Assessing the Impacts of Ship Automation Using the Functional Resonance Analysis Method

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The maritime industry is experiencing a steady evolution towards a concept of fully automated ship operation. The implementation and use of automated systems have been debated for many decades, and yet substantial issues remain regarding its achievements in terms of improved safety and efficiency (Wiener & Curry, 1980). The assessment of potential impacts (i.e. risk assessment) emerging from the introduction of automation remains a key challenge. The integration and streamlining of operations significantly increase complexity, and the transformations that are introduced tend to produce unforeseen side effects, often with serious safety consequences (Dekker et al., 2011).

The developments towards autonomous shipping have heavily focused on the ship side and concept developments for shore centres (e.g. Rolls-Royce Shore Control Centre), but less on how shore-based vessel operations may potentially be integrated into the current maritime transport system. It will likely require transformations, which are to have legal, economic, and organizational impacts across the industry greatly extending beyond the availability of technology. Suitably addressing these challenges requires a predictive and integrated investigation of these

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potential transformations. Particular attention should be devoted to how increased operational interdependency may generate new complexity-related aspects and how this in turn will affect the system's ability to resilient operations.

This chapter serves as a basic discussion for how the Functional Resonance Analysis Method (FRAM) can be used to explore and design functional set-ups for potential complex maritime operational scenarios. It focuses not only on the traffic management system, but also considers shore-based control centres (SCC) and other services that can be foreseen as requirements for the operation of autonomous vessels. We have identified three safety critical scenarios and described them based on different focus group activities carried out with subject matter experts. We further use the FRAM to highlight where potential future critical coordination aspects may emerge amongst different functional requirements and discuss how these may impact on the system's ability to resilient operations. The discussion builds around how the pursuit of a FRAM-based analysis of future operational concepts may contribute to enhanced resilience in increasingly dynamic and variable maritime operational conditions.

1 Maritime Traffic Management and Autonomous Vessels

Currently, navigation in and out of ports is organized as a distributed control system (Praetorius et al. 2015, Van Westrenen & Praetorius 2014). Vessels navigate according to their individual voyage plan. They may be assisted by a pilot, who is a navigational expert with specific local knowledge to increase safety of navigation, and represent the coastal state. Furthermore, coastal states often install so-called Vessel Traffic Services (VTS) in port approaches. In shore-based VTS centres, VTS Operators (VTSOs) monitor the traffic, assist in navigational matters, and provide information to all commercial vessels in a designated area, normally port areas or areas that pose navigational difficulties. It is important to note that while VTS is a support to maritime traffic, the decisions and responsibility for a vessel's safe conduct remain with the Master on board (IALA, 2016). VTSOs are thus not able to steer or direct the traffic from shore.

In the current maritime traffic system, communication from and to the VTS serves an important function as it is a source of information about the overall state of traffic and potential dangers within the VTS area. The information is public and broadcasted on dedicated radio channels that navigational crews can listen to. This in turn enables the vessels to adjust and adapt to changes as they occur. However, this is anticipated to be affected of changes to the organizational frame of traffic management once shore centres for autonomous vessel operations are introduced. Shore-control centres (SCC) are likely to represent an additional centralised control layer, which may significantly impact on the coordination resources that VTS currently ensures via its information services.

While the degree of automation in the operation of merchant vessels has steadily increased throughout the past 30 years, the maritime domain is now on the verge of a new technical revolution towards autonomous vessels, sometimes labelled shipping 4.0. (Lambou & Masaharu 2017). Recently, the International Maritime Organization has defined four levels of autonomy for Maritime Autonomous Surface Ships (MASS) (IMO, 2019):

- Ship with automated processes and decision support: Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated.
- Remotely controlled ship with seafarers on board: The ship is controlled and operated from another location, but seafarers are on board.
- Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.
- Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself.

However, despite the efforts to define a common terminology, several researchers argue that the usage of "autonomy" in the industry is somewhat misleading. While automation and autonomy are closely related concepts, the first will not automatically lead to the latter as assumed by many maritime stakeholders. As discussed by among other such as Relling et al. (2018) and Hult, Praetorius & Sandbrerg (2019), the current concepts of autonomous vessels represent a system with supervisory control from shore rather than being an autonomous actor in the traffic system.

As the degree of automation within operations increases, new perspectives are needed to explore the complexity of everyday work. Within the maritime domain, resilience engineering and its concepts have received an increasing amount of attention. Previous research has successfully applied the resilience abilities to understand everyday adaption and flexibility, as well as several researchers have modelled shore services and ship-to-shore operations to understand how safety is promoted by the various services and actors within the maritime transport system (Praetorius & Hollnagel, 2014; DeVries, 2017). The analysis and discussion in this chapter build upon earlier work and use the Functional Resonance Analysis Method to explore potential system transformations that may emerge beyond the change of its individual components (i.e. ship-board and shore-side automation, communication technologies, among others).

