Defence, Safety & Security
Kampweg 55
3769 DE Soesterberg
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

www.tno.nl

T +31 88 866 15 00
F +31 34 635 39 77

TNO report

TNO 2019 R12184

JIP Autonomous Shipping – WP5 Report Design for Unmanned Operations

Date	December 2019
Author(s)	Dr. Hans van den Broek
Number of pages	55 (incl. distributionlist)
Sponsor	This research project is partly funded by the TKI-Maritiem allowance of the Dutch Ministry of Economic Affairs and Climate Policy
Project name	Joint Industrie Project Autonomous Shipping (JIP AS)
Project number	060.31999

Contents

1 Introduction

The concept of autonomous maritime shipping has considerable potential for transporting goods and performing other maritime operations in a cost-effective and safe way (Krikke, 2019).

In the Joint Industry Project Autonomous Shipping (JIP AS), a multitude of partners (companies, research institutes, governmental bodies and educational institutes) collaborate to inventory, and assess (the status of) the available technology required for autonomous shipping.

This report is the deliverable of JIP AS work package five (WP5), called ‘Design for Unmanned Operations’ which is aimed to *define conceptual solutions for replacement of the functions assigned to the crew*.

1.1 Overview of JIP AS WP5: Design for Unmanned Operations

In order to be able to define conceptual solutions for replacement of the functions assigned to the crew, one needs a functional breakdown of generic ship and system functions. Within JIP AS WP3 ‘Analysis of safety and reliability of ship and systems’ the functional breakdown of ship systems and the associated autonomy levels is discussed and described (Kooi, 2018). The main focus of the WP3 report, called ‘a functional breakdown of generic ship and system functions’ is on the functional breakdown of technical systems and components.

The crew of a vessel is subdivided in two sections. One crew section is responsible for the technical systems and machinery, consisting for instance of an engineer (support) officer, an electro technical officer, etc. This *engineering department* is responsible for the safety, performance and efficiency of the vessel’s machinery. It is their job to maintain the mechanical and electrical operations, ensuring robust maintenance schedules are implemented and troubleshooting problems efficiently.

The second crew section is the deck crew. This section is responsible for the manoeuvring and navigation functions as they are executed from within the (navigation) bridge of a vessel, executed by deck (navigation) officers. Under the captain’s direct management, this *deck department* is responsible for the safe navigation and operation of the vessel, both at sea and in port. Deck officers are a vital part of the onboard management team, taking charge of an expensive vessel and its equally valuable crew, cargo and passengers. Deck officers maintain watches on the bridge at sea. They are responsible for passage planning, the safe navigation of the vessel, cargo loading and discharge, ship stability, communications and the maintenance of the hull and deck equipment. The ship’s captain or master is in overall command with ultimate responsibility for the safety of the crew, vessel, cargo and environment. Only navigation officers can be promoted to the rank of master. This JIP AS WP5-report will focus solely on the functional breakdown and replacement concepts of the *deck crew* functions.

The main goal of this report is to identify the role of the deck crew in the fulfilment of each function. This in turn will serve as a starting point for a detailed analysis of the challenges and possible solutions when crew members are removed from a ship.

Based on TNO's broad knowledge and experience in manning reduction and manning and automation, performance criteria are developed, and potential function allocation solutions and their technical feasibility are described. Based on this assessment, researchers will be able to define viable clusters of function allocation solutions that will enable the removal of one or more crew members.

1.2 Structure of this report

This aim of this report is to define conceptual solutions for replacement of the functions assigned to the deck crew. The view taken in this report is that the performance of an autonomous ship will depend on the quality and intelligence of the onboard technical control systems (the artificial navigator), the complexity of the maritime environment, and the human support that is made possible by means of a human-autonomy collaborative system. This means that at some system level, interaction between autonomous systems and human actors need to be taken into consideration and need to be part of the overall system design. The outline and general specification of such an overall (socio-technical) system design is described from the human factors perspective.

In order to understand the concept of function allocation, chapter two provides some background to the issues related to manning and automation. It will be argued that the (partial) replacement or reallocation of functions traditionally assigned to the deck crew is not a new development and is taking place in everyday practice. To be able to discuss replacement and reallocation issues in a structured way, it is essential, for the industry and the research community, to have a common view of the functional breakdown of the operations onboard a vessel. Such a functional breakdown is provided and discussed in chapter three. Also, in discussions and literature on maritime autonomous surface ships different conceptualizations exist about the meaning of 'autonomy', and because these conceptualizations are translated into proposals for the (level) of human involvement, chapter four will provide a brief discussion on the concept of autonomy and the related levels of automation. In addition, chapter five will provide an overview of the human factors challenges of providing meaningful human control over MASS-s. Chapter six will address issues concerning the conditions needed for providing adequate and effective supervisory control support within a future Shore Control Centre.
Finally, chapter seven will provide a summary and discussion.

2 Background

The (partial) replacement or reallocation of functions traditionally assigned to the deck crew is not a new phenomenon and is taking place in an evolutionary fashion in everyday practice. The evolutionary process of technology development and its application on board (newly designed) ships, is called ‘Smart Shipping’.
Smart Shipping is the highly automated sailing support at sea and inland waterways and facilitating vessels, which contributes to the competitiveness, safety and sustainability of the sector.

2.1 Smart Shipping

An example of highly automated sailing support is the announcement of the Swedish shipping company Stena Line to use Artificial Intelligence (AI) to make its ships more economical. Together with the Japanese technology company Hitachi, a trial is currently underway whereby a self-learning computer will help to sail the most favourable route (Hitachi, 2018). An example of a standing practice is the use of software on board large container vessels to calculate which layers of containers have to be fixed with rods ('lashing'). Also, when these container vessels are on the way, at open sea, nobody is behind the helm anymore. The route is neatly set out in the operating system.

In addition to this kind of technological support, large shipping companies provide back office support to facilitate their fleet. Back office operations are the shore-based delivery of a range of non-core service functions, including routine administration tasks, customer service and technical support. Currently, a back office of a shipping company typically defines the transport mission, the initial sail plan, voyage support on request by the ship, logistics and maintenance planning.
In this way, functions traditionally carried out on board, became 'outsourced' step by step to the back office.

The design goal of Smart Shipping is primarily automated digital sailing support. Despite the fact that manning reduction is not the main design objective, the long-term effect of applying smart technology is that fewer people are needed to sail a ship. The CEO of Maersk, Søren Skou, stated: “that it is thanks to the latest technological developments that the number of crew members on board Maersk Line’s ships halved when compared to two decades ago, which has, in turn, helped cut salary cost” (Bloomberg, 2018). Figure 1 shows that the optimal crew size from a cost perspective lies at the point where the total operating costs (total cost of ownership) is the lowest. This point is determined by the balance between *costs of automation* and *crew costs*. If a shipowner invests more than can be saved on personnel cost over the total lifespan of the ship (life cycle), then there is technological overkill. Conversely, we speak of personnel overkill when the manning costs are not reduced through, relatively low, investments in technology.

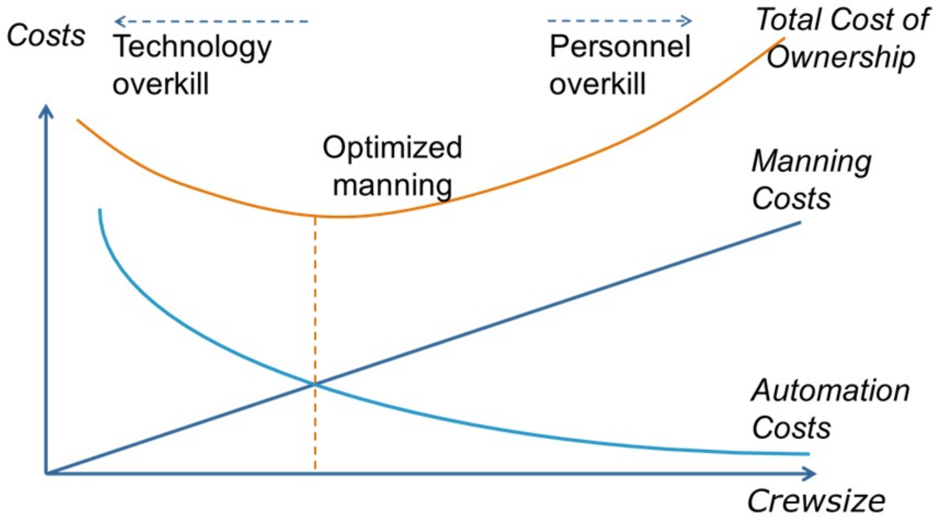

Figure 1 Within optimized manning, the crew and automation costs are in balance.

In addition, the investment costs to get the 'last man' off board will increase exponentially. If we apply the Pareto principle (80/20 rule), then the last 20% crew reduction will consume 80% of the total development costs. That is why the curve of the automation costs on the left shows a steep climb.

2.2 Maritime Autonomous Surface Ships

For the purpose of regulatory scoping, the International Maritime Organization (IMO), defined a Maritime Autonomous Surface Ship (MASS) as a ship which, in varying degree, can operate independently of human interaction (IMO, 2018).

In contrast to Smart Shipping, the radical MASS design solution requires the replacement of *all functions* assigned to the deck crew with sophisticated automation, Artificial Intelligence (AI), and machine learning capabilities. The way to achieve that, is to increase the level of automation to such an extent that the ship is able to operate independently of human interaction, generally conceptualized as ships sailing without on onboard crew and supported, in varying degree, by a shore based human operator with navigational skills.

The rationale for developing MASS-s is the widespread belief that autonomous ships will reduce operational cost and will increase the safety at sea.

2.2.1 Cost reduction

As is illustrated above, cost savings can only be achieved for specific instances in which personnel cost is a large proportion of the total operational cost and in which the cost of replacing human seafarers with technology will not exceed the savings on manning cost. For this reason, the expectation is that large triple E-class container ships of more than 18,000 TEU will not become the frontrunners of autonomous technology simply because the personnel costs are a small fraction of the total cost of ownership.

In contrast, the expectation is that the development and introduction of MASS will emerge in operational niches in which autonomous (short) sea transport is of additional business value and in which the ship and infrastructure can be optimally designed or adjusted. A good example of a business case that adds value and logistic opportunities is the Yara Birkeland, the first ever zero emission, autonomous ship (Skredderberget, 2018). The added value is the expectation that by moving container transport from land to sea, the Yara Birkeland will contribute in fulfilling Norwegian environmental impact goals. Not only the ship, but also the terminals and (battery charging) infrastructure will be newly built and, hence, are fully adjusted to accommodate the Yara Birkeland operation. Also, the Trondheim Fjords provide an ideal marine area to pilot a MASS operation. First, the Yara Birkeland will sail on two fixed routes, between Herøya and Brevik (7 nautical miles; 13 km) and between Herøya and Larvik (30 nautical miles; 56 km). Second, because of low marine traffic intensity, the area does not provide that much navigational complexity. In addition, the Yara Birkeland will be monitored and facilitated by three Shore Control Centres (SCC's) one for the logistic processes (located at the Yara factory site), one for technical and maintenance assistance (located at a Kongsberg site) and one for nautical aspects and sailing support (located at VTS station at Brevik).

The involvement of one or more SCC's means that some form of function allocation still is essential for operating a MASS. As a consequence, SCC's must be set up and will, most likely, be manned 24/7 to allow human support in varying degrees and for varying functional aspects. It means that 'manning costs' will not be reduced fully, but will shift, to some extent, from ship to shore. Additional costs are involved in developing operator support systems and operator training. Costs are also involved in setting up a robust communication infrastructure to enable communication between MASS and SCC's (Bastiaansen et al., 2018). Sailing close to landmasses makes it possible to incorporate existing land-based telecommunication networks. Out on sea however, communication bandwidth would be many times more expensive compared to short sea and inland shipping.

The Yara Birkeland example shows that the development of a MASS is not only about the development of the ship itself and onboard technology, but is also about:

- establishing a solid business case,
- creating a tailor-made infrastructure,
- embedding the ship within an overarching logistic process (Bastiaansen et al., 2019),
- creating a communication and data sharing infrastructure,
- providing human supervisory control.

These aspects are all cost drivers, which, often, are not accounted for when discussing cost reduction in case of MASS exploitation.

2.2.2 *Improving safety*

In regard to safety, the other rationale behind the development of MASS, the line of reasoning is that because seventy to eighty per cent of accidents are due to human error, the replacement of humans by technology will therefore reduce the number of accidents with that percentage.

However, this assumption is fuelled by the fact that the label 'human error' is always interpreted differently and has become a collective term for every involvement of 'humans' in situations where 'things are going wrong' (Hollnagel, 2016). Furthermore, on statistical basis, the conclusion that if seven (or eight) out of ten accidents are partly due to humans, that sailing without a crew is safer is not valid without knowing in how many cases crews have turned a near-disaster into a safe situation, that otherwise would have been a disaster. Also, currently it is not possible to determine whether automation is able to provide the same operational resilience in the future as socio-technical systems can. Based on this, the question whether the development of MASS will increase safety at sea is at best an unproven theorem.

3 The identification of deck crew functions.

This chapter is largely based on a TNO-report called “Formal Safety Assessment (FSA) Bulk Carriers: Phase 1: Identification of critical functions”, that was commissioned by Global Maritime (Breda et al., 2001). The report describes and explains a generic functional description of carrier operations. The reason for selecting and elaborating on carrier operations in this report is because it is representing the nautical functions that are carried out by the deck crew on all sea going ships namely, to provide transportation.

3.1 Functional decomposition

Functional decomposition has a long tradition as a human factors’ method for engineering and design (Stanton, 2005). In particular, the method of Hierarchical Task Analysis (HTA) is used to produce an exhaustive description of the tasks that are carried out by the deck crew. In an HTA, the tasks are described in a hierarchical structure of goals, sub-goals, operations and plans. Also, tasks are broken down into progressively smaller units. At the highest level we choose to consider a task as consisting of an operation and the operation is defined in terms of its goal.
The goal implies the objective of the system in some real terms of production units, quality or other criteria. The operation can be broken down into sub- operations each defined by a sub-goal again measured in real terms by its contribution to overall system output or goal, and therefore measurable in terms of performance standards and criteria. Operations are the actions performed by people interacting with a system or by the system itself, and plans explain the conditions necessary for these operations. Operations describe the smallest individual task steps in the HTA, i.e. those that cannot be broken down into further operations.

