This is the author's accepted version of the following published article:

de Vries, L. (2017) Work as done? Understanding the practice of sociotechnical work in the maritime domain. *Journal of Cognitive Engineering and Decision Making.* pp. 1-26.

DOI:10.1177/1555343417707664.

Work as done? Understanding the practice of sociotechnical work in the maritime domain

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Keywords: sociotechnical systems; safety; Functional Resonance Analysis Method (FRAM); Resilience Enginnering; pilotage; vessel traffic services (VTS); 'work as done'

Abstract

Pilots and Vessel Traffic Service (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. Empirical studies of navigational assistance were analysed using the Functional Resonance Analysis Method (FRAM) in order to understand what pilots and VTS operators do and how it contributes towards maritime safety. 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 ethnographically-inspired work studies traditions, with their strong grounding in empirical studies and themes of 'making work visible', symmetry between human/non-human, and work as activity. This approach indicates 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.

1. Introduction

Work and work systems have become increasingly complex over the previous decades, allowing data to be integrated and disseminated between humans and technology, across disciplines and over multiple geographical locations. In safety-critical domains, new technologies are often introduced with the aim of improving safety and efficiency of operations. This article discusses the case of the maritime domain, in which technological advances have supported on board navigation and communication, and created possibilities for increased monitoring, assistance and control from shore, thereby changing how work is performed. This development is ongoing (e.g. IMO, 2014), and affects the safety of navigation, but also efficiency, security and ship-shore administration. The article will focus on services intended to improve the safety of navigation, usually performed on board by maritime pilots and from shore by Vessel Traffic Services (VTS) operators, under the collective term *navigational assistance*.

Navigational assistance will be explored by analysing empirical studies of pilotage and VTS with the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012; Hollnagel, Hounsgaard & Colligan, 2014), but borrowing inspiration from ethnographically-inspired approaches such as Workplace Studies (WS) (Suchman, 1993, 1995, 2007), Science and Technology Studies (STS) (Czarniawska, 2014, 2017; Latour, 2005) and Activity Theory (Karlsson, 1999; Leont'ev, 1981) - or *Work Studies* for short (after Haavik, Antonsen, Rosness & Hale, 2016). The aim is to describe the work performed by pilots and VTS operators today in order to understand what they do and how it contributes towards maritime safety, in order that this knowledge may be utilised when designing future work systems. This approach will attempt to show how FRAM may be a valuable tool for describing sociotechnical work, provided it is based upon a good empirical understanding of that work, which may be aided by ideas from Work Studies. Furthermore, that bringing ideas from different traditions together to understand a real work practice may bring us closer to describing 'work as done' (Hollnagel, 2012).

1.1. Overview of navigational assistance

The term *navigational assistance* will be used to encompass 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* 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, 2016), comprising 'activities related to navigation and ship handling in which the pilot acts as an advisor to the master of the ship' (IALA, 2012:10). It is generally conducted on board the vessel but, in some areas and in certain, often weather-related, circumstances, remote pilotage may also be conducted (Hadley, 1999; IMPA, 2014). *Vessel Traffic Services (VTS)* is a shore-based service, established to 'improve the safety and efficiency of vessel traffic and to protect the environment' (IMO, 1997:3); it aims to 'aid the mariner in the safe use of navigable waterways' (IALA, 2016:27). 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 VTS operator or pilot does not relieve the master of this responsibility (IALA, 2016; IMO, 1997).

2. Background

2.1. Some theoretical perspectives on sociotechnical work

Understanding the interaction between humans, their workplaces and work systems - and its relationship with safety - in order to integrate this understanding into design, has occupied researchers from a multitude of disciplines for over half a century. A common theme is that that safety may be seen as an emerging property of sociotechnical work. There is increasing interest is studying everyday work as performed by practitioners - or 'work as done' - to understand how safety is created in practice, rather than focusing on 'work as imagined' by management and codified in routines and procedures, or safety in principle, as defined by rules, regulations and safety management systems (Hale & Borys, 2013; Hollnagel, 2012, 2014; Suchman, 1993). A sociotechnical systems approach (e.g. Checkland, 2000; Hendrick & Kleiner, 2001; Rasmussen, 1997; Wilson, 2014) is becoming usual, but there is often a lack of clarity on what this entails (Wilson, 2014). Real world problems may sometimes be too 'messy' to be adequately captured by 'harder' systems engineering approaches, and a 'softer' approach may be more beneficial (Checkland, 2000; Kirwan, 2000). Studying sociotechnical systems 'in the wild' can account for 'real variance in real practice' (Wilson, 2014:7; after Hutchins 1995a), an idea which has long been a central theme of Work Studies (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). WS focus on describing how everyday work is performed, often highlighting practices which are 'invisible' to the outside world (Suchman, 1993, 1995, 2007). STS and Actor-Network Theory (ANT) investigate how work and work systems or *networks* emerge through the building and maintaining of associations between actors

(Czarniawska, 2014; Latour, 2005); it treats humans and non-humans, and the social and the technical, as equal and traces the connections between them (e.g. Callon, 1986; Latour, 1986, 2005). Activity Theory views work in terms of *activities*, investigating the relationship between actors and their tools (technology, systems etc.) in achieving their goals (Engeström & Middleton, 1996; Karlsson, 1999). Drawing on these traditions, a large body of studies within safety-critical domains such as aviation (e.g. Hutchins, 1995b), aircraft ground operations (Suchman, 1993), navigation (Hutchins, 1995a) and offshore (Haavik, 2011; 2014) highlight how successful work depends on collaboration and coordination between between human and non-human actors, dynamically responding and reconfiguring in time and space to deal with emerging situations.

Similar themes may be found in cybernetics-based systems theory traditions. Focus is on how feedback from the system itself and its environment is used to maintain *control* by dealing with *variability*, which may affect other components or lead to unwanted outcomes (e.g. Hollnagel & Woods, 2005; Rasmussen, Petjersen & Goodstein, 1994). Systems are per definition teleonomic, or goal-seeking, implying that maintaining control will result in a successful (i.e. safe) outcome. While safety is not necessarily an inherent characteristic of the system components, it may be an *emergent* property of the system.

Most recently, Resilience Engineering (RE) (Hollnagel, Pariès,Woods & Wreathall, 2011), looks at the ability of a system to adapt and create a successful outcome in everyday operations, focusing on 'work as done', rather than 'work as imagined' (Hollnagel, 2012). The aim is thus to shift attention from Safety-I thinking (focusing on what goes wrong) to Safety-II (looking at what goes right) (Hollnagel, 2014), or away from Weick's proverbial 'dynamic non-events' (1987) towards everyday operations or 'events' (see also Haavik et al., 2016). Hollnagel (2012:9) states that 'safety is something a system *does* rather than something it *has*' [author's emphasis], therefore to understand safety, we should, as in Work Studies, look at how sociotechnical work is performed.

2.2. Navigational assistance in literature

Given the inherent interaction between humans, technology, organisation etc., on board and between ship and shore, previous research has viewed the maritime domain as a sociotechnical system (Perrow, 1984). More specifically, most current research into pilotage (e.g. Mikkers, Henriqsen & Dekker, 2012; van Westrenen, 1999) and VTS (Praetorius & Hollnagel, 2014; Praetorius, Hollnagel & Dahlman, 2015) and maritime traffic management (van Westrenen & Praetorius, 2012) is firmly based within the traditions of Cognitive Systems Engineering and Resilience Engineering, focusing mainly on the role of navigational assistance in maintaining tactical (short-term, localised) and strategical (longer term, system-wide) control. 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; Bruno & Lützhöft, 2009) and ship-shore (Hadley, 1999; Bruno & Lützhöft, 2009).

This research has produced detailed system models of either on board and shore-side assistance (Praetorius & Hollnagel, 2014; Praetorius et al., 2015; van Westrenen, 1999). However, although pilotage and VTS have also been modelled as a single, distributed Joint Cognitive System by van Westrenen & Praetorius (2012), there is otherwise very little research which views both the on board and shore-side aspects of navigational assistance as an integrated sociotechnical system.

2.3. The Functional Resonance Analysis Method (FRAM)

FRAM is 'an analysis tool that reflects Resilience Engineering and Safety-II thinking' (Hollnagel et al., 2014:12). It provides a method to describe a sociotechnical system in terms of its *functions*, and the interactions between these, in order to analyse where performance variability may arise and *'resonate'* or spread throughout the system, - using the metaphor of stochastic resonance between signals with varying amplitudes and frequencies - and how the system may adapt to keep performance within the required parameters. The underlying principles of FRAM are discussed in detail by Hollnagel (2012) and practical instructions on its use may be found in Hollnagel et.al. (2014).

Hollnagel states[1], that: 'The use of the FRAM […] involves two stages. 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 below]. The second is to use the model to create instantiations of the activity (or performance) and then to analyse these [Steps 2-4].' To clarify:

> 'The FRAM model represents the set of functions that together account for the activity being analysed and the potential couplings among functions. An instantiation describes the couplings that existed or may exist for a given scenario or set of conditions, and thus respresents a realisation of the model.' (Hollnagel, 2012:77)

The method is relatively new and has been used mainly for analysis of a specific situation (e.g. accident analysis) (Carvalho, 2011; Herrera & Woltjer, 2010), in which both stages have been performed retrospectively with reference to a single event. It has also been used to produce general system descriptions for risk analysis purposes (Rosa, Haddad & Carvalho, 2015), or understand the resilient capabilities of a sociotechnical system, exemplified within oil spill response (Cabrera Aguilera, Bastos da Fonseca, Ferris, Vidal & Carvalho, 2016) and the VTS domain (Praetorius et al., 2015). Here both stages of the analyses were performed at the work system level, discussing common operations across several emergency response centres (Cabrera Aguilera et al., 2016) and comparing everyday work at two VTS centres (Praetorius et al., 2015), rather than creating instantations around specific events or incidents. Hollnagel et al. (2014) also propose the use of FRAM in assessing variability in future system design.

