European Maritime Safety Agency

FRAMEWORK FOR GENERIC RISK ASSESSMENT TOOL FOR MASS CONCEPTS

REPORT 1 OF 2

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EMSA

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EXECUTIVE SUMMARY

The accelerating technological developments in recent years has opened for new opportunities, and Maritime Autonomous Surface Ships (MASS) represents a promising area for the maritime industry. However, new risks may emerge as technologies with advanced automation are introduced into the highly regulated and inherently complex maritime environment. In the current absence of clear rules and standards for such technology, safety must instead be ensured by adherence to functional requirements developed using goal-based approaches. As a contribution to this effort, EMSA has contracted DNV GL to perform a functional study with the objective of developing a Risk Based Assessment Tool (RBAT) and software specifically for MASS.

The intention behind RBAT is to enable risk assessment of whether increased or new ways of using automaton as part of vessel operation is as safe or safer than conventional shipping.

In this report, automation is understood as the execution by a machine agent (usually a computer) of a function that was previously carried out by a human. Autonomy can be explained as "technology operates alone". The term automation is preferred over autonomy. One of the arguments behind this preference is that most of the technologies for which RBAT will be applied for are likely to represent incremental developments in automation and not fully autonomous solutions. A second argument is that it is currently difficult to draw a clear distinction between the term autonomy and what can be considered advanced automation. Because RBAT is concerned with risks emerging from joint performance resulting from human-automation interactions, the term autonomy can be considered a too narrow category which excludes large parts of the application area RBAT is intended for.

RBAT is planned to be developed through three consecutive main parts. The main objective of Part 1 is to establish an overall framework for a generic risk assessment tool capable of screening a wide range of MASS concepts for safety related concerns. This consist of developing:

a) a multi-level function map including functions potentially being re-allocated from humans to systems,

b) definitions characterizing use of automation, and a format suitable for collecting data describing such systems and their associated risks,

c) a list of hazardous conditions and events which can be linked to functions being targeted for various levels of automation, and

d) a risk model and methodology which enable identification of high-risk areas and risk reducing measures.

This report is the first of two reports planned to be issued as part of Part 1. It documents the process and deliverables associated with a) and b). Items c) and d) will be documented in the upcoming second report. Part 2 aims to describe three different concepts of MASS, including their automated functions. These are then used to test the RBAT framework and produce the first functional version of the RBAT software. Part 3 shall complete the RBAT framework and, by using a more complex MASS concept description as input, test whether the tool can capture additional risks not identified in the previous round of testing. Knowledge gained through this final round of testing shall be used to update and complete the first version of the RBAT software.

The report acknowledges the extensive work that has already been performed on similar topics, both in the maritime industry as well as in other industries. Consequently, a comprehensive review of existing practices and literature has been carried out to create a solid foundation for the RBAT framework, and to provide justification behind the deliverables proposed for activities a) and b).

<u>Multi-level function maps</u>

Several of the reviewed standards and guidelines support using models with a *hierarchical goal structure*, such as multi-level function maps, for the same purposes RBAT is being developed for (i.e. function allocation and risk assessment). This practice appeared to be well-established and accepted, particularly in the aviation and nuclear industry. Goal hierarchies allows a top-down, yet creative and exploratory, approach to systems engineering and design.

When creating such models for large systems the standard practice across industries is to express the higher levels in terms of *operational goals*. These often represent the commercial, political or public interests behind how a system is designed and operated. 'Mission'-related terminology such as *mission phase* and *operations* appear suitable (and accepted by many) for describing goal hierarchies for vessels. While the terminology could be limited to operational goals and *modes*, such as for nuclear, the term *mission* implies that overall goal is related to transportation and physical re-location, and not only changing the system's operational state.

The operational goals of a system are commonly decomposed into branches of *functional goals* and sub-goals. There appears to be no definite way of dividing and segregating levels of functional goals according to the physical objects they intend to represent. Instead the goal hierarchies are freely broken down to the level of detail which accommodates the model's objectives. For RBAT, the breakdown of functions therefore stops at the function level where it is possible analyse risks emerging from human-automation interactions. This bottom level of the goal hierarchy is referred to as *control functions*.

Based on the review, a hierarchical goal structure for the RBAT multi-level function maps was proposed, consisting of three main parts:

- The upper part consists of the vessel's *operational goals*, described in terms of three layers; a mission goal, mission phases, and operations. This part has been titled the "RBAT mission model".
- The middle part consists of the vessel's *functional goals*, described in terms of top-level functions and layers of sub-functions required to successfully perform the mission operations. This part has been titled the "RBAT function tree".
- The lower (bottom) part consists of the control functions and actions allocated to either humans or the system. This part has been titled the "Human-automation interaction" (HAI) level.

A *functional analysis* was performed to produce a generic mission model (Figure 1) and function tree (Figure 2) according to the hierarchical goal structure proposed for the RBAT multi-level function maps. Both have been included as deliverables in this report (see Appendix A and B) and constitute two of the main building blocks of the RBAT framework.

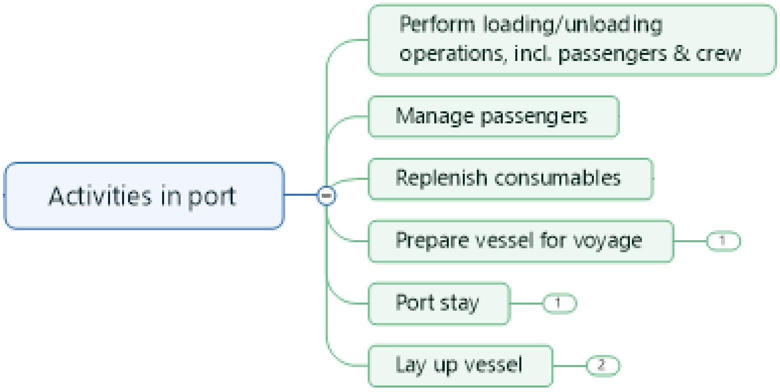

Figure 1 – Extract from the RBAT *Mission Model* (Appendix A) showing the mission phase "Activities in port" and it associated operations.

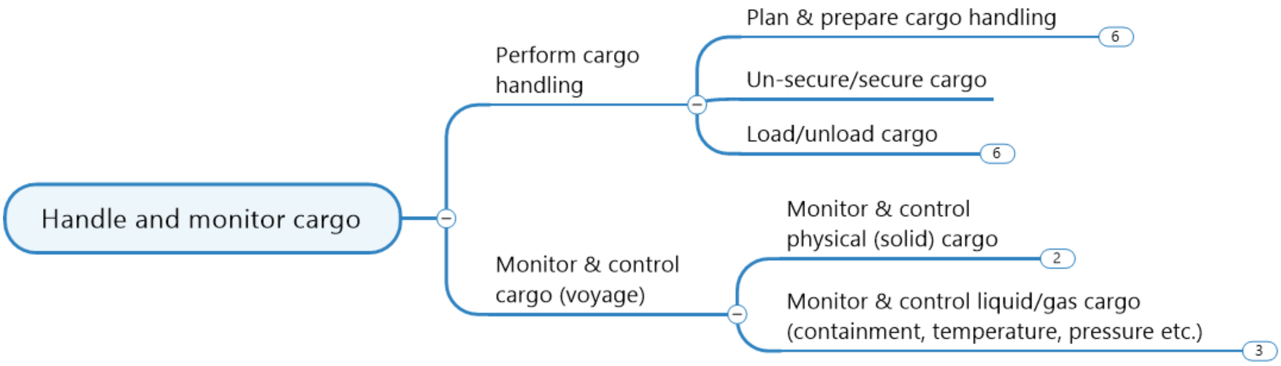

Figure 2 – Extract from the RBAT *Function tree* (Appendix B) showing the top-function "Handle and monitor cargo" and (some of) its associated sub-functions.

Although being documented as two separate deliverables, the mission model and function tree could (in principle) be combined into one complete function map. However, because the more detailed functional goals often serve multiple higher-level operational goals, such a model would become excessively large, complex and thus difficult to read. Furthermore, RBAT is planned to be suitable for scopes ranging from a selected set of functions, to entire vessel concepts. Thus, not all users will benefit from such a complete and pre-defined model. Instead, relationships between higher and lower level goals will be managed through software functionality and protocol for how to use RBAT. It is expected that the mission model and function tree developed as part of creating the RBAT framework can be made generic to a degree where the user mainly will have to specify and modify parts of the model to make it fit the concept being analysed. A preliminary protocol for how to create a multi-level function map when using RBAT is provided below.

<u>Describe the vessel's operational goals (mission model)</u>

A mission model can be developed through the following steps:

- Describe the vessel(s) mission in terms of the commercial, political and/or public intentions (i.e. goal) behind why the vessel is being designed and operated.

- Describe the vessels mission phases according to recognizable transitions in geographical surroundings and locations. Emergency response is also included as a separate phase.
- Describe the operations which are planned to be carried out for each mission phase. Operations which can occur across the various geographical phases can be grouped under other dedicated mission phase headings, such as emergency responses to relevant accident scenarios, specific waterborne operations, and maintenance and repair.

<u>Describe the vessel's functional goals (function tree)</u>

After having a developed a representative mission model, the function tree can be used to describe the functional goals which must be achieved to successfully perform the operations:

- Start by identifying top-level functions which are relevant for each operation. Then, follow the function tree branches to identify relevant lower level sub-functions. Each operation is likely to include a mix of different control functions.
- Add any control functions which are missing from the function tree and update the descriptions to reflect the actual design of the vessel.
- Make sure to not only include the functions which exert direct control of the vessel's operational performance, but also include the required support and auxiliary functions.
- Arrange the list of control functions in an order which best describes the operation, e.g. in the sequence they are most likely to be performed.

Following this protocol should produce sets of goal hierarchies like the (simplified) example provided below.

Mission: Safe and timely transport of cargo from port X to port Y

Mission phase: Port activities

Operations: Perform cargo operations

Functions and sub-functions:

- Perform cargo handling
  - Plan and prepare
  - Un-secure cargo
  - Unload cargo
  - Etc.
- Maintain trim and stability
  - Calculate and confirm trim and stability
  - Operate ballast pumps
- Maintain communication
  - Communication between RCC and crane operator
  - Communication between RCC and port officer

The process of describing functional goals is finalized when a complete set of control functions required to perform the selected operation has been identified. This forms the basis for describing the lowest part of the multi-level function map, namely the human-automation interaction (HAI) and allocation of functions (Figure 3), as explained in the following paragraphs.

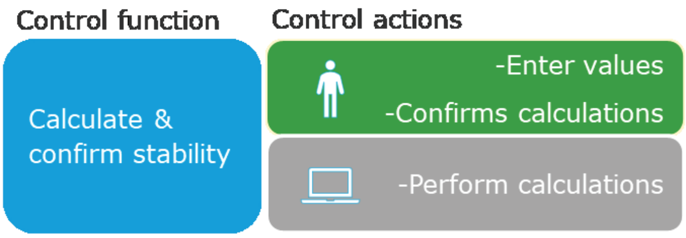

Figure 3 – Allocation of a control function represented by human or automation responsibilities for performing control actions

<u>Describe the concepts Use of Automation</u>

The review of existing standards, guidelines and academic publications was also used to develop definitions and a structure suitable for describing what is referred to as *Use of Automation* (UoA). This refers to how automation is solved and implemented for each affected function, during various operations, including abnormal situations and emergencies, by use of available technologies and human involvement.

UoA is made up of two main elements:

- The first is describing the role of humans or automation in terms of being responsible for supervising, supporting or performing the control function.
- The second is describing control actions in terms of human information processing, meaning the acquisition and analysis of information, making decisions based upon that information, and implementing the actions required.

Definitions of the various terms are provided inside the report.

UoA is intended to be described as a combined product of these two main elements. For example, a human operator can supervise decisions made by an automation system. Such descriptions are likely to be relatively unique for each concept and will be specified by the RBAT user on a case-by-case basis. However, to facilitate that control actions are described in a consistent and unambiguous manner, a list of verbs (see Appendix C) categorized according to the four stages in the information processing model is proposed as part of the UoA framework.

After having defined the vessel(s) and RCCs operational and functional goals, meaning the mission model and function tree, the RBAT protocol is extended with the following three steps for describing UoA, as illustrated in Figure 4.

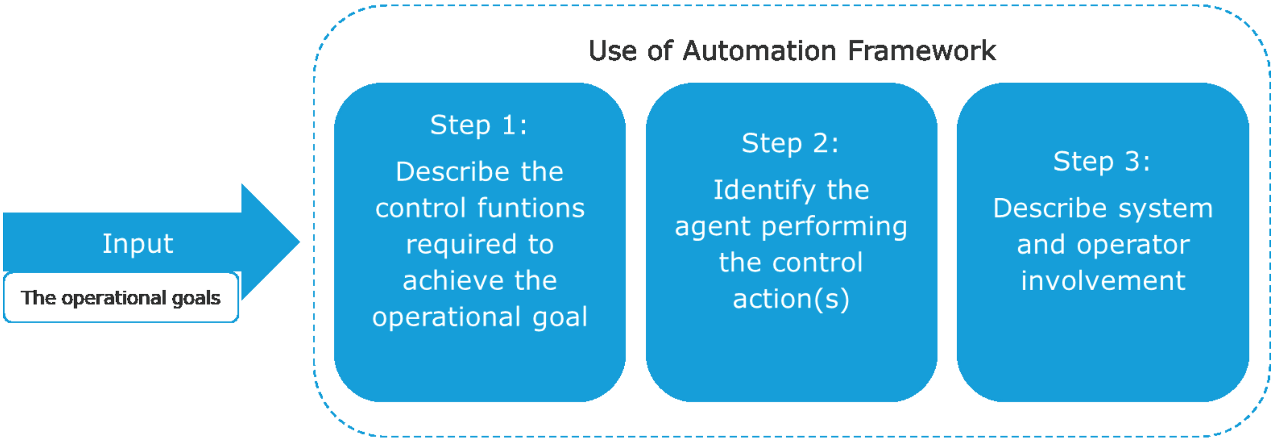

Figure 4 – Steps for applying the UoA framework

The information gathered through the three steps are structured using a table format similar to what is illustrated in Table 1. Abbreviated labels can be used to indicate the location and number of agents, such as remote or local operator 1, 2, 3 etc. This can be used to evaluate implications related to the manning, such as crew workload and physical presence or availability.

Table 1 – Use of Automation table format

Control functions	Control actions	Performing agent	Other agent	Role	Involvement
Harbour manouvering	Detect vessels	Automated navigaton system (ANS)	No other agent	--	--
	Calculate arrival time	Automated navigaton system (ANS)	Remote Operator 1 (RO1)	Support	Load traffic regulation data in ANS

The UoA table can then be extended to also include columns required to perform risk analysis associated with how automation has been solved for each function. Developing this module is the planned scope for the second half of Part 1 for RBAT.

DEFINITIONS

Term	*Definition*
Automation and autonomy	See chapter 3.3.1
Control function	Control actions performed by humans or machines for the accomplishment of a functional goal, including the associated information processing (adapted from IEC, 2000).
Function	Specific purpose or objective to be accomplished, that can be specified or described without reference to the physical means of achieving it (IEC, 2020).
Functional allocation/ assignment	Distribution of functions between human and machine (ISO, 2000). Functional allocation can also be referred to functional assignment (IEC, 2000).
Functional analysis	The examination of the functional goals of a system with respect to available manpower, technology, and other resources, to provide the basis for determining how the function may be assigned and executed (IEC, 2009).
Functional goal	The performance objectives that shall be satisfied to achieve a higher level corresponding function (adapted from IEC, 2009).
Hierarchical goal structure	Relationship between a goal and sub-goals structured in a hierarchical order (adapted from IEC, 2009).
Human-automation interaction	The way a human is affected by, controls and receives information from automation while performing a task (Sheridan & Parasuraman, 2006).
Mission	A definite military, naval, or aerospace task https://www.merriam-webster.com/dictionary/mission. Comment: "Task" in this sense has a different meaning than the definition of task provided in this table.
Operational goals	The ultimate purposes of plant design (IEC, 2009). Comment: The term plant refers to nuclear power plant. For RBAT the equivalent would be the vessel and remote-control centre (if available).
Task	Control actions performed by humans for the accomplishment of a functional goal (IEC, 2000).

1 INTRODUCTION

1.1 Background

The accelerating technological developments in recent years opens for new opportunities for new and different concepts. Maritime Autonomous Surface Ships (MASS) is one promising area for the maritime industry. However, the use of new technologies with autonomous functionality in a complex and highly regulated maritime environment provides a significant challenge. The development of MASS depends on proving safety equivalence by risks being identified and mitigated to an as low as reasonably practicable and acceptable extent.

1.2 Objective and scope

The objective of Part 1 is to develop an overall framework and structure for a generic risk assessment tool capable of screening MASS concepts for safety related concerns. This consists of:

e) a multi-level function map including functions potentially being re-allocated from humans to systems,

f) definitions characterizing use of automation, and a format suitable for collecting data describing such systems and their associated risks,

g) a list of hazardous conditions and events which can be linked to functions being targeted for various levels of automation, and

h) a risk model and methodology which enable identification of high-risk areas and risk reducing measures.

The framework shall accommodate assessments of a wide range of MASS concepts and application of risk acceptance criteria and safety equivalence for risk reduction, as described in Part 2.

The focus is on safety-related aspects, and not concerns related to cybersecurity (unless they have implications for safety).

The first report of Part 1 (this report) is limited to document parts a) and b). Parts c) and d) will be included in a second report.

2 DEVELOPMENT OF MULTI-LEVEL FUNCTION MAP

2.1 Purpose

Design and use of automation are commonly considered in terms of how *functions* are performed. Developing a generic "multi-level function map" is therefore a key part of building the RBAT framework. Function maps provide an overview of what goals the system is intended to achieve. This, in turn, can be used as a basis for further design considerations, such as allocation of functions between a control system and human operators, and for assessing risks associated with function failures and degradation.