HTA can be used to describe both teamwork and non-human tasks performed by the system. For that reason, HTA is a necessary precursor for other analysis techniques, including task allocation. Moreover, the HTA principle has also been applied in the Crew Design Tool (CDT) (Van Diggelen et al., 2016). Developed to be applied in the early design phase of a vessel, the tool captures and shares knowledge of ambition levels, personnel, automation, and concepts of operations, using reusable, formally (digitally) specified modules and computes ship configurations that are assembled from these modules.

Since, (sub) functions are the means to achieve (sub) goals and because the purpose of this report is to analyse allocation of system function to human and computers, the terms ‘functions’ and ‘sub-functions’ will be used in the remainder of this report. Also, goals are regarded as the highest abstraction layer and will be further decomposed into subsequent sub-goal levels of lower abstraction but with higher levels of detail. So, when it is stated that a layer is added, this means that a layer of sub-goals is added.

3.2 The functional description of Bulk Carrier operations

In this paragraph, the functional description of the ship operations will be used to elaborate and reflect on conceptual solutions for the (re-) allocation of system functions from human to (computer) automation.

Three main operation goals are identified to describe bulk carrier operations: 1) *Provide transportation, 2) Conduct port operations, and 3) Plan ship lifecycle*. On the second hierarchical level an elaboration of functions per mission segment are described as follows:

1. Provide transportation
   1.1. Sail
   1.2. Maintain platform
   1.3. Monitor and maintain cargo status
   1.4. Monitor status crew and all others on board
   1.5. Anticipate emergency

2. Conduct port operations
   2.1. Maintain stable operations platform
   2.2. Conduct maintenance and inspections
   2.3. Conduct cargo operations
   2.4. Monitor status crew and all others on board
   2.5. Anticipate emergency.

3. Plan ship lifecycle
   3.1. Set up maintenance framework
   3.2. Plan maintenance

Because we want to provide an overview of the nautical functions that are generic for all sea going vessels, the focus of the remainder of this report is on providing transportation and the goals and sub-goals attached. This does not mean that the operation segment *Conduct port operations* is not relevant for MASS. Conducting cargo operations, for instance, is a function that still needs to be accommodated even on autonomous cargo ships. However, the sub-goal description will strongly vary from ship type to ship type. Also, most of activities conducted within that operation segment will be performed by the *engineering crew section.*

3.3 Provide transportation

In this section a third layer of sub goals is added:

1. Provide transportation
   1.1. Sail
      1.1.1. Plan and prepare voyage
      1.1.2. Conduct voyage
      1.1.3. Terminate voyage
   1.2. Maintain platform
      1.2.1. Clean vessel
      1.2.2. Control garbage
      1.2.3. Control sewage
      1.2.4. Control ballast
      1.2.5. Prepare for next cargo
      1.2.6. Conduct Maintenance
      1.2.7. Maintain seaworthiness

1.3. Monitor and maintain cargo status
    1.3.1. Take cargo temperatures
    1.3.2. Take samples in holds
    1.3.3. Ventilate holds
    1.3.4. Take soundings
    1.3.5. Conduct inspection rounds
1.4. Monitor status crew and all others on board
    1.4.1. Ensure health and safety
1.5. Anticipate emergency
    1.5.1. Prepare drills
    1.5.2. Conduct drills
    1.5.3. Terminate drills

From this list of goals and sub-goals it becomes apparent that some functions become redundant when sailing without an onboard crew (and passengers). This holds for 1.4 and 1.5 and for some sub-functions of 1.2, e.g. *garbage and sewage control*. However, sub-functions like 1.2.4 *control ballast*, 1.2.6 *conduct maintenance,* and 1.2.7 *maintain seaworthiness* are functions that still need to be carried out on board ships. Compartmentalization and pressure chambers for instance, are potential techniques to provide seaworthiness in case of hull damage. The cleaning of the ship (and sensors) is a function that could be performed regularly by a service crew when the ship is docked in port. Also 1.3 *monitor and maintain cargo status* will remain a MASS (design) goal and therefore that function must be reallocated to a technical system on board which perhaps should be mimicked and monitored from within a SCC.

In the remainder of this chapter, we will zoom in on the functions that are related to sailing (1.1)

3.3.1 Sail

In this section a further abstraction layer is added and discussed.

1.1. Sail
    1.1.1. Plan and prepare voyage
        1.1.1.1. Gather voyage information
            1.1.1.1.1. Check sail instructions (owner / charterer)
            1.1.1.1.2. Cather current / tidal information
            1.1.1.1.3. Gather ship characteristics
            1.1.1.1.4. Gather previous experience
            1.1.1.1.5. …
        1.1.1.2. Plan Transit (voyage plan)
            1.1.1.2.1. Propose route sections
            1.1.1.2.2. Select route
            1.1.1.2.3. Log route plan
            1.1.1.2.4. Approve route plan
        1.1.1.3. Plan routine navigation
            1.1.1.3.1. Determine watch standing crew
            1.1.1.3.2. Anticipate on system breakdown
                1.1.1.3.2.1. Prepare back-up navigation
                1.1.1.3.2.2. Prepare back-up conning
        1.1.1.4. Discuss route plan with watch officers

1.1.1.5. Prepare vessel for sea passage
1.1.1.5.1. Muster crew
1.1.1.5.2. Sea fastening cargo
1.1.2. Conduct voyage
1.1.2.1. Depart
1.1.2.2. Navigate
1.1.2.3. Control Heading and speed
1.1.2.4. Monitor automatic control
1.1.2.5. Execute logging
1.1.2.6. Comply with master's instructions
1.1.2.7. Take-over navigational watch
1.1.2.8. Arrive
1.1.3. Terminate voyage
1.1.3.1. Command "finish with engines"
1.1.3.2. Complete logbooks
1.1.3.3. Communicate with owner/charterer

From this list of goals and sub-goals it becomes apparent that sailing is subdivided into two main functions: 1.1.1 *Plan and prepare voyage* and *1.1.2 Conduct voyage* (we leave *1.1.3 Terminate voyage* for what it is). From the perspective of replacing these functions with technology, the question that needs to be answered is: what kind of digital technology is required to execute these functions?

The distinction between both functions is that *planning* and *preparing* can be characterized as a function that requires strategic considerations whereas *conducting a voyage* can be best characterized as a tactical or operational function. Planning and preparing not only require gathering information (geographic, climatological, current and tidal), it also requires knowledge of the ship characteristics, local rules and regulations, and learning from previous experience. In everyday practice, different route sections will be proposed and the selection of the route and defining the waypoints depends heavily on judgement and experience of (experienced) sea fearers. Because of these strategic characteristics, a valid reallocation concept for *voyage planning* is to execute this function in a back office or SCC by means of human operators with nautical expertise and experience. A thus compiled voyage plan, that consists among other things of waypoints, speed profile, and expected time of arrival (ETA), is then uploaded to a MASS for operational execution.

Of course, some of the aspects of preparing like mustering crew and determining watch standing of the crew become redundant, but others like sea fastening of cargo and anticipating on system breakdown are still functions that need to be fulfilled (e.g. Rødseth and Burmeister, 2015).

The next section will zoom in on the functions related to conducting a sea voyage and will discuss the replacement concepts.

3.3.2 Conduct voyage

1.1.2.Conduct voyage
- 1.1.2.1. Depart
- 1.1.2.2. Navigate
- 1.1.2.3. Control Heading and speed
- 1.1.2.4. Monitor automatic control
- 1.1.2.5. Execute logging
- 1.1.2.6. Comply with master's instructions
- 1.1.2.7. Take-over navigational watch
- 1.1.2.8. Arrive

From the above listed functions, *1.1.2.5. Execute logging*, *1.1.2.6. Comply with master's instructions* become redundant in case of unmanned sailing.
However, from a transparency point of view, technical systems also need to log their activities so that a system's status and manoeuvring activities can be retraced and analysed if needed. Function *1.1.2.4. Monitor automatic control* is a special function because it is in essence this function that will be executed by operator supervisory control, operating from within an SCC. Moreover, next to voyage planning, *monitoring automatic control* will be a core functionality within a SCC of the future. This will be addressed in detail in chapter 6. Also function *1.1.2.7. Take-over navigational watch* will not take place on board of a MASS but will be replaced by *Take-over supervisory control watch* in a SCC, meaning that a shift handover takes place from one SC-operator to another probably accompanied by a shift handover form and briefing.

Below the function *1.1.2.1 Depart* is decomposed further.

1.1.2.1. Depart
- 1.1.2.1.1. Organize departure
  - 1.1.2.1.1.1. Inform crew (Agent, Pilot, Tug(s), Linesmen, VTMS)
- 1.1.2.1.2. Start engine and aux systems
- 1.1.2.1.3. Check manoeuvring system
- 1.1.2.1.4. Conduct pre-departure checklist
- 1.1.2.1.5. Embark Pilot
- 1.1.2.1.6. Prepare mooring equipment
- 1.1.2.1.7. Call 'for' and 'aft' stations
- 1.1.2.1.8. Unmoor ship
- 1.1.2.1.9. Prepare anchors
- 1.1.2.1.10. Manoeuvre ship
- 1.1.2.1.11. Disembark pilot
- 1.1.2.1.12. Commence sea voyage

Two things stand out in this listing. The first is that departure requires interaction with different external actors like agents, pilots, tugs, linesmen, and VTMS (Vessel Traffic Management Service). These interactions make clear that a ship is a socio-technical system (STS) that operates within a larger shipping and transportation system, which also is an STS. The social aspects and interactions (like informing, communication, providing assistance etc.) will not disappear when human seafarers are replaced by technology.

For instance, piloting is obligatory for a large number of ship classes in harbours all over the world and large MASS-s might still need tugboats and linesmen for manoeuvring within the harbour. The question is: how will this be automated and how can MASS-s be designed so that they can be operationally integrated into the existing shipping and transport infrastructure?
How will the interaction between a MASS and a VTMS be organized and take place in the future? Does a MASS still need to follow-up on directions of a VTMS? Will direct human-system communication (e.g. MASS-VTMS interaction) be possible with speech recognition technology, comparable with Siri or Google speech recognition? Or is it better to relay the VTMS communication to the specific SC-operator that monitors the MASS and in turn translates the message into remote control instructions? The latter solution raises questions concerning the effectiveness and speed of these (extended) lines of communication. The first raises questions concerning sense making and robustness.

The second thing that stands out is that autonomous ships will largely be dependent on a suitable infrastructure for instance for berthing, mooring and unmooring. These activities currently depend on human activity both on the ship as on the quay. This means that the development of MASS must go together with the adaptation of the infrastructure along the route of a MASS. It involves for instance automatic mooring systems but also the development of shore-based service providers to assist with loading and unloading, e.g. opening or closing of hatches etc., and the development of robotic cranes.

How the social, interaction, and interoperability aspects between a MASS and the overall shipping and transport infrastructure should be organized and addressed is a major topic. However, in literature and research proposals this interoperability topic is rarely addressed because the focus of MASS oriented research is mainly on the onboard automated control technology.

Because function 1.1.2.1. *Depart* is comparable to *1.1.2.8 Arrive* in reversed order, the same conclusion holds for *Arrive* and will not be discussed separately.

3.3.3 Navigate

Below the function *1.1.2.2. Navigate,* is decomposed further.

- 1.1.2.2. Navigate
    - 1.1.2.2.1. Monitor environment
        - 1.1.2.2.1.1. Monitor traffic and fairway
        - 1.1.2.2.1.2. Communicate with VTMS / Traffic Control / Reporting systems
        - 1.1.2.2.1.3. Monitor local traffic status
        - 1.1.2.2.1.4. Monitor ARPA
        - 1.1.2.2.1.5. Monitor visual (lookout)
        - 1.1.2.2.1.6. Communicate with other vessels
    - 1.1.2.2.2. Observe sky, water and wind
        - 1.1.2.2.2.1. Read messages
        - 1.1.2.2.2.2. Check radar
        - 1.1.2.2.2.3. Check forecast
    - 1.1.2.2.3. Maintain current route (and time) plan

1.1.2.2.4. Adjust current route (and time) plan
1.1.2.2.4.1. Avoid collision
1.1.2.2.4.1.1. Identify threat vessels
1.1.2.2.4.1.1.1. Determine change in bearing of vessels
1.1.2.2.4.1.1.2. Determine heading of vessels
1.1.2.2.4.1.1.3. Determine speed of vessels
1.1.2.2.4.1.1.4. Determine CPA
1.1.2.2.4.1.1.5. Determine TCPA
1.1.2.2.4.1.1.6. Determine intention of vessels
1.1.2.2.4.1.1.6.1. Communicate
1.1.2.2.4.1.1.6.2. Check behaviour
1.1.2.2.4.1.1.6.3. Utilise knowledge
1.1.2.2.4.1.1.7. Determine whether danger of collision
1.1.2.2.4.1.2. Apply collision avoidance regulations
1.1.2.2.4.1.3. Determine margins for evasive actions
1.1.2.2.4.1.4. Determine evasive course and speed actions
1.1.2.2.4.1.5. Select evasive course and speed actions
1.1.2.2.4.1.6. Communicate intentions
1.1.2.2.4.1.6.1. Make use of own vessel aspect
1.1.2.2.4.1.6.2. Use VHF (minimal)
1.1.2.2.4.1.6.3. Use whistle
1.1.2.2.4.2. Avoid Grounding
1.1.2.2.4.2.1. Maintain knowledge of local situation
1.1.2.2.4.2.2. Maintain awareness of own ship characteristics
1.1.2.2.4.2.3. Monitor charted depths
1.1.2.2.4.2.4. Monitor echo soundings
1.1.2.2.4.2.5. Maintain lookout
1.1.2.2.4.2.6. Monitor radar
1.1.2.2.4.2.7. Select option for course and speed
1.1.2.2.4.2.8. Initiate evasive action
1.1.2.2.5. Respond on changing weather/sea condition (update voyage plan)
1.1.2.2.5.1. Determine disturbing factors
1.1.2.2.5.2. Check charter conditions
1.1.2.2.5.3. Check ship related data
1.1.2.2.5.4. Define new route section / track
1.1.2.2.6. Log plan deviations

The reason the *navigation* function is described in more detail is because this function describes in essence what an artificial navigator, i.e. the control system that navigates and manoeuvres a MASS, must be capable of. The situation awareness concept will be introduced as an internal model that actors hold of the world around a ship (Grech, Horberry and Koester, 2008), and how that knowledge is build-up and is maintained based on (human) cognitive and information processing capabilities. Subsequently, the question will be addressed what kind of digital technology is required to replace a human navigator in executing the (safe) navigation (system) goal. The next section provides a short introduction into the concept of situation awareness.