According to Hollnagel (2012) and Hollnagel et al. (2014), to conduct a full FRAM analysis, one should first **Recognise the purpose of the FRAM analysis (Step 0)** - e.g. work system analysis - then follow fours steps:

Step 1: Identify and describe the functions.

A FRAM *function* describes 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). (This distinguishes FRAM from other systems approaches such as Cognitive Work Analysis and Work Domain Analysis (Hoffman & Lintern, 2006; Lintern, 2009; Naikar, 2017), which view functions as *structural* properties of a work system, whereas activities or actions relate to the *process*.) Functions may be performed by humans or technology, separately or collectively. Hollnagel et al. (2014:39) state that 'the best source of information about activities of interest is the people who actually perform the work'; thus qualitative data collection methods such as interviews, field observations and document review are recommended.

Analysis may be performed by directly identifying functions from transcribed records of the data (as in Hollnagel et al., 2014) or first performing a hierarchical task analysis or goals-means analysis (Hollnagel, 2012) or grounded theory analysis (Praetorius et al., 2015). Performance Shaping Factors (PSF) may also be identified and integrated directly as functions (Hollnagel, 2012:57-58; also Cabrera Aguilera et al., 2016). However, please note that PSFs in the context of FRAM are simply 'conditions which influence the events being studied' (Hollnagel, 2012: 57) in a broad sense, rather than quantifiable measures of human behaviour and environment as usually found in Human Reliability Assessment (HRA) (Hollnagel, 1993); consequently no link should be implied between PSFs and 'human error'.

Functions should be described in terms of six characteristics, or 'aspects', which claim to enable a better understanding of how variability may arise and spread. These are: *input*; *output*; *precondition* (without which the function cannot be performed); resources (which are consumed during the

[1] http://functionalresonance.com/how-to-build-a-fram-model/index.html

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). Figure 1 shows an example function 'monitor weather conditions' which will be discussed in detail in Section 5.2, and its aspects described in Table 3 below.

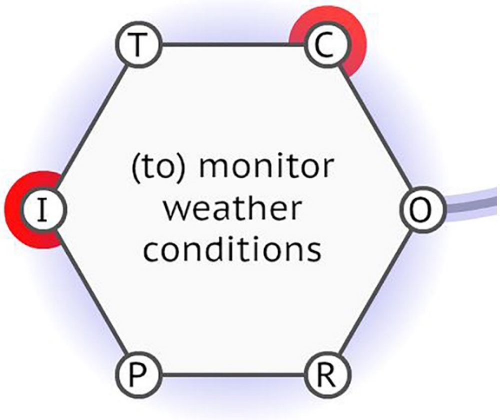


Figure 1. Example FRAM function 'monitor weather conditions'.

Functions should also be 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 coupling; coupled functions may be *upstream* (occuring before another function) or *downstream* (occuring after) of each other.

Step 2: The identification of variability.

FRAM categorises functions into human, technological or organisational, similar to most sociotechnical systems approaches (Hollnagel et al., 2014) and describes how a function's output may vary due to *endogenous* (i.e. internal), *exogenous* (external) variability. The effects of variability on a function may be expressed as a change in the *timing* or *precision* of its performance. Step 2 focuses on determining how each separate function may potentially be affected by internal or external variability (Hollnagel, 2012).

Step 3: The aggregation of variability.

This steps investigates how the output of one function may affect another (*upstream-downstream* variability), thus enabling variability to spread thoughout the system. The metaphor of resonance is used to describe how variability in and between functions may combine to produce an expected or unexpected outcome (*functional resonance*). *Aggregation* of variability may be seen as the net effect of variability across the system. Hollnagel (2012) indicates that this step should normally refer to a specific situation, or instantation of the model, but both Praetorius et al. (2015) and Cabrera Aguilera et al. (2016) have discussed potential performance variability on a system level.

Step 4: Consequences of the analysis.

The final step focuses on managing or controlling variability in order to both reduce unwanted outcomes, but also to promote successful ones (Hollnagel, 2012); it enables discussion of how this is, was or may be achieved in practice. This could result in suggestions for effective countermeasures or improvements to how the system currently manages performance variability (Cabrera Aguilera et al., 2016; Praetorius et al., 2015).

The FRAM analysis which will be presented here is similar to the system-level variety performed by Praetorius et al. (2015) and Cabrera Aguilera et al. (2016). Unlike Praetorius et al. (2015), who modelled specific VTS centres, it aims to describe the general practice of navigational assistance 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. It thus produces a generic FRAM model, but additionally develops an instantiation of the model to discuss a specific scenario, as described below in Section 4.

However, when performing this analysis, several aspects of the method were found to be open to interpretation, particularly regarding the choice and analysis of empirical data and how to describe work in terms of functions. Work Studies - with its strong grounding in empirical studies and themes of 'making work visible' (Suchman, 1995), symmetry between human/non-human, social/technical (Czarniawska, 2014; Latour, 2005), and work as activity (Karlsson, 1999) - provided a useful guide in 'filling the gaps', as summarised in Figure 2 below. The FRAM analysis will be presented in Section 5 and discussed in Section 6.

3. Empirical studies of navigational assistance

The empirical basis for this article is a series of qualitative studies which aimed to understand the work of pilots and VTS operators, as performed and described by its practitioners. They were not expressly conducted with the intent to provide input to systems models such as FRAM. Rather, they were part of an iterative, explorative approach, using various methods derived from Czarniawska (2014) and Stanton, Salmon, Walker, Baber and Jenkins (2013), and described below. The research moved backwards and forwards between data collection and analysis, field and office, in a process loosely inspired by grounded theory (Charmaz, 2006/2014). Similarities may also be seen with abduction (Magnani, 2001) - making the best possible explanation given the available data - or a hermeneutic circle (Heidegger, 1927) - attempting to understand the whole with reference to the parts and vice versa.

3.1. Qualitative data collection methods

The studies consisted of focus groups and interviews outside the workplace, and field visits to vessels and VTS centres, covering VTS and/or pilotage areas in four countries (summarised in Table 1). Participants were of five different nationalities and their level of experience ranged from trainee to over twenty years' experience in their current role. The choice of sites, participants and methods included in the studies were to some degree opportunistic, aiming to triangulate between ship/shore, geographical areas and types of participants. Successful assistance was an overarching theme throughout, but the specific questions asked developed as the studies progressed; issues highlighted as important in one study were investigated in more detail in subsequent studies.

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

Focus group

The studies started with a focus group (Stanton et al., 2013) for three deep sea pilots, working in the Baltic and North Sea areas, but also as harbour or coastal pilots in three different local areas within this region. Facilitated discussions evolved around one theme - success factors for navigational assistance. Participants emphasised many generic issues - which became an initial hypothesis, or empirical theory (Denscombe, 2010), about what constitutes successful navigational assistance - namely the importance of *integration of information from various sources* and *communication between pilot, vessel and VTS*. Participants often illustrated these points using examples related to specific situations or locations.

Expert workshop

An expert focus group-style workshop with two VTS operators gave a shore-side perspective. It focused on communication between vessels and shore, which had been emphasised in the focus group, and how this contributes to successful operations. The tendency of the pilots to illustrate their viewpoints with location- and situation-specific examples was integrated into the methodology by asking the VTS operators to draw maps of their areas on a whiteboard to aid in the discussions. This helped to highlight similarities and differences between the respective work practices in different areas, and between land and sea. Many points were repeated, though some new information arose, thus a richer, more detailed picture of navigational assistance as a cooperative practice between ship and shore began to emerge.

Training session and trainer interview

Local knowledge and experience had been repeatedly highlighted by both pilots and VTS operators. A VTS training session (in which one VTS trainer and eight Master Mariner students were present) and an unstructured group interview with two pilot trainers investigated how these are obtained. This provided a valuable insight into how knowledge is imparted to new employees and which factors are emphasised internally within the branch. In the training session this was enacted by the participants and observed by the author; in the interview it was described by the participants. The use of real cases, scenarios and incidents as a means of sharing knowledge became very obvious.

Field observations and workplace interviews

Site visits gave the opportunity to understand how the various factors described in previous studies manifest themselves in everyday work (Czarniawska, 2014; Wilson, 2014). An individual observation plan for each visit was written in advance, listing topics of interest rather than structured interview questions. Each visit took between two hours to a day.On-site observations and semi-structured workplace interviews enabled the participants to discuss their work in context, demonstrating the interaction with their various tools and systems, and communication with other actors. Events inevitably unfolded during the visits, prompting more specific questions, which in turn led to discussion of related topics of interest, initiated both by the participants and the author.

During pilotage, the methodology changed from direct observation to a more non-intrusive form of shadowing (Czarniawska, 2014) once on board, although the pilots were encouraged to think aloud as they worked. The vessels themselves also became objects for shadowing (see also Callon, 1986; Latour, 1986). Following how they were represented (physical objects, symbols on an electronic chart, radar echoes, details in an email etc.) and how the different actors interacted with them, also became part of the observation strategy.

3.2. Grounded theory-inspired thematic analysis: coding and categorisation of empirical data

A grounded theory-inspired thematic analysis (Charmaz, 2006/2014) was conducted 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' 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; open coding was used to generate codes and categories, which were interlinked and consolidated into themes using axial coding. 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). Images were analysed together with the written data. An empirical theory (Denscombe, 2010) - effectively a summary of the emergent themes - was formulated after analysing data from the first study. This process was repeated iteratively after every data collection, and the empirical theory refined throughout, the resultant model thus summarising the success factors for navigational assistance, and the relationships between them (Fig. 2).

