist in understanding the conditions which enable safe operations and how they vary?

3. How can knowledge of the practice of work be harnessed in order to inform the design of future work systems and provide a context for evaluating the impact of new technologies?

In attempting to answer the first question, it was found that safety is not easily defined or quantified, but is an emergent property of sociotechnical work, which manifests itself through the interaction between humans and other actors in the context in which work is performed. Therefore in order to understand safety, we must first understand work.

An approach which facilitates the study of successful everyday work as performed by practitioners allows us to understand the conditions which enable safe operations. This was achieved in this thesis by describing work using a sociotechnical systems model (the generic FRAM model and its instantiations) but complementing with insights from the work studies traditions, with their strong grounding in empirical observations and themes of 'making work visible', symmetry between human/non-human, and work as activity. In viewing work as a sociotechnical system, one sees that the configuration of a work system is not necessarily pre-defined, and that the performance of work is dependent on the interaction between various human, technological, organisational, natural and other factors. It is inherently uncertain, variable and must continuously adapt to emerging circumstances. Or as Law would say, it is a 'monster', an 'outrageous and heterogeneous collage' (1990:18).

This implies that, in order to inform the design of future work systems or evaluate the impact of new technologies, one should take account of the factors which affect how work is normally performed, and also how it is actually performed in specific circumstances to enable safe operations. Although this thesis does not fully answer the third research question, it describes one approach which has the potential to go beyond understanding and describing work, to communicating this knowledge to multi-disciplinary stakeholders such as designers and managers, thereby informing and evaluating the design of new systems and technologies.

REFERENCES

Adams, D. (1987). *Dirk Gently's Holistic Detective Agency.* UK: Heinemann.

Andersson, J., Bligård, L.-O. and Osvalder, A.-L. (2011). To develop viable human factors engineering methods for improved industrial use. *In A. Marcus (Ed.), Design, User Experience, and Usability, Pt I, Human Computer Interaction International, Orlando FL 2011. Lecture Notes in Computer Science 6769*, 355–362.

Aven, T. (2012). *Foundations of Risk Analysis, 2nd edition*. Chichester, UK: John Wiley and Sons.

Bedford, T. and Cooke, R. (2001). *Probabilistic Risk Analysis: Foundations and Methods*. Cambridge: Cambridge University Press.

Birkler, J. (2008). *Vetenskapsteori. En grundbok. (original title: Videnskabsteori. En grundbog)*. Stockholm: Liber.

Broberg, O., Andersen, V. and Seim, R. (2011). Participatory ergonomics in design processes: The role of boundary objects. *Applied Ergonomics, 42*(3), 464-472.

Brödje, A., Lundh, M., Jenvald, J. and Dahlman, J. (2012). Exploring non-technical miscommunication in vessel traffic service operation. *Cognition, Technology & Work, 15*(2013), 347-357.

Bruno, K. and Lützhöft, M. (2009). Shore-based pilotage: Pilot or autopilot? Piloting as a control problem. *Journal of Navigation, 62*(3), 427-437.

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

Cabrera Aguilera, M. V., Bastos da Fonseca, B., Ferris, T. K., Vidal, M. C. R. and Carvalho, P. V. R. d. (2016). Modelling performance variabilities in oil spill response to improve system resilience. *Journal of Loss Prevention in the Process Industries, 41*, 18-30.

Callon, M. (1980). Struggles and negotiations to define what is problematic and what is not: The sociology of translation. In K.D. Knorr, R. Krohn & R.D. Whitley (Eds.), *The Social Process of Scientific Investigation* (pp. 197-220). Boston, MA: Reidel.

Callon, M. (1986). Some elements of a sociology of translation: domestication of the scallops and the fishermen of St Brieuc's Bay. In J. Law (Ed.), *Power, Action and Belief: A New Sociology of Knowledge?* (pp. 196-223). London: Routledge.

Callon, M. and Latour, B. (1981). Unscrewing the big Leviathan or how do actors macrostructure reality and how sociologists help them to do so. In K.D. Knorr, A. Cicourel & P. Kegan (Eds.), *Advances in Social Theory and Methodology. Toward an Integration of Micro and Macro Sociologies* (pp. 277-303). London: Routledge.