Situation Awareness
The concept of Situation Awareness (SA) was first introduced in 1988 by Mica Endsley (Endsley, 1988a), “as the pilot’s internal model of the world around him at any point in time (p. 97)”. In later publications (Endsley, 1995), the author clearly distinguishes the term *situated awareness* “as a state of knowledge, from the processes used to achieve that state (p. 36)”.

Furthermore, it is explained that “these processes, which may vary widely among individuals and contexts, will be referred to *situation assessment* or as the process of achieving, acquiring, or maintaining SA (p. 36)”. The mechanisms of situation awareness are embedded within the information processing capabilities (and constraints) of individual cognitive actor and are influenced by individual factors (e.g. experience, training, goals, expectations) and task and system factors (e.g. interface design, stress and workload, automation, complexity).

This individually oriented view on SA as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future Endsley, 1995, p. 36)” is heavily debated (e.g. Carsten and Vanderhaegen, 2015; Endsley 2015). The core of the criticism is that SA is not (only) a mental representation inside someone’s head (Dekker, 2015). To overcome this individually oriented approach, the concept of distributed SA was introduced (Stanton et al., 2015). Within this view the bridge is regarded as a joint cognitive system in which SA is the overall result of system performance and interaction processes that take place on the bridge. In this view, SA is not something that can be attached to a single actor (the radar picture, the helmsman’s mental picture etc.) but is about **all** the bits and pieces of information of the current maritime situation that the (socio-technical) system has gathered and has put together, hence the phrase ‘building and maintaining SA’.

Bearing in mind that SA is the result of a joint cognitive system, the classic SA model is a helpful model to describe the navigation function as a continuous (joint) cognitive process that can be analysed on three different levels, depicted in Figure 2.

Figure 2 The basic model of situation awareness (adopted from Grech et al., 2008).

Level 1 situation awareness represents the notion that a system needs to be able to perceive the operational world in order to understand it. This applies to sub-functions like *monitor environment* (and the sub goals), *observe sky*, *water and wind,* and *identify vessels in the vicinity*. Perception may refer to the visual input of the helmsman or outlook but also refers to navigation support systems like ARPA and AIS which also provide information and help to build-up the maritime operational picture. When the ‘maritime operational picture’ is as expected and no threats are identified, then situation awareness will be maintained on level 1.

Level 2 situation awareness refers to a state in which the ‘maritime operational picture’ is interpreted and assessed by the system for its relevance in relation to the task and objectives (e.g. *safe navigation*). When the suspicion is raised that a vessel might be a threat for collision, the system will zoom in to assess the situation in more detail.
Additional actions to understand the situation better might be taken, for instance taking radar bearings and monitor the ARPA vector. Contacting the other vessel over VHF to ask for its intentions is also an option in certain situations.

Level 3 situation awareness refers to the notion that the system has built up a projection of the future status of the ships and, consequently, must decide on appropriate actions in order to prevent the projected status becoming reality.
The projected status could be anything that is relevant for the ship in the timeframe of its current mission, i.e. sea voyage or operation. Bad weather conditions for instance could lead to the decision to change course and sail around the bad weather area to avoid possible damage to ship and cargo. Based on the adjusted expected time of arrival (ETA), sailing around the bad weather area takes more time, the captain decides to inform the agent that a delay in the logistic chain has occurred, because he understands the consequences of the delay for the follow-up processes.

A possible collision is another example of a projected status. In that case the helmsman must decide to an evasive action to avoid a collision. Endsley (1995), explicitly separates the SA concept from decision making and performance.
“Even the best trained decision makers will make wrong decisions if they have inaccurate or incomplete SA. Conversely, a person who has perfect SA may still make wrong decisions (from a lack of training on proper procedures or bad tactics, etc.) or show poor performance (from an inability to carry out the necessary actions) (p. 36)”. However, determining on the appropriate evasive course and speed to avoid a collision (projected state) requires comprehension also. For instance, the navigator should be aware of the possible margins for evasive actions (e.g. sailing the fairway might limit the margins because of the risk of grounding) and of the manoeuvring capability of the ship (e.g. rate of turn, and rate of slowing down etc.). Also, the projected state as outcome of an action should be assessed (e.g. moving away from one vessel could mean moving towards another vessel). Also, other ships in vicinity may change their speed and course in reaction which could lead to complex interaction patterns. Therefore, individual ships (i.e. navigators) are not always passive observers of a static normative situation, rather, they are actors in an interactive dynamic system, creating new ‘formative’ situations to become aware of (Stanton et al., 2017). It is therefore, that the SA assessment process is depicted as a continuous feedback loop in Figure 2.

Artificial situation awareness
The outline above illustrates that SA is a complex cognitive process that builds-up from perception, via comprehension to anticipation in a non-linear way.
The consequence is therefore, that the navigation function cannot be divided into separate sub-functions like perception and assessment. Of course, similar to the conventional socio-technical bridge, different technical subsystems will gather bits and pieces of information that need to be put together. Hence, the future artificial navigator will be a distributed system working as a joint intelligent system in order to achieve and maintain situation awareness (Bastiaansen et al., 2018).

Because ‘information’ and ‘situation’ are not neutral concepts, people seek or search actively for information guided by expectations and interpret the information based on expectations, experience and context.
Hence, building SA is not only a ‘bottom-up’ process but also a process with ‘top-down’ characteristics; this holds for socio-technical systems as well as for artificial systems.

As a consequence, also the artificial navigator controlling a MASS must be able to learn from experience, that the relevance of elements in the environment depends on the context, and that complexity of the environment influences the ability and speed to build-up SA (this will be addressed in chapter 4).

On a sub-function (sub-goal) level the information processing technology underlying the situation assessment process will be different, i.e. the human cognitive and information processing capabilities will be replaced by artificial Intelligence, the lookout will be replaced by a sensor suite (for instance, a LiDAR systems in combination with radar), and the helmsman will be replaced by an electro-mechanical actuator. But the navigational function as executed on board a MASS and as executed on board a conventional ship will be exactly the same regarding the overall goal: the process of achieving, acquiring, or maintaining situation awareness in order to provide safe navigation.

3.4 Summary

This chapter describes a generic functional decomposition of carrier operations as an approximation of the nautical functions that are carried out by the deck crew in general. The focus of this chapter is on providing transportation as the main operation segment. This segment is sub-divided into *sail*, *maintain platform*, *monitor and maintain cargo status*, *monitor status crew and all others on board, and anticipate emergency*. It is apparent that the latter two functions become redundant when sailing without an onboard crew (and passengers). *Monitor and maintain cargo status* will remain a MASS goal and will be reallocated to a technical system on board which probably should be mimicked and monitored from within a SCC.

The *sailing* function is subdivided into *plan and prepare voyage, conduct voyage*, and *terminate voyage.* The distinction between the first two functions is that *planning* and *preparing* are functions that require strategic considerations. Whereas *conducting a voyage* is characterized as a tactical or operational function. Because of its strategic characteristic, a valid reallocation concept for *voyage planning* is to execute this function in a SCC by means of human operators.

Execute logging and *Comply with master’s instructions*, as sub-functions of *conduct voyage* become redundant in case of unmanned sailing. *Monitor automatic control* on the other hand is the core function executed from within a SCC.

The sub-functions underlying *depart* illustrate that departure requires interaction with external actors (e.g. agents, pilots, tugs, linesmen, and Vessel Traffic Management Services). Also, it illustrates that a MASS largely depends on a suitable infrastructure for berthing, mooring and unmooring.

The *navigation* function describes, in essence, what an artificial navigator, i.e. the control system that navigates and manoeuvres a MASS, must be capable of.

The sub-functions basically contribute to building-up and maintaining situation awareness being the internal model of world outside a ship at any point in time.

The navigational function as executed on board a MASS by an artificial navigator and as executed on board a conventional ship is exactly the same regarding the necessity to build-up and maintain SA in order to provide safe navigation. On a sub-function level however, the technology that is needed to produce SA and to execute the navigation function will be different. Human cognitive capabilities will be replaced by artificial Intelligence, the lookout will be replaced by a sensor suite, and the helmsman will be replaced by an electro-mechanical actuator.

4 On autonomy and levels of automation

The concept of ‘autonomy’ and the concept of ‘automation’ have been used interchangeably in the literature (e.g. Bradshaw et al., 2013; Johnson et al., 2011). Differences in perception and interpretation of these concepts can create different expectations and principles for the collaborative design between system and humans. For instance, when one takes the position that it is possible to design a highly automated ship that can sail without any human support under all circumstances, then the human support role will be very limited if not non existing. This is in contrast with the position that human’s involvement still will be an important aspect in autonomous sailing. Therefore, it is important to have a clear understanding and definition of both concepts and the relation between them.
This chapter will address the relation between ‘automation’ and ‘autonomy’ and will outline that ‘autonomy’ cannot be defined in absolute terms but depends highly on the context in which automation will be applied.

4.1 Defining autonomy

Despite the fact that automation and autonomy are related in terms of make-up of a ship, they are not equivalent constructs. *Automation* is physical technology (mechanized or computerized) viable for application in a defined environment. *Autonomy* is a state-of-being for a ship implying: *robustness to the environment*, *independence in action or function*, and *self-determination of goals and resource allocation*. Or to put it another way, autonomy can be a desirable design goal for automated systems (Kaber, 2018) and hence for a MASS.

Autonomy is a multi-faceted construct. According to Kaber (2018), a system is autonomous when the following system facets are present:

- *self-sufficiency* or ‘viability’ in a given environment,
- *self-directedness* or capacity to function and to perform independently from other agents,
- *self-governance* or the freedom to define own goals and to allocate resources.

The facets are complex, for instance, self-governance is not just the absence of external control, it requires specific cognitive capabilities to learn but also to reason on a strategic level. Also, self-directedness does not mean that self-sufficient ships are independent in action. An autonomous vessel is part of a larger maritime system involving legislation, other vessels, pilot assistance, vessel traffic service etc. (Bastiaansen et al., 2019).

According to Kaber (2018), to say that a system is ‘semi-autonomous’ is a misnomer since there are no levels of autonomy; a system is either autonomous or not. Automation must enable and satisfy all three constraints to be an autonomous system. Hence, Kaber views autonomy as either-or.

4.2 Directions for replacement solutions

Defining *autonomy* as a multi-faceted construct has serious impact on the design specification of human-automation collaboration. The level of intelligence and sophistication of artificial systems that will be developed to control a MASS is key for the range of conditions the system can deal with, is key for how much of the human executed tasks can be replaced with technology, and the level of remote human control that is needed in specific situations.

The next paragraphs will discuss the capabilities of automation that will be required to fulfil the three system aspects.

4.2.1 Self-governance

When we look more closely to the system aspect of *self-governance*, the question is whether artificial systems can be (or will be) developed that are sufficiently capable of learning and reasoning on *a strategic* level. When we look at different projects and research proposals concerning the development of MASS, the focus is primarily on automating the ability of *safe navigation* (see chapter three, section 3.3.3, function 1.1.2.2). This understandable selective focus means that aspects like logistic (strategic) planning remain allocated to a human planner in an SCC.
As indicated in section 3.3.1, this also holds for *voyage planning*. Because of the strategic characteristics, a valid reallocation concept for voyage planning is to execute this function also in a SCC by means of human operators with nautical expertise and experience. A thus compiled voyage plan, that consists among other things of waypoints, speed profile, and expected time of arrival (ETA), is then uploaded to a MASS for operational autonomous execution. This also entails the question whether the ship can implement this plan under all circumstances.
Setting your own targets also means that the ship must be able to deviate from the route under unexpectedly severe circumstances.

Based on this it is fair to conclude, that it is expected that the system ability to *define own goals and allocate resources,* an aspect that is currently executed by humans, will remain the domain of the human actor because of its strategic nature. Of course, this may change when artificial technology is developed that can reason on a strategic level.

The idea that it is not likely that a MASS will decide in the near future where cargo should be picked up and where it should be brought to and at what price, is generally accepted. This also means that *self-governance*, defined as having the freedom to define own goals and allocate resources, is not a condition that will be met in the foreseeable future.

4.2.2 Self-sufficiency and self-directedness

The above conclusion means that *self-sufficiency* and *self-directedness* remain as the key system facets of autonomous systems (see also Bradshaw et al, 2013). Apart from the manoeuvrability and hydrodynamic aspect (a MASS must be sea-worthy and must be able to direct speed and course) self-sufficiency and self-directedness are strongly related to the ability of *safe* navigation, because safe navigation is the ability of a ship (being autonomous or a conventional manned) is the ability to (safely) *handle a range of nautical conditions.*

SA is the ability of a system to know and understand the nautical world outside the ship, i.e. “knowing what is going on” (section 3.3.3). Because manoeuvrable decision are taken on basis of situation assessment, SA is crucial element for safe navigation, i.e. even the best trained helmsmen will make wrong decisions if they have inaccurate or incomplete SA. Unfortunately, having ‘perfect’ SA does not mean that decisions will always be correct.

Stated in terms of information processing abilities, autonomous ships therefore need to have the generic ability of a) situation assessment, b) decision-making (sometimes based on procedures and rules), and c) action taking (i.e. the ability to manoeuvre). One way of improving self-sufficiency is to improve to the ability of achieving, acquiring, or maintaining SA. Conversely, self-sufficiency will be impaired when the process of SA is sub-optimal. The ability to build-up and to maintain SA could be reduced due to difficult or extreme environmental conditions, e.g. high sea state, darkness, rain, snow, inferences etc. This may influence the MASS ability of perceiving elements in the environment (Level 1 SA: perception of the elements in the environment.).

Also, the nautical situation may be (too) complex. For instance, a large number of ships in the vicinity, little room to manoeuvre, and conflicting COLREG’s might create a complicity that is difficult to comprehend (SA level 2). Especially ‘reading’ the intent of elements in the environment is very difficult. The complexity of the environment can be defined as:

- the number of (relevant) elements in the environment,
- the number of possible solutions,
- time pressures.

Finally, it is not always straight forward to project the future actions of the elements in the environment (SA level 3). The behaviour of other ships is not always rational or according to the ‘rules’. Also, people could react on reactions of other causing complex interaction patterns.

In summary, the level of self-sufficiency within a situation strongly relates with the SA ability of a system, combined with the ability to make the right decisions, and take action taking.