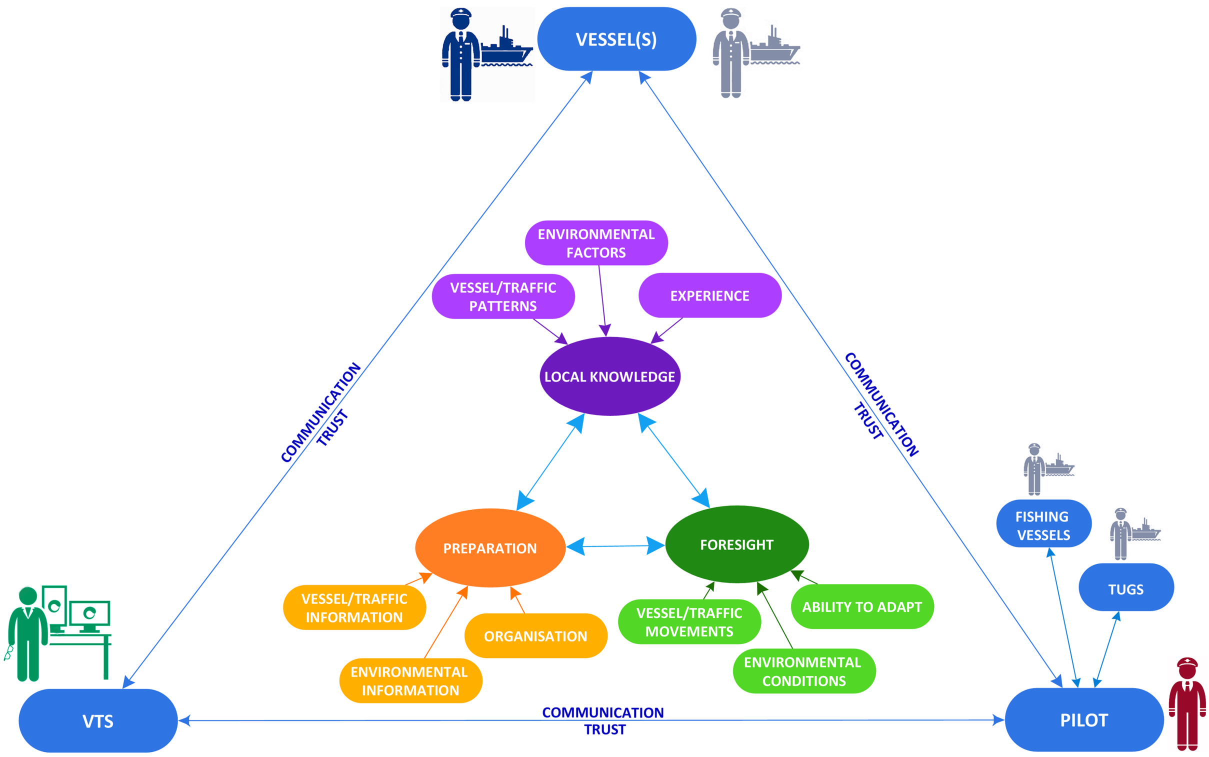


Figure 2. Empirical model of success factors for navigational assistance.

4. FRAM analysis: Building a FRAM model of navigational assistance

The data were (post-coding and -categorisation) analysed using the FRAM, following the procedure described in Section 2.3. Figure 3 summarises how the method was applied and how it was informed by various Work Studies themes. 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.

Step 1: Identify and describe the functions.

In identifying and describing the functions (Step 1), Praetorius et.al. (2015) used a grounded theory analysis of interviews, observations and focus groups, with similar results to the thematic analysis performed here (success factors = shape preconditions & create foresight: p.14), as the basis for further discussion with experts to establish the functions. Cabrera Aguilera et al. (2016) used ergonomic field studies, observations, interviews and document analysis to establish functions using Common Performance Conditions (CPCs), a variation on Hollnagel's PSFs (2012).

In the present case, 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 factors were, similar to CPCs and PFSs, translated into activities (see Hollnagel, 2012:40-41; also Cabrera Aguilera et al., 2016), and incorporated directly into the model as functions. For example *environmental conditions* (observations/measurements of wind, waves, currents, water level, visibility etc.), regarded by all as a central factor for successful assistance, expressed as an activity became function *'monitor weather conditions'*. (see Table 3).

However, this approach raised some questions about the implications of describing work in terms of activities or functions. Tacit knowledge, e.g. *'use local knowledge',* is a central feature of both pilotage and VTS (see e.g. IMO, 2016; Mikkers et al., 2013), but discussions with other researchers questioned whether it is a valid function in the same way as a concrete action e.g. *'check weather forecasts'*? Monitoring, e.g. *'monitor weather conditions'*, though a generally invisible or unobservable practice, is seen as a cornerstone of resilience (Hollnagel et al., 2011) and thus generally considered a valid function. We will return to this in Section 6.2.

Steps 2 - 4: Identification, aggregation and management of variability

A generic FRAM model showing the functions and their potential couplings was developed using the FRAM Model Visualiser tool[2] (Fig. 4 below). Though this paper will focus mainly on the FRAM model itself, a short analysis of a typical scenario - which demonstrates how potential variability may be identified (Step 2), then how it may propagate (Step 3) and be managed (Step 4) - will be presented (Section 5.2) and discussed (Section 6.3).

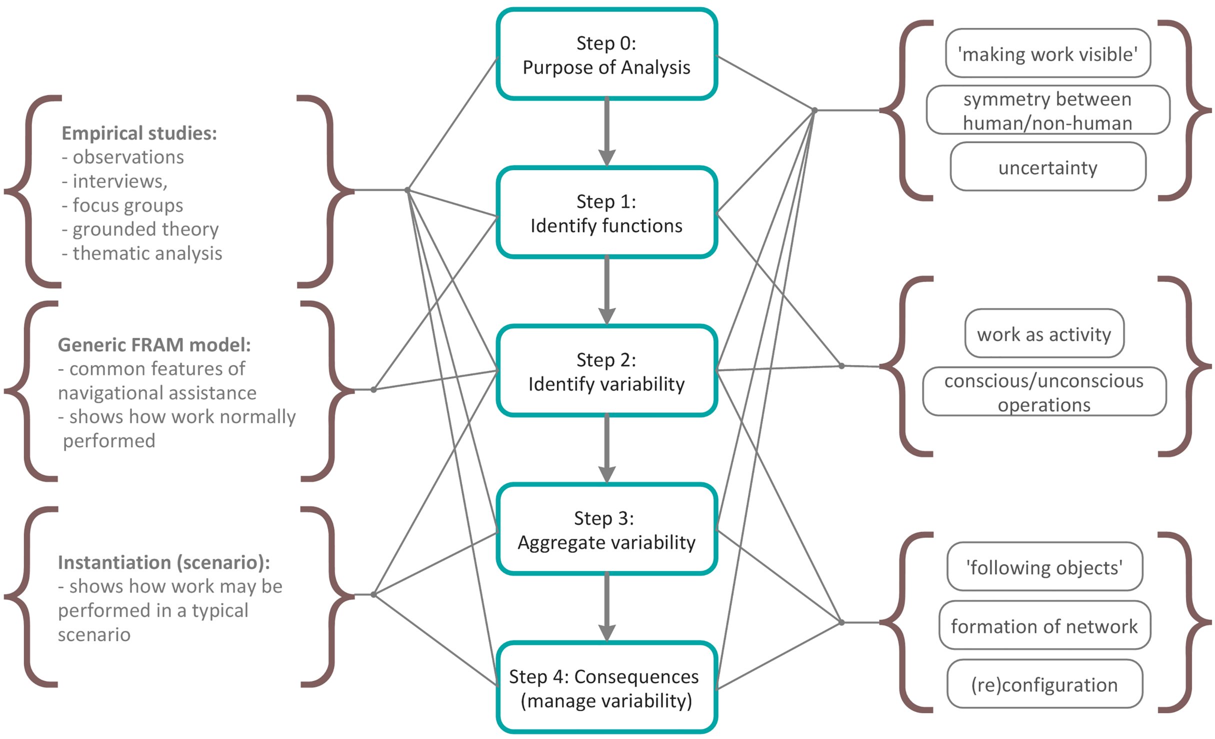


Figure 3. FRAM method, models and borrowed themes.

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

5. Results

Navigational assistance will be described here in two stages: first, its common features, represented by the generic FRAM model and functions, and arranged according to the themes (i.e. success factors) from the thematic analysis (Section 5.1), and; second, how these manifest themselves in practice, using an instantiation of the model (5.2). These results are a synthesis of the information gained from the various sites and participants, and are illustrated with examples and quotes (in *italics*) from pilots and VTS operators. Then follows a discussion of some implications of the use of the FRAM in attempting to describe 'work as done', and how this may be aided by ideas from the Work Studies traditions (Section 6).

5.1. An empirically grounded FRAM model of navigational assistance

The empirical theory which emerged from the thematic analysis is that the work performed by pilots and VTS operators (whether on board or shore-based) may be summarised as being 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. Successful assistance depends on the pilot or VTS operator having an understanding of how all these factors vary, how they are interlinked and how to handle them in a given situation. The success factors were treated as PSFs (Hollnagel, 2012), and consequently became the primary functions of the FRAM model.

The main indicator of successful navigational assistance is, in their own words, *'no incidents'.* This includes *'no groundings and no collisions… '* but also *'when we have done something proactive to prevent something from happening'.* Actions taken to avoid or mitigate incidents, *whether or not* these actually lead to a safe outcome, may still be considered a success, for example *'if I have an incident and it went aground, but I have tried to do anything, that's a success as well'.*

Figure 4 and Table 2 below introduce the FRAM model, in which these factors are shown as functions within the model. The core themes of the thematic analysis were used to arrange the functions into 'clusters' related to local knowledge (top left), preparation (middle left), foresight (bottom left) and communication functions (right). How work is actually performed was described as being very situation-dependent, thus the couplings between functions will vary depending on the situation. At this stage (Step 1 of the FRAM analysis), functions are linked by a simple input-output to show typical interactions as indicated by the synthesis of data from all sites and participants. All functions may be performed by pilots or VTS operators, except the four purple functions (with thick borders) which are usually performed by the pilot.