Carvalho, P. V. R. d. (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 and System Safety, 96*(2011), 1482-1498.

Charmaz, K. (2000). Grounded theory: Objectivist and constructivist methods. In N. Denzin & Y. Lincoln (Eds.), *Handbook of qualitative research, 2nd ed.* (pp. 609-635). Thousand Oaks, CA: Sage.

Charmaz, K. (2006/2014). *Constructing grounded theory, 2nd ed.* London: Sage.

Checkland, P. B. (2000). Soft systems methodology: a 30 year retrospective. *Systems research, 17*, 11-52.

Corbin, J. M. and Strauss, A. L. (2008). *Basics of Qualitative Research: Techniques and procedures for developing grounded theory, 3rd ed.* Thousand Oaks, CA: Sage.

Council, N. R. (1994). *Minding the Helm: Marine Navigation and Piloting*. Washington, D.C.: National Academy Press.

Crotty, M. (1998). *The foundations of social research: Meaning and perspective in the research process*. London: Sage.

Czarniawska, B. (2014). *Social science research: from field to desk*. Lund: Studentlitteratur.

Czarniawska, B. (2017, in press). Actor-Network Theory. In Ann Langley & Haridimos Tsoukas (Eds.), *The SAGE Handbook of Process Organization Studies*. London: SAGE.

Czarniawska, B. and Hernes, T. (Eds.). (2005). *Actor-Network Theory and Organizing.* Copenhagen: Liber and Copenhagen Business School Press.

Darbra, R. M., Crawford, J. F. E., Haley, C. W. and Morrison, R. J. (2007). Safety culture and hazard risk perception of Australian and New Zealand maritime pilots. *Maritime Policy, 31*(6), 736-745.

de Vries, L., Costa, N. A., Hogström, P. and Mallam, S. C. (2015). Overcoming the challenges of integration of Human-centred Design within the Naval Architecture ship design process. In *Proceedings 19th Triennial Congress of the IEA (International Ergonomics Association)*. 9-14 August 2015, Melbourne.

de Vries, L., Hogström, P., Costa, N. A. and Mallam, S. C. (2016, forthcoming). Designing for safe operations: A human-centred approach to complex vessel design. *Under review for international publication*.

Dekker, S. and Hollnagel, E. (2004). Human factors and folk models. *Cognition, Technology & Work, 6*(2004), 79-86.

Denscombe, M. (2010). *The Good Research Guide: For small-scale social research projects, 4th edition*. Maidenhead, UK: Open University Press.

Elahi, S. (2011). Here be dragons... Exploring the 'unknown unknowns'. *Futures, 43*(2011), 196-201.

Engeström, Y. (1996). The tensions of judging: Handling cases of driving under the influence of alcohol in Finland and California. In Yrjö Engeström & David Middleton (Eds.), *Cognition and communication at work*. Cambridge, UK: Cambridge University Press.

Engeström, Y. and Middleton, D. (Eds.). (1996). *Cognition and Communication at Work*. Cambridge, UK: Cambridge University Press.

Gadamer, H.-G. (1972). *Wahrheit und methode: Grundzüge einer philosophischen Hermeneutik, 3rd ed. (English title: Truth and method: Principles of a philosophical hermeneutics)*. Tübingen: Mohr.

Galvan, J. (2006). *Writing literature reviews: a guide for students of the behavioral sciences, 3rd ed.* Glendale, CA: Pyrczak Publishing.

Glaser, B. and Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. Chicago, IL: Aldine.

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

Grimmett, G. and Stirzaker, D. (2001). *Probability and Random Processes, 3rd edition*. Oxford: Oxford University Press.

Grøtan, T. O. (2013). Hunting high and low for resilience: Sensitization from the contextual shadows of compliance. In Steenbergen, van Gelder, Miraglia & Vrouwenvelder (Eds.), *Safety, Reliability and Risk Analysis: Beyond the Horizon*. London: CRC Press.

Grøtan, T. O. and Størseth, F. (2012). Integrated safety management based on organizational resilience. In C. Berenguer, A. Grall & C Guedes Soares (Eds.), *Advances in Safety, Reliability and Risk Management: ESREL 2011*. London: CRC Press.