4.3 Autonomy levels

Because self-sufficiency is related to *the range of conditions the system can deal with* and self- directedness refers to *the range of conditions the system is given authority to conduct autonomously*, a much broader range of possible ‘autonomy states’ emerge when taking these underlying system aspects of autonomy into consideration, as shown in Figure 5. For instance, when self-sufficiency is higher than self-directedness (bottom right), the system is not used optimally. When it is the other way around (top left), the system may handle situations itself that it is not capable of handling. Overreliance is a dangerous condition that should be avoided for all critical systems. As self-sufficiency is increasing with more advanced intelligent software, choosing the appropriate level(s) of self-directedness is an important task. Higher levels of self-sufficiency enable higher levels of self-directedness. With increasingly more intelligent software available, the blue curve should be followed for optimal human-automation system performance.

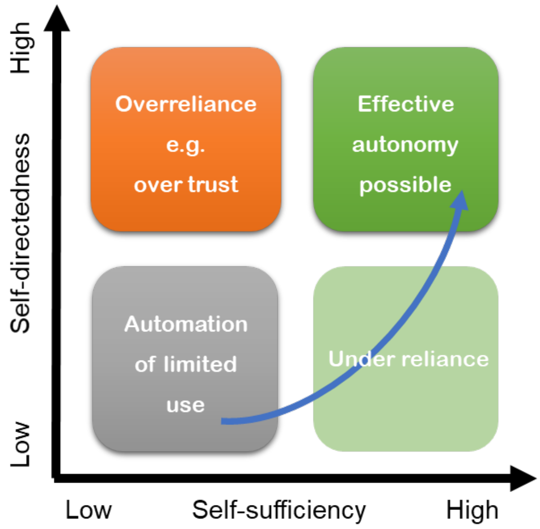

Figure 3 Autonomy consists of two dimensions. The blue curve shows the trajectory to follow when a gradual approach is chosen (based on Bradshaw et al., 2013).

The fact that self-directedness and self-sufficiency may vary mean, that the self-sufficiency of an autonomous ship could be sufficiently high or ‘viable’ in environment ‘A’, but could be sub-optimal or less ‘viable’ in environment ‘B’, with the same (high) level or automation. Therefore, to state that self-directedness and self-sufficiency vary, mean that they vary *relatively* to the complexity of the operational environment. Self-sufficiency is therefore, not an absolute or given system aspect, but a system aspect that is *context dependent*. The same holds for self-directedness. Because of the contextual dependency a (large) variation of different autonomy states are possible, which, in turn, require a varying degree of human support and/or support from other autonomous systems. From this it follows that *autonomy* as a system characteristic *cannot be defined in absolute terms*.

The variation of different autonomy states, possible in the two-dimensional space depicted in Figure 3, is difficult to translate to any number of discrete autonomy levels as is done, for instance, in Figure 4, let alone be normative i.e. prescriptive in any strict sense. Also, this, and related taxonomies describe the varying role of human support, but fail te describe what the support in essence entails within the discriminated levels, because there are just too many parameters in the real world to include. Therefore, is better to describe how, within a joint human-automation framework, to adapt towards a more suitable collaboration style for the situation, without the operator taking over tasks from the automation. This is further described in chapter 5.

Figure 4 Levels of autonomy (Blanke, Henriques, & Bang, 2017. Format adopted from SmartPort 2019).

When comparing the levels of autonomy description in Figure 4, and others (e.g. Bureau Veritas, 2017; Rødseth and Nordahl, 2018), with the ‘levels of Automation’ (LoA) description of Sheridan and Verplank (1978)[1], depicted in Figure 5, two things stand out.

First, the LoA taxonomy has been mapped out to describe the (varying) role of automation in *support of humans* in teleoperation scenarios. This is in contrast to the levels of autonomy description which maps the (varying) human role in *support of automation.* The Sheridan and Verplank taxonomy (also) describes one ‘autonomy level’. It is the level at which the automation is considered as ‘perfect’ in the sense (e.g. to an extent) that it can ignore the human (without harming the operation).

[1] With describing ‘levels of automation in man-computer decision-making’ in 1978, Sheridan and Verplank have been credited with originating the idea of ‘levels of Automation’ (LoA). It’s more than likely that this description served as source of inspiration for different levels of autonomy taxonomies that can be found in literature.

Viewing autonomy as perfect automation, and with that as an either-or system characteristic, is a too narrow concept because, with that, it also reduces the varying role of humans to an either-or level.

Low	1	The computer offers no assistance, human must take all decisions and actions
	2	The computer offers a complete set of decision/action alternatives, or
	3	Narrows the selection down to a few, or
	4	Suggests one alternative, and
	5	Executes that suggestion if the human approves, or
	6	Allows the human a restricted veto time before automatic execution
	7	Executes automatically, then necessarily informs the human, and
	8	Informs the human only if asked, or
	9	Informs the human only if it, the computer, decides to
High	10	The computer decides everything, acts autonomously, ignores the human

Figure 5 Levels of automation in man-computer decision-making (Sheridan & Verplank, 1978).

Secondly, the principle motivation of Sheridan and Verplank for that 1978-taxonomy was to clarify that automation is not an either-or but that there were, or could be, *manly* levels of automation from which to *choose* (Sheridan, 2017). This is in contrast to autonomy levels, i.e. autonomy states, which *cannot* be selected because, as explained, they are an emergent property of the level of self-directedness and self-sufficiency in relation to the complexity on the environment (see also Rødseth and Nordahl, 2018). However, it is conceivable that a shore control operator chooses to reduce the level of self-directedness in order to avoid a situation of over reliance (top left Figure 3).

The fact that 'autonomy' cannot be defined in absolute terms, also means that it is without meaning to state for instance, that the aim is to build a ship with autonomy level 6 without describing the actual nautical complexity and variability the autonomous ship is designed to handle, and without describing the suitable collaboration styles within a joint human-automation framework in case the complexity is beyond the capability of the vessel.

4.4 The contextual and situational dependence

From the above it follows, that the level of SC-operator involvement and the related workload is not fixed and also will vary from situation to situation. Every voyage takes place in a context. This refers to the factors with static nature for a given space and time. In these contexts, the restricting factor is the available space, e.g. the density of the archipelago, the width of the fairway, available water etc.
These all do restrict the space available for manoeuvring and, together with manmade constructions such as buoys, piers, pillars, oil rigs, cranes hanging over the water, have to be accounted for when manoeuvring (Prison et al., 2013).
Furthermore, in any given context there are situational factors acting upon the ship. These refer to the dynamic factors such as weather and time of day. Factors related to weather are wind (direction and speed), waves (direction and speed), current (direction and speed) and visibility. These factors and their magnitudes affect each other in different ways (Prison et al., 2013). All these situational factors affect the way the ship handler (artificial and human) has to act.

One way of dealing with contextual dependence from the perspective of a SC-operator is that during a ship voyage the level of self-sufficiency may vary for different contexts. Prison et al. (2013), discriminate four different contexts for which the efforts of manoeuvring differ. The contexts are: open sea-fair weather, open sea-foul weather, close manoeuvring, and archipelago. Rødseth and Nordahl (2018), discriminate five voyage stages (leave berth, part departure, sea passage, exception) for which the autonomy *mode* changes. One can imagine that self-sufficiency is high when sailing the Atlantic Ocean and that SC-operator involvement is not demanded for, whereas the self-sufficiency in case of harbour approach or sailing in an archipelago might be lower, meaning that the SC-operator involvement increases accordingly, see Figure 6. The fact that different voyage stages are on a timeline and known in advance, provides the SC-operator the opportunity to anticipate the situation so that enough time is left to build-up an appropriate SA of the nautical situation and, on a meta level, of the SA of the artificial navigator.

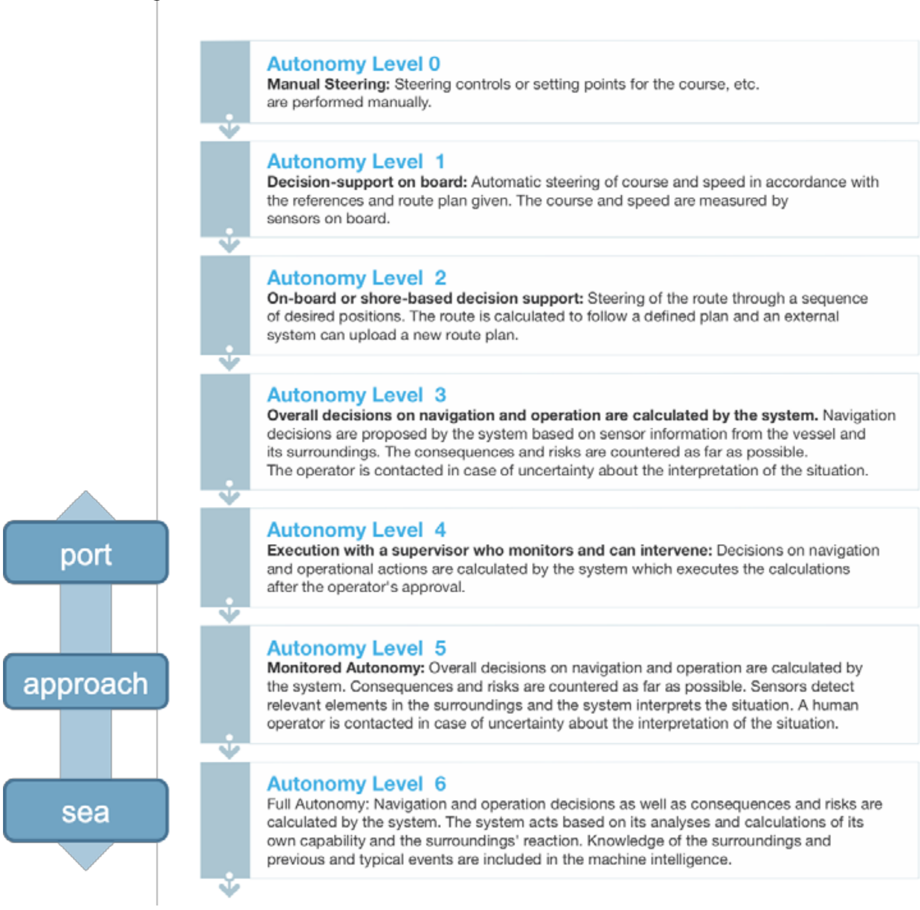

Figure 6 Example of how voyage stage transitions can be map on the level of autonomy taxonomy.

It becomes really difficult, when the SC-operator needs to respond to exceptional unanticipated situations in which ship automation falls short for whatever reason. Because in supervising highly automated autonomous systems, the SC-operator has no direct need to constantly know what the status of all parts of the system is, because the system is controlling all components itself. Also, a SC-operator supervises several MASS-s.

An inadequate SA due to a high level of automation makes that the operator cannot intervene quickly and effectively if the automation fails. This is known as the out of the loop performance problem (Endsley and Kiris, 1995; Tjallema et al., 2007). To assess the situation and take appropriate action(s) requires retrieval of relevant information via interfaces. The search for information and settings takes time. This can be problematic because the time available to respond to an unexpected situation may well be very short and the chance of preventing an accident decreases rapidly after the fault-initiation (Chen & Moan, 2004; Sandhåland, Oltedal, Hystad & Eid, 2015). These kinds of hand-over control situations have been studied in regard to operating dynamic positioning systems (Van der Kleij, 2015).

Because the level of autonomy depends on the context and situation that changes during the MASS-voyage, the question how many MASS-s a SC-operator can supervise, and handle simultaneously *cannot be answered in absolute terms*.

The related workload issue will be further discussed in chapter 6, as will the question how to support SC-operators in dealing with unexpected hand-over control.

4.5 Social aspects and interaction

An autonomous vessel is part of a larger maritime system involving legislation, other vessels, pilot assistance, vessel traffic services, etc. As such a MASS should also be considered as a social actor. Meaning that the system behaviour will be influenced by and will influence other systems in an operational area. Especially, the ability to detect and understand the intent of other vessels is an important aspect, as is the ability to coordinate with other vessels, VTS, pilots etc. on the basis of a shared and constructed understanding.

The way to convey meaning and understand each other is to communicate using a shared structured interlingua. Between multiple MASS-s that could mean that vessels exchange data using technical protocols. But an autonomous vessel will also encounter conventional vessels and therefore need to be able to generate and understand natural language. As an alternative, it is possible to allocate the communication function to a Shore Control Station where it is performed by SC-operators.

4.6 Summary

In this chapter it has been argued that autonomy is a multi-faceted construct implying robustness to environment, independence in action or function, and self-determination of goals and resource allocation. The latter system aspect, self-determination of goals and resource allocation, is simply not included in system design concepts or is allocated as function to a shore control centre or a back office of a ship owner. The reason is that planning requires learning and reasoning on *a strategic* level. The question whether artificial systems can be (or will be) developed that are sufficiently capable of executing such a function remains unanswered.

In general terms the autonomy concept encompasses the system facets self-sufficiency and self-directedness. Self-sufficiency is related to the *range of conditions the system can deal with*, whereas self- directedness refers to t*he range of conditions the system is given authority to conduct autonomously*. Both aspects are strongly related to safe navigation. If self-directedness is higher than self-sufficiency, the system may handle situations itself that it is not capable of, which could lead to undesired states or even dangerous situations. On the other hand, if self-sufficiency is higher than self-directedness, the system is not using its full potential.

Whether the save navigation ability of a MASS can be executed without help or assistance from other autonomous systems, artificial or human, depends on the sophistication of the automation and the complexity of the operational area. Self-sufficiency is high when the range of conditions the system can deal with is broad. From this it follows that autonomy cannot be described in absolute terms and is not an attribute of a system but is an emergent property of the interaction of the system and its environment.

One way of dealing with lower autonomy states is to divide a sea voyage into different stages for which the self-sufficiency level can be distracted and with that SC-operator s can plan their support effort in advance. Of course, the unexpected situations in which a lack of self-sufficiency or self-directedness occurs is difficult to handle. However, autonomy also means that the system has self-awareness to an extend that (expected) sub-optimal performance can be communicated with the shore control operator, or any other autonomous system.

For this reason, autonomous systems are highly automated systems that may operate without external help in some situations but need assistance, to some extent, in other situations. In this sense autonomy is more than perfect automation. It is the ability of a MASS to replace the role of the conventional socio-technical ships, in all its facets. This includes safe navigation but also social capabilities, including the capability to communicate and coordinate with other ships (and actors within the maritime system) and to have the ability to assess its own self-sufficiency in relation to the conditions of the situation.