2.2 Review of existing practices

Because the RBAT multi-level function map shall form the basis of a framework and eventually a software, a thorough review of existing practices for developing and applying such models was deemed as necessary. The goal was to provide a refined methodology backed up by justifications from reliable and well-established sources, so that it can be assured that further work is performed on a solid foundation.

The following sub-chapters summarize a review of what was identified as key publications. It should be noted that the review uses the terminology as it is written in each respective source.

2.2.1 DNV GL

DNV GL issued a Class Guideline titled *Autonomous and remotely operated ships* (DNV GL, 2018a) in September 2018. The guideline states that the functionality of the system should be described as part of a risk-based qualification and approval process (p. 42).

More specifically, the purpose is to demonstrate required functionality regarding the following aspects:

1) Normal operation: A description of how the function works and behave under normal conditions. If applicable, the functionality may be divided into several sub-functions.

2) Autonomy and remote-control modes: A description of how the function behaves in different modes with regards to decision support, autonomy and remote control. The expected human interaction should be described, and how the function behaves if expected/required human input or intervention is not available (e.g. due to a communications failure with the remote-control centre).

3) Sequences and timing: Automated sequences and timing aspects of the functionality should be described. If the system is expecting input from a remote operator, there should normally by a time-out action which prevents the function from 'hanging' if the input does not happen as expected.

4) Man-machine interfaces: The interface between the system and the human users shall be designed according to best practises for user interfaces and with defined responsibility modes for the operator. Especially situations where a human is expected to 'take over' control because of system-limitations or failures should be designed to allow ample time for the human to get the required situational awareness in order to be able to make good decisions (this is sometimes referred to as the control latency).

5) Degraded/limited functionality: A description on how the function behave when it is not able to operate at 100%. The characteristics of the degraded/limited functionality should

be described along with the consequences of the limitation(s). Loss of redundancy should be regarded as a degraded mode.

6) Safe state(s): A description of the state(s) the function is going to end up in the event of a failure. The function should be designed so that the safe states are predictable and controllable.

Given that a risk-based approach should be applied with an operational focus to achieve an equivalent level of safety, the design methodology should specifically address all functions of the auto-remote infrastructure needed to achieve this objective. Some of these functions are traditional ship-functions, others are related to the automatic and remote operation.

The Class Guideline provides a list which can be used to identify such key functions. It is stated that the list is not exhaustive and may be extended, depending on e.g. vessel type and the intended level of autonomy and remote operation.

Key functions of the auto-remote infrastructure:

- remote control and supervision
- communication
- navigation and maneuvering
- propulsion
- steering
- electrical power supply
- control and monitoring
- watertight integrity
- fire safety
- ballasting
- drainage and bilge pumping
- anchoring
- cargo handling
- maintenance

The functions listed above are on a high abstraction level, and it is often desirable to make only parts of these functions remote-controlled or autonomous. The Class Guideline therefore recommends that further analysis of the function is needed to identify the different parts that should be automatic, autonomous, remote-controlled or manual. A detailing of the functions starts already during the analysis of the operational aspects, where individual tasks and sub-functions are identified to be performed automatically or by remote control. This is normally described in Concept of Operations (CONOPS) document and can be re-iterated throughout the various design stages.

For complex systems, DNV GL recommends using a system engineering approach consisting of building a hierarchical structure where technology expectations (i.e. goals) are linked to functions and sub-functions. This approach is inspired by Technology Assessment required as part of DNV GLs Recommended Practice (RP) for technology qualification (DNV GL, 2019). Here the aim is to decompose system goals into a hierarchy consisting of main and sub-functions. The lowest level functions can be linked to the evidence used for qualifying the technology, such as testing, analyses, inspections etc. (Figure 5) This is referred to as 'goal modelling' or 'goal decomposition'.

Because a function may be covered by varying degree of automation/autonomy, the Class Guideline proposes to divide the control of a function into four main parts; detection, analysis, planning, and action. This can be used to define which part of a function that is intended to be solved by a human and which to be solved by a system.

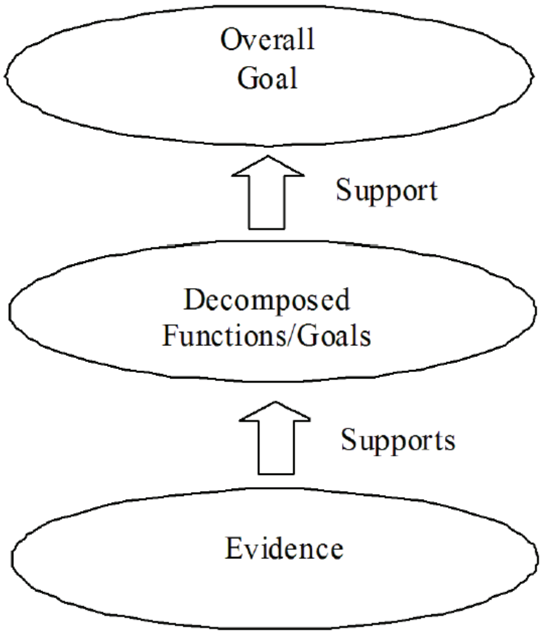

Figure 5 – Goal model from DNVGL-RP-A203 Technology Qualification, ed. 2019

2.2.2 American Bureau of Shipping

The American Bureau of Shipping (ABS) issued in 2020 an *Advisory on Autonomous Functionality* note (ABS, 2020) providing a framework and structured process to guide stakeholders in the application of autonomous functionality. With references made to IMO[1], ABS acknowledges the need for a goal-based framework (Figure 6) as part of regulating developments of new technology.

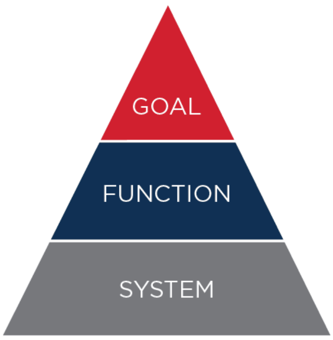

Figure 6 – Goal-based framework autonomous functionality (ABS, 2020)

Specifically, ABS states that "In the implementation process during the development of autonomous vessels, the over-arching goals would be that the *autonomous functionality is to be designed, constructed, operated and maintained for its planned mission safely, reliably and predictably*." [p. 9]. Furthermore, they recommend that functional requirements are defined for each of the autonomous functions being implemented. Like DNV GL, ABS suggests that these functions can be categorized according to what is referred to as an *operational decision loop*, consisting of monitoring, analysis, decision(-making), or actions. The functional requirements

[1] IMO Generic Guidelines for Developing IMO Goal-Based Standards (MSC.1/Circ. 1394)

are intended to provide criteria for how each of the functions must perform in order to achieve the goals of the system (vessel).

In ABS's framework, functional requirements are further underpinned by a set of foundational requirements intended to be used for verifying that functional requirements and goals are met. Foundational requirements target the reliability, integrity, robustness and operability of systems responsible for performing or supporting the autonomous functions, i.e. monitoring, analysis, decision making and action taking.

To facilitate the process of defining functional and foundational requirements, ABS proposes a framework which includes breaking down the high-level objectives (i.e. goals) of a system into a set of sub-goals (see Figure 7).

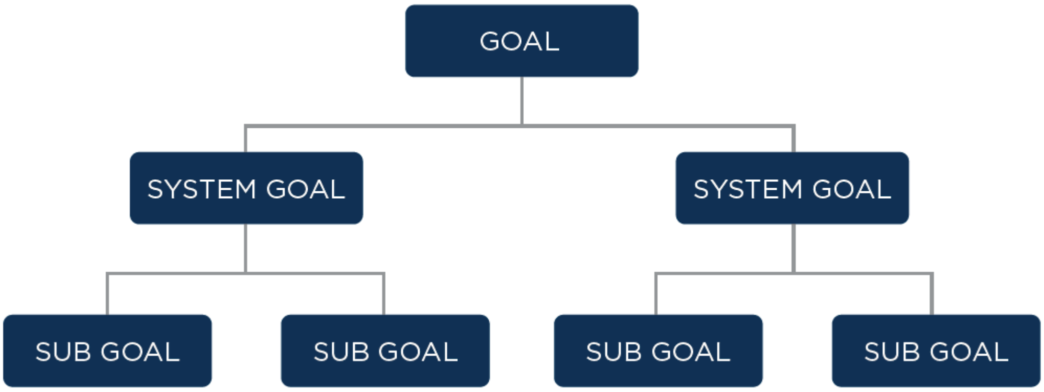

Figure 7 – Scalability of goal-based framework (ABS, 2020)

This framework is intended to be scalable and can be applied by itself to a single autonomous function or system. For more complex functions or for the development project of a fully autonomous vessel with multiple functions and systems, it can be scaled up with multiple functions/systems forming system goals and subordinate goals (sub-goals) which feed into and support an over-arching goal.

2.2.3 Bureau Veritas

In their guidance note *Guidelines for Autonomous Shipping* (BV, 2019), Bureau Veritas (BV) states that "At the first stage of the risk assessment, all main systems of a ship, including Remote Control Centre (RCC), should be split into several groups of functions covering essential services." (p. 18). As guidance, BV provides a list of typical functions to be considered, much similar to the ones provided in the DNV GL Class Guideline, namely;

- Voyage
- Navigation
- Detection
- Communication
- Ship integrity, machinery and systems
- Cargo and passenger management
- Remote control
- Security

In addition to being used as a basis for risk assessments, it is encouraged to specify how roles and responsibilities have been distributed between the human and the system for each of the identified functions. BV recommends using a four-stage model of human information processing as an initial categorisation for types of tasks in which automation can support the human. This model is similar to the one described in DNV GLs Class Guideline (DNV GL, 2018a), as mentioned in section 2.2.1.

2.2.4 Lloyd's Register

At the time of the review, four different publications by Lloyd's Register (LR) on autonomous or unmanned vessels were identified:

- Cyber-enabled ships: Deploying information and communications technology in shipping – Lloyd's Register's approach to assurance, First edition, February 2016
- Cyber-enabled ships: ShipRight procedure – autonomous ships, First edition, July 2016
- ShipRight Design and Construction: LR Code for Unmanned Marine Systems, February 2017
- Cyber-enabled ships: ShipRight procedure assignment for cyber descriptive notes for autonomous & remote access ships, Version 2.0, December 2017

The documents contain a comprehensive set of functional performance requirements for different systems expected to be subjected to automation as part of unmanned operations.

2.2.5 AUTOSHIP

A report titled *D3.1 – Autonomous ship design standards* was recently issued by members of the EU Horizon 2020 research consortium titled AUTOSHIP (Rødseth et al., 2020). The report is comprehensive both when it comes to suggesting terms and definitions, as well as methodologies for how to create models required to address automation in a systematic manner. This includes proposals of an operations model and mission phases (chapter 7), as well as a breakdown of high-level operations into functions and tasks (chapter 8).

The operations model consists of the phases illustrated in Figure 8. In addition, the report includes categories of various sub-phases, such as abnormalities and those considered to be specific for inland waterways (IWW).

Figure 8 – Operations model from AUTOSHIP report (Rødseth et al., 2020)

A set of high-level operations are proposed as categories under which various functions and tasks can be grouped. This includes ship management operations, such as administration, fleet management, and technical services, as well as activities performed by the ship such as coastal operations, port operations, IWW operations and on-site operations. AUTOSHIPs proposed grouping of functions under operations is illustrated in Figure 9.

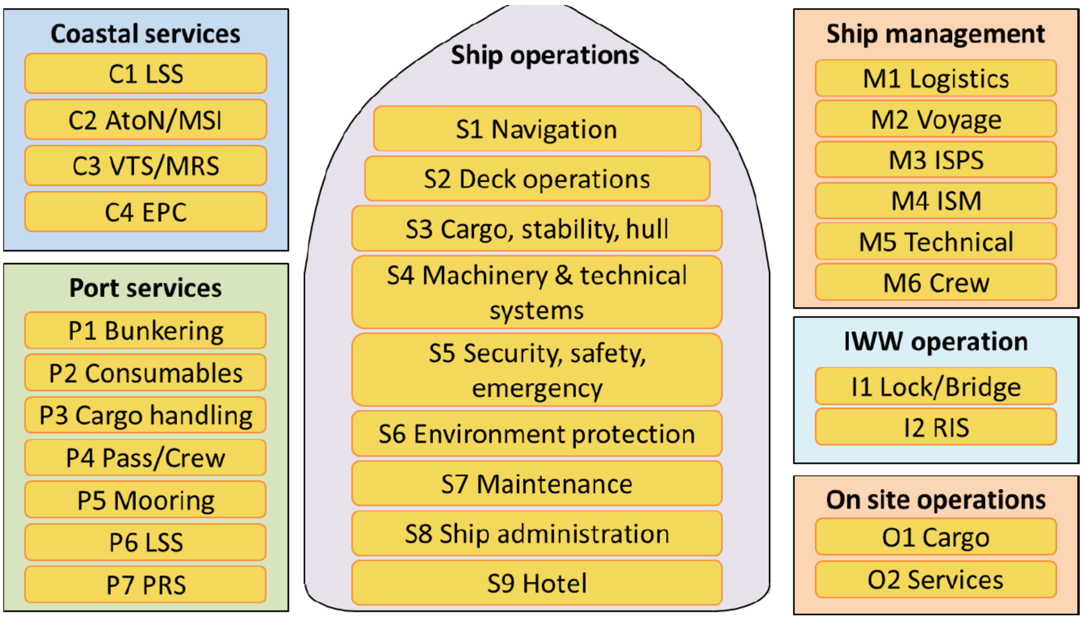

Figure 9 – Breakdown of operations into functions from AUTOSHIP (Rødseth et al., 2020)

In addition to the functions listed in Figure 9, the AUTOSHIP report's appendix also includes a complete list of what is defined as tasks and sub-tasks for each function.

AUTOSHIP (ibid., p. 63) states that a function breakdown can help to serve the following purposes:

1. A formal reference system for information: The codes on the functions and tasks can be used as reference for information that is passed through the development phases and between tools.
2. A generic model of functions and tasks: This can, e.g. be used to structure a Hazard Identification session and as guidewords during the session, or to check completeness of use case specifications. It can also be used as starting point for defining sub-divisions of the operational envelope.

2.2.6 International standards and industry guidelines

The project has also reviewed a selected set of well-established international standards and guidelines, most from other industries. This includes nuclear power generation, military aeronautics and commercial aviation, space technology, and process industries (e.g. petroleum). These industries have a long tradition of applying function decomposition techniques for various engineering purposes. The reviewed documents are listed below, followed by a brief summary of key take-aways on the topics considered relevant for RBAT:

Nuclear:

- IEC 61839 Nuclear power plants – Design of control rooms – Functional analysis and assignment
- IEC 60964 Nuclear power plants – Control rooms – Designs
- IEC 61226 Nuclear power plants – Instrumentation, control and electrical power systems important to safety – Categorization of functions and classification of systems

- IAEA-TECDOC-668 The role of automation and humans in nuclear power plants
- INL/EXT-13-30117 Development of a Technical Basis and Guidance for Advanced SMR Function Allocation

Aviation/aeronautics:

- NASA Contractor Report 4374 An Exploration of Function Analysis and Function Allocation in the Commercial Flight Domain
- ARP4754 Guidelines for Development of Civil Aircraft and Systems
- ARP4761 Guidelines and methods for conduction the safety assessment process on civil airborne systems and equipment

Defence:

- MIL-HDBK-46855A Department of defense handbook: Human engineering program process and procedures
- MIL-STD-46855A Department of defense standard practice: Human engineering requirements for military systems, equipment, and facilities

Industry generic:

- ISO 11064 Ergonomic design of control centres – Part 1: principles for the design of control centres

The documents for each industry all contain comprehensive descriptions of frameworks, methods, definitions and processes intended to address automation through analysis and allocation of functions between humans, systems and geographical locations (e.g. remote control). A full review of all documents is beyond the scope of this report, extract of relevant parts is instead included in the review summary presented in sub-chapter 2.2.7.

Due to the need for limiting the scope, standards from the automotive industries have not been included as part of the review. Although these standards can be considered relevant, automotive systems (vehicles) represent smaller and in some ways simpler systems than ships and their required infrastructure. Instead the similarities were considered to be larger when compared to aviation/aeronautical systems and industries with long tradition of centralized and remote control of functions, such as nuclear power generation and petroleum.

2.2.7 Review summary

The paragraphs below outline what are considered the key take-aways for developing the framework and structure for RBAT.

<u>Hierarchical goal structure</u>

Several of the recently published guidelines on maritime automation, autonomy and smart ships highlight the need for decomposing higher level functions into a set of sub-functions. This process is intended to facilitate an understanding how automation of functions should be implemented to achieve various objectives of the system being designed. This approach was supported by DNV GLs guideline for autoremote vessels (DNV GL, 2018), the ABS guidance note (ABS, 2020), and the AUTOSHIP report (Rødseth et al., 2020). Albeit the BV and Lloyds guidelines (BV, 2019) does not explicitly advocate the use of function breakdown, they adopt a functional approach to automation and autonomy.

The nuclear industry breaks down plants' safety and availability goals into a set of functions and sub-functions as part of designing their control centres, including the layout of rooms, information presentation on human-machine interfaces, and allocation of functions between human operators and automation systems (IEC, 2000; 2009). This practice is also adopted by generic industry standards for control centre design (ISO, 2000). Hierarchical goal models are also used both in civil (commercial) (NASA, 1991; Kritzinger, 2017; SAE Aerospace, 1996) as well as military aviation (DOD, 1999; 2011) for similar purposes. This includes unmanned aircraft systems (Lee & Mueller, 2013).

Key take-away #1; most of the reviewed standards and guidelines support using models with a *hierarchical goal structure* (i.e. multi-level function maps) for the same purposes RBAT is being developed for.

The following paragraphs provide a more detailed explanation of such models' logical structure.