2 Defining Scenarios for Future Operations

Three focus group interviews were conducted to design and explore future traffic scenarios to capture, on the one hand, relevant aspects of current everyday operations (Work as Done – WAD), but also identify the transformations that are most likely to be introduced in the future, as the industry progresses towards increased automation.

The first focus group was used to develop three scenarios. Seven experts from the northern European maritime cluster representing different stakeholders in the maritime domain and academia participated in the group interview. The scenarios were developed as open-ended as possible to trigger the participants to freely discuss potential shore-based services, activities of those services, system requirements, and competence needs.

1. Reduced crew scenario

After an 8 h shift, the navigation of the vessel is handed over to a shore- based centre. The Master remains on board and can quickly be called to the bridge in case of any complications.

2. Convoy

A convoy of (unmanned) vessels is led and steered by a manned support vessel through ship–ship communication. The support vessel offers an opportunity to intervene and quickly react in case of any unanticipated events on any of the convoy's vessels. The incentive for this traffic solution was the low cost for manning. The convoy is in coastal traffic and several of the vessels are going to leave it in the approach to the next port.

3. Going to port

A vessel approaching one of Europe's major ports. During the voyage across the Atlantic, the vessel has been unmanned and steered from a shore centre. Now she is going to port to take on new cargo.

After the scenarios had been defined, two new group interviews were conducted to discuss the actual changes to and impacts of future operations. The participants were presented with the short description of the scenarios and ask to elaborate on two questions; what shore functions/activities are needed for the scenario to be realised, and who does what in terms of the identified functions and activities. The discussions were captured in terms of notes on a whiteboard to facilitate the discussions among the participants. Follow-up questions were used to explore particularly critical interactions between shore-based services and the autonomous traffic.

The experts' discussions first focused on the overall services, or service functions that would be required for operations in general. Approaching a port, even if the vessel is steered from shore during sea voyage, will require a navigator or pilot who can take the vessel to the berth. Additionally, a crew is needed for mooring and cargo handling operations. Upon arrival at the berth, linesmen and other port services, such as port authority and customs will remain a part of the infrastructure to ensure the safe and secure handling of the cargo.

It is also likely that a traffic information services, such as VTS today, will remain as shore-based function. VTS is the only service directed towards overseeing the overall traffic flow, thus efficiency and safety within a port approach. There is still a large uncertainty surrounding the coordination and communication functions between shore and ship. The participants in the two follow-up focus groups also highlighted that an unmanned sea voyage and port approach is likely to require two different SCCs, one that is focused on open sea and one centre that is area-specific, and which will take over once the vessel is approaching. Some of the local control functions could potentially be taken over by the VTS, if traffic control services become centralized in an analogy to Air Traffic Control and the VTS would gain an increased mandate beyond what is provided today. However, the participants emphasized that this would require the shipping companies to transfer some of their autonomy to services representing the coastal state, which may not be desired.

For the navigation support, a local Shore Control Centre (SCC) may be established by the shipowner in the port. The SCC will, however, not be manned by pilots or VTS operators, nor will it be the responsibility of the maritime administration to implement such a centre. Given the interest of shipowners, the centre will be manned through the shipping companies to secure the business and trade secrets.

Pilots have an important role for the safety in port approach. In today's setting, they provide three important functions to a vessel: the local language, expert ship handling in a specific area assisting manoeuvring, and they are representative of the coastal state, that is, an important safety measure to ensure safe operations in the approach. While a vessel may be unmanned and operated from shore, it is important to consider how to ensure that there is a last safeguard before a vessel can enter the port. In the current traffic system, the pilot represents this function as he or she is able to see whether a ship and crew are in the condition to enter port. Further, having to board a pilot to the vessel, especially if she is unmanned, represents additional safety risks. If there is no crew on board, the boarding procedures will have to be determined. Further, the legal implications and split of command between navigator and pilot need to be clarified. Currently, the pilot is assisting the Master, but does not have the legal responsibility and accountability for the vessel's safe voyage.

3 Modelling Future Maritime Operations

To explore future maritime operation, the functional resonance analysis method (FRAM) (Hollnagel, 2012) was used. FRAM is a method to analyse and model complex sociotechnical systems, in which functions are distributed over human operators, organizations and technology. It provides the means to model future operation concepts with a focus on overall system aspects, despite the substantial uncertainty that persists relating to the design and operation of individual system elements.