5 The challenges regarding the Human Factor

Although a continuous scale, three different stages are distinguished for highly automated human-automation collaboration that require different designs for human-automation collaboration:

1. *Supervision stage*. The human operator is 100% of his time supervising the system(s) and is not involved in other tasks. All Human Factors risks as presented in the introduction are of relevance. This level strongly relates to Sheridan's model of supervision (Sheridan, 2011, 2012). Self-direction of the automation is low.
2. *Partial supervision/autonomy stage*. Self-directness is higher. The human operator spends part of his or her time conducting secondary tasks. If required, the operator is called back to deal with complex or critical situations.
3. *Intervener/full autonomy stage*. Both self-sufficiency and self-directedness are high. The system is working autonomously `99.99%' of the time. The operator is working on other tasks or on other systems. But even fully autonomous systems fail sometimes, and in these exceptional cases the operator does have to intervene or even take over control.

The supervision stage (stage 1), has been well-studied and is already common practice in many work environments. Therefore, this chapter will look at the directions for solutions for the latter two less studied and well-known stages.

The main challenge for stage 2, partial autonomy, is to keep the operator posted of the status of the critical task and to enable him or her to resume control effectively when required. Both the human operator and the automation develop situation awareness (SA) relevant for the primary task (Stanton et al., 2006). Automation and human operators will continuously update their situation awareness. Both the union and the symmetric difference of their respective SA models are of importance (Arciszewski, De Greef, & Van Delft, 2009), both for the detection of early signals as well as the need to adjust the human-automation collaboration agreements.

Ways to support human-automation collaboration at this level are:

1. Support upkeep of operator SA using supervisory displays (St. John, 2013). This will help the operator decide whether his or her involvement at the primary task is required, and in case of incidents provide a better starting position for decision making.
2. Provide SA recovery support after returning to the main task, for example using change detection support (Van der Kleij, Hueting, and Schraagen, 2018). This enables better and faster switching to the primary task.
3. Increase reaction time by detecting early signals and providing on-time alerts for the primary task.
4. Just in time awareness: provide change detection and option awareness support for quick decision making when a critical event has occurred at the primary task.

At the intervener stage for human-automation collaboration, active involvement of the operator is very rare, hence, it is not feasible or cost-effective to maintain a minimal level of SA of the primary task.

Incidents are just too rare to warrant this effort. Also, regular SA recovery is not required, as the operator would not conduct this task anymore under regular circumstances. In this configuration only the last two types of support for the *partial supervision* stage are relevant. The skill levels of the operator will be much lower than under partial supervision, as he or she hardly controls the system anymore (maybe solely during incident training in simulators). Hence automation support remains essential for safe and effective task completion, even in the intervening mode. This results in partly different types of support:

1. Increase reaction time by detecting early signals and providing on-time alerts for the primary task.
2. Just in time awareness: provide recognition primed decision-making[2] (RPD), change detection and option awareness support for quick decision making when a critical event has occurred at the primary task.
3. Support operator with lack of skills: prevent the need for fully manual control but deliver lower levels of automation support.

Based on the review of the literature and solution concepts, designing human-automation collaboration at high system autonomy levels should meet the following design principles:

- All systems, even “fully-autonomous” systems, should be considered from a joint human-automation collaboration viewpoint, because there will always be instances where human action in some form is required. Co-active design (Johnson et al, 2014), focusing on *observability*, *predictability* and *directability* of all actors involved, has been proposed as a sound method to design this collaboration.
- Both human operators and automation develop an understanding of the situation, especially at the supervision and partial autonomy stages. Because of the predominant stance of distributed SA that SA is not solely ‘in-mind’ or ‘in-world’ but is build-up ‘in-interaction’ is a declaration of the boundaries that need to be applied in human-automation system design. Therefore, the distributed SA paradigm is very suited to develop joint human-automation systems within complex environments.
- The human as intervener does not imply that the operator takes over manual control if automation fails. Because, when automation fails, it does not mean that it stops working on all levels. Human support can be delivered, for instance, by making decisions in case automation fails to do so. But the execution of actions can be allocated to the automation. Because of the lack of skill of operators in complex future human-automation configurations, this kind of adaptive shift in collaboration agreements and authority provides a more promising approach.

5.1 Intelligent operator support

From the human-automation collaboration design principles it follows that meaningful human control entails more than simply mimicking the bridge layout and conning station in an SCC. Especially SA recovery support and the detection of early signals requires a dedicated operator support tool.

[2] The recognition primed decision-making model is based on the assertion that operators can use their experience to generate a plausible option as the first one they consider.

At TNO, an Intelligent Operator Support System (IOSS) has been developed in order to demonstrate the above described design principles in support of dynamic positioning (DP) operators (Van den Broek et al., 2017). Especially within stationary DP operations, human-system collaboration can be categorized as partial supervision/autonomy stage. Stationary DP systems work autonomously 99,99% of the time in which active involvement of the operator is very rare. However, the standing procedure is that four DP operators work in shifts 24/7 to obtain a minimal level of SA in order to prevent any loss of position. From a human factors point of view, maintaining a minimal level of SA is not feasible due to vigilance and out-of-the-loop performance problems (Van der Kleij et al., 2015), also it is not cost-effective.

Therefore, the development of IOSS, an intelligent human-automation collaboration system, is aimed at supporting the operator is such a way that maintaining a minimal level of SA is no longer needed. This makes it possible for an operator to conduct secondary tasks even outside the bridge. If required, the operator is brought back into the loop by the IOSS to deal with a complex or critical situation. When back on the bridge, the SA recovery is further supported by offering context specific information to the operator as well as the state change information, i.e. to indicate what has changed during the time the operator was conducting secondary duties.

In a future SCC, it is envisioned that a single SC-operator has to control and monitor several MASS-s. Since it is not feasibly to constantly cascade from one ship to another to maintain a minimal level of SA of all the ships under control, a mechanism should be in place that warrants to trigger the attention of the operator in case of a complex or critical situation. The trigger mechanism could be the detection of early signals, i.e. anomalies in ship behaviour, the vessel itself based on self-awareness capability, i.e. information that a sensor does not work optimally under certain environmental circumstances, or pre-set voyage state-changes (e.g. harbour approach). Switching from one ship to another and to different contexts comes with task-switching costs (Neerincx, 2003), which mainly consists of time and effort to reconstruct SA of ship and context. Intelligent human-automation collaboration design is well suited for SC-operator support in order to meet these very demanding task-switching demands, including SA recovery and detection of early signals.

5.2 Summary

In this chapter, it is advocated that even highly automated systems for which self-sufficiency and self-directedness are high for a broad range of situations, should be considered within a joint human-automation framework. Because even fully autonomous systems fail sometimes. In these exceptional cases the operator must be able to intervene or take over control. The need for fully manual control should be avoided and instead control should be delivered on lower levels of automation support.

As different stages for highly automated human-automation collaboration,
we distinguished:
1. the supervision stage,
2. the partial supervision/autonomy stage,
3. and the Intervener/full autonomy stage.

Co-active design, focusing on observability, predictability and directability of all actors involved, has been proposed as a sound method to design this collaboration. The prerequisite for human-automation collaboration design is that operators and automation develop an understanding of the situation, especially at the supervision and partial autonomy stages.

The main challenge for partial autonomy is to keep the operator posted of the status of the critical task and to enable him or her to resume control effectively when required. Both the human operator and the automation develop situation awareness relevant for the primary task. Automation and human operators will continuously update their situation awareness. Both the union and the symmetric difference of their respective SA models are of importance, both for the detection of early signals as well the need to adjust the human-automation collaboration agreements.

We identified four ways to support human-automation collaboration at the partial autonomy level:
1. Support for upkeep of operator situation awareness using supervisory control.
2. Provide situation awareness recovery support after returning to the main task.
3. Increase reaction window by detecting weak signals and providing on-time notifications for the primary task.
4. Just in time awareness support.

Based on these design and support principles an Intelligent Operator Support system has been introduced as an alternative design for intelligent human-automation collaboration system. The adaptive human-machine task division will depend on the operational context.

6 Shore Control Centre design concept

This chapter describes a SCC design concept that meets the conclusions and principles outlined in the preceding chapters.

The goal of a future SCC is to continuously control and monitor several maritime autonomous surface ships (MASS-s) of the same or different type. In order for a SC-operator to exercise meaningful human control, both the operator and MASS should be part of an intelligent human-automation collaboration system. In that sense, a SCC should be considered as a functional extension of an autonomous ship.

In the remainder of this chapter, a distinction will be made between a Shore Control Centre, being a service centre that, apart from nautical support, also conducts the indirect support (e.g. logistics, maintenance, and repair), a SC-operator, being the person conducting nautical support, and a Shore Control Station (SCS), being the individual physical workstation which presents the necessary information and which enables the operator to exercise control (comparable with a conning station or a DP-station on the bridge).

The SCC facilitation starts with logistic planning and uploading voyage data to the ship. The voyage plan describes the full voyage from departure to arrival, and weather forecast will be defined and at any time by a shore-based operator.
The data for navigational and weather forecasts will be obtained from combined external third-party sources. The voyage plan will entail waypoints, headings, turning angles and safe and economic speeds the ship must maintain during the voyage. The artificial navigator, the software system that controls a MASS, will execute the sail plan relying on the ship embedded dynamic positioning, route control and speed control functions. During the voyage, the weather data gathered by the ship will be compared and evaluated with the weather forecast of the SCC, to make a valid estimation of current and upcoming weather conditions along the navigational and voyage plan of the ship. Combined with predefined parameters and taking into account stability and manoeuvrability conditions a route optimization should be conducted under weather routing criteria.

Demarcation between SCC and autonomous ship is a key issue in autonomous ship operations and comes down to both a clear and adaptable (depending on the level of self-sufficiency and self-governance within a situation) allocation of functions and responsibilities. In case of manned ships, the captain and the crew are responsible for carrying out the voyage and taking appropriate action to ensure the safety of ship and cargo, for example reducing speed in heavy weather to avoid damage to the ship. In a future MASS-scenario the artificial navigator should take this kind of decision and reduce speed in heavy weather. There could however be situations, such as unforeseen obstacles or events, that will delay the ship to reach her discharging port on time, which has an impact on the ship's voyage plan.
A change of plans could be necessary, for example discharging cargo at another port. Such decisions are taken by the ship owner and belong therefore within the authority of the SCC. Within a SCC, further decisions will be made on maintenance and repair actions to be carried out in ports in coordination with relevant stakeholders (authorities, suppliers, services etc.).

From this and the functional decomposition described in chapter 2, it follows that three main functional sections within a SCC can be identified:

1. Nautical support.
2. Logistics, business, and service support.
3. Technical support.

Logistics and business support relate to the fact that a MASS is part of an overarching chain of logistic processes, with its own dynamics. Currently, logistics, business, and service support are allocated to the back office of a ship owner, hence nothing much will change regarding this type of support.

This is slightly different for technical support since technical support is currently executed on board by the engineering crew section. However, especially larger ship owner companies have the facilities to monitor the technical status and performance of their fleet in detail, thanks to advanced sensor and data transmission techniques. So, also, for remotely monitored ship systems nothing much will change, except that it will become more difficult to solve or mitigate technical problems remotely. Solutions can be found in reducing the number of mechanical parts and increasing system redundancy as is the case with class 2 and 3 dynamic positioning systems. These DP-systems are configurated in such a way that the redundancy levels are sufficient enough to ensure the continuation of safety critical operations even if parts of the technical system fail or repair is needed. Additionally, the function *monitor and maintain cargo status* should be part of the technical support section.

Concerning nautical support, it is necessary to distinguish between *plan and prepare voyage* and *conduct voyage*. Given the nature of these functions (strategic versus tactical) and the different competencies required for these functions, these functions can be best executed by different staff in different sub-sections of the SCC.

In general, it is advisable to integrate the three functional sections into one SCC instead of three separate SCC's in order to keep the lines of communication as short as possible and to provide a stronger sense of working together on a common goal.

6.1 Nautical support during the voyage

This section zooms in on the nautical support during the voyage and on the working conditions for the operators manning a shore control station.

The SCS design concept must facilitate the presentation of suitable information, the decision-making process and remote control for the operator. Also, the SC-operator must be able to communicate with conventional ships which sail in the vicinity of a targeted MASS but also with other actors within the global maritime system, like Vessel Traffic Services (VTS), port authorities and perhaps also with pilots and tugboats by using existing communication technologies (e.g. GSM, WiMax, VHF or satellite).

6.1.1 Workload balancing

The general expectation is, that a SC-operator will supervise several MASS-s, of the same or different type, at the same time. e.g. in parallel mode. The related SC-operator workload is not fixed and will vary from situation to situation. Therefore, the question concerning the span of control of an individual SC-operator, i.e. the number of individual ships a SC-operator can supervise and handle simultaneously, *cannot be expressed in absolute numbers*. It highly depends on the level of self-sufficiency and self-directiveness of the ships under supervision and how it is distributed over the number of ships that constitute the case load of the operator. For instance, when all the ships under super vision cross the Atlantic Ocean, their self-sufficiency and self-directiveness levels will be sufficiently high (see Figure 3) and the SC-operator workload will be relatively low (and with that, the span of control could be enlarged). Whereas, if one of the vessels under supervision enters a confined sea line or a busy harbour, the self-sufficiency and self-directiveness levels will (relatively) drop, resulting in higher SC-operator workload and vigilance level. As a consequence, the span of control of the SC-operator will drop, and may even, de facto, be reduced to one.

Also, communication with third parties (e.g. other ships, vessel traffic service stations etc.) is a workload driver. From research on naval frigates, it is known that communication (external and internal) is difficult to combine with a primary task (van den Broek et al., 2004, Strobach et al., 2018). Altogether it means that workload fluctuations cannot always be predicted. The way forward to mitigate work overload is to establish an adaptive workload balancing approach among several SC-operators to deal in a dynamic way with these fluctuations (Post and van den Broek, 2005). For instance, when the attention resources and workload are demanded for one ship, the other ships that fall within the responsibility of the heavily occupied operator should be transferred to another SC-operator, within the same SCC or within another SCC. Also, when ships are crossing time zones it is conceivable, and perhaps even necessary, to convey the supervisory responsibility from one SCC, e.g. in Europe, to another SCC, e.g. in the USA.