Haavik, T. K. (2011). On components and relations in sociotechnical systems. *Journal of Contingencies and Crisis Management, 19*(2), 99-109.

Haavik, T. K. (2013). *New tools, old tasks: Safety implications of new technologies and work processes for integrated operations in the petroleum industry*. Farnham: Ashgate.

Haavik, T. K. (2014). On the ontology of safety. *Safety Science, 67*, 37-43.

Haavik, T. K. (2014). Sensework: Conceptualising Sociotechnical Work in Safety-Critical Operations. *Computer Supported Cooperative Work (CSCW), 23*(2014), 269-298.

Haavik, T. K., Antonsen, S., Rosness, R. and Hale, A. (2016). HRO and RE: A pragmatic perspective. *Safety Science*. doi: http://dx.doi.org/10.1016/j.ssci.2016.08.010

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

Hale, A. and Borys, D. (2013). Working to rule, or working safely? Part 1: A state of the art review. *Safety Science, 55*, 207-221.

Heidegger, M. (1927). *Sein und Zeit (English title: Being and Time)*. Tübingen: Max Niemeyer Verlag.

Hendrick, H. and Kleiner, B. (2001). *Macroergonomics: an introduction to work system design.* Santa Monica, CA: Human Factors and Ergonomics Society.

Hepsø, V. (2014). Mediating Business Process Models with an Anthropological Voice: "Double-level Language" in the Norwegian Oil Industry. In Rita Denny & Patricia Sutherland (Eds.), *Handbook of Anthropology in Business*. Oxford, UK: Routledge.

Herrera, I. A. and Woltjer, R. (2010). Comparing a multi-linear (STEP) and systemic (FRAM) method for accident analysis. *Reliability Engineering and System Safety, 95*(2010), 1269-1275.

Hoffman, R. R., Feltovich, P. J., Ford, K. M., Woods, D. D. and Feltovich, A. (2002). A rose by any other name... would probably be given an acronym. *IEEE Intelligent Systems, 17*(4), 72-80.

Hollnagel, E. (2009). *The ETTO Principle: Efficiency-Throughness Trade-Off*. Farnham, UK: Ashgate.

Hollnagel, E. (2011). Epilogue: RAG - The Resilience Analysis Grid. In E. Hollnagel, J. Pariès, D. D. Woods & J. Wreathall (Eds.), *Resilience Engineering in Practice: A Guidebook*. Aldershot, UK: Ashgate.

Hollnagel, E. (2012). *FRAM - The Functional Resonance Analysis Method: Modelling Complex Socio-technical Systems*. Farnham, UK: Ashgate.

Hollnagel, E. (2014a). Human factors/ergonomics as a systems discipline? "The human use of human beings" revisited. *Applied Ergonomics, 45*(1), 40-44.

Hollnagel, E. (2014b). *Safety-I and Safety-II: The past and future of safety management*. Farnham, UK: Ashgate.

Hollnagel, E., Hounsgaard, J. and Colligan, L. (2014). *FRAM – the Functional Resonance Analysis Method: A handbook for the practical use of the method*. Middelfart, Denmark: Centre for Quality.

Hollnagel, E., Pariès, J., Woods, D. D. and Wreathall, J. (Eds.). (2011). *Resilience Engineering in practice: A Guidebook*. Farnham, UK: Ashgate.

Hollnagel, E. and Woods, D. D. (2005). *Joint Cognitive Systems: An Introduction to Cognitive Systems Engineering*. London: CRC Press.

Hollnagel, E., Woods, D. D. and Leveson, N. C. (Eds.). (2006). *Resilience engineering: Concepts and precepts*. Aldershot, UK: Ashgate.

Howson, C. and Urbach, P. (2006). *Scientific reasoning: the Bayesian approach, 3rd edition.* La Salle, IL: Open Court.

Hutchins, E. (1995a). *Cognition in the wild*. Cambridge, MA: MIT Press.

Hutchins, E. (1995b). How a cockpit remembers its speeds. *Cognitive Science, 19*(3), 265-288.