The method focuses on the concept of performance variability and ways in which systems manage and monitor potential and actual variability. FRAM is based on the principle of equivalence of successes and failures, principle of approximate adjustments, principle of emergence, and the principle of functional resonance (Hollnagel, 2012).

The modelling focused on the approach to port as one of the most safety critical scenarios of maritime operations. The analysis set-up was followed on previous exploratory work carried out in relation to automation in the context of air traffic management (Ferreira & Cañas, 2019), in which FRAM was used to investigate how foreseeable steps towards automation would impact on overall air traffic control operations. For the purpose of this exploratory work, basic assumptions were derived from the scenario description:

- VTS services are expected to be maintained under formats similar to current ones, as multiple types of “conventional” merchant vessels are expected to remain in operation within a foreseeable future.
- Interactions between the autonomous vessel approaching port, and, therefore, coming into the VTS area, and the VTS itself, will be carried out via the SCC. Since no crew is expected to be aboard, all legal and operational responsibility will necessarily be with the Officer of the Watch (OOW) in the shore-based centre.
- A pilot and minimum crew requirements are considered needed to navigate in and out of ports. Safe navigation in close interaction with a wide variety of vessels was not considered realistic under autonomous, nor remote control modes. In the approach to ports (at least major and busiest ports), a pilot and crew will, therefore, have to be dispatched and board autonomous vessels.

The maritime operations taken into account range from the approach of an autonomous vessels to a VTS area, to the manual takeover of that vessel by crew and pilot to be dispatched aboard. The model obtained is shown in Fig. 1. Different shades of grey are used to highlight three operational areas:

- VTS functions are represented in dark grey/black.
- SCC functions are represented in medium dark grey. They essentially focus on the gathering of information relating to autonomous vessels and about general traffic from VTS, and the communication, both to VTS and to autonomous vessels.
- Functions in light grey represent the operations carried out on board the vessel, once pilot and crew have boarded. These mainly relate to the necessary checks of vessel operation and systems, and all the requirements for vessel control handover.

The function represented with thinner lines (confirmation of pilot and crew) relates to pilot and crew arrangements, prior to the vessel boarding operations. Based on the model developed, two fundamental aspects of coordination are further explored:

- Interactions between SCC and VTS
- Interactions with autonomous vessel during pilot and crew boarding

These aspects of coordination were investigated through the insight on functional variability that FRAM enables. The FRAM Model Visualiser (FMV – www.functionalresonance.com) provides useful insight to investigate the “resonance effect” based on the description of the potential variability in the output of functions, with regard to its time (too early, on time, too late, or not at all) and its precision (precise, acceptable, or imprecise).