6.1.2 Situation Awareness recovery

The consequence of supervising multiple ships is that the SC-operator must switch between different ships and contexts, which comes with so-called (cognitive) task switching costs (Neerincx, 2003), being the mental effort and time, it takes to reconstruct the situation awareness of the ship state and nautical context to which the attention shifts. The key question concerning shift of attention is however:
How does an operator know or determine which ship needs attention and which ship doesn't? Is it for instance expected that the operator checks all the critical data from each ship on a regular basis? As argued above, it is not feasible to maintain a minimal level of SA of all the ships under control by cascading constantly from one ship related information set to another. This requires a mechanism, i.e. a support concept, that helps the SC-operator to focus his or her attention.

The following mechanism is based on expected and pre-defined state changes:

- Divide a ship voyage into voyage stages of which levels of self-sufficiency are established or pre-set (based on experience). This could mean that a harbour approach, defined as a waypoint, triggers the attention of the SC-operator.

- This trigger should be accompanied by a process of SA-recovery, i.e. the build-up of the nautical-picture including a risk assessment and the decision to intervene or not.

Additionally, a mechanism is needed to trigger the attention of the SC-operator in case of a (unexpected) complex or critical situation. The trigger mechanism could be:

- The detection of early signals, i.e. anomalies in ship behaviour.
- The MASS itself triggering the attention of the operator based on a self-awareness capability. For instance, based on feedback that a sensor does not work optimal under certain environmental circumstances or based on ambiguity of ships in the vicinity.
- This trigger class should (also) be accompanied by a process of SA-recovery, i.e. the build-up of the nautical picture including a risk assessment and to decide on the appropriate intervention.

In case everything else fails, the MASS should be able to switch to a 'safe mode', for instance reduce speed and hold a stationary position (either with DP of lowering an anchor).

6.1.3 SC-operator competence enhancement

The primary task of a SC-operator can be divided into two aspects. One, is to build-up SA of the nautical aspects, i.e. the operational picture, of the marine area the MASS is sailing. The other aspect is that the SC-operator needs to be able to establish whether or not the self-sufficiency is high enough to deal with the situation and in which self-directedness is appropriate and safe. This not only requires an assessment of critical information on the basis of which the artificial navigator bases its decisions, it also requires an assessment whether the ship manoeuvres as it is expected. Assessment on a meta level could be characterised as a remote navigator controlling and collaborating with a remote artificial navigator.

From accident report it is known that safe navigation could be difficult even when a human navigator is on the bridge (i.e. a located navigator). It is safe to state that safe navigation is even more difficult for a remote navigator because the behaviour of a vessel and the environmental circumstance (wind, waves, currents) must be assessed in an indirect way by means of a two-dimensional display, instead of being immersed and tangible connected with the ship and the elements.

Therefore, SC-operator support requires specific information (perhaps even haptic feedback) and presentation on the manoeuvrability characteristics and external factors (wind, wave direction, currents, water depth under the keel, etc.) influencing the behaviour of a ship in order to be able to determine if the ship is manoeuvring in the right way and to determine the appropriate moment to intervene.

Furthermore, it also means that a SC-operator must have at least the required nautical competences and skills according to the STCW standard and also that a future SC-operator must have experience as a seafarer to understand the dynamics of manoeuvring a ship under various weather and hydro dynamic conditions.

On another level the SC-operator should have the competence and skills of a supervisor and must be able to assess a nautical situation on the basis of 2D-data presentation. From experience with training experienced pilots as remote pilots for manning a remote piloting station, not every experienced pilot is able asses the remote situation of the remotely piloted ship on basis of 2D-information, i.e. on basis of a radar picture.

One can expect that nautical skills and competences are very difficult to uphold when SC-operators work within a SCC for a long time. For this reason, it is vital to design a simulator training program to train SC-operators and to uphold their nautical skills.

6.1.4 Summary

The goal of a future SCC is to continuously control and monitor several maritime autonomous surface ships (MASS-s). In order for a SC-operator to exercise meaningful human control, both the operator and the MASS should be part of an intelligent human-automation collaboration system. In that sense, a Shore Control Centre should be considered as a functional extension of the autonomous ship.

A distinction has been made between a Shore Control Centre, being a service centre that conducts indirect support, a SC-operator, being the person conducting nautical support, and a Shore Control Station (SCS), being the individual physical workstation which presents the necessary information and which enables the operator to exercise control.

Demarcation between SCC and autonomous ship is a key issue in autonomous ship operations and comes down to both a clear and adaptable (depending on the level of self-sufficiency and self-governance within a situation) allocation of functions and responsibilities. Three main functional sections within a SCC can be identified:
1. Nautical support.
2. Logistics, business, and service support.
3. Technical support.

In general, it is advisable to integrate the three functional sections into one SCC instead of three separate SCC's in order to keep the lines of communication as short as possible and to provide a stronger sense of working together on a common goal.

The design concept of a SC-station must facilitate the presentation of suitable information, the decision-making process and remote control for the operator. Also, the SC-operator must be able to communicate with conventional ships which sail in the vicinity of a targeted MASS but also with other actors within the global maritime system.

The question concerning the span of control of an individual SC-operator, i.e. the number of individual ships a SC-operator can supervise and handle simultaneously, cannot be expressed in absolute numbers. It will depend on the level of self-sufficiency and self-directiveness of the ships under supervision and how it is distributed over the number of ships that constitute the case load of the SC-operator.

When self-sufficiency and self-directiveness levels are sufficiently high, the SC-operator workload will be relatively low and the span of control could be enlarged. Conversely, when self-sufficiency and self-directiveness levels drop (relatively due to a more complex environment), SC-operator workload and vigilance will be higher, resulting in lower maximum span of control, which maximum will probably be reduced, de facto, to one.

Communication with third parties is also a workload driver. Al in all, workload fluctuations cannot always be predicted. The way forward to mitigate work overload is to establish an adaptive approach for workload balancing among several SC-operators to deal in a dynamic way with these fluctuations.

As a consequence of supervising multiple ships, the SC-operator must be able to switch between different ships and contexts from time to time. This comes with so-called (cognitive) task switching costs, being the mental effort and time it takes to reconstruct the situation awareness of the ship state to which the attention shifts. The key question concerning shift of attention is however: How does an operator know or determine which ship needs attention and which ship doesn't? Since it is not feasible to maintain a minimal level of SA of all ships under control by cascading constantly from one ship to another, a mechanism, i.e. a support concept needs to be in place that helps the SC-operator to focus.

The following support concept has been proposed:
- Divide a ship voyage into voyage stages of which levels of self-sufficiency are established or pre-set (based on experience). This could mean that a harbour approach, defined as a waypoint, triggers the attention of the SC-operator.
- This trigger should be accompanied by a process of SA-recovery, i.e. the build-up of the nautical-picture including a risk assessment and the decision to intervene or not.
- Detection of early signals, i.e. anomalies in ship behaviour.
- The MASS itself triggers the attention of the SC-operator based on self-awareness capability.
- Provide SA-recovery.

The primary task of a SC-operator contains two major aspects. One, is to build-up SA of the nautical aspects, the other is that the SC-operator needs to able to determine the self-sufficiency levels and assess whether they are sufficiently high to deal with the situation. This not only requires an assessment of critical information on the basis of which the artificial navigator bases its decisions, it also requires an assessment whether the ship manoeuvres as it is expected.

Supporting the remote navigation task requires specific information and information presentation on the manoeuvrability characteristics and external factors (wind, wave direction, currents, water depth under the keel, etc.) influencing the behaviour of a ship in order to be able to determine if the ship is manoeuvring in the right way and to determine the appropriate moment to intervene.

This means that a SC-operator must have the required nautical competences and skills, meaning that an SC-operator must be trained according to the STCW standard and that an operator must have experience as a seafarer to understand the dynamics of manoeuvring a ship.

On another level the SC-operator should have the competence and skills of a supervisor and must be able to assess a nautical situation, of which the operator is not part and of which the operator has no direct tactile feedback, on the basis of 2D-data presentation on a Shore Control Station.

One can expect that nautical skills and competences are very difficult to uphold when SC-operators work with a SCC for a long time. For this reason, it is vital to design a simulator training program to train SC-operators and to uphold their nautical skills.

7 Summary and discussion

This rapport is about defining conceptual solutions for replacement of the functions assigned to the crew on board conventional ships. In order to develop Maritime Autonomous Surface Ships, a radical and complete task and function re-allocation from manned execution to automated execution (mechanized and computerized) is necessary. The International Maritime Organization (IMO), defines a Maritime Autonomous Surface Ship (MASS) as a ship which, in varying degree, can operate independently of human interaction.

7.1 Defining autonomy

For those who regard ‘autonomy’ as ‘perfect automation’ the sheer discussion on concepts of task allocation in itself is regarded as ‘void’, since ‘perfect automation’ can do without any human involvement, i.e. can ignore the human.
Furthermore, in this line of reasoning, autonomous systems cease to exist as autonomous systems in case they need ‘outside’ help.

This either-or view on autonomy is both wrong and incomplete. It’s wrong because the autonomy concept incorporates more than ‘perfect automation’. It’s incomplete because it neglects the notion that autonomous systems are part of a collaborative system. This is easy to see when autonomy is embodied as a robot that shares the public space with humans and other robots. Because of the ‘sharedness’ robots need the ability to interact with other autonomous systems (human of artificial) and need the have the ability to understand the ‘other’ in order to be able to interact and cooperate. Translated to the maritime context, it means that MASS-s are part of an overall maritime shared space consisting of other vessels (both autonomous and conventional manned), vessel traffic service stations, harbour pilots, tugboats, area specific regulations etc. Because of this ‘nautical sharedness’, MASS-s need the ability to understand (the role of) the other actors in order to interact and cooperate. Hence, the ability to interact and ask for support (e.g. information, confirmation, manoeuvre assistance etc.) is an intrinsic quality of autonomous systems and not a disqualifier.

Despite the fact that automation and autonomy are related in terms of make-up of a ship, they are not equivalent constructs. *Automation* is physical technology (mechanized or computerized) viable for application in a defined environment. *Autonomy* is a state-of-being for a ship implying: robustness to the environment, independence in action or function, and self-determination of goals and resource allocation. Or to put it another way, autonomy can be a desirable design goal for a MASS which (system characteristic) is embedded within physical technology, i.e. is an emergent property of that technology in relation to its operational environment.

In order to understand why it is necessary that autonomous systems are part of a collaborative systems, in this case a human-autonomy collaborative system, ‘autonomy’ is conceptualized as a multi-faceted construct, consisting of the following system facets:

- *self-sufficiency* or 'viability' in a given environment,
- *self-directedness* or capacity to function and to perform independently from other agents,
- *self-governance* or the freedom to define own goals and to allocate resources.

As stated above, self-governance is not just about the absence of external control, it requires specific cognitive capabilities to learn but also to reason on a strategic level. Also, self-directedness does not mean that self-sufficient ships are independent in action as autonomous vessels will be part of a larger maritime system involving legislation, other vessels, pilot assistance, vessel traffic service etc.

7.2 The contextual dependence

When taking the underlying system aspects of autonomy into consideration a much broader range of possible 'autonomy states' emerge. This is because, self-sufficiency is related to *the range of conditions the system can deal with* and self- directedness refers to *the range of conditions the system is given authority to conduct autonomously*. If self-sufficiency is higher than self-directedness, the system is not used optimally. If it is the other way around, the system may handle situations itself that it is not capable of handling, which could lead to undesired states or even dangerous situations. This form of overreliance is a dangerous condition that should be avoided for all critical systems. Higher levels of self-sufficiency enable higher levels of self-directedness. As self-sufficiency is increasing with more advanced intelligent software, choosing the appropriate level(s) of self-directedness is an important (design) task.

The fact that self-directedness and self-sufficiency are dimensions that may vary from low to high means that the self-sufficiency of an autonomous ship could be sufficiently high or 'viable' in environment 'A' but not high enough or less 'viable' in environment 'B'. Hence, self-sufficiency is not an absolute or given system aspect, but instead is a system aspect that is *context dependent*. The same holds for self-directedness. From this it follows that 'autonomy' as a system characteristic cannot be defined in absolute terms.

The variation of different autonomy states, possible in the two-dimensional space, is difficult to translate to any number of discrete autonomy levels as is done is some taxonomies in which six or sometimes four autonomy levels are described, let alone be normative in any strict sense. Also, these taxonomies describe a continuously diminishing role of human support but not what the human support actually entails. Therefore, it is better to describe how, within a joint human-autonomy framework, to adapt towards a more suitable collaboration style for different situations.
Because autonomy is an emergent property of the level of self-directedness and self-sufficiency in *relation* to the operational environment, human support starts with establishing *what is lacking* in order for the system (ship) to become self-sufficient. What is lacking, could be the ability to build-up adequate situation awareness, the ability to make the right decisions, and the ability to manoeuvre is an adequate way. Once an omission is detected and established, support can be offered, ranging from providing additional critical information, decision support, additional actuator instructions, and (worst case) diminishing the level of self-directedness.

7.3 The characteristics of SC-operator support

The level of intelligence and sophistication of artificial systems that will be developed to control a MASS is key for the range of conditions the system can deal with, and is key for how much of the current, i.e. traditional human executed tasks can be replaced with technology and the level of remote human control that is needed in specific situations. When we look at the function *save navigation* (the ability of a ship (autonomous or conventional manned) to (safely) *handle a range of nautical conditions),* the level of self-sufficiency strongly relates to the ability to build-up and to maintain situation awareness.

Situation awareness (SA) is loosely defined as the ability of a system to know and understand the nautical world outside the ship, i.e. “knowing what is going on”. The classic SA model describes the information-processing and cognitive process on three different levels. Translated in terms of the navigation function, level 1 situation awareness represents the notion that a system needs to be able to perceive the operational world in order to understand it. This applies to sub-functions like *monitor environment* (and the sub goals), *observe sky, water and wind*, and *vessels in the vicinity*. Level 2 situation awareness refers to a state in which the ‘maritime operational picture’ is interpreted and assessed by the system for its relevance in relation to the task and objectives (e.g. safe navigation). When the suspicion is raised that a vessel might be a threat for collision, the system will zoom in to assess the situation in more detail. Additional actions to understand the situation better might be taken, for instance taking radar bearings and monitor the ARPA vector. Contacting the other vessel over VHF to ask for its intentions is also an option in certain situations. Level 3 situation awareness refers to the notion that the system has built up a projection of the future status of the ships and, consequently, must decide on appropriate actions in order to prevent the projected status becoming reality. The projected status could be anything that is relevant for the ship in the timeframe of its current mission, i.e. sea voyage or operation. SA is important for self-sufficiency because even the best trained helmsmen will make wrong decisions if they have inaccurate or incomplete SA. Unfortunately, having ‘perfect’ SA does not mean that decisions will always be correct.