Operational goals

The inherent logic in models with a hierarchical goal structure is that all levels can be considered as goals to be achieved through performance of systems and humans. Nevertheless, several of the frameworks and techniques used to generate such models often attempt to differentiate between the various levels of goals. At the higher goal levels, such as those used to define the purpose of a nuclear plant, aircraft or vessel, the goals are often expressed in terms of the operations performed to generate commercial, political or public values. Both generic standards (ISO, 2000) and standards specific to the nuclear industry standards (IEC, 2000; 2009) refer to this as *operational goals*. Operational goals are often categorized as availability (commercial) goals, such as controlled generation of electricity, and safety goals, such as prevention of release of radioactivity to the environment. Furthermore, it is often a requirement that the operational goals shall take into consideration (and reflect) the plant's anticipated operational modes, including steady-state operations, normal transient operations (start-up/shut-down), emergency/abnormal operational states, as well as scheduled and unscheduled maintenance (ISO, 2000). The rationale is that automation and other design aspects may be solved differently across these different modes.

In aviation, the term *mission* is commonly used to label the purpose (i.e. operational goals) of commercial aircrafts (NASA, 1991; SAE, 1996) as well as various defence systems (DOD, 1999; 2011). Design requirements, such as how to automate functions, are generated from thorough analysis of the mission(s) planned to be accomplished by an aircraft. A report about function allocation published by NASA (1991) recommends decomposing a mission into a hierarchical (goal) structure consisting of three levels; mission periods, phases and segments. The breakdown of periods and phases is illustrated in Figure 10 ('segments' are not shown).

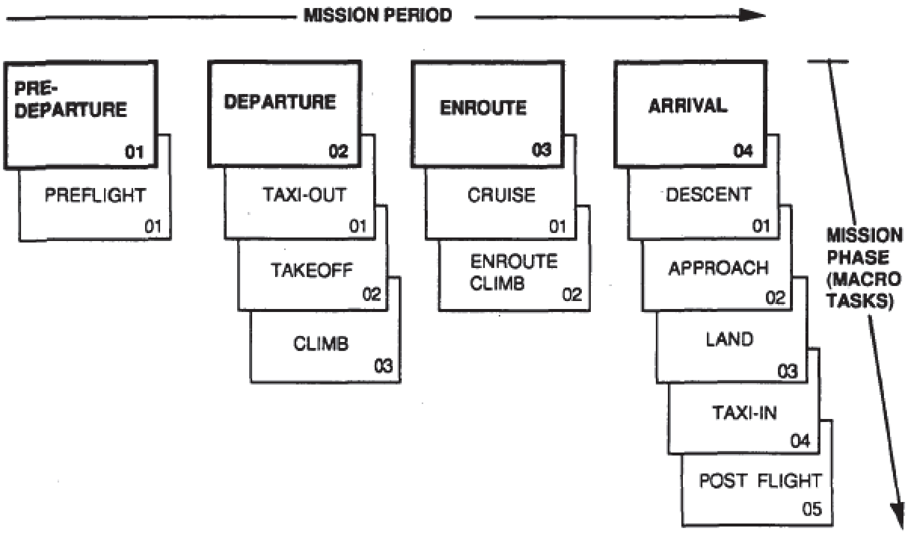

Figure 10 – NASAs (1991) proposed mission decomposition for commercial aircrafts

Like the method for developing mission hierarchies described in NASAs report, The US Department of Defence handbook for human engineering applies what is referred to as *mission analysis* (DOD, 1999). Specifically, it is stated that a mission analysis shall define what operations the total system (hardware, software and liveware) must perform. Furthermore, the mission or operational requirements are a composite of requirements starting at a general level and progressing to a specific level. Mission requirements define the system in terms of the operational capabilities needed to accomplish the mission.

Returning to maritime publications, one of the AUTOSHIP publications (Rødseth et al., 2020) also advocate the need to define hierarchical operational models consisting of system and mission objectives, mission phases, operations, tasks and sub-tasks. One of the intentions behind this process is to provide a "…description of the cyber-physical interactions in the system, i.e. automation and the physical components that together perform the functions and tasks, including the humans' role in the system and the allocation of functions and tasks to equipment, automation or humans." (p. 22-23).

Key take-away #2: When creating models with hierarchical goal structures for the purpose of system engineering, the standard practice across industries is to express the higher levels in terms of operational goals. These often represent the commercial, political or public interests behind how a system is designed and operated.

Key take-away #3: 'Mission'-related terminology such as mission phase and operations appear to be accepted for describing operational goal hierarchies for vessels. While the choice of terminology could be limited to 'operational goals' and 'modes', such as for nuclear, the term mission can arguably be considered more suitable. It implies that overall goal is somewhat related to transportation and execution of something which requires physical relocation, and not only changing the system's operational state. The term 'voyage' is considered too narrow as it mainly implies a vessel's sailing phases. This will exclude other more stationary activities, such as those performed when at quay or when performing waterborne operations, such as a heavy lift.

Functional goals

In systems engineering the terms "goal" and "function" are interchangeable. However, at higher levels of a hierarchy, a system design concept is considered and better expressed in terms of operational goals, where at lower levels it is more appropriate to refer to a *functional goal* (IEC, 2000). Functional goals therefore constitute the levels of functions and sub-functions performed with the objective of achieving the higher-level (operational) goals.

The separation between higher-level operational goals and lower-level functional goals is evident in several of the reviewed documents. The NASA guideline (NASA, 1991) for function allocation in commercial aviation recommends identifying a functions and sub-functions required to successfully perform mission segments, the lowest level of operational goals in the mission hierarchy description. The nuclear standards include definitions (IEC, 2009) and flowcharts for engineering processes which explain how functions and sub-functions shall derive and be identified from an initial definition of operational goals (IEC, 2000). This process is commonly referred to as *functional analysis*, a term adopted by most industries (ISO, 2000).

The standards and guidelines describing functional analysis techniques often differentiate between functions according to their abstraction levels. The highest-level functions are often labelled as abstract functions that can be specified or described without reference to the physical means of achieving it. At the next level(s) there are system-level functions which can be associated with a category of equipment (e.g. communication equipment). At the lowest level there are equipment/component functions. An example is provided in Figure 11 which illustrates parts of a flow diagram for functional analysis and allocation activities, extracted from IEC 61839 (IEC, 2000). A similar way of categorizing function levels in terms of the physical systems they are intended to represent have been suggested for unmanned aircraft systems (Lee & Mueller, 2013). However, despite such conceptual illustrations and explanations of how to categorize functions according to their abstraction levels, none of the reviewed documents included a method containing prescriptive rules and definitions for how to put this into practice.

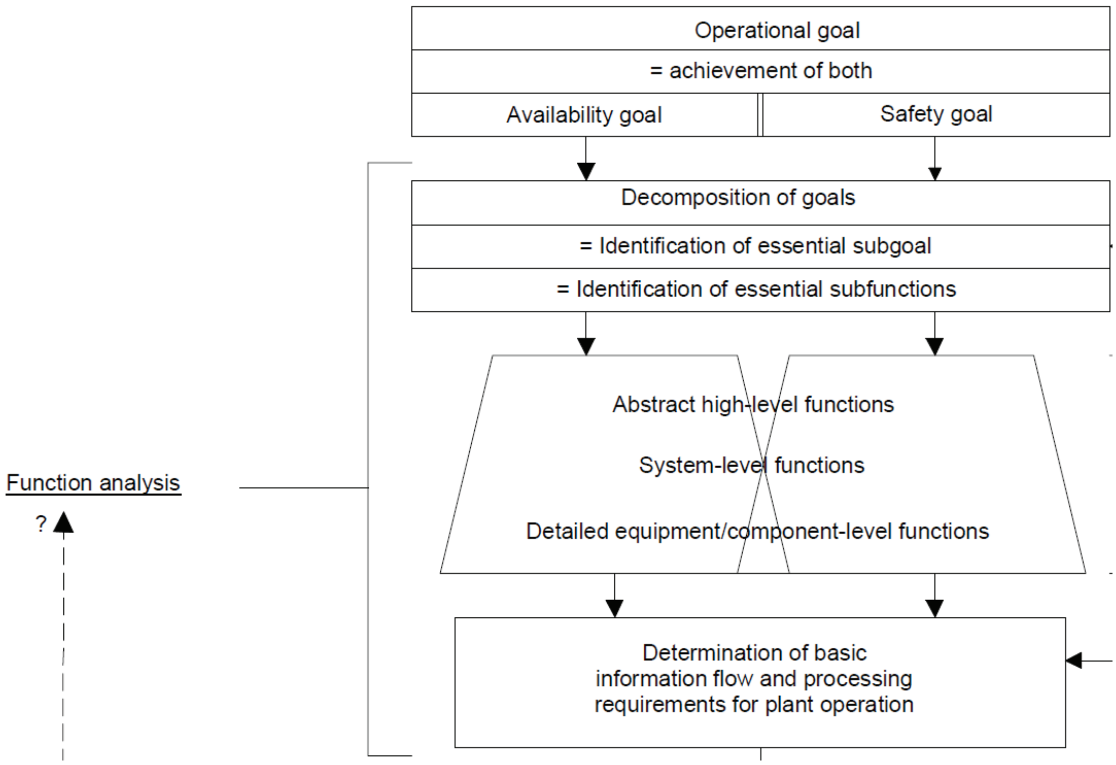

Figure 11 – Functional analysis of operational goals (IEC, 2000)

A functional analysis decomposes functions to a level of detail which meets the objectives of the study. In cases where the purpose is to generate human-centred designs the decomposition is typically stopped at the level where operator actions required to achieve functional goals can be described (e.g. human-automation interaction). This forms the bottom level of the function hierarchy and is commonly referred to as *control functions* (IAEA, 1992; IEC, 2000; INL, 2013). Control functions are defined as *control actions* performed by humans or machines for the accomplishment of a functional goal including the associated information acquisition and processing (IEC, 2000).

Task is a term normally used to describe a set of (cognitive or physical) actions performed by humans to accomplish a functional goal (ibid.). It is worth mentioning that the review revealed a certain inconsistency in how the term task was defined and applied. Some of the documents appeared to compare task with function, for example when describing sub-divisions of operations (e.g. Rødseth et al., 2020; DNV GL, 2018a). The current report sides with the stance taken by most of the reviewed documents, including those published by IEC (2000), ISO (2000), NASA (1991), US Department of Defence (1999) and IAEA (1992). These promote that the term task is reserved for describing activities performed by humans, such as those parts of one or more control functions which has been allocated to the human operator.

Key take-away #4: Operational goals are decomposed into functional goals using functional analysis techniques.

Key take-away #5: There appears to be no definite way of dividing levels of functional goals according to the physical items they intend to represent.

Key take-away #6: The term control function is used to describe a function level where human-automation interactions can be described. This is normally the lowest level in a function hierarchy developed with the intention to support automation and human-centred design activities.

Key take-away #7: The term task is reserved for describing activities performed by humans, not systems. Humans perform tasks. Systems perform functions. A human task can be to support or supervise a function performed by a system.

Allocation of (control) functions

Most of the documents included in the review is either partly or fully concerned with the topic of function allocation. Notably, however, very few of them apply the levels of automation (LoA) concept as part of this process. The reference to LoA models was by far most dominant in the maritime publications, including the report from AUTOSHIP (Rødseth et al., 2020) and the class society guidelines. Instead of categorizing automation in terms of levels, the publications tend to provide requirements and guidance on *how* to automate. The distribution or sharing of responsibilities to execute control functions is typically decided by taking the capabilities and limitations of both humans and systems into account. This process is often supported by tools and techniques such as Fitts' list, MABA-MABA lists, as well as relative comparisons of task requirements (e.g. workload) against which potentials for automation are considered feasible within the constraints of cost and other resources.

Key take-away #8: The use of LoA models is not predominant among several well-established industry standards and guidelines.

Risk assessments

Civil aviation also uses 'function trees' (Figure 12) and lists to determine the scope of risk assessments at various stages in the design process (e.g. Kritzinger, 2016). In the early design stages, (high level) aircraft level function trees are developed to identify functions to be included in a functional hazard analysis (FHA). This is a type of detailed preliminary hazard analysis which is used to determine which functions require more in-depth analysis during detailed design. Functions which, in case of failures, has a critical effect on the aircraft's performance and safety are screened out and included as part the scope for failure mode effects and criticality analysis (FMECA) and fault tree analysis (FTA).

The benefit of using functions as study nodes and guidewords for hazard identification sessions was also mentioned in the AUTOSHIP report (Rødseth et al., 2020).

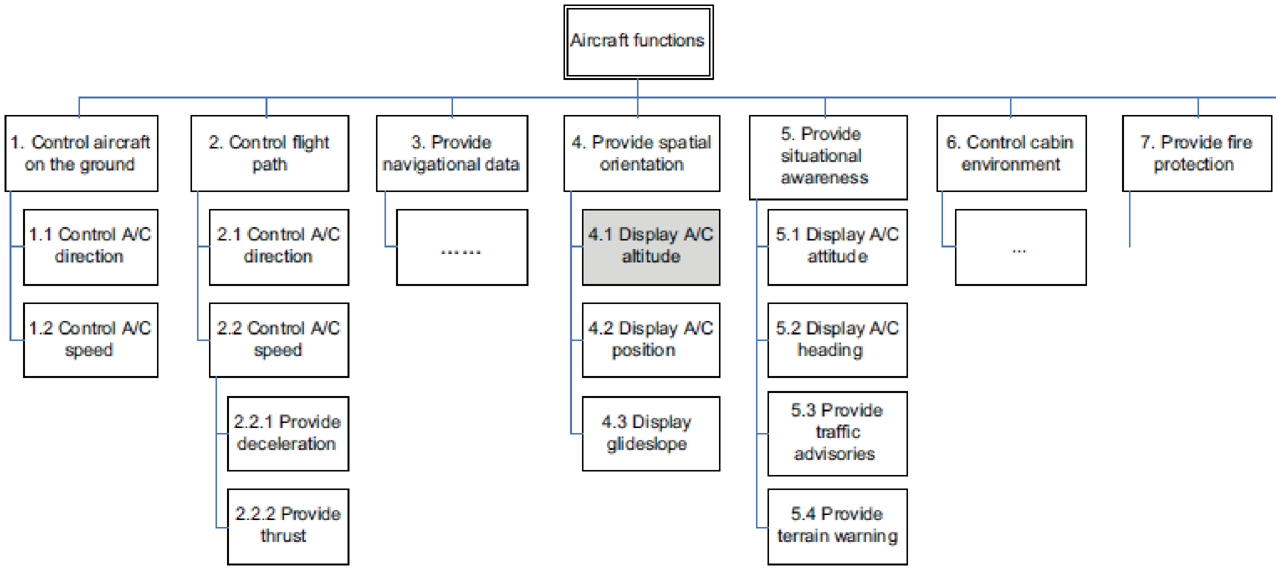

Figure 12 – Function tree for commercial aircrafts (Kritzinger, 2016)

2.3 Proposed structure for 'multi-level function maps'

Based on this report's review of industry standards and guidelines, the current sub-chapter propose a *hierarchical goal structure* for the 'multi-level function maps' requested by EMSA.

Figure 13 illustrates the hierarchy in its entirety. As can be seen, it consists of three main parts:

- The upper part describes the structure of what goes under the working title *mission model*. This is formed by breaking down the mission's operational goals into a set of mission phases, operations and sub-operations. For RBAT, the mission model defines the *context* for which different variations of automation shall be considered, per function.
- A function tree makes up the middle part. It includes a map of the functional goals required to successfully carry out the various operations. Functional goals are made up of functions and sub-functions, forming what is commonly referred to as a function tree. There is no clear rule about how many levels the function tree should consist of – this is a result of how the functions are hierarchically arranged, and the varying degree of complexity among different functions.
- The bottom part is referred to as *human-automation interaction* level and is where functions are allocated to humans, systems or a combination of both. Which functions these are is determined by a "stopping rule". For RBAT, this is the level where human actions required to achieve functional goals can be observed and described.

A more detailed description of what defines each part in the model is provided in the following sub-chapters below.