IALA. (2012). *Pilotage Authority Forum (PAF) Report on Best Practice for Competent Pilotage Authorities, Edition 1.1.* Saint Germain en Laye, France: International Association of Marine Aids to Navigation and Lighthouse Authorities.

IALA. (2016). *Vessel Traffic Services Manual, Edition 6*. Saint Germain en Laye, France: International Association of Marine Aids to Navigation and Lighthouse Authorities.

IMO. (1972). *Convention on the International Regulations for Preventing Collisions at Sea (COLREGS)*. London: International Maritime Organisation.

IMO. (1997). *IMO Resolution A.857(20) Guidelines for Vessel Traffic Services*. London: International Maritime Organisation.

IMO. (2014). Proceedings of the Sub-Committee on Navigation, Communications and Search and Rescue (NCSR), 1st session, 30 June to 4 July 2014. Retrieved 2016-12-01 from: http://www.imo.org/en/MediaCentre/MeetingSummaries/NCSR/Pages/NCSR-1st-Session.aspx

IMO. (2016). About IMO. Retrieved 12 Oct 2016 from http://www.imo.org/en/About/Pages/Default.aspx

IMO. (2016). Pilotage. Retrieved 01-08-2016 from: http://www.imo.org/OurWork/Safety/Navigation/Pages/Pilotage.aspx

IMPA. (2014). *IMPA (International Maritime Pilots' Association) on Pilotage*. Livingstone: Witherby Seamanship International.

ISO. (2010). *ISO 9241-210:2010 - Ergonomics of human-system interaction - Part 210: Human-centred design for interactive systems.* Geneva: International Standards Organisation.

Johansson, B. and Persson, P.-A. (2009). Reduced uncertainty through human communication in complex environments. *Cognition, Technology & Work, 11*, 205-214.

Kaghan, W. N. and Bowker, G. C. (2001). Out of machine age?: complexity, sociotechnical systems and actor network theory. *Journal of Engineering and Technology Management, 18*(2001), 253-269.

Karlsson, M. (1999). A Framework for the Study of the Relation between User and Artefact. In Don Harris (Ed.), *Engineering Psychology and Cognitive Ergonomics. Volume 4. Job Design Product Design and Human-Computer Interaction* (pp. 379-386). Aldershot: Ashgate.

Kirwan, B. (2000). Soft systems, hard lessons. *Applied Ergonomics, 31*(6), 663-678.

La Porte, T. R. and Consolini, P. M. (1991). Working in practice but not in theory: Theoretical challenges of high reliability organizations. *Journal of Public Administration Research and Theory, 1*(1), 19-47.

Latour, B. (1986). Visualisation and Cognition: Thinking with Eyes and Hands. *Knowledge and Society: Studies in the Sociology of Culture Past and Present, 6*, 1-40.

Latour, B. (1995/1999). Circulating reference *Pandora's Hope* (pp. 24-79). Cambridge, MA: Harvard University Press.

Latour, B. (1996). *Aramis, or the Love of Technology*. Cambridge, MA: MIT Press.

Latour, B. (2005). *Reassembling the Social: An Introduction to Actor-Network Theory*. Oxford: Oxford University Press.

Latour, B. and Woolgar, S. (1979/1986). *Laboratory Life: The Construction of Scientific Facts*. Princeton, NJ: Princeton University Press.

Law, J. (1990). Introduction: Monsters, machines and sociotechnical relations. *The Sociological Review, 38*(S1), 1-23.

Law, J. (Ed.). (1991). *A Sociology of Monsters: Essays on Power, Technology and Domination*. London: Routledge.

Le Coze, J.-C. (2013a). New models for new times. An anti-dualist move. *Safety Science, 59*, 200-218.

Le Coze, J.-C. (2013b). Outlines of a sensitising model for industrial safety assessment. *Safety Science, 51*(1), 187-201.

Le Coze, J. C. (2015). Reflecting on Jens Rasmussen’s legacy. A strong program for a hard problem. *Safety Science, 71, Part B*, 123-141.