The ability to navigate in a safe way, is in principle the same on board of a conventional ship as on board of a MASS. Stated in terms of information processing abilities, autonomous ships need to have the ability of a) situation assessment, b) decision-making (sometimes based on procedures and rules), and action taking (i.e. the ability to manoeuvre). The difference is, however, that on board of a conventional ship, it is the socio-technical bridge system that executes safe navigation, whereas on board of a MASS it will be a (intelligent) artificial navigator that executes the function. Hence, equal in function but different concerning the underlying information processing and decision-making technology and mechanisms.

One way of improving self-sufficiency is to improve to the ability of achieving, acquiring, or maintaining SA. Conversely, self-sufficiency will be impaired when the process of SA is sub-optimal. The ability to build-up and to maintain SA could be reduced due to difficult or extreme environmental conditions, e.g. high sea state, darkness, rain, snow, inferences etc.
This may influence the MASS ability of perceiving elements in the environment (Level 1 SA: Perception of the Elements in the Environment.).

Also, the nautical situation may be (too) complex. For instance, a large number of ships in the vicinity with little room to manoeuvre and conflicting COLREG's might be difficult to comprehend (SA level 2). Especially 'reading' the intent of ships in the environment is very difficult. The complexity of the environment can be defined as:
- the number of (relevant) elements in the environment,
- the number of possible solutions,
- time pressures.

Finally, it is not always straight forward to project the future actions of the elements in the environment (SA level 3). The behaviour of other ships is not always rational or according to the 'rules'. Also, people could react on reactions of others causing complex interaction patterns.

Because 'self-directedness' and 'self-sufficiency' are dimensions that both vary from low to high it means that a (large) variation of different autonomy states are possible, which require a varying range of support of humans and other autonomous systems. Based on this, the support that may be needed from outside the ship on what is lacking, could be on the following elements:
- Situation Awareness support.
- Decision-making support.
- Manoeuvring support.

7.4 The challenges regarding the Human Factor

Outside support could be organized from within a Shore Control Centre (SCC). The role of such a centre is to continuously control and monitor several maritime autonomous surface ships (MASS-s) of the same or different type. A distinction has been made between a Shore Control Centre, being a service centre that, apart from nautical support, also conducts the indirect support (e.g. logistics, maintenance, and repair), a SC-operator, being the person conducting nautical support, and a Shore Control Station (SCS), being the individual physical workstation which presents the necessary information and which enables the operator to exercise control.

In regard to nautical support during the voyage, the SCS design concept must facilitate the presentation of suitable information, the decision-making process, and remote control for the operator. Also, the SC-operator must be able to communicate with conventional ships which sail in the vicinity of a targeted MASS but also with other actors within the global maritime system, like vessel traffic service stations, port authorities, and perhaps also with pilots and tugboats by using existing communication technologies (e.g. GSM, WiMax, VHF or satellite).

Because of cost reduction, the expectation is that a SC-operator will have to supervise several MASS-s (the same or different types) at the same time. The related SC-operator workload is not fixed and will vary from situation to situation. Therefore, the question concerning the span of control of an individual SC-operator, i.e. the number of individual ships a SC-operator can supervise and handle simultaneously, *cannot* be expressed in absolute numbers.

It will depend on the level of self-sufficiency and self-directiveness of the ships under supervision and how it is distributed over the number of ships that constitute the case load of the operator.

For instance, when all ships under supervision cross the Atlantic Ocean, the self-sufficiency and self-directiveness levels will be sufficiently high, and, as a consequence, the SC-operator workload will be relatively low (and, hence, the span of control could be enlarged). Whereas if one of the vessels enters a confined sea line or a busy harbour the self-sufficiency and self-directiveness levels will drop (relatively) resulting in higher workload and vigilance levels, which influences the maximum span of control, which maximum will probably be reduced, de facto, to one.

Communication with third parties could also be a workload driver. From research on naval frigates, it is known that communication (external and internal) is difficult to combine with a primary task. Altogether it means that workload fluctuations cannot always be predicted. The way forward to mitigate work overload is to establish an adaptive workload balancing approach among several SC-operators to deal in a dynamic way with these fluctuations. For instance, when the attention resources and workload are demanded for one ship, the other ships that fall within the responsibility of the heavily occupied operator should be transferred to another SC-operator, within the same SCC or within another SCC. Also, when ships are crossing time zones it is conceivable, and perhaps even necessary, to convey the supervisory responsibility from one SCC, e.g. in Europe, to another SCC, e.g. in the USA.

As a consequence of supervising multiple ships, the SC-operator must be able to switch between different ships and contexts from time to time. This comes with so-called (cognitive) task switching costs, being the mental effort and time it takes to reconstruct the situation awareness of the ship state to which the attention shifts. The key question concerning shift of attention is however: How does an operator know or determine which ship needs attention and which ship doesn’t? Since it is not feasible to maintain a minimal level of SA of all ships under control by cascading constantly from one ship to another, a mechanism, i.e. a support concept needs to be in place that helps the SC-operator to focus.

The following support concept has been proposed:
- Divide a ship voyage into voyage stages of which levels of self-sufficiency are established or pre-set (based on experience). This could mean that a harbour approach, defined as a waypoint, triggers the attention of the SC-operator.
- This trigger should be accompanied by a process of SA-recovery, i.e. the build-up of the nautical-picture including a risk assessment and the decision to intervene or not.
- Detection of early signals, i.e. anomalies in ship behaviour.
- The MASS itself triggers the attention of the SC-operator based on self-awareness capability.
- Provide SA-recovery.

In order for a SC-operator to exercise meaningful human control, both the operator and MASS should be part of an intelligent human-automation collaboration system. In that sense, a SCC should be considered as a functional extension of an autonomous ship.

Another important consequence of the fact that autonomy cannot be defined in absolute terms, but fluctuates in relation to its context, is that also the level of SC-operator involvement and related workload is not fixed and will vary from situation to situation.
Hence, the question how many MASS-s an individual SC-operator can supervise and handle *cannot be answered in absolute terms* because it all depends on the level of MASS self-sufficiency in a particular situation.

7.5 SC-operator competences and skills

From the human-automation collaboration design principles it follows that meaningful human control entails more than simply mimicking the bridge layout and conning station in an SCC. Due to the expectation that a MASS will be sailing autonomously most of the time, maintaining a minimal level of SA is not feasible due to vigilance and out-of-the-loop performance problems, also, it is not cost-effective to stay focussed on one system at the time. Therefore, it is envisioned that a single SC-operator will have the responsibility of several MASS-s and will need the ability to switch between different ships and contexts. Hence, somehow a mechanism should be in place that warrants to trigger the attention of the operator towards a complex or critical situation. The trigger mechanism could be the detection of early signals, i.e. anomalies in ship behaviour, the vessel itself based on self-awareness capability, i.e. information that a sensor does not work optimally under certain environmental circumstances, or pre-set voyage state-changes, i.e. harbour approach. Intelligent operator support should be part of human-automation collaboration design to meet very (cognitive) demanding task-switching demands.

The required SC-operator competences are divided into two aspects. One, is the ability to build-up SA of the nautical aspects, i.e. the operational picture, of the remote marine area in which the MASS is sailing. The other aspect is that the SC-operator needs to be able to establish whether or not the self-sufficiency is high enough to deal with the situation and in which self-directedness is appropriate and safe. This not only requires an assessment of critical information on the basis of which the artificial navigator bases its decisions, it also requires an assessment whether the ship manoeuvres as it is expected. This requires supervisory competences and skills (and strong nerves). Furthermore, a future SC-operator must have experience as a seafarer to understand, among other things, the influence of environmental circumstances (wind, waves, currents) on the manoeuvrability of a ship. This requires nautical competences and skills according to the STCW standard.

The goal of a future SCC is to continuously control and monitor several maritime autonomous surface ships (MASS-s) of the same or different type. This requires more than nautical support, i.e. safe navigation support, as provided by SC-operators. The SCC facilitation starts with logistic planning and uploading voyage data to the ship. The voyage plan describes the full voyage from departure to arrival, and weather forecast will be defined and at any time by a shore-based operator. The artificial navigator, will execute the sail plan relying on the ship embedded dynamic positioning, route control and speed control functions.
During the voyage, the weather data gathered by the ship will be compared and evaluated with the weather forecast of the SCC, to make a valid estimation of current and upcoming weather conditions along the navigational and voyage plan of the ship.

Combined with predefined parameters and taking into account stability and manoeuvrability conditions a route optimization should be conducted under weather routing criteria.

There could however be situations, such as unforeseen obstacles or events, that will delay the ship to reach her discharging port on time, which has an impact on the ship's voyage plan. A logistic change could be necessary, for example discharging cargo at another port. Such decisions are taken by the ship owner and belong therefore within the authority of the SCC. Within a SCC, further decisions will be made on maintenance and repair actions to be carried out in ports in coordination with relevant stakeholders (authorities, suppliers, services etc.).

From this it follows that three main functional sections within a SCC can be identified:

1. Nautical support.
2. Logistics, business, and service support.
3. Technical support.

Logistics and business support relate to the fact that a MASS is part of an overarching chain of logistic processes, with its own dynamics. Currently, logistics, business, and service support are allocated to the back office of a ship owner, hence nothing much will change regarding this type of support.

This is slightly different for technical support since technical support is currently executed on board by the engineering crew section. However, especially larger ship owner companies have the facilities to monitor the technical status and performance of their fleet in detail, thanks to advanced sensor and data transmission techniques. So, also, for remotely monitoring ship systems nothing much will change, except that it will become more difficult to solve or mitigate technical problems remotely. Solutions can be found in reducing the number of mechanical parts and increase system redundancy. Concerning nautical support,
it is necessary to distinguish between *plan and prepare voyage* and *conduct voyage*. Given the nature of these functions (strategic versus tactical) and the different competencies required for these functions, these functions can be best executed by different staff in different sub-sections of the SCC. In general, it is advisable to integrate the three functional sections into one SCC instead of three separate SCC's in order to keep the lines of communication as short as possible and to provide a stronger sense of working together on a common goal.

7.6 Discussion

7.6.1 Knowledge-based view on navigation

The above discussion on situation awareness in relation to safe navigation was based on a cognitive theory, i.e. from a knowledge-based control paradigm for dynamic systems. It describes the process of perception (observe), understanding (orient), decision-making (decide), and action. It is stated that in regard to situation awareness an artificial navigator goes through the same assessment process but based on different underlying (artificial) information-processing and decision-mechanisms. The feature of a knowledge-based system is that (in principle) it can explain why certain decisions are taken or why not, i.e. it can reproduce the reasoning mechanism.

Because automation and human operators both are knowledge-based systems, they have the shared ability to continuously communicate and update their situation awareness.
Both the union and the symmetric difference of their respective SA models are of importance from the perspective of support.
Another approach to artificial intelligence is known as deep learning or machine learning. Machine learning is based on the principle that a system can learn on basis of examples. For instance, when a machine learning mechanism gets a lot of different pictures of cats and docs as training input, it learns to make a distinction between the two after the training period, on basis of a match with the exposed picture. The same principle is applied to safe navigation. In that case the system is fad with nautical situations in which the human captain reacts in a certain way. When these circumstances are recognized later, the system reacts with the learned response. When the training set gets sufficiently large the machine learning systems is capable of recognizing and react to a broader spectrum of conditions and circumstances. A machine learning mechanism is based on statistics and will indicate that what is observed matches with a certain level of probability with what is learned, and that the associated action X will probably be the best option. Hence, a lower probability means more uncertainty that an action is appropriate for the situation. An important feature of such a probabilistic learning mechanism is, that it cannot explain why certain actions are taken. It can only express how confident the system is about selecting a certain action. Some think that artificial learning is a panacea for all problems and can create perfect ‘automation’. But there will be always situation that fall outside the problem solution space however rich the training set. Also, when a system has the capability of learning the ‘right’ things, it has also the capability to learn the ‘wrong‘ things. So much of the effort is involved of learning not to do the ‘wrong’ things.

The lack of explainability, transparency will lead to poor directability of operators who are in charge of supervising these machine learning systems. For instance, at what level of uncertainty is intervention useful, i.e. necessary? Because machine learning systems and human operators have different mechanisms for situation assessment and decision-making they lake the ability to continuously communicate and update their situation awareness causing additional problems from the perspective of support. For this reason, the field of explainable AI is gaining momentum, because the exchange of SA is vital for human-autonomy collaboration.

7.6.2 Safety improvement

The claim that autonomous shipping will be safer than conventional shipping is based on statistics that eighty per cent of ship accidents are due to human error and, therefore, when humans are replaced by technology ship accidents will be reduced with that percentage. First, this assumption is fuelled by the fact that the label 'human error' is always interpreted differently and has become a collective term for every involvement of 'humans' in situations where 'things are going wrong’. Also, on statistical basis, to conclude that if seven (or eight) out of ten accidents are partly due to humans, that sailing without a crew is safer is not valid, without knowing in how many cases crews have turned a near-disaster into a safe situation, that otherwise would have been a disaster. Second, it’s not true to state that autonomous shipping takes out the humans ‘out-of-the-loop’. Yes, the bridge crew is taken of the ship, but replaced by SC-operators.

From accident report it is known that safe navigation could be difficult even with a human navigator is on the bridge (i.e. a located navigator). It is safe to state that safe navigation is even more difficult for a remote navigator (remote pilot) because the behaviour of a vessel and the environmental circumstance (wind, waves, currents) must be assessed in an indirect way by means of a two-dimensional display, instead of being immersed and tangible connected with the ship and the elements. Also, the brittleness and rigidity of artificial systems could lead to reduced resilience to deal with fussy or less well-defined situations, i.e. in terms of the above, could lead to reduced levels of self-sufficiency in unexpected and difficult situations. This means that a SC-operator mostly gets involved in *critical and difficult situations* the artificial navigator cannot handle for whatever reason and requires assistance and outside help. The frequency with which this kind of (edge) situations will occur will be very low, resulting is low experience and training opportunities for SC-operators which adds to the challenge to deal with these problems. Furthermore, the question in relation to responsibility who is too blame when things go wrong, i.e. when an accident cannot be avoided, the AI-navigator, the SC-operator, or the design of the human-autonomy collaboration system?
The fact that this question is difficult to answer is an additional argument why it is better to analyse accidents and near misses on a system level instead of focusing on one single factor, i.e. focussing on humans or technology.