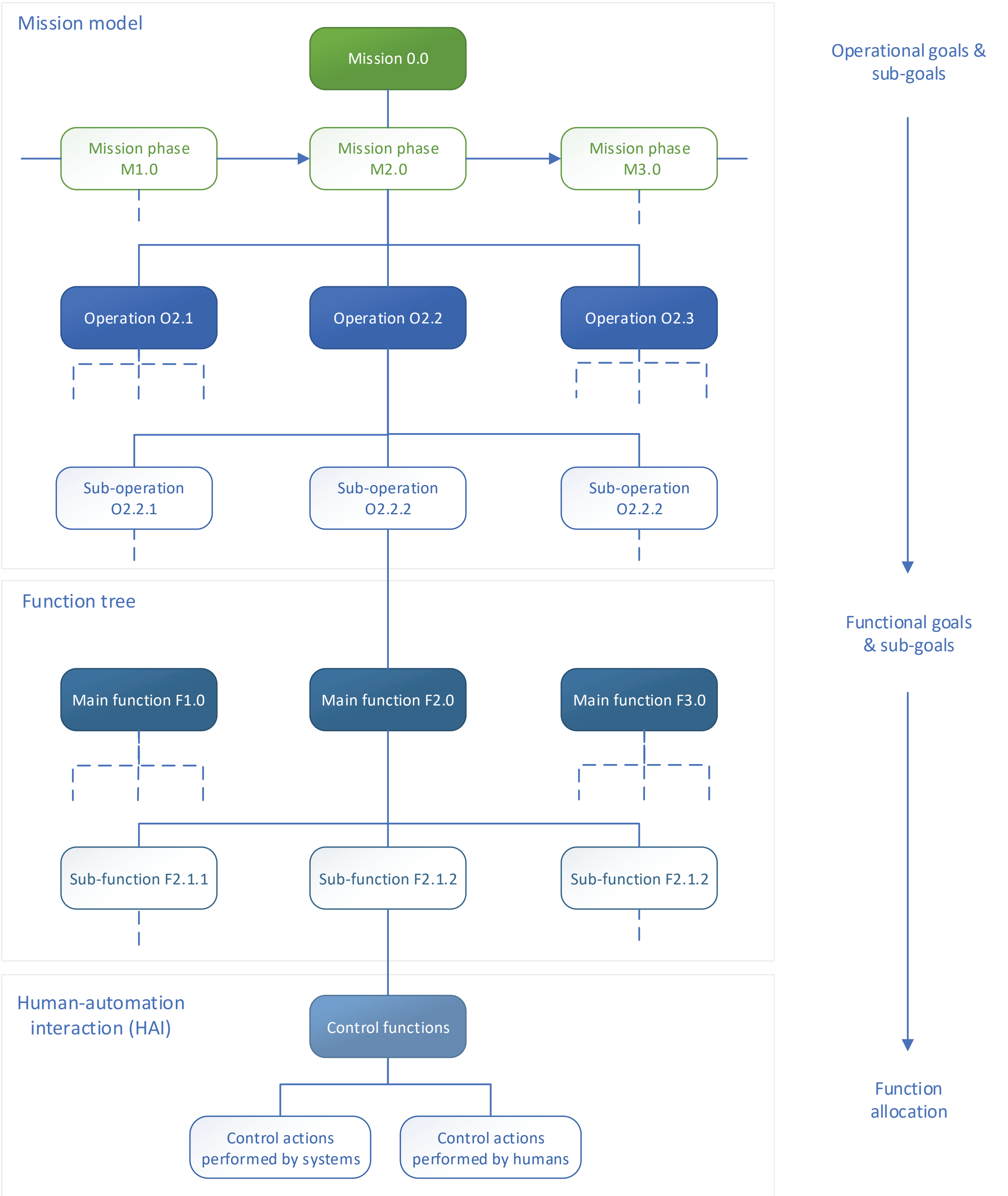

Figure 13 – Proposed structure for the RBAT multi-level function map

2.3.1 Mission model: Breakdown of operational goals

The term *mission* is used to describe a vessel's operational goal at the highest level of abstraction. For example, the mission (i.e. goal) of a container ship is to safely and efficiently transport containers from one location to another. Similarly, a car ferry's mission consists of safely transporting cars and passengers from one dock to another, in a timely manner according to schedule.

A mission is completed by successfully carrying out a sequence or set of *mission phases*. These represent the next level of operational goals and are typically characterized by a recognizable shift in where the vessel is located and what it is doing (i.e. operations). Port activities and transit (to location) are examples of two different mission phases.

A mission phase is accomplished by performing one or several *operations*. 'Cargo operations' is an operation associated with the mission phase 'port activities', while 'harbour manoeuvring' is an operation carried out as part of the mission phases 'port arrival' and 'port departure'.

In some cases, it may be useful to further decompose operations into a set of lower level *sub-operations*. This need can arise when having to explain how more complex and comprehensive operations are intended to be carried out. However, when broken down into smaller sub-units, operations will soon start to resemble functions.

2.3.2 Function tree: Breakdown of functional goals

As indicated above, operations (or sub-operations) are performed by use of one or more *functions*. Functions can, similarly to operations, be further decomposed into sets of lower level *sub-functions*. 'Cargo handling' is an example of a function, which has 'cargo loading' as one (of several) sub-functions.

Logically, when building the function tree, lower level functions are identified by asking "how" the higher-level functions are performed. Oppositely, justification for the identified lower level functions can be found by asking "why" they are required. When it comes to abstraction levels, functions identified at the highest levels are here referred to as 'main-functions', while the term 'sub-function' is used generally to describe the offspring of a (any) higher-level parent function.

Operations and higher-level (main) functions may in some cases bear close resemblance, somewhat depending on how they are phrased. In principle, a distinction can be made by how a top-level function can include one or several sub-functions which are required to achieve several different operational goals. For example, the function 'maintain stability' can be required for several different operations, such as cargo handling and damage control in case of flooding.

2.3.3 Human-automation interaction: Allocation of functions

Because there are significant variations in both the size and complexity of technical systems, there is however no fixed rule for what defines the various sub-function levels (e.g. a system- or component level). Instead, this is guided by what is referred as a "stopping rule" which is commonly made to help ensure that the function decomposition is done in a manner which aids the analysis' scope and objective. The ship's top-level functions can, in principle, be broken down from high abstract-level functions and all the way down to a component level. For the purpose of RBAT, the initial breakdown of functions will stop at the level where the *control actions* required to perform *control functions* can be described. This part of the hierarchy where functions are allocated to humans, systems, or both, and is referred to as the *human-automation interaction* (HAI) level.

As stated in EMSAs tender specification, the focus shall be on identifying (sub-)functions in which humans have a role in normal operations. RBAT is developed to enable risk informed decisions about how to safely implement automation design, at a conceptual design stage. If functions are decomposed to a too detailed level, they may start to resemble actual designs and be difficult to keep generic.

Although not reflected in Figure 13, yet worth explaining, is how the term *task* reflects a piece of work (i.e. set of actions) that an operator, or team of operators, is performs in order to achieve an [operational] goal. This may involve performing actions associated with several different functions, but which share the same overall purpose within a given context.

Table 2 – Description of abstraction levels in the RBAT multi-level function map

Term	*Description of abstraction level*	*Example*
Mission (goal)	A set of mission phases, operations and functions performed to achieve the intended purpose of why the vessel is designed and operated.	Safe and efficient transport of cargo from one port to another.
Mission phase	A subdivision of the mission typically characterized by a recognizable shift in where the vessel is located in terms of geographical surroundings, or the start and end of one or more operations.	Arrival to port.
Operations (and sub-operations)	Activities performed as part of a mission phase in order to achieve the mission goal. Sub-operations are offspring (sub-goals) of higher level, parent operations.	Perform docking.
Functions	How systems perform to successfully accomplish operations. Sub-functions are offspring (sug-goals) of higher-level, parent function.	Perform manoeuvring.
Task	A set of actions taken by humans to enable functions and perform operations. A task may involve interactions with several different functions. Task goals are similar to operations.	Monitor ship traffic during harbour manoeuvring.

2.4 Methodology

A function analysis (IEC, 2000; ISO, 2000) was performed to generate the RBAT multi-level function map according to the hierarchical goal structure outlined in 2.3. The process was iterative and incorporated input from several sources of information, including;

- the SAFEMASS study (DNV GL, 2019a; DNV GL, 2019b),
- the ROMAS project (DNV GL, 2018b),
- class society guidelines (misc.),
- the AURA project (Rødseth et al., 2020),
- various ConOps reports (undisclosed).

The products were also reviewed and updated by DNV GLs in-house experts on autoremote and autonomous vessel technology.

2.5 Results

The following sections presents the output from the functional analysis; 1) the mission model consisting of generic mission phases and operations, and 2) a function tree consisting of a set of top-level functions decomposed into layers of sub-functions.

To accommodate the intended purpose of RBAT, both the mission model and function tree were made as generic as possible, to accommodate application of the tool for a wide variety of operational concepts and vessel types. The deliverables therefore consist of compiled and condensed descriptions based on relevant input from all the different sources.

The sub-chapter also includes a section which explains the interface between the mission model and function tree; i.e. how they should be combined when put into practical use.

2.5.1 Mission model

The review of reports which included various breakdowns of missions and voyages into operations showed that, at the mission phase level, most of the descriptions were similar or nearly identical. The exemption was limited to a slightly different choice of wording in some cases. Each mission phase was broken down into a set of operations, as seen in the list below. At the operations level there were more variations between the descriptions presented in available sources. Efforts were made to develop a compilation of generic descriptions.

Arrival in port

- Perform port/harbor maneuvering
- Perform docking/berthing

Activities in port

- Perform loading/unloading operations, incl. passengers & crew
- Replenish consumables
- Port stay, incl. shutdown
- Prepare vessel for voyage, incl. start-up
- Lay-up vessel, incl. cold and hot lay-up/ idle ship

Depart from port

- Perform undocking/un-berthing
- Perform port/harbour manoeuvring

Transit to location

- Navigate along coast
- Navigate on open ocean/deep sea
- Navigate on inland waterways, incl. channels, river, sluices

Inspection, maintenance & repair (at sea, port, quay, yard)

- Perform planned maintenance
- Perform corrective maintenance (repairs)
- Perform/support inspections

Emergency responses to;

- Mitigate fire/explosion
- Respond to loss of stability/flooding
- Limit emission/spills to environment
- Handle sabotage/piracy
- Respond to cyber attack
- Assist vessel in distress
- Rescue man overboard
- Perform damage control in case of;
    - Collision
    - Allison
    - Grounding
    - Contacts
    - Structural failure
- Handle blackout/loss of main power
- Emergency towing of own vessel
- Handle loss of communication link
- Perform evacuation (by sea, air, gangway)
- Maintain ship safety in extreme weather
- Emergency repair @ sea

The complete mission model can be found in Appendix A.

It was decided to adopt parts of the operational model from AUTOSHIP (Rødseth, et al. 2020) due to its relevance and simplicity (see Figure 8), but with some adjustments. The model also includes “Hinterland activities” and “Planning of mission” as phases occurring prior to “Arrival in port”. Because the focus of RBAT is on more on automation systems and human-automation interaction, and less on higher level processes such as logistics and other administrative tasks, these phases have so far been considered as out of scope for RBAT.

As indicated with a “gap” in the AUTOSHIP model, *maintenance and repair* is not necessarily a sequential phase of the mission. While it could be expected that most such activities is likely to take place while the vessel is located at port (at least for unmanned vessels), increased automation and digital solutions may also allow for certain functions to be performed during and as part of the other operational phases. As such, being in a maintenance and repair mode was extracted as a separate mission phase, or mode, as is also indicated by the AURA model. “Inspection” was also added to the description to facilitate inclusion and consideration of functions such as those related to remote Class surveys.

It was also decided to include *emergency response* as a separate, albeit undesired, mission phase. The rationale is, for practical purposes, that RBAT should include an evaluation of how automation is designed to handle abnormalities and accident scenarios. As such, successful responses to accidents are to be considered operational goals.

2.5.2 Function tree

A function tree was developed, consisting of main- and sub-functions required to achieve the various mission phases’ operational goals. As explained in sub-chapter 2.3, the functions were organized to form a hierarchical goal-tree structure, where each higher-level function represents the goal and purpose each of the lower-level functions.

The top-level functions comprised of:

- Handle and monitor cargo
- Manage payload
- Perform bunkering
- Re-stock vessel supplies
- Embark/disembark crew & passengers
- Manage security
- Observe weather conditions
- Perform navigation
- Perform manoeuvring
- Maintain communication
- Perform anchoring
- Perform mooring
- Ensure watertight integrity
- Perform ballasting (trim & stability)
- Manage bilge and drainage
- Provide power management
- Perform auxiliary/other functions
- Integrated monitoring & control
- Engage in towing of own vessel
- Provide means for evacuation
- Provide means for search and rescue
- Respond to medical incidents
- Provide fire protection
- Control environmental hazards
- Provide accommodation services
- Perform administrative functions

The complete function tree can be found in Appendix B.

2.5.3 Interface between the mission model and function map

While the mission model and function tree are reported as two separate deliverables, they could in principle be combined into one. This is possible by creating one complete hierarchy which includes a decomposition of all goals, starting from the highest-level operational goals and all the way down to the lowest level sub-functions and control actions. Such an approach was also tested as part of the functional analysis used to develop the function tree. The disadvantage is that it results in excessively large and complex function trees, with a lot of the same functions and sub-functions being repeated across the different operations. This is a result of how bottom level functions in the hierarchy have a role in achieving several different goals in the levels higher up.

The RBAT multi-level function map is intended to provide a structure for systematic evaluation of how functions are automated. Rather than creating complex models attempting to illustrate all casual relationships, is here argued that this purpose is best served through models which are well arranged and easy-to-understand. This is one of the reasons behind the choice of dividing the multi-level function map into three main parts (i.e. mission model, function tree and HAI). Instead it is suggested that the complexities can be captured and dealt with through how the interface between the two models is managed as part of using the tool. With the support from software functionalities, this can potentially be designed in a way which prevents use of RBAT to become overly complicated.

The simplest way of illustrating the relationship between a vessel's operational and functional goals is by an operation/function-matrix, as exemplified[2] in Table 3. The table shows which top-level functions are required for each of the operations, as indicated with "X". Because the table includes the function tree's highest-level goals, the table does not indicate whether one, a few or all of the sub-functions are required. However, an expanded version of the table, including all the sub-functions, could in principle capture all operation-function relationships. This could be a feature of the RBAT software and would provide the user with valuable insights and overview of how automation has been solved for various purposes. Such a feature assumes that the operations and functions are provided with a set of unique IDs, accompanied with the necessary functionality for allowing drill-down, selection and filtering of items.

[2] The table is incomplete and only includes a sample of the identified operations and functions.

Table 3 – Operations and functions matrix

		Top-level functions								
Mission phases	Operations	Perform cargo handling	Manage payload	Perform bunkering	Re-stock vessel supplies	Perform ballasting	Ensure watertight integrity	Embark/disembark vessel	Manage security	…
Arrival in port	Perform port/harbour manoeuvring					X	X		X	…
	Perform docking/berthing					X	X		X	…
Activities in port	Perform cargo operations	X	X			X	X		X	…
	Manage passengers					X	X	X	X	…
	Replenish consumables			X			X		X	…
	Prepare ship for voyage		X				X		X	…
	Port stay						X	X	X	…
	Lay-up vessel						X		X	…
Depart from port	Perform undocking/un-berthing					X	X		X	…
	Perform port/harbour manoeuvring					X	X		X	…
Transit to location	Navigate along coast					X	X		X	…
	Navigate on open ocean/deep sea					X	X		X	…
	Navigate on inland waterways					X	X		X	…
…	…	…	…	…	…	…	…	…	…	…

A second way of illustrating the interface between the mission model and function tree can be done through a complete breakdown[3] of a selected set of branches in the hierarchy:

Mission: Safe and timely transport of containers from port X to port Y

Mission phase: Port activities

Operations: Perform cargo operations

Functions and sub-functions:

- Perform cargo handling
    - Plan and prepare
    - Lift containers onboard
    - Lash containers
- Maintain trim and stability
    - Calculate and confirm trim and stability
    - Operate ballast pumps
- Maintain communication
    - Communication between RCC and crane operator
    - Communication between RCC and port officer

The breakdown illustrates how cargo operations is a common goal for three different top-level functions. It also shows that some of the functions and sub-functions can be specific to a mission phase and operation, while others can be relevant for several. For example, cargo handling is specific for when the vessel performing port activities, while functions like ballasting and communication is performed as part of a wide variety of operations.

2.6 Recommendations for further use

Below is a preliminary recommended approach for how a mission model and function tree can be put into practical use as part of the RBAT framework and structure. It is expected that the models presented in this report are generic enough to be implemented as a part of RBAT, for the purpose of providing guidance and standardisation. However, some adjustments and updates should be expected, especially for the most detailed parts. If a RBAT user's scope is limited to concern automation of a specific system intended for specific operations, only the relevant parts of the models are used.

Describing the vessel's operational goals (mission model)

A mission model can be developed through the following steps:

- First the overall purpose behind why the vessel is being designed and operated need to be defined. This refers to the commercial, political (e.g. defence) or public values and interests which have contributed to the development of the concept.

[3] Note that this is a simplified example

- The next step is to select the relevant mission phases. Any phases which have not been pre-defined as part of the generic model must be added. The division of each phase should be made according to recognizable transitions in geographical surroundings and locations.
- Identify relevant operations for each mission phase. Operations which can occur across the various geographical phases can be grouped under other dedicated mission phase headings, such as emergency responses to relevant accident scenarios, specific waterborne operations, and maintenance and repair.

Describe the vessel's functional goals (function tree)

After having a developed a representative mission model, the function tree can be used to describe the functional goals which must be achieved to successfully perform each of the operations:

- Start by identifying relevant high-level functions, and then drill down to select the relevant lower level sub-functions. Each operation is likely to include a mix of different functions, as explained in 2.5.3.
- As with the mission model; add any functions which are missing and update the descriptions to reflect the actual design of the vessel.
- Make sure to not only include the functions which exert control of the vessel's operational performance, but also include the required support and auxiliary functions.
- Arrange the list of sub-functions in an order which best describes the operation, e.g. in the sequence they are most likely to be performed.
- The process of describing functional goals is complete when the functions are described at a level of detail where considerations about how to allocate functions between humans and the system can be made. This is further described in Chapter 3.

2.7 Additional considerations and justifications

Hierarchical goal models, such as function trees, are powerful tools when it comes to identifying functions and understanding how they contribute to the overall objectives of the system. The downside with such models is that their hierarchical (instead of sequential) structure does not make them suitable for demonstrating causal relationships and dependencies between functions. This is also made complex by how function trees tend to contain a wide variety of different function types. This limitation of the method has certain implications for how it can be applied to other parts of the RBAT framework (e.g. risk analysis). A summary of the main aspects is therefore provided below. These are listed here primarily for the purpose of highlighting various considerations which should be brought forward as part of developing RBAT. It is expected that these issues can be resolved through the Use-of-Automation structure. This will become evident when the RBAT framework is tested and further developed using case studies in Part 2 of the project.

Communication

When considering communication functions, it is first necessary to determine who is communicating, what is being communicated, and for which purpose (i.e. operational goals). When this is known, the suitable means for communication can be identified, such as equipment for conveying audible messages (voice or sounds), but also via visual signalling (e.g. lights), and data transmission (text and imaging). Currently, most communication systems are used manually and provide both a flow of information necessary for performing analysis and making decisions, but also as for implementing actions intended to exert control. Examples include receiving a distress signal and notifying a vessel to give way to avoid collision. The implication is that communication, when identified as a standalone function, has an interface with many other functions which, in turn, is required for achieving several different operational goals. This interface is traditionally mediated by human operators.