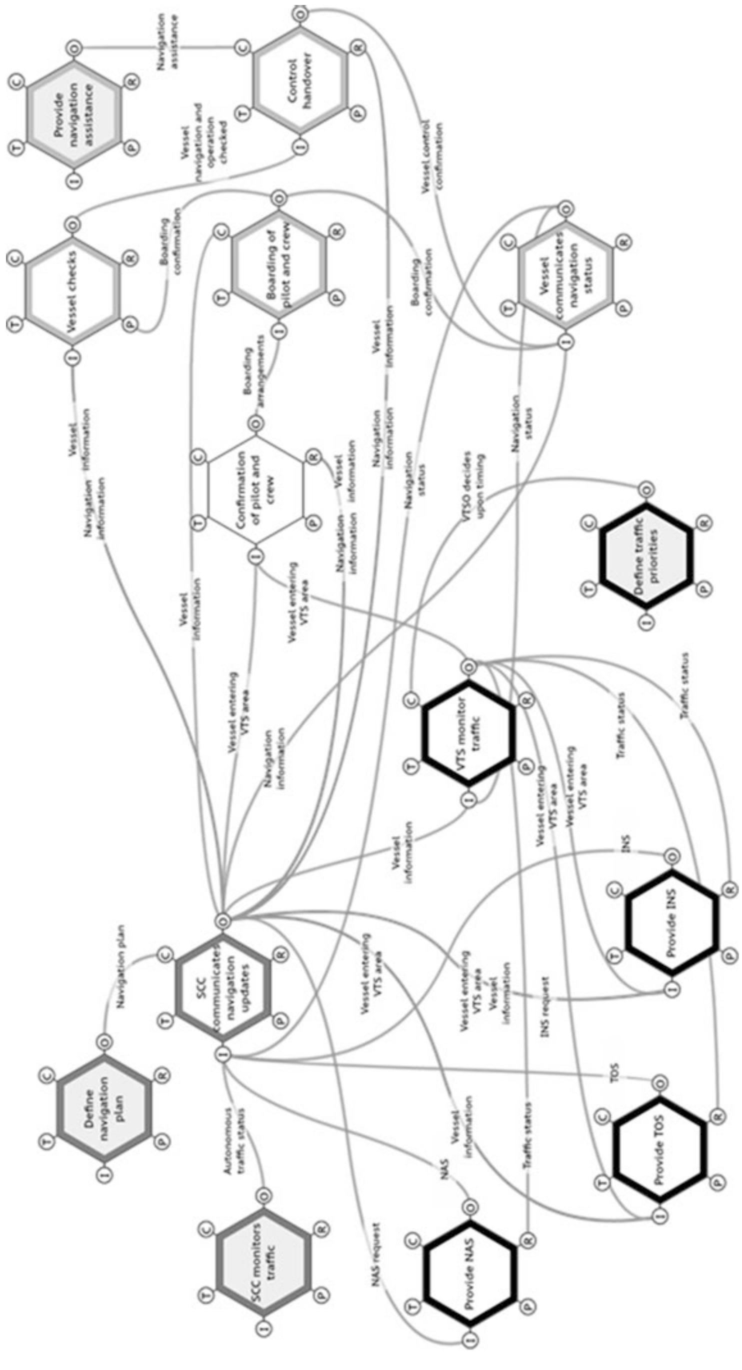

Fig. 1 FRAM model

4 Interactions Between SCC and VTS

The SCC communication is the most coupled function (SCC communicates navigation updates). This is not surprising when, to a great extent, in the scenario in question, the SCC is conveying to the autonomous vessel, information sourced through VTS services, not only to navigate the autonomous vessel (under remote control conditions), but also to assist crew as they board the vessel and make the arrangements for a control handover. As the diversity and number of vessels navigating within port areas can be expected to increase, the ability of SCC to generate a suitable overview of navigation conditions becomes increasingly limited. Hence, SCC would still rely on VTS services to develop overall traffic conditions and accordingly navigate autonomous vessels under their control. SCC is also likely to feed to VTS information and navigation data relating to the vessels under its control. This would generate the feedback loops between VTS, SCC, and autonomous vessels that are illustrated in Fig. 2.

The feedback loops in Fig. 2 also indicate that, to some extent, the VTS would need to rely on the SCC to provide the service with updated information on the state and status of autonomous vessels within their area. However, similar to current maritime regulations and procedures, the SCC is unlikely to be under obligation to provide information to the VTS, which means that these loops may not necessarily be suitably balanced. For instance, if the workload of the SCC operator becomes critical due to some particular traffic conditions, or when operating under some degraded mode, the service may withhold information from the VTS. Naturally, the VTS's ability to provide information is mainly grounded on the broader monitoring of port traffic (function "VTS monitor traffic"), but communication with traffic is an important part of their ability to generate an overview of navigation conditions and anticipate potential risks and opportunities in the traffic organization. This is where the additional centralised control layer that SCC creates, may become critical, as there is no foreseeable framework to ensure the coordination between VTS and SCC information needs.

5 Interactions Between the Autonomous Vessel and Boarding a Crew

The exchange of information between the SCC and the VTS will have a critical impact on how the boarding and handover processes will be carried out. This will most likely require a certain amount of systems check, in addition to the planning and decision-making related to navigation requirements, for which input from the VTS will be fundamental. The formal handover of vessel control between onboard crew and SCC is unlikely to be carried out before the crew aboard has completed all necessary checks, such as testing equipment and vessel response, accepting or adjusting the voyage plan made by the SCC, and has taken certain position required