Leont'ev, A. N. (1981). The problem of activity in psychology. In J. V. Wertch (Ed.), *The concept of activity in Soviet Psychology* (pp. 31-71). Armonk, NY: Sharpe.

Lind, M., Hägg, M., Siwe, U. and Haraldson, S. (2016). Sea traffic managment - beneficial for all maritime stakeholders. *Transportation Research Procedia, 14*(2016), 183-192.

Lindahl, M. (2005). The little engine that could: On the "managing"qualities of technology. In Barbara Czarniawska & Tor Hernes (Eds.), *Actor-Network Theory and Organizing*. Copenhagen: Liber and Copenhagen Business School Press.

Lintern, G. (2009). *The Foundations and Pragmatics of Cognitive Work Analysis*. Cogntive Systems Design: Gavan Lintern.

Magnani, L. (2001). *Abduction, Reason, and Science: Processes of Discovery and Explanation*. New York: Kluwer Academic Plenum.

Mikkers, M., Henriqson, E. and Dekker, S. (2012). Managing Multiple and Conflicting Goals in Dynamic and Complex Situations: Exploring the Practical Field of Maritime Pilots. *Journal of Maritime Research, Vol. IX. No. 2*(2012), 13-18.

Nævestad, T.-O. (2009). Mapping Research on Culture and Safety in High-Risk Organizations: Arguments for a Sociotechnical Understanding of Safety Culture. *Journal of Contingencies and Crisis Management, 7*(2), 126-136.

Orr, J. (1996). *Talking about machines: An ethnography of a modern job*. Ithaca, NY: Cornell University Press.

Peirce, C. P. (1903). *Pragmatism - the logic of abduction. CP 5. pp 195–205.*

Perrow, C. (1984). *Normal Accidents*. Princeton, NJ: Princeton University Press.

Praetorius, G. and Hollnagel, E. (2014). Control and Resilience Within the Maritime Traffic Management Domain. *Journal of Cognitive Engineering and Decision Making, 8*(4), 303-317.

Praetorius, G., Hollnagel, E. and Dahlman, J. (2015). Modelling Vessel Traffic Service to understand resilience in everyday operations. *Reliability Engineering and System Safety, 141*(2015), 10-21.

Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man and Cybernetics, 13*(3), 257-266.