Propulsion & steering

While propulsion and steering represent key functions in a *mechanical* sense, their role is to implement actions based on various input variables provided from other functions, such as navigational decisions. In that sense, propulsion and steering could be argued not to represent what is here defined as "top-level functions". Instead, when modelled hierarchically, it could be regarded as a navigational sub-function which performance depends on input from other sub-functions, such as object detection or weather monitoring. Nevertheless, the current function map includes propulsion and steering functions as part of the functional goal of manoeuvring.

Integrated monitoring and control

Integrated monitoring and control of vessels/RCC systems was in several of the reviewed reports described as what can be considered a separate top-level function. Physically, integrated monitoring and control is performed by equipment such as ICT and control system, instrumentation, and operator workstations. As indicated by the term *integrated*, the function of these systems is to monitor and control the condition of other system functions. When considering operational goals as being performed by a set of sub-functions, monitoring and control are not identified as separate functions, but instead as inherent and enabling properties (e.g. the opportunity to control thrust, or to monitor electricity consumption). In principle it should therefore not be necessary to identify monitoring and control as separate functions. However, because the loss of such functions can be critical, for example in case of an RCC power outage, it has been decided to identify it as a separate top-level function.

Auxiliary functions

As with integrated monitoring and control, auxiliary functions could be argued not to represent a top-level function in an isolated sense. Instead they are functions which are required for several other control functions to work. As such they should, in principle, be grouped under the various functional goals for which they are relevant, like propulsion systems requiring lubrication. However, in case of auxiliary functions failing, their importance and criticality become clearer. The main auxiliary functions are therefore grouped under a common functional goal.

Inspection, maintenance & repair

Inspection, maintenance and repair is to a large extent carried out as manual tasks, characterized by moving and replacing parts, trouble shooting, fitting etc. This, plus the fact that some of the activities are irregular and difficult to predict, disqualifies such 'functions' as prime candidates for automation. Nevertheless, they are impacted indirectly by introduction of increased automation, particularly if the effects from such solutions are periods with lower or no manning. Such implications may introduce the need for increased redundancies and reliability, enhanced systems monitoring, and alternative ways of planning maintenance. It was therefore chosen to include inspection, maintenance and repair as a separate top-level function.

3 USE OF AUTOMATION FRAMEWORK

3.1 Purpose

To perform a risk assessment that is consistent and fit-for-purpose by all users, it is necessary to describe the use of automation (UoA) in future systems. The word *use* refers to how automation is solved and implemented for each affected function, during various operations, including abnormal situations and emergencies, by use of available technologies and human involvement. Function allocation is a significant part of the use of automation. However, to underline a broader approach than the function allocation itself, the term use of automation is used, and this includes:

a. Functions to be automated.

b. Full/partial use of automation in sub-functions such as detection, analysis, planning and implementation of control actions.

c. The human involvement in functions where automation is introduced

d. The manning level in functions where automation is introduced

e. The operator location for functions where automation is introduced

Class societies are important stakeholders for safe autonomous operations. Sub-chapter 2.2 presented a review of the class societies guidelines for autonomous vessels with the purpose of establishing a method for how to create multi-level function maps. Sub-chapter 3.2 extends this review to also consider how use of automation topics have been addressed.

Sub-chapter 3.3 presents an approach for the use of Automation. Initially by discussing the terms of automation and autonomy and the main elements to be discuss use of automation, and finally a suggested approach for a Use of Automation framework is presented.

3.2 Review of use of automation in class guidelines

An extensive amount of literature exists on allocation of functions between automation and operators. The topic has been relevant for decades and the accelerating technology development makes it constantly more relevant. The literature review in this report focuses on the class societies' approach to function allocation.

3.2.1 DNV GL

Table 4 from DNV GLs Class Guideline (2018a) proposes how autonomy can be described in terms of five incremental levels (i.e. degrees). As can be read, the levels are intended to provide description of autonomy levels on a *function* level, as opposed to a ship, or system level. The definitions mostly concern decision-making and control/operation of functions and is stated to be inspired by LoA models adopted by the automotive industry.

Table 4 – DNV GLs definition of autonomy levels (DNV GL, 2018a)

Autonomy level	*Description of autonomy level*
M	Manually operated function.
DS	System decision supported function.
DSE	System decision supported function with conditional system execution capabilities (human in the loop required acknowledgement by human before execution).
SC	Self-controlled function (the system will execute the operation, but the human is able to override the action. Sometimes referred to as ‘human in the loop’).
A	Autonomous function (the system will execute the function, normally without the possibility for a human to intervene on the functional level).

Furthermore, DNV GL argues that a (main-/ higher level) function can be covered by a varying degree of autonomy, and that to understand the autonomous solution it is necessary to consider how it should be solved for various (or subsets) of the function. For this purpose DNV GL propose that a function can be divided into four main parts:

- Detection: Acquisition of information that is relevant for control of a function. The information may be based on sensors and/or human perceptions.
- Analysis: Interpretation of the aquired information into a situational understanding relevant for control of the function.
- Planning: Determination of needed changes in control parameters in order to keep the function performance within applicable frames.
- Action: Effectuating the planned changes of control parameters, typically via actuators operated via a control system.

As stated in the guideline, dividing a function into the abovementioned elements can be applied to most control functions, but is particularly suitable for the navigation function as illustrated in Figure 14.

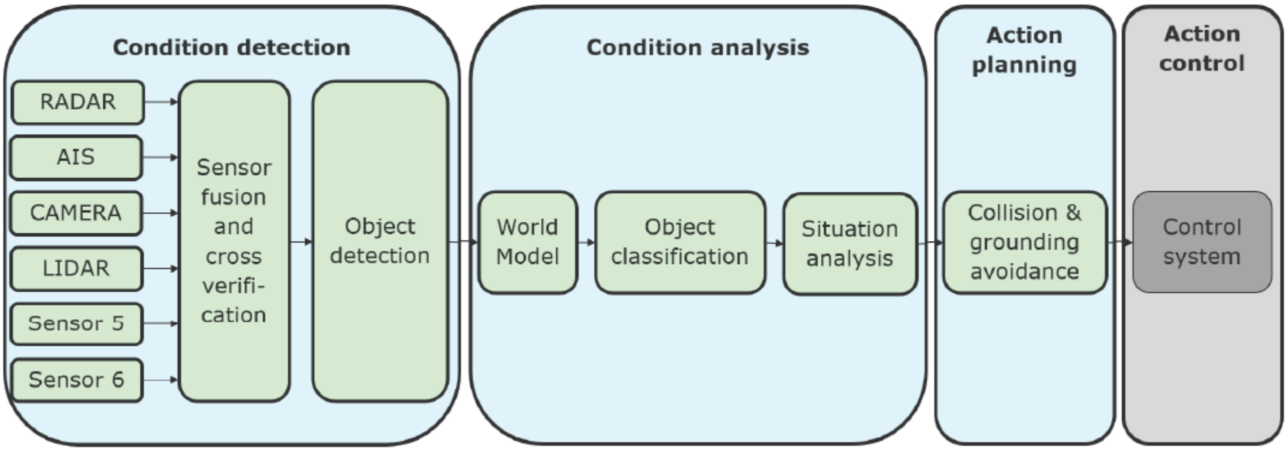

Figure 14 – Technology and software properties in control of the navigation function

The guideline also explains how the breakdown and division of functions can be used to clarify how the various parts (i.e. sub-functions) can be performed by the system, a human, or by both (ibid.). This is illustrated in Figure 15 and is commonly referred to as function allocation or assignment by other industry publications (IEC, 2000; ISO, 2000).

DNV GL also states that the combined human/machine capabilities for one element (e.g. condition detection) should be the same or better than the conventional capabilities (for a similar function). The principle is to achieve an equivalent or better level of safety.

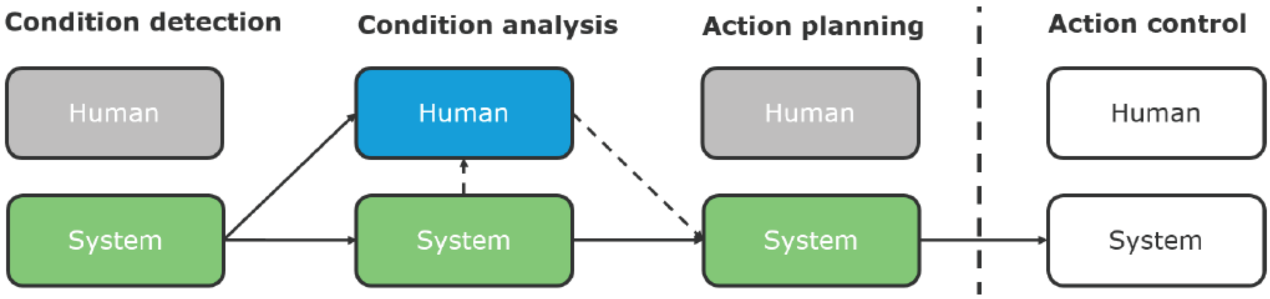

Figure 15 – Allocation of function between human and system (DNV GL, 2018a)

Although no clear definitions or taxonomies are offered, the guideline also encourage to define human operators(s) location; i.e. whether operator(s) are on board the vessel or located remotely.

3.2.2 Bureau Veritas

Bureau Veritas (BV) issued a Guidance Note in October 2019 titled *Guidelines for Autonomous Shipping* (BV, 2019). Despite using the term *autonomous* as part of the document title, BV states that the use of this term should be limited to the highest degree of automation, as defined by their taxonomy (see bullet-points below and Figure 16). For the lower degrees, the term *automation* should be used. However, the guidance note does not offer any definition of autonomy or automation. Instead a list of definitions and explanations of associated terms is provided (e.g. *automation system*). *Degrees of automation* is explained as the degree of decision making (authority) deferred from the human to the system.

It recommends defining the degrees of automation to make a distinction between the role of the human and the role of the system among the various functions of the system. Similar to

DNV GL, BV suggest considering functions based on a four-stage model of human information processing which can be consider equivalent to a system function:

a) Information acquisition

b) Information analysis

c) Decision and action selection

d) Action implementation

While no specific definition is given for what constitutes each 'stage', it is mentioned that the four functions (i.e. stage) can provide an initial categorization for types of tasks in which automation can support the human. It is however stated that:

- a degree of automation Ax (x from 0 to 4) should be defined for each automation system[4], and that;
- several different degrees of automation could be considered for the duration of a single voyage.

For determining *degrees of automation*, BV offers a LoA model consisting of five levels, ranging from A0 to A4:

- Degree A0 – Human operated:
  - The system or ship can perform information acquisition, but cannot analyse information, take decisions and execute operations on behalf of human.
  - Human makes all decisions and controls all functions.
  - Human is located aboard (crew).
- Degree A1 – Human directed
  - The system or ship can perform information acquisition, information analysis and suggest actions but cannot take decisions and execute operations on behalf of human.
  - Human makes decisions and actions.
  - Human can be located aboard (crew) or remotely outside the ship in a remote control centre (operators).
- Degree A2 – Human delegated:
  - The system or ship can perform information acquisition, information analysis, take decisions and initiate actions, but requests human confirmation. System invokes functions waiting for human confirmation.
  - Human can reject decisions.
  - Human can be located aboard (crew) or remotely outside the ship in a remote control centre (operators).

[4] system based on one or more devices whose implementation can be adjusted in advance, including, where appropriate, devices whose behaviour depends on unforeseeable factors. An automation system can be composed of various types of devices: mechanical, electrical, digital, electronic, magnetic, hydraulic or other. An automation system may be used, for example, for control, protection, lookout, recording or monitoring functions (BV, 2019).

- Degree A3 – Human supervised:
  - The system or ship can perform information acquisition, information analysis, take decisions and execute operations under human supervision. System invokes functions without expecting human confirmation.
  - Human is always informed of the decisions and actions, and can always take control.
  - Human can be located aboard (crew) or remotely outside the ship in a remote control centre (operators).
- Degree A4 – Full automation
  - Self-operating system or ship at defined conditions and in specific circumstances.
  - The system or ship can perform information acquisition & analysis, take decisions and executes operations without the need of human intervention or supervision. System invokes functions without informing the human, except in case of emergency.
  - Human can always take control.
  - The supervision can be done aboard (crew) or remotely, outside the ship from a remote control centre (operators).

BV provides an extended definition of the various degrees of automation by describing whether each part of the four stage "human information processing" model is allocated to a human, the system, or a combination of both. This is illustrated in Figure 16 which is the image of a table snagged from BV's guidance note. The table also includes (vessel) manning as part of the definition for each level, which basically states that vessels with no or limited automation (level A0) will always be manned, while for all the higher levels of automation can include both manned and unmanned concepts.

Degree of automation		Manned	Definition	Information Acquisition	Information Analysis	Authority to make decisions	Action initiated by
A0	Human operated	Yes	Automated or manual operations are under human control. Human makes all decisions and controls all functions.	System Human	Human	Human	Human
A1	Human directed	Yes/No	Decision support: system suggests actions. Human makes decisions and actions.	System	System Human	Human	Human
A2	Human delegated	Yes/No	System invokes functions. Human must confirm decisions. Human can reject decisions.	System	System	Human	System
A3	Human supervised	Yes/No	System invokes functions without waiting for human reaction. System is not expecting confirmation. Human is always informed of the decisions and actions.	System	System	System	System
A4	Full automation	Yes/No	System invokes functions without informing the human, except in case of emergency. System is not expecting confirmation. Human is informed only in case of emergency	System	System	System	System

Figure 16 – BV's 'degrees of automation

In addition to defining degrees of automation, BV includes a taxonomy for what they refer to as *degree of control*. Degree of control is split into two distinct categories; direct (on board) and remote control. Each category consists of four levels; DC0-DC3 for direct control and RC0-RC3 for remote control. The levels are defined by the (human) presence of crew or operators, e.g. whether they perform active monitoring, are available to respond on alarms, and so forth. The degrees of control are described in Figure 17, also extracted from BVs guidance note.

Degree of control			Human presence	Location of control station
Direct control	DC0	No direct control	No crew available to monitor and control the system, nor to take control in case of warning or alert.	(1)
	DC1	Available direct control	Crew available aboard, ready to take control in case of warning or alert But they may be not at the control station	Aboard
	DC2	Discontinuous direct control	Monitoring and control may be discontinuous during a short period Crew always available at the control station, ready to take control	Aboard
	DC3	Full direct control	System is actively monitored and controlled at any time	Aboard
Remote control	RC0	No remote control	No operator available to monitor and control remotely the system, nor to take control in case of warning or alert.	(1)
	RC1	Available remote control	Operators available in the RCC, ready to take control in case of warning or alert But they may be not at the remote control station	RCC
	RC2	Discontinuous remote control	Remote monitoring and control may be discontinuous during a short period Operators always available at the remote control station, ready to take control	RCC
	RC3	Full remote control	System is actively monitored and controlled remotely at any time	RCC
(1) See also [2.8.3]: there may not be any integrated control station				

Figure 17 – BV's 'degree of control' taxonomy

BV states that the degrees of automation and degrees of control taxonomies should be used to characterize "…any system…" and "…any ship covered by the present Guidance Note.". Furthermore, it is also stated that the specifications of all automation systems (i.e. documents to be submitted) should clearly specify for each *function* the distribution of roles and responsibilities between the human and the system. A reference is made to the previously mentioned "four-stage model of human information processing" which indicates that BV encourages function allocation to be described at a sub-function level (i.e. information acquisition, information analysis etc.).

The guidance note also states that the following distributions of roles and responsibilities should be clearly defined and described in the operational limitations:

- aboard, between automation systems and the crew
- at the remote-control centre, between automation systems and remote operators
- between the crew and remote operators.

3.2.3 Lloyds Register

Lloyds Register (LR) issued their Code for Unmanned Marine Systems in February 2017. They define Autonomy Levels from AL0 to AL6. These levels describe the location of the operator, the human/technology involvement by performing, presenting decision-support, supervision (including various degrees of supervision) and the opportunity to intercede and over-ride.

The code describes that a system can consist of systems with lower AL level, and complex systems can be a combination of many systems with different AL levels.

AL 0) Manual – no autonomous function.
All action and decision making is performed manually – i.e. a human controls all actions at the ship level. **Note:** systems on board may have a level of autonomy, with 'human in/on the loop'; for example, pms and engine control. Straight readouts, for example, gauge readings, wind direction and sea current, are not considered to be decision support.

AL 1) On-ship decision support
All actions at the ship level are taken by a human operator, but a decision support tool can present options or otherwise influence the actions chosen, for example DP Capability plots and route planning.

AL 2) On and off-ship decision support
All actions at the ship level taken by human operator on board the vessel, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or off the ship, for example DP capability plots, OEM configuration recommendations, weather routing.

AL 3) 'Active' human in the loop
Decisions and actions at the ship level are performed autonomously with human supervision. High-impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them. Data may be provided by systems on or off the ship.

AL 4) Human on the loop – operator/supervisory
Decisions and actions are performed autonomously with human supervision. High impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them.

AL 5) Fully autonomous
Unsupervised or rarely supervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.

AL 6) Fully autonomous
Unsupervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.

Figure 18 – Lloyds Register's Autonomy Levels

LR presents a goal-based structure with a hierarchy of tiers with lower levels with increasing details. The structure allows for identifying goals, functional objectives, performance requirements and solutions for a concept.

3.2.4 ClassNK

ClassNK issued their Guidelines for Automated/Autonomous Operation on ships in 2020 (ClassNK, 2020). This guideline aims to support the design and development of technology to allow for reducing crew onboard to ultimately become unmanned or to automate functions to support onboard crew. The purpose of the guideline is to provide requirements and for verifying the functions in automated/autonomous operations. The guideline describes that tasks, and the sub-tasks that compose the tasks, need to be defined.