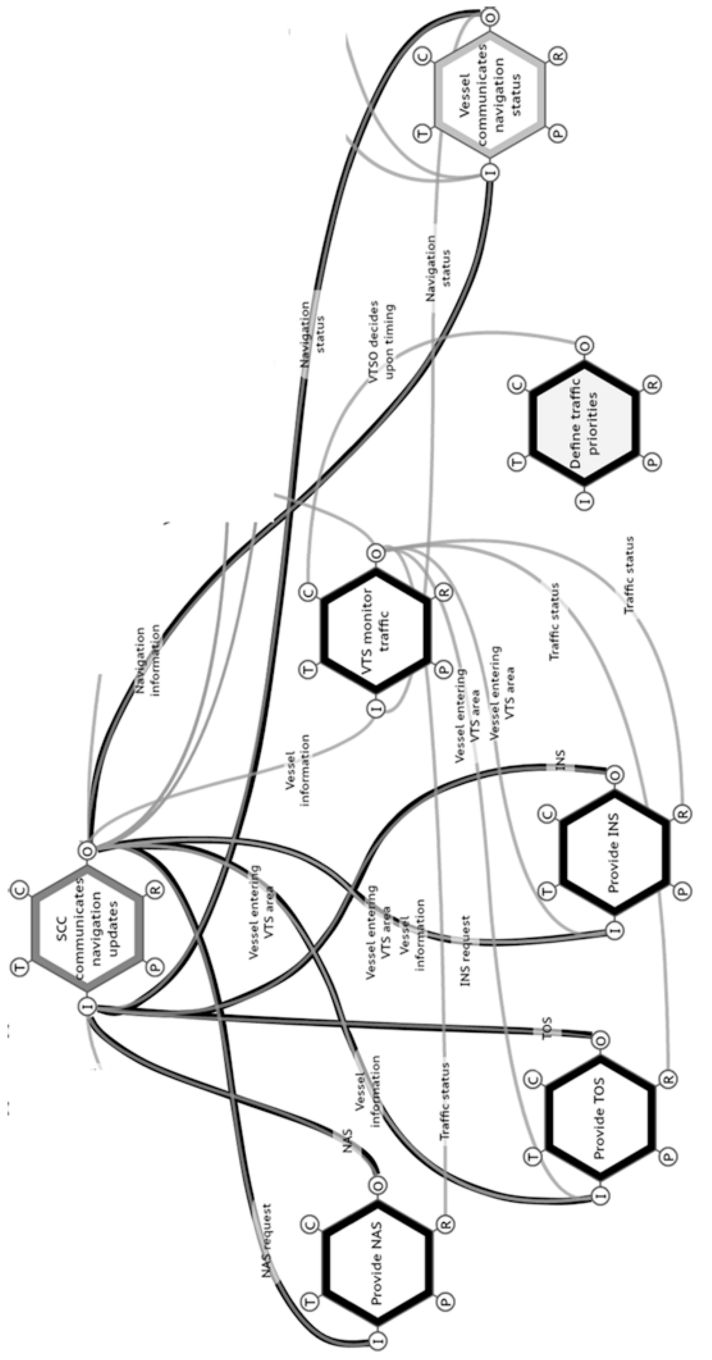

Fig. 2 Feedback loops around SCC communications

for the safe conduct of the vessel. Until that handover takes place, the responsibility for safe navigation will stay with the OOW in the SCC, which means that all requests from the autonomous vessel to the VTS will have to be transmitted through the SCC. SCC operators may be able to anticipate some or most of the information needs and ensure that VTS provides it before the crew aboard the vessels communicates its request, or the crew may also request information before it actually becomes necessary. However, while the whole control transfer process is ongoing, the vessel will keep navigating towards the port under remote control or autonomous mode and traffic around the port area will naturally also remain in full operation. This means that time pressure may easily become a critical factor and the ability to respond to any unanticipated events becomes quite unclear.

Figure 3 shows an instantiation of the FRAM model for what could be the control handover process, with a particular focus on the exchanges of information that are likely to be needed. The numbers in black indicate the sequence of activation of the functions that are likely to be directly involved in the handover process. The colour codes on the functions illustrate the amplitude of variability in the output of that given function. The colour at the top of the function represents an estimation of the potential variability in the output of that function with regard to time, whereas the colour at the bottom represents an estimation of that variability in terms of the precision of the output. Progressively darker red tones are used to indicate increasing amplitude of variability that is actually observed in the output of the function, and blue and green colours indicate lower amplitude of variability. Naturally, each output may assume many different degrees of variability, but for the purpose of this discussion, the instantiation in Figure 8.3 shows what could be considered a “worst case scenario”, with particular focus on high amplitude variability in the output of the function “control handover”, as this represents the operational goal of the system here modelled.

While this is a simplified overview of the process and other interactions are likely to be carried out, it illustrates how coordination may become a critical aspect of future operations and how the ability to respond to unforeseen circumstances may compromise the entire handover process. A more thorough analysis would be needed to detail all the potential issues that may arise during boarding and handover. Based on data currently available, the following ones were highlighted:

- The crew is delayed due to difficulties in boarding the vessel (i.e. weather or sea conditions).
- The systems check report failures that were not previously detected from remote control.
- Conditions aboard the vessel do not match what was expected by the crew, and adjustments have to be made to planned operations.
- Navigation information is not provided in a timely way, which may lead to the need to revise plans for navigating into port or even the voyage plans.