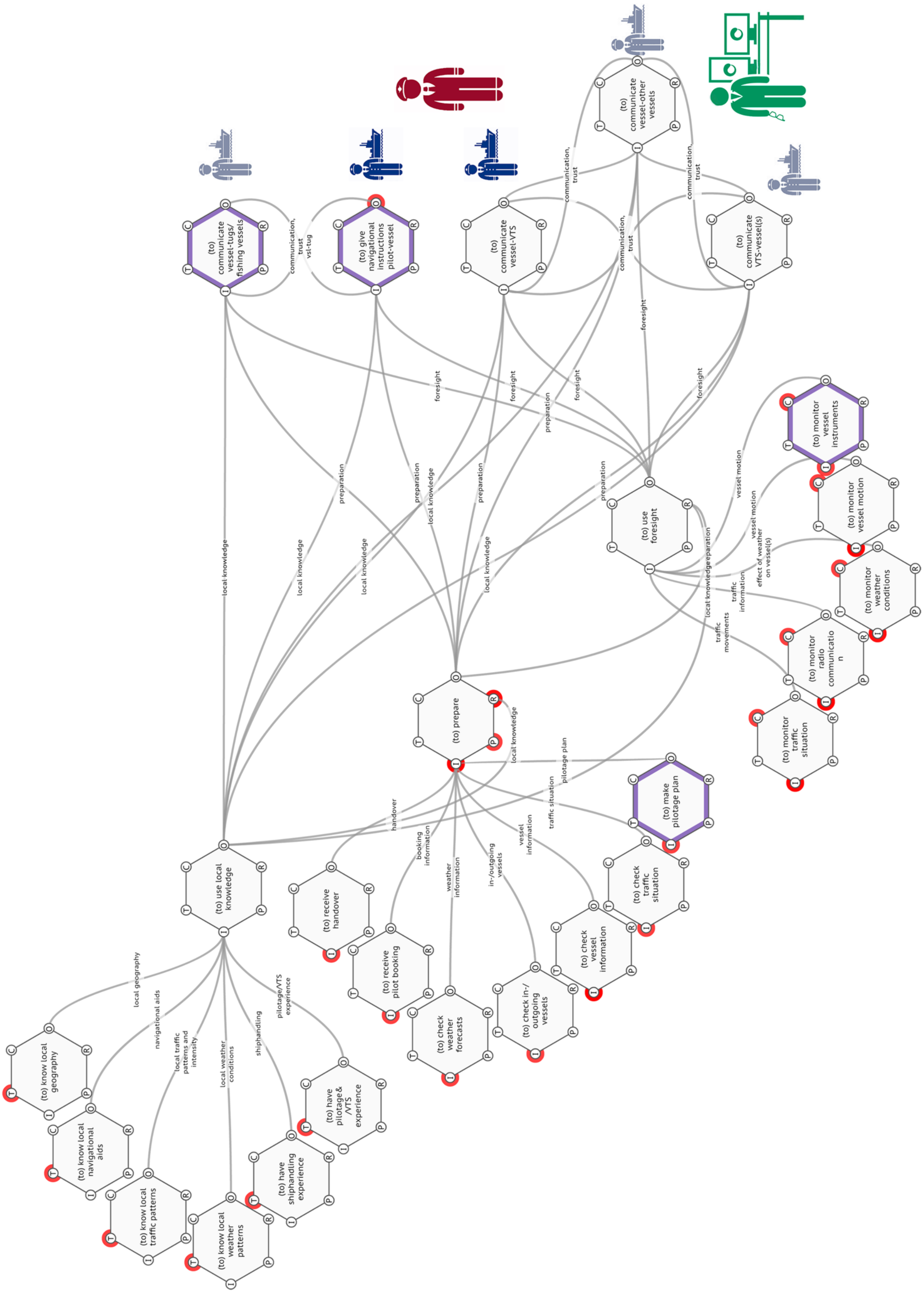


Figure 4. Generic FRAM model of navigational assistance.

Table 2. FRAM functions and corresponding success factors.

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

5.1.1. Local knowledge

To provide local knowledge to vessels was described as a central feature of pilotage and VTS. In training, pilots and VTS operators should learn and be able to demonstrate their mastery of all aspects of local knowledge which affect the safety of navigation in their area. This is widely confirmed in regulations and training procedures for pilots (IALA, 2012; IMO, 1968, 2003; IMPA, 2014) and VTS (IALA 2016; IMO, 1997) (see also Mikkers et al., 2012). Local knowledge may be roughly divided into three categories: vessel and traffic patterns, environmental factors and experience.

Vessel/traffic patterns are concerned with the number, types, sizes etc. of vessels which operate within the area, types of cargoes they carry, usual routes, schedules, and the nationalities of their crews. In one narrow channel *'it can be everything from maybe extreme case only 6, 7 vessels in there, up to around 40, 45, 50'*. Pilots and VTS operators should understand the factors which affect traffic patterns and density, and how these may vary. For example, seasonal variations such as large numbers of sailing vessels or pleasure craft in summer: *'This is a limitation. There can be lots of traffic, lots of vessels, and* *on the bridge they don't have a sporting chance of seeing all the vessels and knowing where they're going.'*

Environmental factors may be geographical, such as the location of narrow channels or shallow waters, which were present in all the participants' areas, or the presence of islands or sandbanks. Several participants reported that *'there are certain geographical points, we notice that there are incidents there'*. Navigational matters such as the location and characteristics of navigational marks, buoys, lighthouses, traffic separations schemes, pilot boarding points and so on are important elements of local knowledge. Environmental factors may also be weather-related, such as local weather patterns e.g. pressure systems, wind, currents or waves, or variations in water depth due to sea level or tide. In several areas, *'the problem to enter is the currents… also the water level… otherwise they would go aground'*. In terms of workload, *'the worst is bad visibility - fog'.*

Experience, both in general navigation and shiphandling, and as a pilot or VTS operator, were deemed essential to successfully perform the work. Although in some VTS areas the minimum qualification for a VTS operator was a Master Mariner exam, rather than actual seatime, practical shiphandling experience was considered desirable by all. Experience of handling different vessels within the specific area was compulsory for pilots, but also desirable for VTS operators: *'you know that this is a vessel, and how it moves and how it thinks… I thinks it's really beneficial to have been on a vessel before you work in a VTS'*. On-the-job experience of interpreting the various sources of information, and communicating with the vessel crew, other vessels, pilots and VTS is also important. In depth knowledge of the systems (VTS systems, portable pilot units, on board navigational systems, VHF radio) and procedures used (handovers, incidents reporting etc.) is thus vital.

Functions associated with local knowledge are thus: *'use local knowledge'; 'know local traffic patterns'; 'know local geography'; 'know local navigational aids'; 'know local weather patterns'; 'have shiphandling experience'*, and; *'have pilotage/VTS experience'* (Fig. 5).

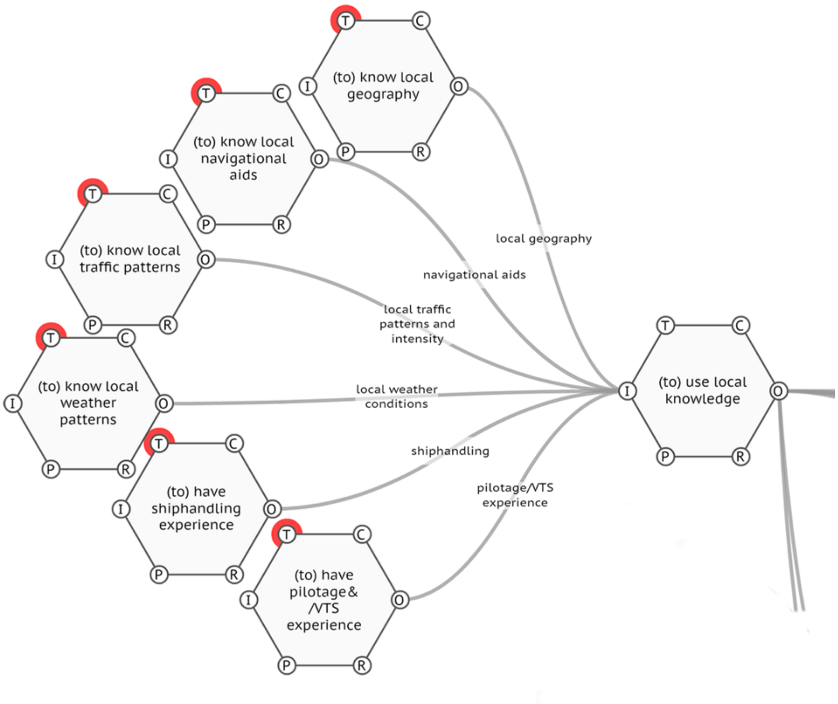


Figure 5. Functions relating to local knowledge.

5.1.2. Preparation

Preparation was considered a vital ingredient in ensuring success for all involved. Again this may be divided into three main categories: vessel and traffic information, environmental information and organisation.