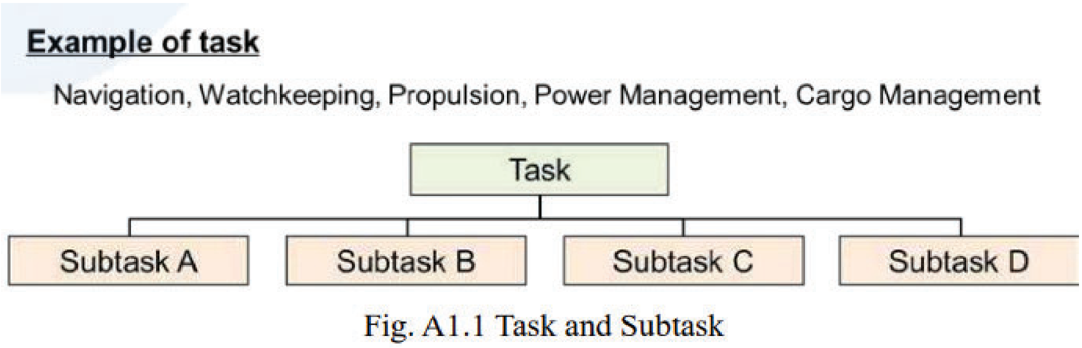

Figure 19 – ClassNKs visualisation of breakdown of tasks to sub-tasks

Further, the division of roles between humans and automated operation systems must be clarified and set up in a manner that will not affect safety. ClassNK defines the guideline to be relevant to automation of decision-making sub-tasks such as situation awareness-, decision-, and action-processes.

The guideline underlines that only parts of decision-making processes can be automated and remotely operated. In such occasions, the guideline describes that tasks can be carried out by the joint effort of human and technical sub-system

3.2.5 Review summary

The review shows that the guidelines concern the distribution of function in various degree and with different definitions and explanations, when a distribution between humans and technology will take place, where the involved humans are located and how humans are involved.

Information processing

Most of the guidelines refer to information processing stages to describe the automation process. DNV GL uses condition detection, condition analysis, action planning and action control. BV refers to information acquisition, information analysis, decision and action selection and action implementation. ClassNK uses situation awareness, decision-making and action. The use of the information processing stages indicates that there is different implication of automation in the various stages.

Key take-away #9: The information processing stages are useful to provide a context to the function allocation process.

Human involvement

Describing where and how humans are involved, the guidelines concur on describing human and system involvement at a function level but have some differences on how to describe the involvement. In addition to distribute functions to either humans or technology, variables such as involvement in the different information processing stages (e.g. decision support), location (remote or local) and involvement degree (perform, direct, delegate, supervise) fulfil the function allocation.

Key take-away #10: The function allocation process should provide additional details than distribution between humans and technology. The process should detail the human involvement and the human location.

Joint human-technology performance

Several of the guidelines discusses a joint performance between humans and technology to reach functional goals. DNV GL describes a combined human/machine capability, BV and LR discuss the human and system cooperation in various degrees and ClassNK describes how tasks can be carried out by humans and systems in a joint effort.

Key take-away # 11: The function allocation process should provide details about human involvement and the human location rather than simply distributing function between humans and technology.

3.3 Use of Automation

Academia, the transport industry in general, and specifically the maritime industry, have all made an extensive effort to facilitate the successful use of automation in maritime transport. The review in sub-chapter 2.2 and 3.2 shows that the class societies have started to develop guidelines for a sustainable development of automated and autonomous solutions. When this report develops a framework to describe the use of automation, it is not the intention to create something new or completely different than the on-going work in the maritime industry. The use of automation described in the following chapter will apply and operationalize the principles in the guidelines. The chapter will initially discuss the relationship and differences between automation and autonomy, and subsequently, present the main principles of an information processing model and method for function allocation.

3.3.1 Automation and autonomy

The terms automation and autonomy are currently used interchangeably, and it is challenging to create a distinct difference between the two terms. Automation is defined by Parasuraman and Riley (1997, p. 231) as *"the execution by a machine agent (usually a computer) of a function that was previously carried out by a human"*. The present focus on autonomy has many of the same properties – it is still about using technology in more and different ways than before. This makes it difficult to diverge between automation and autonomy, and to a certain extent it is not necessary to draw a hard line between what is automation and what is autonomy. Both share the same property of more use of technology with the purpose of transferring functions from humans to technology. Krogmann (1999) describes the difference as automation being to employ logic-based programming, where autonomy leverages computational *intelligence* to adapt to unanticipated and changing situations. As such, the difference between automation and autonomy is the capabilities of the technology, and consequently, the way technology is applied in systems.

Future MASS-concepts will use technology more and in different roles. However, to categorize this use of technology as either automation or autonomy is challenging. In this report, the emphasis is on clarifying the roles of both technology and humans in future systems. The term autonomy can be understood as "technology operates alone", and to avoid this misunderstanding, the report uses the term automation broadly about the incremental use of technology for performing functions. However, this is not to reject that future technological capabilities will be different than the present but to put emphasis on the joint human and technological performance.

Levels of automation/autonomy (LoA)

Levels or degrees of automation or autonomy (LoA) are used to describe the use of technology in a system. The levels usually span from no involvement of technology at the lowest level, to technology being responsible and executes all actions in the highest level. The use of LoA has been criticized for not considering the complexity of operating environments, and this leads to imprecise and unreliable predictions, and becoming difficult to apply in practice (Jamieson and Skraaning, 2017). On the other hand, the use of LoA is argued to serve a practical purpose for communicating the range of automation-choices to stakeholders, to understand how various LoAs affect human performance and situational awareness, and for guiding design of systems (Endsley, 2017). Both defenders of and skeptics to the LoA-concept agree that there is a need for converting it into models with a higher degree of practical value (Kaber 2017; Jamieson and Skraaning, 2017; Wickens, 2017).

In this report, the use of automation framework intends to operationalize the LoA-term. To avoid an oversimplification by using LoA in isolation, the framework will allow the involvement of technology and humans in specific functions to be described. Consequently, the report does not explicitly adopt the LoA concept, instead it draws on several of principles found in the LoA literature for building the UoA framework.

3.3.2 Main elements in the Use of Automation framework

Chapter 2 describes the structure and methodology to identify the functions intended to automate. For these functions, the Use of Automation (UoA) framework will describe how the technology is used, the human involvement, the required manning level and location of operators.

3.3.2.1 Information processing model

The process of achieving a functional goal can be described in stages. The most used model is based on the human information processing stages: sensory processing, perception/working memory, decision making and response selection. These stages have equivalence to the system functions of information acquisition, information analysis, decision selection and action implementation (Parasuraman, Sheridan and Wickens, 2000). The objective of describing the function through these stages is to underline that a function consisting of four stages that can be carried out by humans, automation or by both.

The four-staged information processing model is widely accepted in the literature. And as the review of the class guidelines show, it has also recently been introduced to the maritime industry. With the intention to draw on previously established knowledge, and to meet EMSAs expectations outlined in the RBAT tender specification, a similar four stage model will be included as part the UoA-framework. However, there are several aspects that must be considered when applying the information model. One is that the stages are not independent; they are successive and depend on the previous one and sometimes rely on multiple iterations between the stages. Another important element is that automation in these four stages cannot simply supplant human activity but will change the human activity (Sheridan and Parasuraman, 2006).

Table 5 defines the four stages of information processing. These definitions are based on the original description by Parasuraman, Sheridan and Wickens (2000), but adapted after reviewing application of information stages in other industries and the specific class societies’ autonomy guidelines.

Table 5 – Definitions of information processing stages in the UoA

Information processing stages	*Definitions*
Stage 1: Information acquisition	Information acquisition is the process of sensing and registration of input data relevant to achieve the function goal. The process can involve both organization and prioritization of information
Stage 2: Information analysis	Information analysis is the process of interpreting information that is relevant for deciding which actions are necessary to achieve the function goal. The process can include one or more of the following analysis: threshold analysis, trending, prediction and/or integration of information. Threshold analysis is to assess information related to predefined values. Trending of information is to analyze historical information to determine a development. Predicting of information is to combine historical information with an anticipated development. Integration of information is to apply various information variables to a single value. In the process of achieving a function objective, it can be necessary to assess various goals, which potentially can be contradictory. The information analysis should provide a situation analysis for each of these various goals.
Stage 3: Decision-making	Decision making is the process of generating, comparing and selecting options for how to implement actions necessary to achieve the function goal. The generation of options is based on the information analysis and considers the trade-off between various goals, which can potentially be contradictory and conflicting.
Stage 4: Action implementation	The action implementation is the execution of the decided action(s).

3.3.2.2 Function Allocation

Function allocation is the distribution of functions between human and technology (ISO, 2000, IEC, 2000). The process of allocating functions to either humans or technology would be a simple task if humans and technology had the exact same characteristics and if the stages in the information processing model were distinct and independent. As discussed in the previous chapter, this is not the case. The function allocation process must consider several variables and Pritchett, Kim and Feigh (2014) provide guidance on principles for successful function allocation:

1. Capable to perform the assigned function

   Considering the function in isolation, the 'agent' must have the capability, which is the ability and properties required to reach a desired outcome, to perform the assigned function

2. Capable to perform the collective set of functions

The ‘agent’ must have the capability to perform the collective set of assigned functions. This includes an assessment of workload, avoiding too high workload caused by multiple normal work tasks are triggered at the same time or abnormal situations requiring several tasks to be carried out. Low workload can be caused by taking the humans out of the loop and cause lack of engagement or boredom.

3. Realizable within reasonable teamwork

   Different function allocation of the same taskwork demands teamwork functions to coordinate the taskwork. This includes both human-technology interaction and human-human coordination. These teamwork functions must be possible to carry out and need to be assessed in isolation and in the collective set of assigned teamwork functions.

4. Must support the dynamics of the work

   The function allocation must consider the dynamics caused by external factors, such as the work environment and internal factors, by the interplay between agents. The required performance variability needs to be considered. This includes both a reaction from the agent on the dynamics and proactive actions derived from predictions.

   The cognitive workload can be affected by the function allocation results in divides the information process between humans and technology. If the human-technology interaction dictates a specific sequence of humans, this can result in workarounds or disuse of automation.

5. A deliberate design decision

   The metrics of function allocation should predict each agent’s experience related to the allocated tasks, but also predict metrics of cost and performance resulting from the combined human-technology interaction.

3.3.3 The Use of Automation framework

The UoA-framework will use the information processing model and the principles of function allocation to describe the distribution between humans and technology. This includes considering the relevant variables for a successful function allocation. The UoA-framework consists of three steps as visualized in Figure 20.

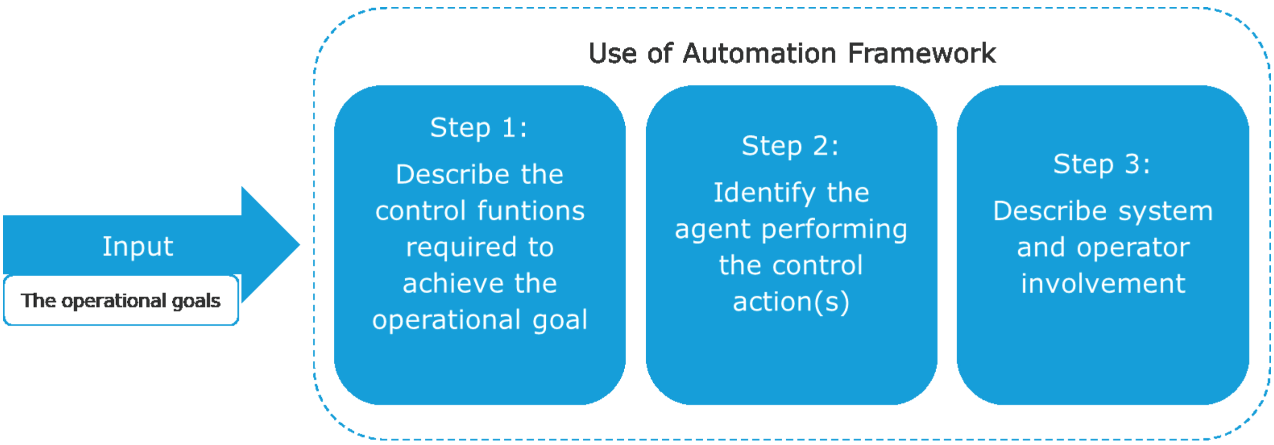

Figure 20 – The three steps that constitutes the UoA-framework

The input to the framework is the identified functional goal of the function where automation is introduced. The detail level of the function may vary. The identified function should consist of control functions that again is fulfilled by a set of control actions where technology is intended to take over a task normally performed by humans.

To facilitate that control actions are described in a consistent and unambiguous manner, a list of verbs categorized according to the four stages in the information processing model is proposed as part of the UoA framework. The verbs are collected from a list originally complied by NASA (1991) for use in the aviation industry. An extract of this list is presented in Table 6, while a complete list of these verbs can be found in appendix C.

Table 6 – Extract of verbs related to the information processing stages.

Information acquisition	Information analysis	Decision-making	Action implementation	Not recommended
Access	Alert	Command	Accelerate	Adjust
Detect	Classify	Conclude	Acknowledge	Advice
Observe	Compare	Consider	Activate	Analyse
Organize	Compute	Generate	Align	Assess
Prioritize	Calculate	Select	Anounce	Begin
Receive	Define	Determine	Approve	Call for

3.3.3.1 Step 1 – describing the control functions and control actions

The first step is describing the control functions and the control actions that need to be implemented to reach the functional goal. A significant challenge is to decide how many control actions, and which detail level, to include in the framework. The UoA-framework uses the information processing stages from Table 5 to describe categories of functions to be used when describing the control actions. It is recommended that control actions representing the various stages of the information processing model are described. I.e. when describing the control actions required to achieve a control function, they should not be limited to only include implementation of actions (stage 4), but also the control actions leading up to the control action (stages 1 to 3). However, it should not always be necessary to describe the control action in a linear manner, resembling the sequential representation of the four stages. This could result in having to “shoehorn” description of functions into an unrealistic structure. Instead the sequence of control functions should naturally follow the functional goals and operations they intend to model. This way the information processing model will help the RBAT user to consider how the human operator should be involved in the execution of automated functions. Two different approaches are suggested to describe the relevant control action.

A) If the control function to be automated consists of a sequential set of control actions the suggested approach is to identify the control actions related to the information stages *implemented actions* necessary to complete the overall function.

Example: The control function objective of unloading containers is fulfilled by a sequential subset of control action as shown in Table 7.

Table 7 – Example of a sequential set of control actions

Control-functions	Control-action
Unload container	
	Unlash container
	Attach container to crane
	Lift container from deck to quay
	Detach container

B) A control function where the control actions are realized in a non-sequential order can require a different approach to identify the relevant automated control actions. A guidance is listing the control actions that are automated by applying the relevant verbs from the information processing stages presented in Table 6. The control actions can be either action where a system will perform the actual control action, or it is control action where a system will be involved in supporting or supervising the control action.

Example: The control function of harbor maneuvering is fulfilled by a subset of control actions. These control actions are not necessarily performed in a sequence.

Table 8 – Example of a non-sequential set of control actions

Control-functions	Control-action
Harbour manouvering	
	Detect vessels
	Calculate arrival time
	Predict distance to vessels and shore
	Select route
	Follow selected route
	Communicate with other vessels

3.3.3.2 Step 2 – identifying the performing agent

Identifying the performing agent is to allocate the control action to an agent and perform is defined as:

Perform:

The performing agent is the agent that either performs all parts of the control function or integrates support from other agents. The performing agent is responsible for the outcome of the control function. Identifying the performing agent is carried out in the previous step and listed under "Performing Agent".

The allocation to either humans or technology is the overall objective when identifying the performing agent. However, the process should also provide more details about the humans or systems involved. The process should describe which operator is performing the control action, the location of the operator or in case of allocated to technology, which systems are planned to be used. If the allocation process is performed in early design process, details of operators and systems description might not be concluded. However, the allocation should aim at providing as much details as possible.

Example:

Table **9** *shows a sequential set of control* action *being described by the action implementation necessary to complete the control function of unloading containers. The allocation to agent is to either LO1 or ACLS. LO1 refers to Local Operator 1, indicating the operator is located locally and further the number 1 indicates that more than one operator is located at this site. The abbreviation ACLS points to an imagined Automatic Cargo Loading System.*

Table 9 – Example of linking sequential control actions to performing agent

Control-functions	Control-action	Performing Agent
Unload container		
	Unlash container	LO1
	Attach container to crane	ACLS
	Lift container from deck to quay	ACLS
	Detach container	LO1

Example:

Table **10** *shows a process where the important automated processes are found in all four information stages. The information steps are not mentioned explicit; however, one can recognize the verbs related to the various stages. The allocation in this example is between an imagined Automatic Navigation System (ANS) and a Remote Operator (RO1).*

Table 10 – Example of linking non-sequential control actions to performing agents

Control-functions	Control-action	Performing Agent
Harbour manouvering		*RO1*
	Detect vessels	ANS
	Observe vessel movements	RO1
	Calculate arrival time	ANS
	Predict distance to vessels and shore	ANS
	Generate route options	ANS
	Select route	RO1
	Follow selected route	ANS
	Communicate with other vessels	RO1

3.3.3.3 Step 3 – Describe the joint human and technology performance

The automation process refers to replacing humans with technology; however, this should not be understood as it always refers to humans being completely removed from the process. The control actions will in many cases be a joint process between humans and systems. This underlines that the automation process must not be oversimplified to become a simple exchange where technology takes over a human function. It is highly relevant to understand the human role also for automated functions and the system's role in functions performed by humans. The UoA framework uses two main identifiers describing the operator or system involvement in addition to performing; supporting or supervising.

> *Support:*
>
> Support is to perform a sub-level of the control action or provide any other support that assist the agent that performs the function. To describe the support, the verb list shown in Table 6 and included in appendix C should be used and the support should be allocated to an operator.