As this instantiation only presents one possible situation, the process may be adjustable to changes, and it may not have to be precisely carried out according to the sequence that is represented in Fig. 3. As suggested by the numbers, some

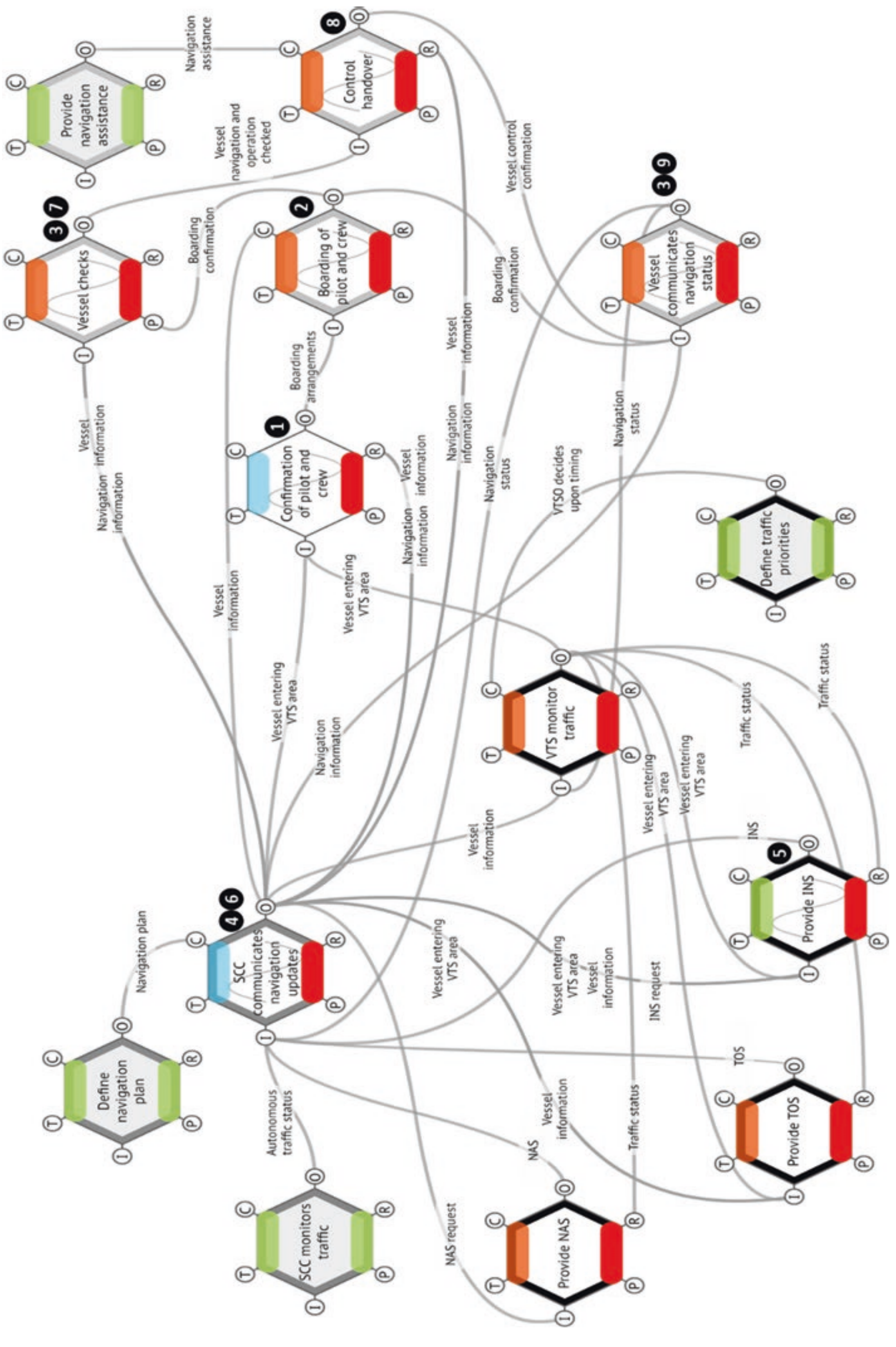

Fig. 3 Instantiation for vessel control handover

functions may even be carried out simultaneously. However, this will surely have repercussions in terms of the overall uncertainty and complexity that emerges from shifting control while the vessel keeps moving towards the port. Hence, the variability of functions to be carried out by the crew boarding the autonomous vessel becomes critical for whole system operation, particularly when other similar processes are likely to be ongoing simultaneously, which will increase uncertainty on SCC operations. Generating capacity for the crew onboard to adjust to unforeseen circumstances without compromising the safety of navigation into port also requires that the crew initiates boarding arrangements with much more anticipation that, for instance, currently pilots do. This will naturally impose additional resource constraints and may often be compromised by sea conditions.