Vessel/traffic information is potentially the most critical preparatory element. A multitude of parameters should be known in advance to facilitate safe passage, such as vessel name, length, breadth, draught, air draught, tonnage, type of vessel, type of cargo, bunker figures, number of persons on board, destination, estimated time of arrival (ETA) at relevant waypoints and more. These may be communicated by various means e.g. email, web forms, transmitted by AIS (Automatic Identification System) transponder, VHF radio communication or telephone calls. Written information *'gives the other side the time to read it and to try to understand it'*, whereas VHF information helps vessels plan their routes, e.g. *'a departure of a large tanker or container vessel, when they will take the northern fairway, then you can inform, then everyone knows that they should take the southern fairway since there won't be space'.* By compiling the information received from various sources, an overall picture of the expected traffic situation and intensity may be gained. However, accuracy of pre-information is a cause for concern for both pilots and VTS operators: '*it's not always correct [...] that gives lots of problems sometimes*'. It is often not updated, or multiple sources give conflicting information. Often information needs to be checked directly with the vessel crew, either via VHF or once on board, and uncertainty will not necessarily be resolved.

Environmental information during preparation is mainly concerned with checking the weather. Environmental factors (described above) may vary, therefore forecasts and observed measurements of e.g. wind, waves, currents, water level and visibility must be obtained and interpreted. Weather predictions may be obtained from service providers, usually a national meteorological institute or similar. Real-time measurements from sensors within the area may be obtained, either via a national service provider, or local providers, such as port or harbours. Predictions and observations may be viewed online or in a purpose-built software, or received via email. They may be displayed in the form of maps, graphs, tables, text or infographics. Once again, different sources may differ, for example *'the predictions we make [locally], and that is the battle between us, is sometimes different from what they [meteorological institute] do, what they predict… we make more, better predictions because we're on the spot'.* Navigational information should also be checked. There may be temporary navigational restrictions due to e.g. diving operations, dredging or military exercises which may require speed reductions or avoidance of certain areas.

Organisation on various levels also plays a part. The schedules of both pilots and VTS operators are generally based around a rotating schedule of *x* days on/*y* days off, where in the days on they may be on call a certain number of hours within a 24 hour period, and should be guaranteed a specified rest period before working again; travel to and from home may or may not included as work time. Workload per shift varies, and *'if there's a lot of traffic it can be tough, but an equally large problem is if there's too little to do'*. Handovers for the upcoming work period should be shared between on- and off-coming pilots and VTS operators. The individual should be rested and alert, facilitating their ability to receive and assimilate weather and vessel information as needed to create a plan for their upcoming work.

In the FRAM model, these preparation functions (Fig. 6) are: *'prepare'; 'check in/outgoing vessels'; 'check vessel information'; 'check traffic situation'; 'check weather forecasts'; 'receive handover'; 'receive pilot booking'*, and; *'make pilotage plan'* (pilot function).

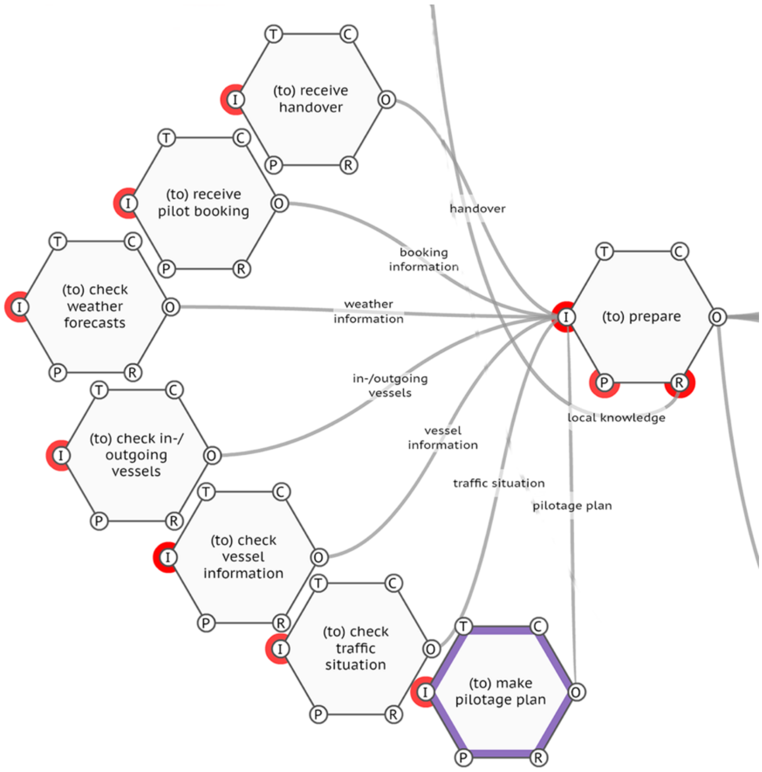


Figure 6. Functions relating to preparation.

5.1.3. Foresight

Both pilots and VTS operators describe foresight in terms of monitoring and interpreting the current situation in light of their local knowledge and preparation, to evaluate the available options and give vessels *time* to take the best course of action. Once again, this may be categorised into vessel and traffic movements, environmental conditions and the ability to adapt to circumstances.

Vessel/traffic movements must be constantly monitored to ensure that vessels are following their intended route, keeping their ETA to important waypoints, avoiding close quarters situations and shallow water. Pilots use mainly visual information, obtained by looking out of the window, to monitor vessel movement and the relative positions of other vessels. On board radar, gyrocompass and chart displays, and their own portable pilot units (PPU), are used primarily for confirmation. PPUs are beneficial since one has *'more real time information about the traffic siutation, such as the VTS have'*. VTS operators monitor vessel movements on their electronic chart and radar displays, and *'know that the ships kind of see the same picture on their bridge that you do. If you talk to somebody you can have an expectation that, well, you should be able to see this'.* There is often a time delay due to the systems' update rate, so the most up-to-date information for pilots comes from their own senses, whereas the VTS operators must rely on their system. VHF communication between vessels and with shore is thus essential for understanding the intentions of the vessels; *'it's very important for the rest of the traffic to hear that so that they can anticipate on it'*. A common theme amongst pilots and VTS operators is that, when they receive information from their systems, it is already old, and that they often rely on subjective judgement to predict what will happen in the next five minutes to half an hour.

Environmental conditions and their effect on vessel and traffic movements are monitored continuously, since *'the traffic situation changes if it's bad weather'*. Observations about current weather conditions may be obtained by visual estimation (e.g. surface currents flowing past a buoy or distance to known landmarks) or by measurements from sensors described above. Forecasts are compared with and re-evaluated in the light of real-time observations to give a more probable estimate of the weather conditions in the near future; e.g. in one area *'deep draft vessels really have* *to enter on top of the flow, of the current flow, so they only have 10 or 15 minutes to be in the right position'*. Again, between five minutes and half an hour is a usual time window both for pilots and VTS operators.

The *ability to adapt* to variation and uncertainty in the traffic situation and the environmental conditions is clearly important, and to facilitate vessels in adapting (see Section 5.2). Subjective expert judgement and local knowledge are central to this ability; sometimes *'the programme says no, the computer says no, and we say yes, then we still pilot it, because later on the computer can say yes'.* Providing vessels with *time* to take appropriate action is seen as paramount. Pilots do this by literally *looking ahead*, mainly at the fairway in front of the vessel, to assess the best course of action, before seeking confirmation from instruments and electronic charts. VTS operators rely heavily on electronic displays (Fig. 7) which predict vessel movements using a *vector* - an arrow indicating where the vessel will be in a certain time, based on current heading, speed etc. Vectors give an indication of potential situations before they develop and allow appropriate action to be taken.

> *'I choose ten minutes [vector length] because then I can see if it has half of the string, I could say, "Okay, you have five minutes till you go aground." You have still time to do something. Because when you have contact with the ship and for example it's heading for shallow waters, it's better to give them a time, time limit, to say "You have five minutes" because … Instead of saying, "Please turn to east or west due to shallow waters.", they will say "Oh, yes, yes. I have plenty of time." If you give them a time, they will do something now.'*

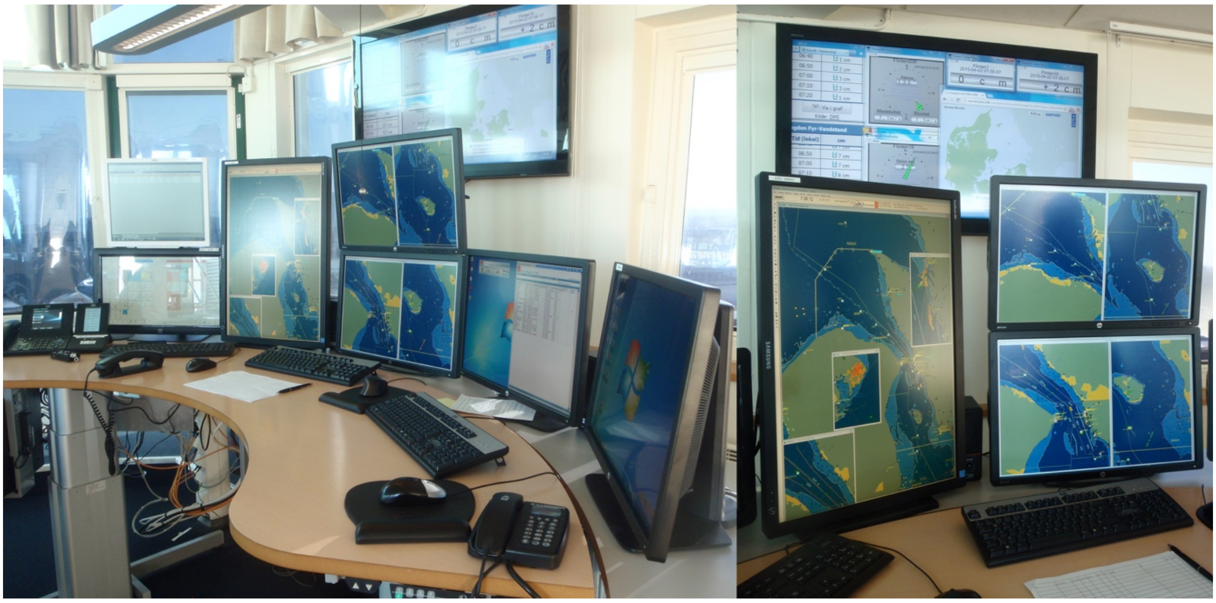


Figure 7. VTS workstation with VHF radio (far left), electronic chart with combined AIS/radar vessel targets (centre/right) and meteorological data (top right).