Example: If the control action *"Calculate arrival time" is automated to an "Automated Navigation System" but relying on data about the routing in the arrival port, an important support function can be "Support - Remote Operator 1 load traffic regulation data in ANS" and included as shown in Table 11 below:*

Table 11 – Example the operator having a *support* role

Control-functions	Control-action	Performing Agent	Operator/system involvement		
Harbour manouvering					
	Detect vessels	ANS			
	Calculate arrival time	ANS	Support	RO1	Load traffic regulation data in ANS

> *Supervise:*
>
> Supervision of an automated function is to control that the system is operational and/or that the function is performed as intended. Consequently, supervision must either be linked to the function or to the system. Allocating a supervision task to an operator must be carefully considered to avoid that the operator is "out-of-the-loop" or being overloaded.

Supervising a function requires the operator to be able to understand and validate the system's information processing stages and be able to intervene, and transparency and trust between the operator and the system is decisive in this process. Intervention can be caused by the operator experiencing that the system is not capable of fulfilling the function either due to system malfunctions or that the external conditions is outside the design parameters of the system.

Supervision can be done by supervising either the system or the function. Supervising the system implies to oversee an aggregation of information and can allow for more use of alarms when the information is out of limits. Supervising a function requires the operator to closely follow the performance of the function steps. The supervision role of the operator can be defined by the criticality of the system and can allow for the operator being available at notice. The workload of an operator must be assessed by collating all supervision and performance tasks.

Example: The control action of "Predict distance to vessel and shore" and "generate route options" are supervised by the Remote Operator 1 (RO1). The operator will be responsible for responding to alarms by the ANS alert management system and in addition taking a more active role in supervising the vessel following the route.

Table 12 – Example of the operator having a supervisory role

Control-functions	Control-action	Performing Agent	Operator/system involvement		
Harbour manouvering					
	Detect vessels	ANS			
	Calculate arrival time	ANS	Support	RO1	Load traffic regulation data in ANS
	Predict distance to vessels and shore	ANS	Supervise	RO1	Respond to alarms from ANS
	Select route	RO1	Support	ANS	Generate route options
	Follow selected route	ANS	Supervise	RO1	Monitor vessel on route and intervene if deviation
	Communicate with other vessels	RO1			

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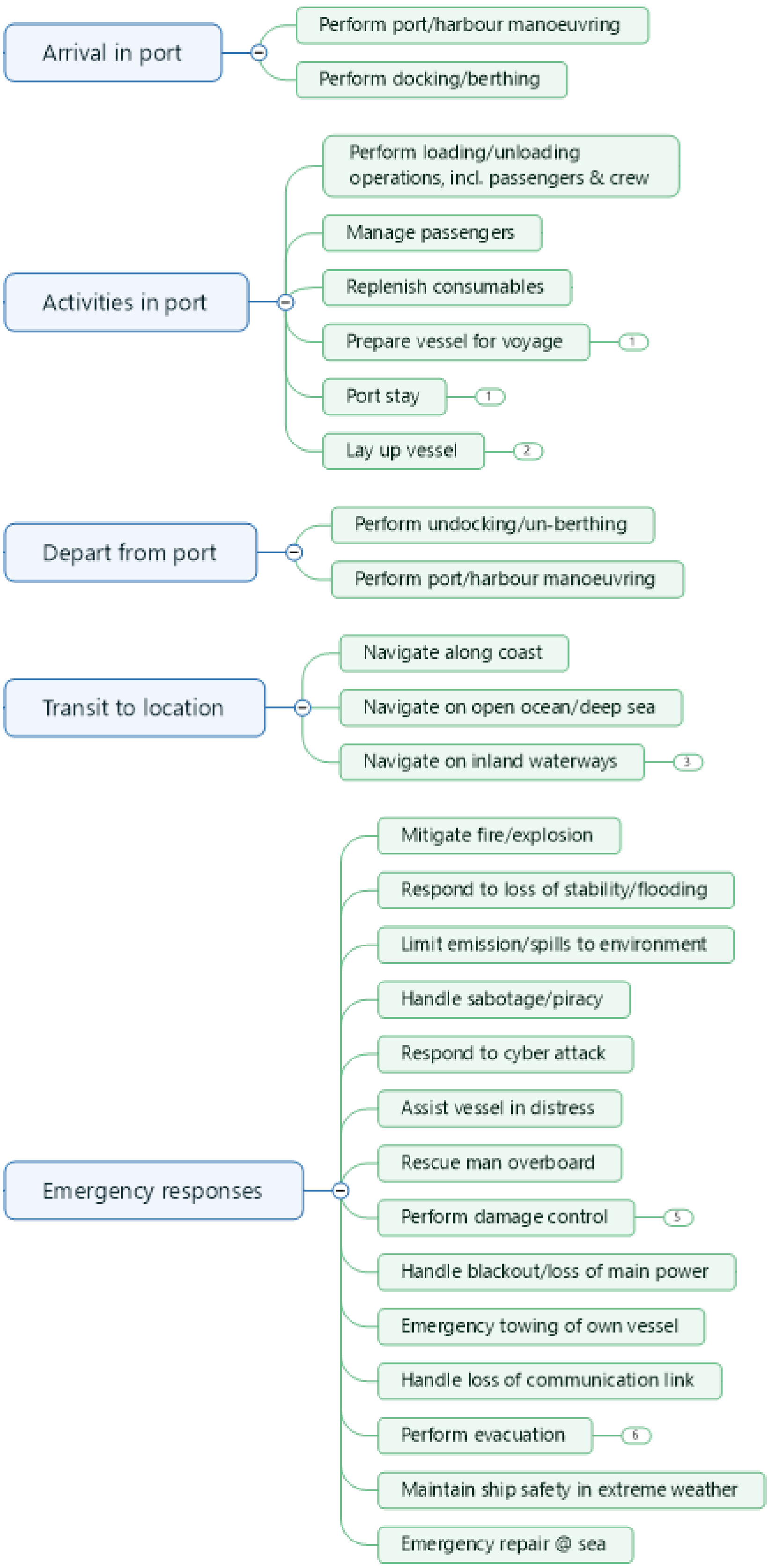
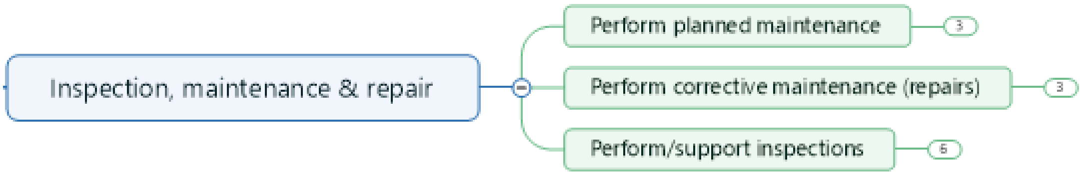
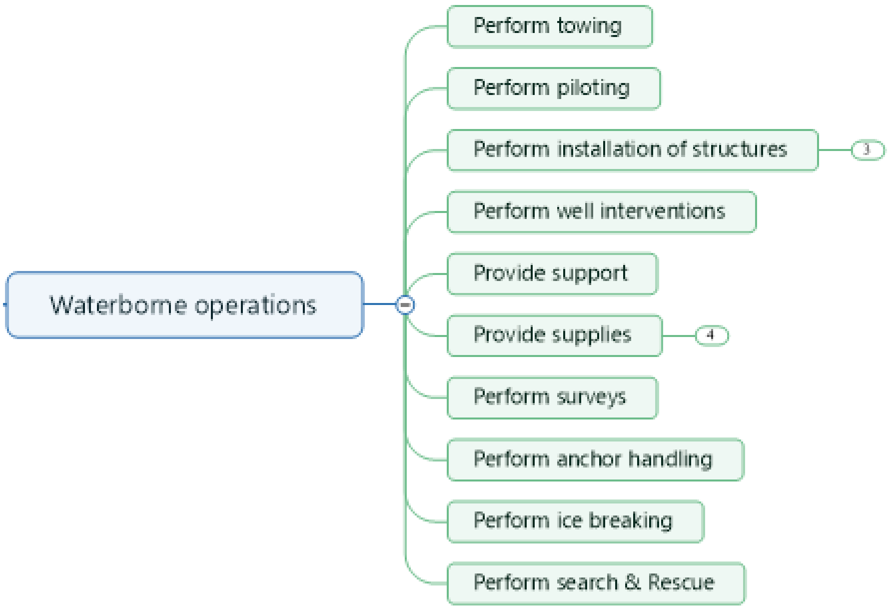
APPENDIX A
Mission Model



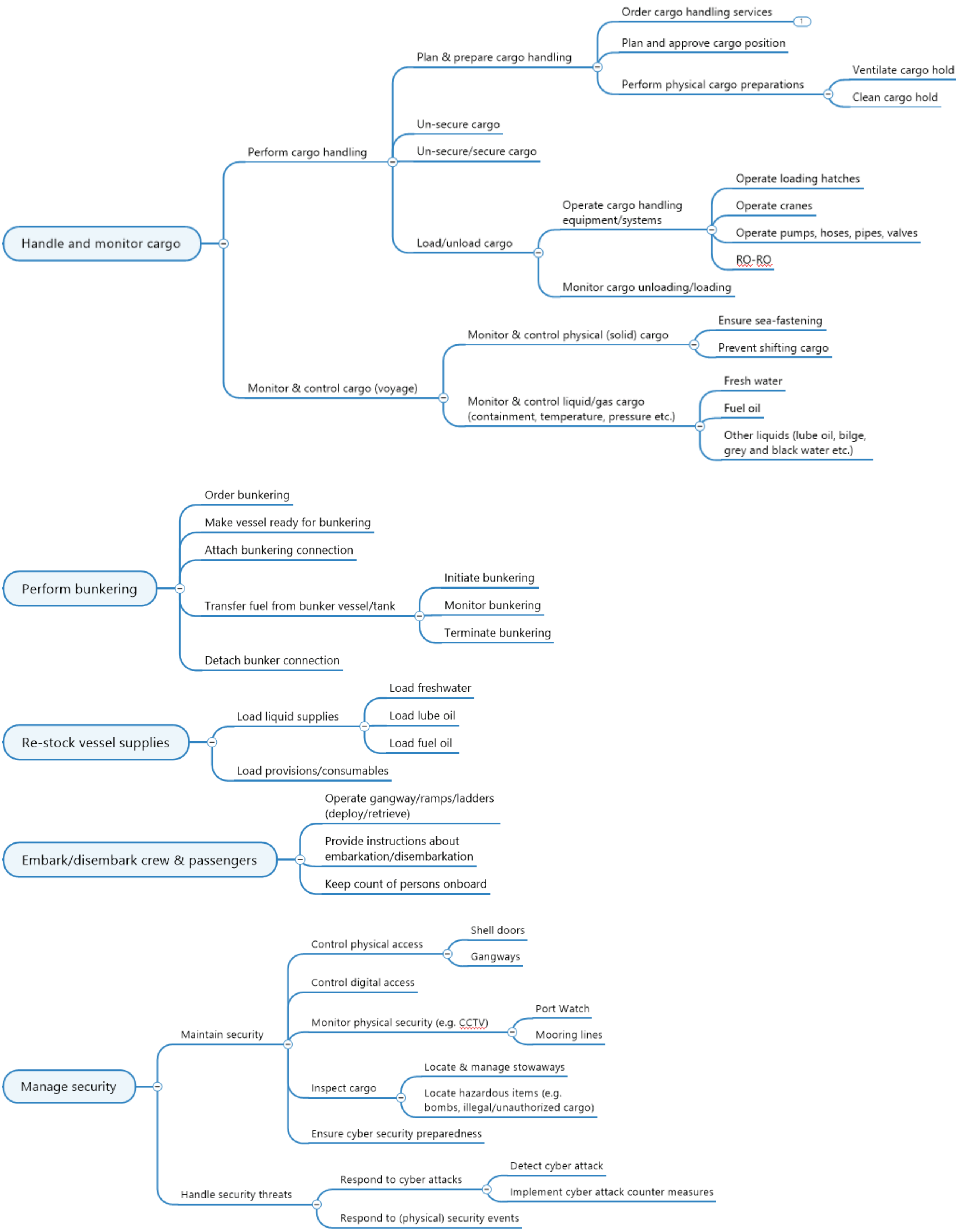


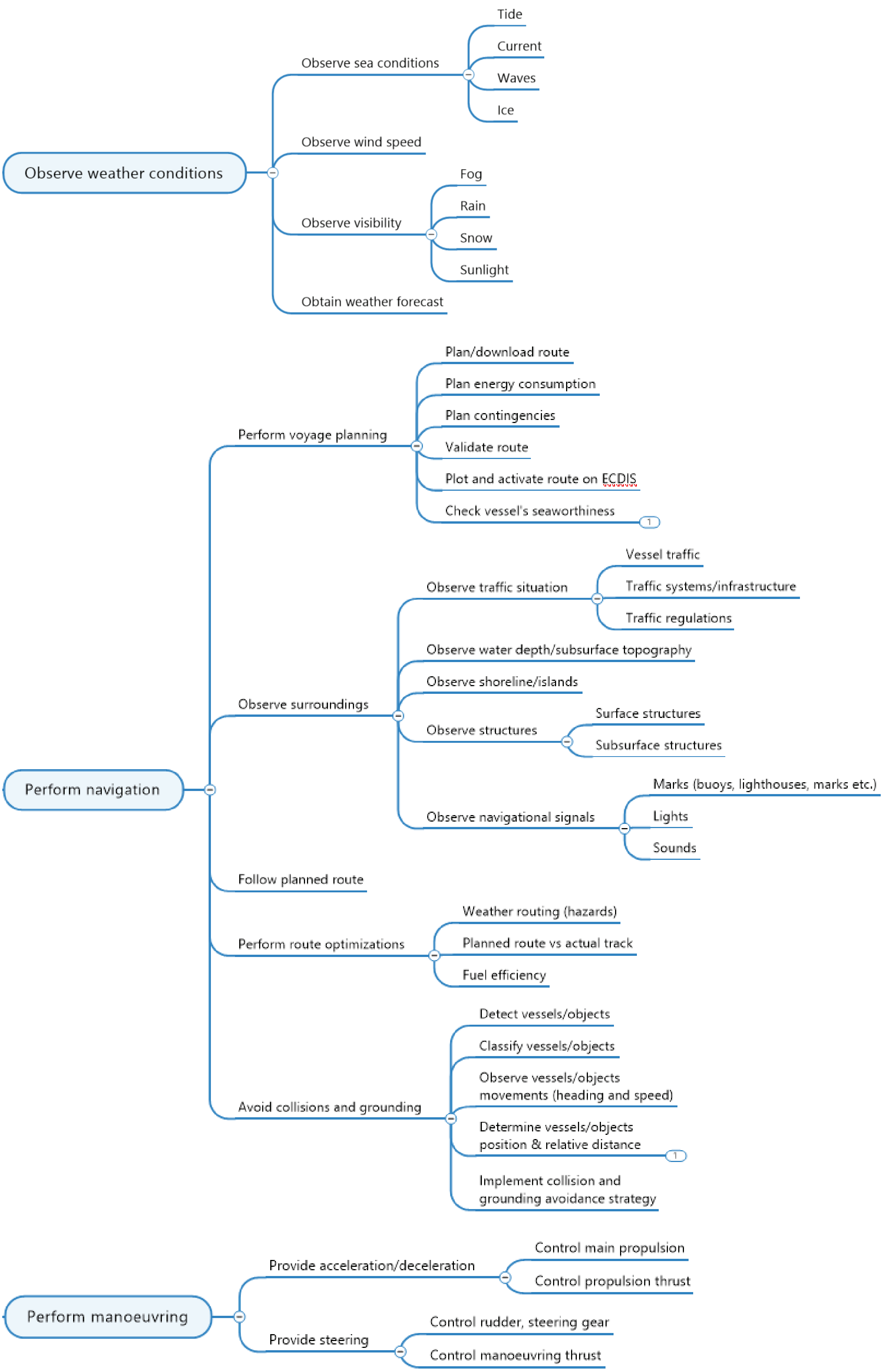
Inspection, maintenance & repair
Perform planned maintenance
3
Perform corrective maintenance (repairs)
3
Perform/support inspections
6