If delayed boarding the vessels and aiming not to compromise port arrival schedule, the crew might attempt to compensate by expediting systems and vessel checks. This may in fact enable the control handover to be undertaken in such a way that the ship may continue navigating into port according to schedule. However, this means that in practice the crew may be operating and deciding based on more substantial and diverse assumptions (i.e. everything is OK to proceed with control handover). The output of the function "vessel checks" would become significantly delayed and/or imprecise, and as illustrated in Fig. 3 by the colour codes, the variability of the output of most other functions may also be amplified, as to a certain extent, they rely on the precision and timing within which the crew boards the vessels and undertakes the necessary arrangements for control handover. The main potential impacts are shown in Fig. 3 through the waves in the functions.

6 Communication, Coordination, and Complexity

The modelling of anticipated functions in the future maritime transport system reveals many crucial aspects, which have up to now not been addressed in the literature. It also shows the potential complexity of introducing an increased degree of automation in vessel operations.

While some of the current service functions will remain largely unchanged, such as the role of the VTS overseeing and informing traffic with the goal to facilitate fluent, efficient, and safe traffic movements in and out of port, the preconditions are changed by the introduction of an additional service, the SCC that is likely to be operated by the shipping company/ies. Thus, an increased need to coordinate and communicate between SCC, conventional vessels, and VTS is anticipated. As traffic dynamics and complexity increase, so will the difficulties for VTS to acquire a suitable overview of navigation conditions in and out of port. This can be expected to significantly increase the exchanges of information, particularly as new control layers are added to the system. Communications might develop an iterative nature, as the need to confirm, verify and update traffic information becomes increasingly frequent and difficult.

Although not fully explored here, degraded operational modes are likely to raise many other related issues. In the case of systems' failures, particularly under the critical scenario of control handover previously explored, operators will have to take over the failing automated functions, and interactions between operators and systems that remain operational will intensify. The operational and safety requirements for automation under similar scenarios have been widely addressed in literature (Bainbridge 1983, Balfe et al. 2012) but nevertheless remain short of expectations.

The interactions between "conventional" vessels, those with advanced automation, and autonomous ones, can be expected to generate additional complexity issues. The coordination among the traffic participants is strongly reliant on the exchange of information. Particularly, for VTS services, there is the need to shift from data link (coming from vessels with automated systems) to voice communication protocols (from "convention" vessels), which is likely to raise complex challenges and an increased workload for the shore-based operators. Further, one of the core problems with shore control identified in the discussion is the aspect of command. If command is transferred from a shore centre to the ship, which is being manned by navigators, crew, and pilot, how is the takeover organized and how is accountability and responsibility for safety of navigation assigned. This will require new procedures with regard to the physical handover between shore and ship and deeper understanding of the roles of different actors.

The high dynamics and complexity aspects outlined are well within the scope of resilience engineering thinking (Nemeth & Hollnagel 2014). The highly distributed and opportunistic nature that maritime navigation currently retains seems compatible with the key principle of generating adaptive capacities (Woods 2015). However, the introduction of different control layers and operational concepts (i.e. centralised and automated systems) will inevitably transform the way navigation conflicts are currently negotiated between vessels. The growing congestion around major ports also erodes the buffering capacities that may have so far facilitated such negotiations. The persistence of collisions and groundings as major safety issues in the maritime domain provides evidence towards the stretching of capacity boundaries under current operation concepts, particularly around worldwide major ports that are already showing capacity problems.

7 Opportunities for Enhanced Resilience in Future Traffic Management

Currently, the maritime transport system can be understood as a loosely coupled complex system. The traffic largely acts independently, and the VTS oversees traffic flows and informs traffic if needed. Despite a limited capability for tactical and strategic control (Praetorius & Hollnagel, 2014), the system is rather well-adapted to the current operational settings with the ability to adapt and cope with quick contextual changes. However, through the anticipated changes with regard to the increased need for coordination and communication, the abilities to respond, monitor, anticipate, and learn will drastically be affected. While some coordination and communication requirements may be effectively formalised, namely, through operational procedures, resilience engineering literature has frequently argued the need for such elements in the scope of informal and flexible adjustment of work to local conditions. In the face of the foreseeable intensification of maritime traffic, particularly in the proximity of major international ports, these local conditions are likely to become increasingly specific and dynamic, which means that the need for informal coordination and communication also becomes more prominent. The FRAM-based approach in this chapter and its further exploration may pave the way towards developing an operational (functional) perspective on critical coordination and communication needs, as opposed to one purely based on the business-oriented needs that tend to focus more on the alignment of responsibilities and the formal roles within organizations. The insights developed through the FRAM can thus inform the design of future operations in such a way that coping with increased variability and uncertainty is better supported by flexible exchanges between actors in the system.