Associated functions are: *'use foresight'; 'monitor traffic situation'; 'monitor radio communication'; 'monitor weather conditions'; 'monitor vessel motion'; 'monitor vessel instruments'* (pilot function) (fig. 8).

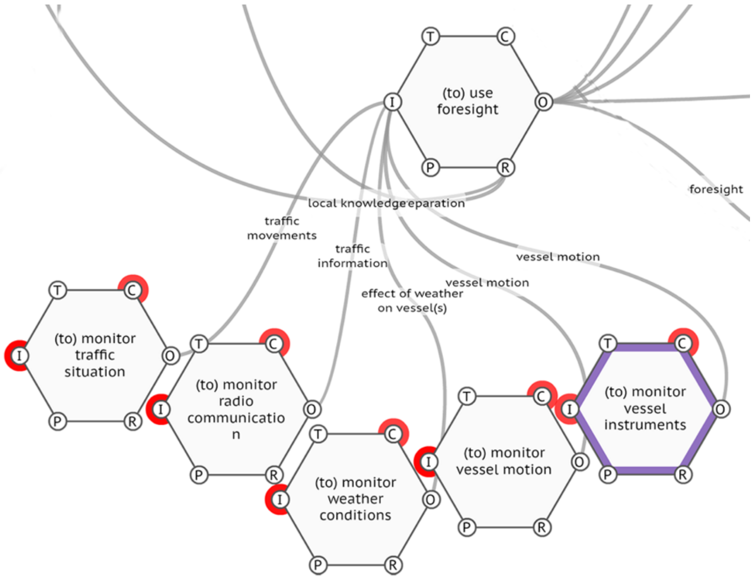


Figure 8. Functions relating to foresight.

5.1.4. Communication and trust

The main form of direct communication between vessels and shore when underway is VHF radio; two separate systems with this short range, line of sight radio are compulsory on board all vessels. Good communication is seen as vital by all: *'It's the most important thing we do, talking. If we have difficulty talking to each other, everything becomes much more difficult.'*; *'It's 90% of my work, communication, or 95%'*; *'As a VTS operator, communication is everything, it's all about the communication, and failure to communicate. But most of the time there's no problem with it.'* This can be illustrated using communication functions (Fig. 9): *'communicate vessel-VTS'*; *'communicate VTS vessel(s)'*; *'communicate vessel-other vessels'*; *'give navigational instructions pilot-vessel'* (pilot function); *'communicate vessel-tugs/fishing vessels'* (pilot function). All the factors or functions previously described provide inputs to the communication functions, i.e. their outputs are distributed between the actors by communication.

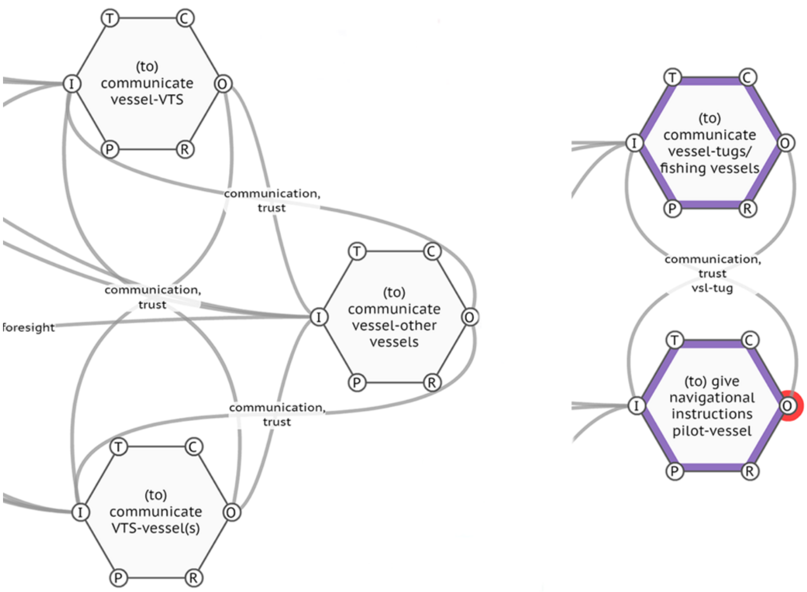


Figure 9. Communication functions, general (left) and pilot (right).

Mutual trust between vessels, pilot and VTS is also essential. Communication, either via VHF or in person, aids in judging whether the other can be trusted (see also Bonini, 2005). Trust was therefore defined not as a function, but as an output, or emerging property, of communication functions. VTS operators describe their *'gut feeling'* on whether or not they trust a vessel based on the first radio contact:

> *'I feel straight away whether I can trust them or not, and it's right spookily often'; 'The first call they do, you know if they will be a rogue vessel or not. It's… it's so true. Like yesterday, I had a vessel… "Oh that one, I will have a problem with that one later". And so it happened, wrong side of the fairway it was. […] I was certain about it so I informed my colleagues here "there will be trouble with that one".'*

Likewise, a pilot describes how:

> *'from the moment I step on board the vessel, on the deck, not even on the bridge, you can sense the mood of the crew. The character of the captain is reflected in the crew. If he is nervous or uncertain, they will also be nervous and uncertain.'*

Part of the pilot's role is to instill confidence in the crew: *'I have "status" as soon as I step on board, they see me as the local navigation expert.'* This role-based trust in the *'local expert'* is also held by VTS operators, who believe that vessels usually follow their advice because of it. Trust is however not guaranteed (see also Bruno & Lützhöft, 2009; TSBC, 1995). Pilots describe a *'spectrum'* or *'scale'* of trust, from being left alone in charge of the vessel, to having one's every movement closely monitored. Therefore *'an important part is making sure the captain feels calm'*, so immediately building a relationship with the crew is vital, primarily using smalltalk, particularly *'laughter is always good'.* Familiarity (as in Bruno & Lützhöft, 2009; van Westrenen & Praetorius, 2012) also plays a part; VTS operators tended to trust vessels with a pilot on board more than those without: *'A vessel with a pilot or without, it shouldn't make a difference to me. I should just do my job, without any judgements. But from experience and in practice, it's not always so.'*

5.2. Performing navigational assistance: integration and communication

This summary of factors or functions may falsely give the impression that navigational assistance is a simple linear process. While it undoubtedly takes place on a time axis, the process is one of continuous updating, reassessing, cross-referencing, communicating and so on in a very dynamic manner. Knowledge about vessels and traffic, the environment and human and organisational aspects of the ship-shore system, while built up on three time scales - long-term local knowledge, short-term preparation, and foresight about the present and near future - is continuously distributed throughout the ship-shore system and brought to bear on the situation at hand (Fig. 8) (see also Mikkers et al., 2012; Praetorius & Hollnagel, 2014; van Westrenen & Praetorius, 2012). The actions of integrating information from this multitude of sources, and successfully communicating this to other actors is what constitutes successful navigational assistance. Thus it closely resembles the act of navigation (as described by Hutchins, 1995a), but with modern technology and the extra layer of assistance from pilot and/or VTS intended to enhance safety.

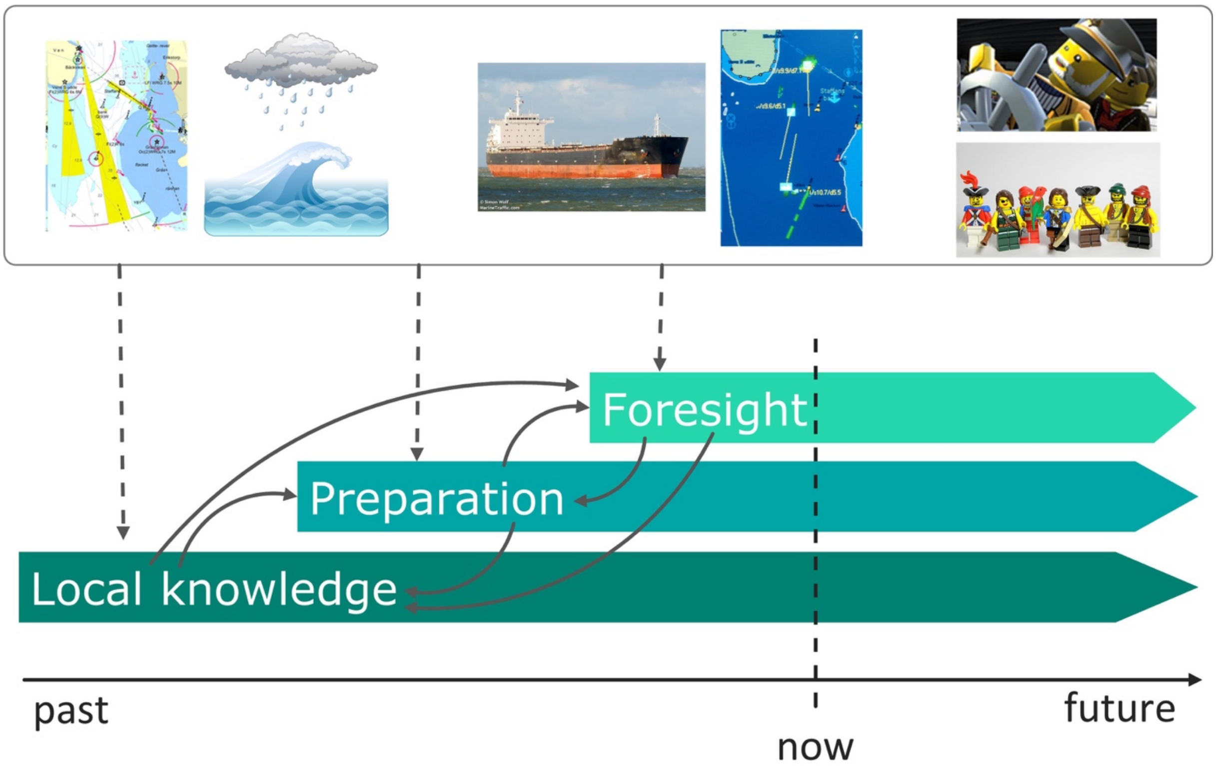
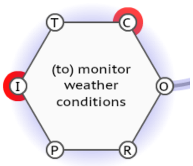


Figure 10. Navigational assistance on a time axis.