Currently, not much is known of the ability of the human-autonomy collaboration systems for safe navigation particular in realistically complex situations. Hence, at this stage of technology and MASS development it is not possible to prove that autonomous shipping can establish safety levels equivalent to conventual shipping, let alone prove that autonomous shipping is or will be safer. Based on this, the question whether the development of MASS will increase safety at sea is at best an unproven theorem.

7.6.3 Cost reduction

Cost reduction is another rationale for the development of autonomous vessels. Especially the fact that ships can sail without an onboard crew is very appealing in terms of cost reduction. However, for a large section of sea going vessels, e.g. large triple E-class container vessel, personnel cost is a fraction of the total cost of operations. The investment in technology that is necessary to be able to sail without onboard crew, including an unmanned engine room, will rise far above the savings on personnel and would introduce unknown vulnerabilities and operational uncertainties which also are cost drivers. Additionally, an autonomous ship will not sail in splendid isolation. Meaning that several measurements have to be made in regard to the maritime infrastructure, e.g. terminals, communication systems, and the vessel traffic and logistics management system, which investments should also be taken into account as additional costs.

Also, ‘manning costs’ will not be reduced fully, but will shift, to some extent, from ship to shore. SCC’s must be set up and will, most likely, be manned 24/7 to allow human support in varying degree and for varying functional aspects. Apart from investments in land and buildings, additional costs are involved in developing operator support systems and operator training. Also the ratio between a SC-operator and the number of MASS-s that effectively can be supported is not known in advance. If the ratio is one-on-one it will be more costly compared to a ratio of one-to-many.

Estimations show that the balance between cost drivers and cost savers tends toward cost reduction. However, despite of this advantage it still is necessary to establish a solid business case which includes creating a tailor-made infrastructure, embedding the ship within an overarching logistic process, creating a communication and data sharing infrastructure, and providing meaningful human supervisory control. When this is done properly, it will help to identify new operational and logistic opportunities, as is the case of the Yara Birkeland development, instead of replacing the current nautical praxis.

8 References

Arciszewski, H. F., De Greef, T. E., & Van Delft, J. H. (2009). Adaptive automation in a naval combat management system. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans, 39(6), 1188-1199.*

Bastiaansen, H.J.M., Lazovik, E., Breejen, E. den & Broek, J. van den. (2019). A Business Process Framework and Operations Map for Maritime Autonomous and Unmanned Shipping: MAUSOM. International Maritime and Port Technology and Development Conference and International Conference on Maritime Autonomous Surface Ships, 13–14 November 2019, Trondheim, Norway. J. Phys.: Conf. Ser. 1357 012017. https://iopscience.iop.org/article/10.1088/1742-6596/1357/1/012017/pdf.

Bastiaansen, H.J.M., Lazovik, E., Breejen, E. den & Broek, J. van den. (2018). JIP Autonomous Shipping – WP4 Report: Collection, processing and communication of data. TNO rapport. TNO 2018 R10444. *TNO the Netherlands.*

Blanke, M., Henriques, M., & Bang, J. (2017). A pre-analysis on autonomous ships. *working paper Technical University of Denmark*. https://www.dma.dk/Documents/Publikationer/Autonome%20skibe_DTU_rapport_UK.pdf.

Bloomberg. (2018). Maersk's CEO Can't Imagine Self-Sailing Box Ships in His Lifetime. Consulted on October 2018 through: https://www.bloomberg.com/news/articles/2018-02-15/maersk-ceo-can-t-imagine-self-sailing-box-ships-in-his-lifetime.

Bradshaw, J. M., Hoffman, R. R., Woods, D. D., & Johnson, M. (2013). The Seven Deadly Myths of "Autonomous Systems". *IEEE Intelligent Systems, (3), 54-61*.

Breda, L. van, Janssen, W.H. & Passenier, P.O. (2001). Formal safety assessment (FSA) bulk carriers: Phase 1 – identification of critical functions. *Report TM-01-C020, TNO, The Netherlands.*

Broek, J. van den, Diggelen, J. van, Kleij, R. van der, Hueting, T.F. Waa, J. van der Schendel, J.A. van & Langefeld, J.J. (2017). Adaptive Maritime Automation: Final Report. *TNO 2017 R11325. TNO the Netherlands.*

Broek, J. van den, Delft, J.H. van, Essens, P.J.M.D., Helsdingen, A.S. & Meessen, W.R.M.J. (2004). Eindrapport toekomstige maritieme commandovoering [Final report future maritime Command & Control]. TNO-rapport. TM-04-A068, TNO, Soesterberg, The Netherlands.

Bureau Veritas (2017). Guidelines for autonomous shipping Guidance. Note NI 641 DT R00 E.

Carsten, O. & Vanderhaegen, F. (2015). Situation awareness: Valid or fallacious? *Cogn Tech Work 17: 157. Doi:10.1007/s10111-015-0319-1.*

Chen, H. & Moan, T. (2004). Probabilistic modeling and evaluation of collision between shuttle tanker and FPSO in tandem offloading. Reliability Engineering & System Safety, 84(2), pp. 169–186.

Dekker, S.W.A. (2015). The danger of losing situation awareness. *Cogn Tech Work 17, 159–161. Doi:10.1007/s10111-015-0320-8.*

Diggelen, J. van, Janssen, J. & Tol, W.A. van den. (2016). Crew Design Tool. *13th Int. Naval Eng. Conf. Bristol, UK.*

Endsley, M. R. (1988). Situation awareness global assessment technique (SAGAT). Proceedings of the National Aerospace and Electronics Conference (NAECON), pp. 789–795. New York, NY: IEEE.

Endsley, M. R. (1988a). Design and evaluation for situation awareness enhancement. Proceedings of the human factors society-32nd annual meeting. Doi: 10.1177/154193128803200221.

Endsley, M. R. (1995). Towards a theory of situation awareness in dynamic systems. *Human Factors, 37, 32–64*.

Endsley, M.R. (2015). Situation awareness: operationally necessary and scientifically grounded. *Cogn Tech Work 17, 163–167. Doi:10.1007/s10111-015-0323-5.*

Endsley, M.R., Kiris, E.O. (1995). The Out-of-the-Loop Performance Problem and Level of Control in Automation. The Journal of the Human Factors and Ergonomics Society, Volume: 37 issue: 2, page(s): 381-394.

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

Hitachi (2018). AI, captain! Hitachi Partners with Stena Line to Implement Digital Technology in Shipping. Consulted in October 2018 through: https://www.hitachi.eu/en/press/ai-captain-hitachi-partners-stena-line-implement-digital-technology-shipping

Hollnagel, E. (2016). The NO view of 'human error'. Consulted on 19 juni 2017, through http://erikhollnagel.com/ideas/no-view-of-human-error.html.

IMO (2020a), IMO takes first steps to address autonomous ships, http://www.imo.org/en/MediaCentre/ PressBriefings/Pages/08-MSC-99-MASS-scoping.aspx

Johnson, M., Bradshaw, J.M., Feltovich, P.J., Jonker, C.M., Riemsdijk, M. B. van and Sierhuis, M., (2014) Coactive design: designing support for interdependence in joint activity. Journal of Human-Robot Interaction, Vol. 3, No. 1, 2014, pp. 43-69.

Kaber, D.B. (2018). A conceptual framework of autonomous and automated agents. *Theoretical Issues in Ergonomics Science Vol.19/4.*

Kleij, R. van der, Brake, G.M. te, & Broek, J. van den. (2015). Enabling swifter operator response in the event of a fault initiation through adaptive automation. MTS DYNAMIC POSITIONING CONFERENCE, (DPC) October 13-14, Houston, Texas.

Kooi, C. (2018). Functional Breakdown of a ship and analysis of the autonomy levels of the functions. Technical report. TU Delft, Delft The Netherlands.

Krikke, M. (2017). Joint Industry Project Autonomous Shipping. Project Outline. NMT Rotterdam.

Neerincx, M.A. (2003). Cognitive task load analysis: allocating tasks and designing support. In Handbook of Cognitive Task Design, Erik Hollnagel (ed.). Published by Lawrence Erlbaum Associates.

Plant, K. L., and N. A. Stanton. (2012). Why did the Pilots Shut Down the Wrong Engine? Explaining Errors in Context Using Schema Theory and the Perceptual Cycle Model. *Safety Science 50 (2): 300–315.*

Post, W.M, Broek, J van den. (2005). Situationeel ontwerpen van teams [Situational team design]. TNO-rapport. TNO-DV3 2005 A089. TNO Soesterberg, The Netherlands.

Prison, J., Dahlman, J. & Lundh, M. (2013). Ship sense—striving for harmony in ship maneuvring. *WMU J Marit Affairs 12, 115–127* https://doi.org/10.1007/s13437-013-0038-5

Rødseth, Ørnulf & Nordahl, Håvard. (2018). Definition of autonomy levels for merchant ships, Report from NFAS, Norwegian Forum for Autonomous Ships, 2017-08-04. Doi: 10.13140/RG.2.2.21069.08163.

Rødseth, Ø.J., Burmeister, H.C. (2015). Risk Assessment for an Unmanned Merchant Ship. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 9, No. 3. Doi:10.12716/1001.09.03.08, pp. 357-364.*

Sandhåland, H., Oltedal, H. A., Hystad, S. W. & Eid, J. (2015). Distributed situation awareness in complex collaborative systems: A field study of bridge operations on platform supply vessels. Journal of Occupational and Organizational Psychology, 88(2), pp. 273–294.

Sheridan, T.B. (2017). Comments on “Issues in Human–Automation Interaction Modeling: Presumptive Aspects of Frameworks of Types and Levels of Automation” by David B. Kaber. Journal of Cognitive Engineering and Decision Making. 12. Doi:10.1177/1555343417724964.

Sheridan, T. B. (2012). Human supervisory control. In Handbook of Human Factors and Ergonomics, Fourth Edition (ed G. Salvendy), John Wiley & Sons, Inc., Hoboken, NJ, USA. Doi: 10.1002/9781118131350.ch34

Sheridan, T. B. (2011). Adaptive automation, level of automation, allocation authority, supervisory control, and adaptive control: Distinctions and modes of adaptation. Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on, 41(4), 662-667.

Sheridan, T.B. & Verplank, W.L. (1978) Human and computer control of undersea teleoperators. Technical report. Cambridge, MA: MIT man-machine laboratory.

Skredderberget, A. (2018). The first ever zero emission, autonomous ship. Consulted in October 2018 through: https://www.yara.com/knowledge-grows/game-changer-for-the-environment/

SmartPort Consortium. (2019). Smart ships and the changing maritime ecosystem: How digitalization and advanced automation of barges, service vessels and sea ships create new opportunities and challenges for the maritime industry. Whitepaper. http://smart-port.nl/wp-content/uploads/2019/04/SmartPort-whitepaper-SmartShipping.pdf

Smith, K., and P. A. Hancock. (1995). Situation Awareness Is Adaptive, Externally Directed Consciousness. *Human Factors: The Journal of the Human Factors and Ergonomics Society 37 (1): 137–148.*

St. John, M.F. (2013). Janus Design Principles and the Acquisition Process for a Supervisory Situation Awareness Display. *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 57, No. 1, pp. 2002- 2006). SAGE Publications.*

Stanton, N.A. (2005). Hierarchical task analysis: Developments, applications, and extensions. *Applied Ergonomics 37 (2006) 55–79*.

Stanton, N.A, Salmon P.M., Walker G. H., Salas E. & Hancock P.A. (2017). State-of-science: situation awareness in individuals, teams and systems. *Ergonomics, 60:4, 449-466, Doi: 10.1080/00140139.2017.1278796*

Stanton, N. A., and Walker, G. H. (2011). Exploring the Psychological Factors Involved in the Ladbroke Grove Rail Accident. *Accident Analysis and Prevention 43 (3): 1117–1127.*

Stanton, N.A., Salmon. P.M. & Walker, G.H. (2015). Let the Reader Decide: A Paradigm Shift for Situation Awareness in Sociotechnical Systems. *Journal of Cognitive Engineering and Decision Making, Volume 9, Number 1, March, pp. 44–50. Doi: 10.1177/1555343414552297*

Stanton N.A., Stewart R, Harris D, Houghton R.J., Baber C, McMaster, R, Salmon P.M., Hoyle G., Walker G.H., Young M.S., Linsell M., Dymott R, Green, D. (2006) Distributed situation awareness in dynamic systems: theoretical development and application of an ergonomics methodology. *Ergonomics 49 (12-13):1288–1311*.

Stanton, N.A., Salmon. P.M., Walker, G.H., Baber. C. & Jenkins, D.P. (2005). Human factors methods: a practical guide for engineering and design. *Ashgate Publishing Ltd*.

Strobach, T., Wendt, M., & Janczyk, M. (2018). Multitasking: Executive Functioning in Dual-Task and Task Switching Situations. Place of publication not identified: Frontiers Media SA.

Tjallema, A., Nat, C. van der, Grimmelius, H. & Stapersma, D. (2007). The road to eliminating operator related dynamic positioning incidents. Proceedings of the Dynamic Positioning Conference, October 9-10

Van der Kleij, R., Hueting, T., & Schraagen, J.M. (2018). Change detection support for supervisory controllers of highly automated systems: Effects on performance, mental workload, and recovery of situation awareness following interruptions. International Journal of Industrial Ergonomics, 66, 75-84. doi.org/10.1016/j.ergon.2018.02.010.

Distribution list

Hardcopy	Ministerie van Economische Zaken en Klimaat Michiel Ottolander
Pdf	Netherlands Maritime Technology Sanne de Vleeschhouwer

TNO

Pdf	Director Science Buildings, Infrastructures & Maritime Prof. dr. ir. Arjen Adriaanse
Pdf	Roadmap Maritiem en Offshore Ir. Pieter Boersma
Pdf	VP Maritiem en Offshore Sander Dragt MSc
Pdf	Projectleider (PL) JIP AS Dr. ir. Harrie Bastiaansen
	Research Manager PL Dr. ir. Job Oostveen
	Afdeling Human Behaviour & Organisational Innovations:
Pdf	Auteur/projectmedewerker: Dr. Hans van den Broek
Pdf	Research manager auteur/projectmedewerker: Ir. Eric Veldkamp
Pdf	Principle Scientist Prof. dr. Jan Maarten Schraagen
Hardcopy/ Pdf	Archief Soesterberg