Responding characterizes a system's ability to know how to react in a given situation. This requires timely information about the system state as well as the possibility to act based on it. Within the anticipated system, a novel control layer is introduced through the SCC. This means partially the introduction of a centralised control feature that may reduce variability and, therefore, increase predictability of traffic movement. Thus, it can be argued that the ability to respond to development could potentially be enhanced in future operations.

Further, as the need for coordination between VTS, traffic, and SCC increases, the ability to monitor and anticipate will gain in importance. New indicators for safe operations need to be developed to be able to determine the system's current and potential future states to be able to prepare for and cope with both routine and irregular operations in a dynamic operational context. This will partially be possible through traditional risk assessments, but will also require to revise potential sets of indicators once SCC and autonomous traffic start to operate. It is important to take the effects of the increased complexity into concern, as these will impact on what indicators can be considered as representative for different system states. Indicators for performance, therefore, need to address both the process of traffic management in autonomous shipping and its potential outcome(s). It is common to assess maritime operations and safety within these by outcome indicators, such as number of incidents and accidents, or traffic density in an area. However, to ensure safety in operation within autonomous vessel settings will also require to ensure that essential buffers in terms or resources (time, manpower, technology, procedures) for deviations in normal operations and abnormal situations are secured to ensure that the traffic system can maintain its functioning and cope with these. Therefore, process and outcome indicators are needed. The above FRAM analysis can serve as a tool to highlight potential challenges and generate discussions on what issues should be taken into consideration, and how they should be approached in view of their wider system relations.

As the need for coordination and communication increases, so do time constraints to find appropriate responses for situations that occur on less regular basis. Thus, the introduction of SCC and autonomous traffic needs to consider how to identify potential safety and security threats early on, that is, how to maintain and probably enhance the ability to anticipate. This requires new strategies to forecast traffic developments, as well as a clear definition of roles among the actors so that uncertainties in responsibilities are reduced as much as possible. Anticipation will play a crucial role to ensure that appropriate indicators to monitor current operations can be developed, maintained, and revised as needed.

This chapter has analysed a system that is still under development. It is, therefore, hard to determined how the ability to learn can be addressed. To ensure learning from positive and negative operational experiences is important, but this requires a system to be in place and operational. However, as maritime operations tend to show a rather reactive way of learning, we emphasize that future developments need to take current everyday work, and challenges therein, into consideration when a novel control and organizational structure is developed. Otherwise, there is a risk that today's operational challenges will just be transferred into future operations in addition to whatever novel demands may arise.

8 Conclusion

This chapter has explored future maritime operations through the lens of FRAM. While most of the research up to now has primarily focused on the ship side, this has been an attempt to understand the consequences of change to maritime traffic management including shore-side services such as the VTS. The analysis has shown that the increased automation primarily affects the system's capabilities and characteristics related to cooperation and communication among ship and shore, especially between the anticipated SCC and VTS.

While many stakeholders currently emphasize the potential of autonomous shipping in terms of efficiency and safety, the analysis has shown that more attention should be paid to the increased complexity and functional dependencies that arise based on the introduction of the SCC. This will affect the amount of information available, as well as the ability of services, such as VTS, to be able to monitor, respond, and anticipate to developments in the area. Furthermore, through the introduction of the SCC functions, the overall control settings in the maritime transport systems are changed from distributed to polycentric control. This will have an effect on the resources, that is, time, communication systems or data streams, required to uphold fluent, efficient, and safe traffic movements within port approaches. As a well-functioning coordination between ship, shore and the VTS is the focal point to ensure safe navigation, it is necessary to secure that the resources needed can actually be deployed in the right time.

Within this chapter, FRAM has enabled the visualization of the complexity within the coordination and communication processes between VTS, vessel, and

SCC. However, this should only serve as a starting point for further exploration. Rationalising around the "four resilience cornerstones" (Hollnagel 2009) in combination with the FRAM models has provided a useful approach for a discussion on future operational and safety-related challenges. For both VTS and SCC functions, monitoring and anticipating will become increasingly relevant, as maritime traffic around ports becomes more complex and difficult to predict; thus more buffering capacity is required to maintain the ability to quickly respond and adapt to changes in the operational context. The FRAM model helps to visualise how the introduction of centralised control features can help to reduce variability, and therefore increase predictability. However, this will also have effects on the system's ability to quickly adapt to situations where operations may deviate from normal procedures. Beyond safety compliance needs and the demonstration of independent systems operability, the exploratory work presented here shows how the FRAM can provide the basis for a prospective analysis of future operation concepts, and support the identification of where the challenges of "working across boundaries" may emerge.

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