Rasmussen, J. (1987). Cognitive control and human error mechanisms. In J. Rasmussen, K. Duncan & J. Leplat (Eds.), *New Technology and Human Error.* Chichester: John Wiley & Sons.
Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety Science, 27*(2–3), 183-213.
Rasmussen, J., Petjersen, A. M. and Goodstein, L. P. (1994). *Cognitive Systems Engineering*. New York: Wiley.
Reason, J. (1997). *Managing the risks of organisational accidents*. Aldershot, UK: Ashgate.
Rosa, L. V., Haddad, A. N. and Carvalho, P. V. R. d. (2015). Assessing risk in sustainable construction using the Functional Resonance Analysis Method (FRAM). *Cognition Technology & Work, 17*, 559-573.
Rosness, R., Grøtan, T. O., Guttormsen, G., Herrera, I. A., Steiro, T., Størseth, F., Tinmannsvik, R.K., Wærø, I. (2010). *Organisational accidents and resilient organisations: Six perspectives. Revision 2.* Trondheim, Norway: SINTEF Technology and Society, Safety Research.
Røyrvik, J. (2012). *Værvinduet, en teknologisk artikulert entitet i oljeindustriens erobring av natur. (English title: Weather window, a technologically articulated entity in the oil industry's conquest of nature).* (Thesis for PhD), NTNU, Trondheim.
Sayes, E. (2014). Actor–Network Theory and methodology: Just what does it mean to say that nonhumans have agency? *Social Studies of Science, 44*(1), 134-149.
Shedd, J. A. (1928). *Salt from my attic*. Portland, Maine: The Mosher Press.
Skyttner, L. (2005). *General Systems Theory (2nd edition): Problems, perspectives, practice*. Singapore: World Scientific Publishing Co.
Stanton, N. A., Salmon, P. M., Walker, G. H., Baber, C. and Jenkins, D. P. (2013). *Human Factors Methods: A Practical Guide for Engineering and Design, 2nd ed.* Aldershot, UK: Ashgate.
Star, S. L. and Griesemer, J. R. (1989). Institutional ecology, ‘translations’ and boundary objects: amateurs and professionals in Berkeley’s museum of vertebrate zoology. *Social Studies of Science, 19*, 387-420.
Suchman, L. (1993). Centers of Coordination: A Case and Some Themes. In L.B. Resnick (Ed.), *Discourse, tools, and reasoning: essays on situated cognition.* (pp. 41-62). Berlin: Springer.
Suchman, L. (1995). Making work visible. *Communications of the ACM, 38*(9), 56-64.
Suchman, L. (2007). *Human-machine reconfigurations: Plans and situated actions.* New York: Cambridge University Press.
Tian, J., Wu, J., Yang, Q. and Zhao, T. (2016). FRAMA: A safety assessment approach based on Functional Resonance Analysis Method. *Safety Science, 85*(2016), 41-52.
TSBC. (1995). A Safety Study of the Operational Relationship Between Ship Masters/Watchkeeping Officers and Marine Pilots. Transportation Safety Board of Canada (TSBC) Report number SM9501.
Turner, B. A. and Pidgeon, N. F. (1997). *Man-made disasters, 2nd edition*. London: Butterworth-Heinemann.
UNCTAD. (2014). *United Nations Conference on Trade and Development Review of Maritime Transport 2014.* New York and Geneva: United Nations.
USCMTS. (2012). US Committee on the Marine Transportation System e-Navigation Strategic Action Plan. Retrieved 2016-10-12 from: http://www.cmts.gov/downloads/CMTS_e-Navigation_Strategic_Action_Plan_Feb_2012.pdf
Vaismoradi, M., Turunen, H. and Bondas, T. (2013). Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. *Nursing and Health Sciences, 2013*(15), 398-405.
van Westrenen, F. (1999). *The Maritime Pilot at Work: The Evaluation and Use of a Time-to-Boundary Model of Mental Workload in Human-Machine Systems.* Doctoral dissertation, Delft University of Technology, Delft, the Netherlands.
van Westrenen, F. (2013). Modelling arrival control in a vessel traffic management system. *Cognition Technology & Work, 16*(4), 501-508.
van Westrenen, F. and Praetorius, G. (2012). Maritime traffic management: a need for central coordination? *Cognition, Technology & Work, 16*(2014), 59-70.

Vicente, K. J. (1999). *Cognitive Work Analysis: Towards safe, productive, and healthy computer-based work*. Mahwah, NJ: Lawrence Erlbaum Associates.

von Bertanlanffy, L. (1968). *General System Theory: Foundations, Development, Applications (revised edition 1976)*. New York: George Braziller.

Weick, K. E. (1987). Organisational culture as a source of high reliability. *California Management Review, 16*(3), 571-593.

Weick, K. E. (1995). What Theory is *Not*, Theorizing *Is*. *Administrative Science Quarterly, 40*(3), 385-390.

Weick, K. E. and Sutcliffe, K. M. (2001). *Managing the Unexpected: Assuring High Performance in an Age of Complexity.* San Francisco, CA: Jossey-Bass.

Weick, K. E., Sutcliffe, K. M. and Obstfeld, D. (1999). Organizing for High Reliability: Processes of Collective Mindfulness. In R.S. Sutton & B.M. Staw (Eds.), *Research in Organizational Behavior, Volume 1*. Stanford: Jai Press.

Wiener, N. (1948). *Cybernetics: or control and communication in the animal and the machine*. New York: Wiley.

Wiener, N. (1963). *God and Golem, Inc.: A comment on certain points where cybernetics impinges on religion*. Cambridge, MA: MIT Press.

Wilson, J. R. (2000). Fundamentals of ergonomics in theory and practice. *Applied Ergonomics, 31*(6), 557-567.

Wilson, J. R. (2014). Fundamentals of systems ergonomics/human factors. *Applied Ergonomics, 45*(1), 5-13.

Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering & System Safety, 141*, 5-9.

Woods, D. D. (2016). *Resilience Engineering Short Course*. Ohio State University (online version, observer section, accessed autumn 2016).