To understand how this is achieved in practice, i.e. how work is actually performed, and how it contributes towards maritime safety, concrete examples may be more helpful. In the language of our empirical model, this involves describing how pilots and VTS operators use local knowledge, preparation and foresight to integrate and communicate information about vessels, traffic and the physical environment to provide timely assistance to vessels. In the language of FRAM, we will identify variability in the functions (Step 2) to understand how it may aggregate or propagate throughout the system (Step 3) and how it may be managed or controlled (Step 4). To illustrate, we will investigate how a phenomenon identified as problematic by all, namely how work is affected by the presence of *fog*, which reduces *visibility,* by creating a FRAM instantiation around the function *'monitor weather conditions'* (Table 3). Incidentally, VTS originated as a shore-based radar service run by pilots to enable vessels to enter and leave harbour in low visibility, thereby increasing safety and efficiency (IALA, 2016).

Table 3. Function 'monitor weather conditions'.

Function	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

In all areas in the studies, narrow channels and shallow waters, combined with strong currents, variations in water depth due to tide or water level, and periods of low visibility, mean that vessels, particularly deep draught vessels, may be restricted in their ability to navigate safely. Although actual collisions or groundings were not seen as common, *'heading towards shallow water'* was a regular occurrence in several of the areas. In one area, VTS operators reported that *'last year we had about 20-25 vessels heading for shallow water, and it's a potential grounding'*. Fog is 'water droplets suspended in the air at the Earth's surface. Fog is often hazardous when the visibility is reduced to 1/4 mile or less'; visibility is defined as 'the distance at which a given standard object can be seen and identified with the unaided eye' (NOAA, 2016). Fog is a regular occurrence in many areas, but planning for low visibility is difficult, since it is difficult to forecast and dependent on '*almost random varying parameters, so they are inherently difficult to forecast at the right time and the right place'.*

Pilots and VTS operators agreed that visibility is best estimated on board vessels and from the VTS centre using the naked eye. However, the effects of fog may be very local, and change rapidly. Aids such as visibility sensors and cameras may also be used, but were often seen to be lacking at strategic points; vessels and VTS often rely on each other for visibility estimates.

For example, in one area, the whole area is visible from the VTS on a *'good'* day, but often *'we can have very good weather here, but [3 miles away] it's completely closed'; 'that is a little bit tricky because we don't have any cameras to see the fog and so we have people on this lighthouse. So sometimes we call them and ask how the visibility is.'* In another area there are sight restrictions for entering and leaving the terminals for large vessels; in loaded condition they must have over two nautical miles visibility and one nautical mile in unloaded condition. However, visibility may vary greatly between entering the area and reaching the terminal. Ultimately the judgement of visibility is up to the pilot, who will often call the VTS to ask for an estimate of visibility from a camera located in the harbour. In areas where pilots are usually transported to their vessel by helicopter, in low visibility they must rely on tranfer by tender (small motor boat). This causes delays and has a knock-on effect on other vessels: *'It is far away, so we don't like to use the tenders, because the tenders take a long time. We don't have them for other jobs.'*

On the vessels (with or without a pilot), keeping a safe distance from other vessels and shallow water becomes more difficult, since they lose the visual references they would normally use to navigate. Reliance on radar and electronic navigation aids tends to increase. However reduced visibility due to heavy rainfall can produce clutter on the radar, making objects difficult to discern, in turn increasing reliance on AIS targets on electronic chart displays. A pilot described how perspective changes depending on the source of information: *'Everything looks much closer together on the screen'; 'Distances observed visually appear greater, they appear smaller on the screen than visual, and they look smaller on the ECDIS [electronic chart display] than the ARPA [radar]. Radar is best to see the relative movement of vessels.'*

As a result, vessels navigating in fog tend to slow down and increase separation between each other, also increasing communication with each other and the VTS. The volume of radio traffic inevitably increases, and consequently the workload of VTS operators: vessels *'want much more information, much more information… You notice that people, that the vessels, are more nervous too. You can say they are on their toes. Then there's much more talk.'* Pilots also reported that this situation requires much closer cooperation between vessels and VTS than usual. This may be illustrated with the following FRAM instantation.

Figure 11 shows how the performance of function *'monitor weather conditions'* is affected by exogenous variability (i.e. due to changes in the physical environment), potentially, though not necessarily, leading to unwanted outcomes. How *'monitor weather conditions'* is performed, i.e. how visibility is known or estimated, also varies depending on situation and the available means. Local knowledge (*'know local geography', '… traffic patterns', '… weather patterns'* etc.) provides a control or guide as to how similar situations are usually handled, and thus a resource for managing the present situation. Likewise, multiple sources of information - visual estimates, sensors, cameras, forecasts etc. obtained from performing functions *'check weather forecasts', 'monitor vessel instruments', 'monitor weather conditions'* - may each provide a check on the reliability of other sources. Such information may then be shared between ship and shore - functions *'communicate vessel-VTS', '… VTS-vessel(s)', '… vessel-other vessels', 'monitor radio communication'*.

One may also say that variability resonates or spreads to functions *'monitor vessel motion' and 'monitor traffic situation'* and *'communication'* functions between vessels and VTS. It affects how vessel and traffic movements are monitored due to alternative (i.e. non-visual) sources of information, thus affecting the behaviour of vessels (e.g. reduced speed and increased separation) and the volume of communication between vessels and shore. Adaptations in how functions are performed are the result of upstream-downstream variability, but also the means by which variability is managed. This also indicates in which circumstances it may not be possible to manage variaibility i.e. when the workload becomes too great, or communication is not functioning.

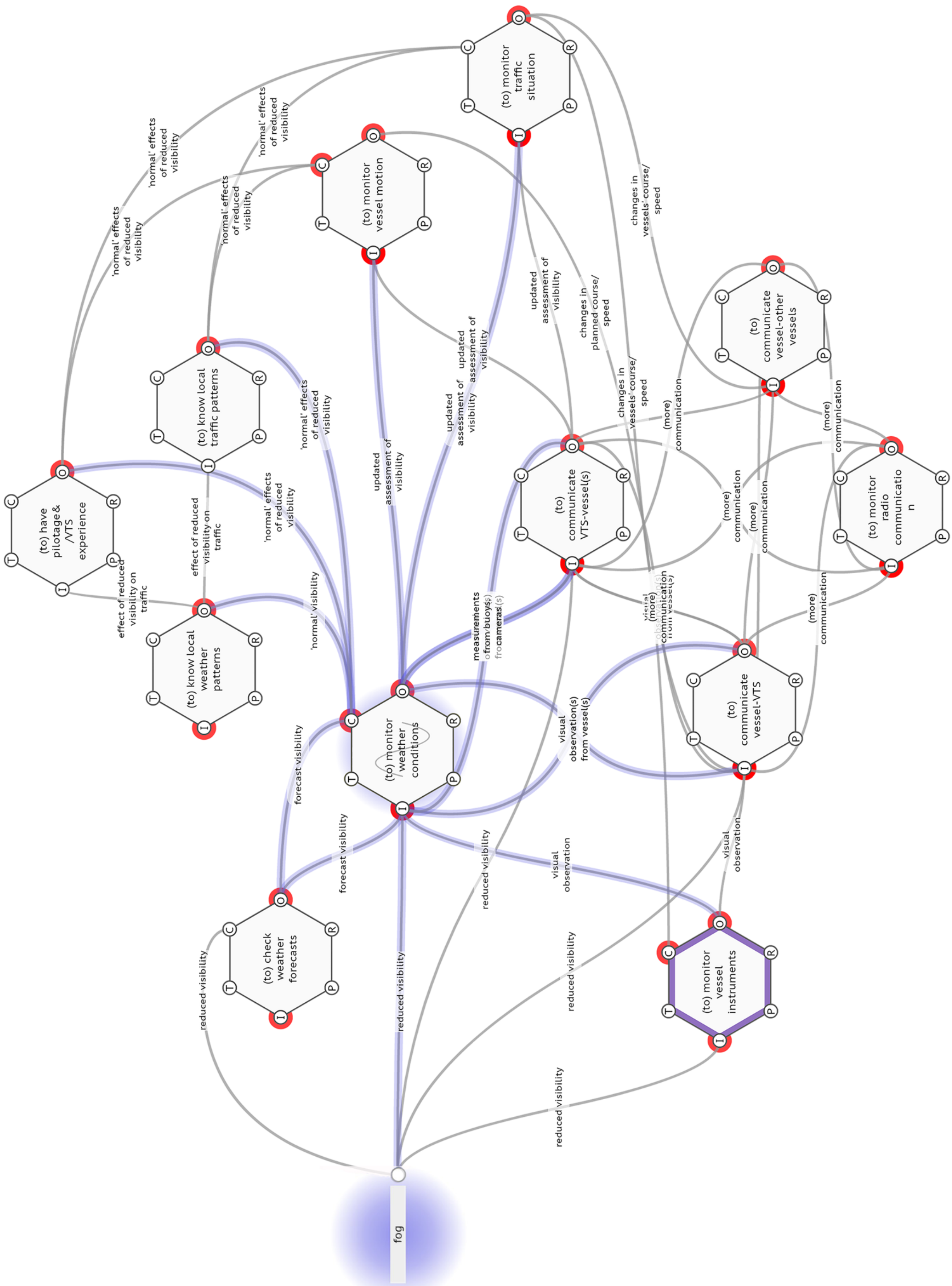


Figure 11. Instantiation showing effects of fog on navigational assistance.

6. Discussion

6.1. Making groundwork visible

As may be seen from the time and space dedicated here to describing the empirical studies, FRAM relies heavily on expert knowledge and extensive, time-consuming groundwork (see also Cabrera Aguilera et al., 2016; Praetorius et al., 2015). One may claim that understanding of the work performed by pilots and VTS operators came less from the FRAM method itself than the studies which preceded it. The author contends that one should explicitly recognise the value of such groundwork in its own right (as implicit in e.g. Praetorius et al. (2015) and Cabrera Aguilera et al. (2016)), not simply as input to a systems analysis or model such as FRAM.

Work studies in safety-critical domains (e.g. Haavik, 2013; Hutchins, 1995a,b; Suchman, 1993) have shown how descriptive narration of empirical studies may make individual work practices visible but also highlight general features of sociotechnical work which may be transferred to other contexts. Checkland (2000), Le Coze (2013a,b), Hepsø (2014) and Haavik et al. (2016) maintain that this type of approach may in fact benefit systems engineering methods, since any model of a work system will necessarily be a simplification of the real thing, and risks becoming a portrayal of 'work as imagined' (Hollnagel, 2012). In order to avoid this, a thorough understanding of the work carried out by practitioners is a precondition for modelling 'work as done'; but consequently, a model build upon extensive empirical groundwork may have greater credibility. This applies not only to FRAM, but conceivably to any systemic representation of work.

Czarniawska (2014:25) describes grounded theory - a common fieldwork strategy both in work studies and systems theory approaches - as 'the common sense of fieldwork'. Perhaps this should be seen as an aim of all empirical studies of sociotechnical work - that if done thoroughly, the results will simply be common sense to those performing the work. As one VTS operator, who had been involved in research in the past, said, *'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'.* The fact that FRAM leaves open the choice of empirical data collection and preliminary analysis (Hollnagel, 2012; Hollnagel et al., 2014), may thus be seen as a strength rather than a constraint, under the proviso that the resulting FRAM analysis is based on thorough empirical studies.

6.2. From success factors to functions

As indicated in Section 4, describing empirical data in terms of FRAM functions is not straightforward. Unlike other systems approaches, FRAM defines functions as activities or means to an end (Hollnagel, 2012:40-41), and promotes the use of (a broad interpretation of) PSFs as functions in this context (2012: 57-58). In order to describe 'work as done', functions should therefore show what people (or technology or organisation) *do*.

The participants emphasised the use of factors such as local knowledge, preparation and foresight, i.e. *tacit expert knowledge*, in their work (as do Mikkers et al., 2012), as well as the central role of *monitoring* of screens, instruments, vessel motion etc. (see also Praetorius et al., 2015). Initially, one may question whether these factors may be 'functions'; they may potentially be criticised as unmeasurable and therefore unfalsifiable (see Dekker & Hollnagel, 2004). However, in keeping with our themes of describing 'work as done' (Hollnagel, 2012) and 'making work visible' (Suchman, 1995), a description of safety-critical work would be incomplete without factors seen by its practitioners as fundamental for safe operations. Also, as Hoffman and Lintern (2006) discuss, the ability to elicit and represent the knowledge of experts is of growing concern for systems design. A method or model which facilitates this may therefore be of practical use in informing design.

Borrowing from activity theory (Karlsson, 1999), activities, in which an actor uses a tool to achieve a goal, may operate on several levels of abstraction. Activities may be concrete *actions* ('*what* must be done') (Karlsson, 1999:381) - e.g. the pilot/VTS operator may *'check weather information'* by accessing an online weather forecast. Activities may also comprise *operations* ('*how* it can be done'); operations may be *conscious* (similar to Heidegger's *present-to-hand tools (1927)*), or *unconcscious* or internalised (*ready-to-hand tools*). For example, the pilot/VTS operator may *'monitor weather conditions'* and provide *'foresight'* by interpreting the effect of the weather on vessel motion. Though internalised, monitoring and using tacit knowledge are performed in the context of work tools and environment (see also Hutchins, 1995a) and may according to activity theory be considered activities, and thus functions within a FRAM analysis.

6.3. Describing sociotechnical work with functions

FRAM categorises functions into human, technological or organisational functions, and its understanding of the likelihood and potential effects of variability are dependent on this classification (Hollnagel, 2012; Hollnagel et al., 2014). However, in our case it may be more helpful to consider the functions themselves as *sociotechnical*. For example, when performing function *'monitor weather conditions'* - superficially a human function - in foggy conditions, the pilot or VTS operator may be 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. As Hutchins (1995a) discussed, such an activity is not simply a human cognitive process, but is performed jointly with the tools of navigation in the work environment, and thus has properties, and by implication potential variability, which are not solely 'human'. By describing work in terms of functions, one highlights its sociotechnical nature and emphasises how humans and non-humans work *together* to perform an activity (see also Latour, 2005). Note that our work 'system' includes non-human actors which are technological or organisational, but also natural phenomenon, as discussed by Le Coze (2013a,b) and Wilson (2014) (see also Callon, 1986; Latour, 1986, 1995/1999, 2005).

Likewise variability in functions can seldom be attributed to only one actor. Both what is being done, how it is being done, and its effects are situation-dependent (Suchman, 2007; also Cabrera Aguilera et al., 2016), as are which functions affect performance (i.e. are upstream) and are affected by it (downstream). How functions and variablity are described is a consequence of the analysis, informed by the empirical data and expressed in the model instantiation, rather than an inherent characteristic of the functions in the system model (see also Haavik, 2011; Latour, 2005). For example, performance and relative importance of the function *'monitor weather conditions'* varies according to the situation, location, vessels, available sensors etc., each of which may themselves vary considerably. Variability is distributed across actors, but is transformed and integrated to shape action and provide navigational assistance, similar to Hutchins' interpretation of distributed cognition in navigation (1995a). *'Monitor weather conditions'* becomes a foreground function in the presence of poor visibility, but which sources of information are relied on, and the effects on e.g. vessel motion and communication, are situation-dependent. This also shows how outcomes (safe or otherwise) emerge from the performance of work, as discussed in the literature of both work studies and sociotechnical systems.

6.4. Work as done?

This leads on to the question of whether the approach taken in this article has actually succeeded in describing the practice of navigational assistance and its contribution to maritime safety. Has it adequately described 'work as done', or has it fallen into the trap of 'work as imagined'? We have discussed how inspiration from the work studies tradition has emphasised the importance of thorough groundwork, and helped to account for tacit knowledge and invisible practices, and the sociotechnical and situation-dependent nature of work.

The explicit contribution of FRAM is that Hollnagel's two-stage method (Hollnagel, 2012; Hollnagel et al., 2014) may produce both a model and instantiations of the same activity. In this paper it was used firstly to produce a *generic system model* (Section 5.1) which describes the common features of navigational assistance, independent of location, situation or whether it is provided from ship or shore.

In common with much sociotechnical work, the factors which affect the performance of navigational assistance are dynamic and variable; in the visibility example we saw how the work system reconfigures to adapt to the circumstances. FRAM allowed us to investigate this by also producing an *instantiation* (Section 5.2), enabling discussion of a particular scenario, in this case reduced visibility, which illustrates how the dynamic and variable nature of work manifests itself in practice. This configurable generic-/specific-model shows how work is *normally done* (similar to Rasmussen's 'space of possibilities' (1997)), and also how it is *actually done* in a specific scenario or situation, both of which are essential elements in understanding 'work as done'.

A generic model may conceivably be transferable to other instances of the phenomenon it describes. From the generic model one could produce further instantiations to discuss other scenarios or analyse specific situations (e.g. events, incidents or training scenarios). Similarly, one could discuss the impact of proposed changes to the work system (e.g. the introduction of cameras in the VTS area). The model/instantiations may thus be used to facilitate discussions between stakeholders, including users, designers, managers and regulators, allowing them to configure or annotate the model. A similar approach has been successfully applied by Hoffman and Lintern (2006) using an 'activity overlay' of a Work Domain Analysis, and by Hepsø (2014) with business process models.

7. Conclusions

This paper aimed to understand the practice of navigational assistance as performed by pilots and VTS operators, and how it contributes to maritime safety. Furthermore it attempted to describe this practice in a way which may potentially be used in the development of future work systems. Using an approach in which empirical studies were analysed using the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012; Hollnagel et al.,2014), navigational assistance was found to be achieved by the interaction between humans, technology, organisation and environment, distributed in space and time and constantly adapting and reconfiguring in order to improve the safety of navigation of seagoing vessels. 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.

It has shown how FRAM may be a valuable tool for describing sociotechnical work, but which may be enriched by borrowing from the work studies tradition, with its strong grounding in empirical studies and themes of 'making work visible' (Suchman, 1995), symmetry between human/non-human, social/technical (Latour, 2005, Czarniawska, 2014), and work as activity (Karlsson, 1999). This approach has allowed us to describe a work practice on a generic level, but also investigate how work is actually performed, how safety is achieved, and how this varies depending on the situation, using both narrative and visualisation. Furthermore, this approach indicates 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.

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Acknowledgements

The author wishes to thank the participants of the studies, the MonaLisa2.0 project for funding the field visits, and also Barbara Czarniawska, Torgeir Haavik and Gesa Praetorius for their inspiration and advice.

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