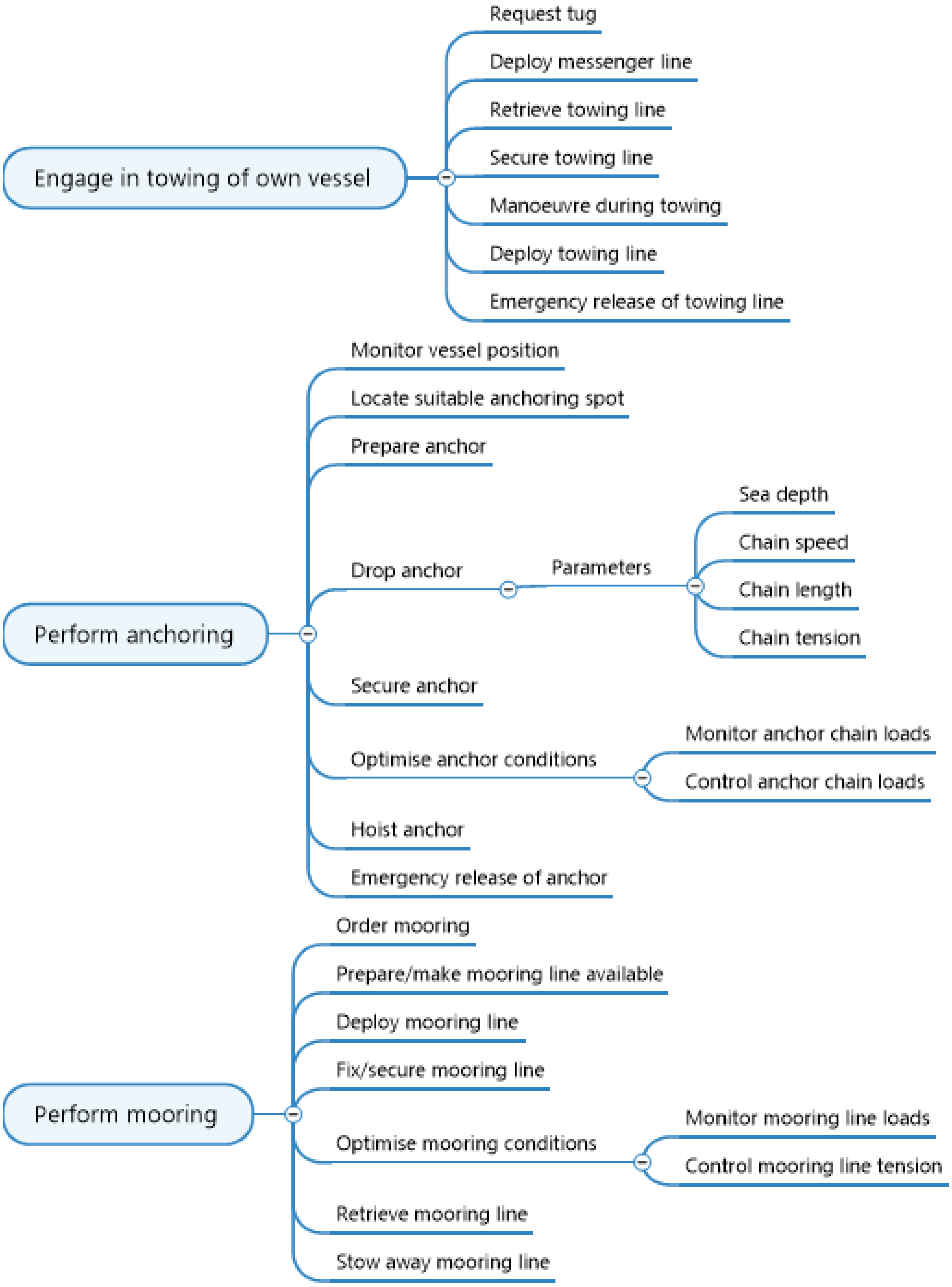
Waterborne operations
Perform towing
Perform piloting
Perform installation of structures
3
Perform well interventions
Provide support
Provide supplies
4
Perform surveys
Perform anchor handling
Perform ice breaking
Perform search & Rescue

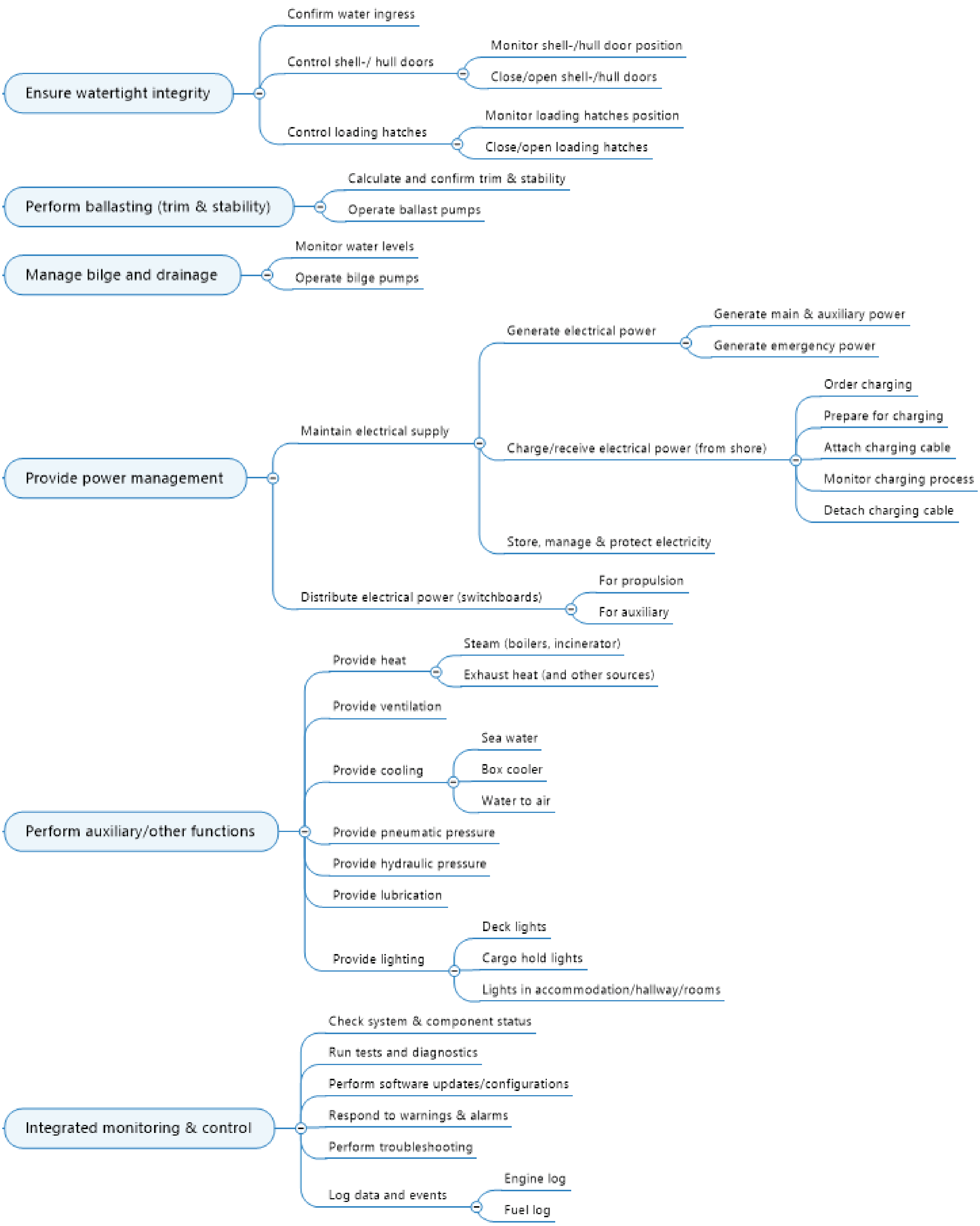
APPENDIX B
Function Tree



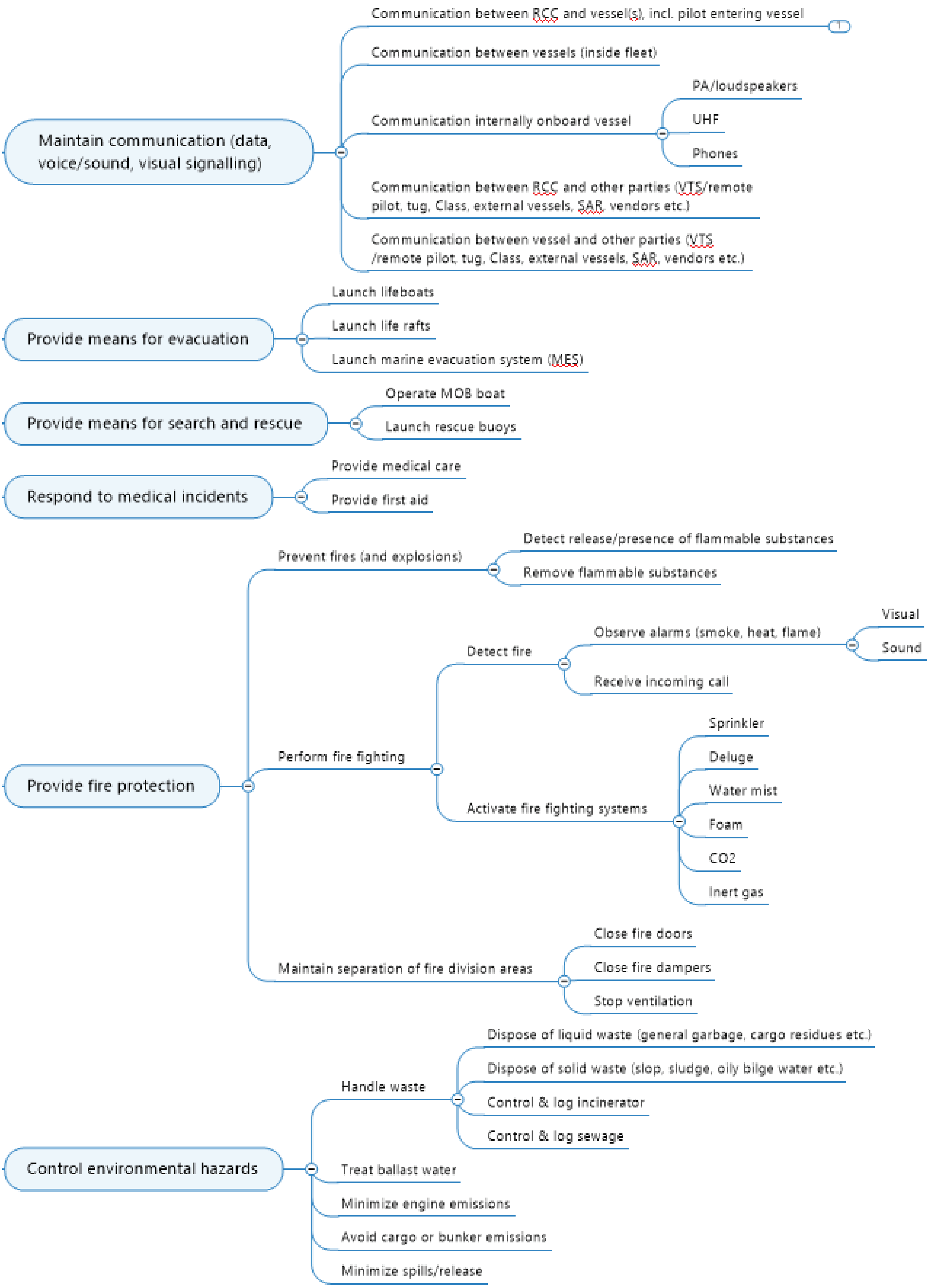


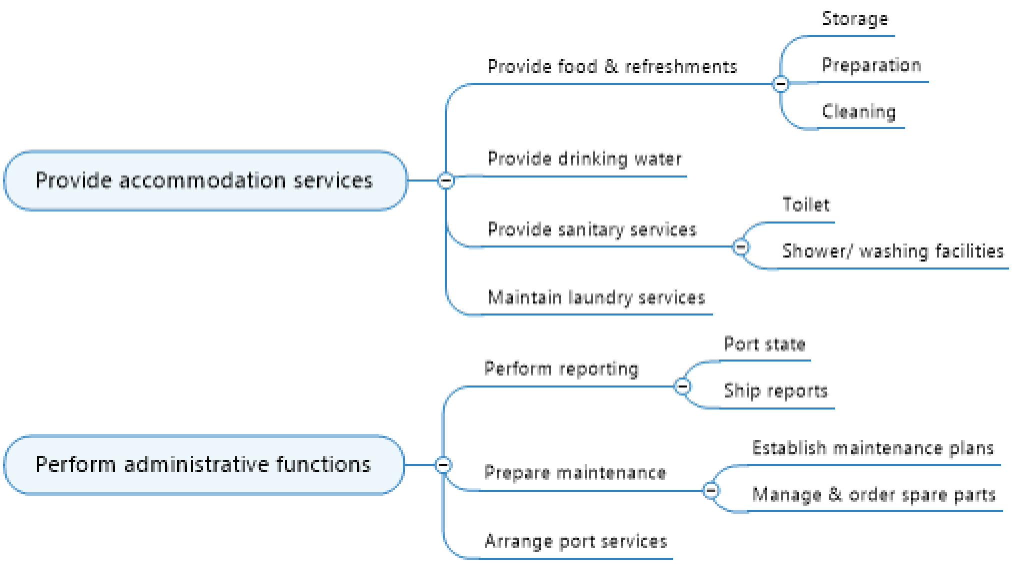
Observe weather conditions
Observe sea conditions
Tide
Current
Waves
Ice
Observe wind speed
Observe visibility
Fog
Rain
Snow
Sunlight
Obtain weather forecast
Perform navigation
Perform voyage planning
Plan/download route
Plan energy consumption
Plan contingencies
Validate route
Plot and activate route on ECDIS
Check vessel's seaworthiness
Observe surroundings
Observe traffic situation
Vessel traffic
Traffic systems/infrastructure
Traffic regulations
Observe water depth/subsurface topography
Observe shoreline/islands
Observe structures
Surface structures
Subsurface structures
Observe navigational signals
Marks (buoys, lighthouses, marks etc.)
Lights
Sounds
Follow planned route
Perform route optimizations
Weather routing (hazards)
Planned route vs actual track
Fuel efficiency
Avoid collisions and grounding
Detect vessels/objects
Classify vessels/objects
Observe vessels/objects movements (heading and speed)
Determine vessels/objects position & relative distance
Implement collision and grounding avoidance strategy
Perform manoeuvring
Provide acceleration/deceleration
Control main propulsion
Control propulsion thrust
Provide steering
Control rudder, steering gear
Control manoeuvring thrust


Engage in towing of own vessel
Request tug
Deploy messenger line
Retrieve towing line
Secure towing line
Manoeuvre during towing
Deploy towing line
Emergency release of towing line
Perform anchoring
Monitor vessel position
Locate suitable anchoring spot
Prepare anchor
Drop anchor
Parameters
Sea depth
Chain speed
Chain length
Chain tension
Secure anchor
Optimise anchor conditions
Monitor anchor chain loads
Control anchor chain loads
Hoist anchor
Emergency release of anchor
Perform mooring
Order mooring
Prepare/make mooring line available
Deploy mooring line
Fix/secure mooring line
Optimise mooring conditions
Monitor mooring line loads
Control mooring line tension
Retrieve mooring line
Stow away mooring line



Ensure watertight integrity
Confirm water ingress
Control shell-/ hull doors
Monitor shell-/hull door position
Close/open shell-/hull doors
Control loading hatches
Monitor loading hatches position
Close/open loading hatches
Perform ballasting (trim & stability)
Calculate and confirm trim & stability
Operate ballast pumps
Manage bilge and drainage
Monitor water levels
Operate bilge pumps
Provide power management
Maintain electrical supply
Generate electrical power
Generate main & auxiliary power
Generate emergency power
Charge/receive electrical power (from shore)
Order charging
Prepare for charging
Attach charging cable
Monitor charging process
Detach charging cable
Store, manage & protect electricity
Distribute electrical power (switchboards)
For propulsion
For auxiliary
Perform auxiliary/other functions
Provide heat
Steam (boilers, incinerator)
Exhaust heat (and other sources)
Provide ventilation
Provide cooling
Sea water
Box cooler
Water to air
Provide pneumatic pressure
Provide hydraulic pressure
Provide lubrication
Provide lighting
Deck lights
Cargo hold lights
Lights in accommodation/hallway/rooms
Integrated monitoring & control
Check system & component status
Run tests and diagnostics
Perform software updates/configurations
Respond to warnings & alarms
Perform troubleshooting
Log data and events
Engine log
Fuel log


Maintain communication (data, voice/sound, visual signalling)
Communication between RCC and vessel(s), incl. pilot entering vessel
Communication between vessels (inside fleet)
Communication internally onboard vessel
PA/loudspeakers
UHF
Phones
Communication between RCC and other parties (VTS/remote pilot, tug, Class, external vessels, SAR, vendors etc.)
Communication between vessel and other parties (VTS /remote pilot, tug, Class, external vessels, SAR, vendors etc.)
Provide means for evacuation
Launch lifeboats
Launch life rafts
Launch marine evacuation system (MES)
Provide means for search and rescue
Operate MOB boat
Launch rescue buoys
Respond to medical incidents
Provide medical care
Provide first aid
Provide fire protection
Prevent fires (and explosions)
Detect release/presence of flammable substances
Remove flammable substances
Perform fire fighting
Detect fire
Observe alarms (smoke, heat, flame)
Visual
Sound
Receive incoming call
Activate fire fighting systems
Sprinkler
Deluge
Water mist
Foam
CO2
Inert gas
Maintain separation of fire division areas
Close fire doors
Close fire dampers
Stop ventilation
Control environmental hazards
Handle waste
Dispose of liquid waste (general garbage, cargo residues etc.)
Dispose of solid waste (slop, sludge, oily bilge water etc.)
Control & log incinerator
Control & log sewage
Treat ballast water
Minimize engine emissions
Avoid cargo or bunker emissions
Minimize spills/release


Provide accommodation services
Provide food & refreshments
Storage
Preparation
Cleaning
Provide drinking water
Provide sanitary services
Toilet
Shower/ washing facilities
Maintain laundry services
Perform administrative functions
Perform reporting
Port state
Ship reports
Prepare maintenance
Establish maintenance plans
Manage & order spare parts
Arrange port services

APPENDIX C
Verbs linked to information processing stages

Information acquisition	Information analysis	Decision-making	Action implementation	
Access	Alert	Command	Accelerate	Coordinate
Detect	Classify	Conclude	Acknowledge	Cycle
Observe	Compare	Consider	Activate	Deactivate
Organize	Compute	Generate	Align	Debrief
Prioritize	Calculate	Select	Anounce	Decelerate
Receive	Define	Determine	Approve	Decrease
Registrate	Identify		Attach	Depressurize
Scan	Integrate		Attain	Detach
Sense	Interpret		Brief	Deviate
	Predicting		Close	Discharge
	Trend		Communicate	Eliminate
			Configure	Enter
			Continue	Evacuate
			Control	Exit

Action implementation (continue)			Not recommended to use	Not relevant to maritime
Extend	Open	Respond	Adjust	Arm
Extinguish	Operate	Review	Advice	Ascend
Fasten	Order	Secure	Analyse	Climb
Fill	Perform	Stabilize	Assess	Descend
Follow	Plan	Start	Begin	Direct
Guard	Position	Steer	Call for	Disarm
Hear	Prepare	Stop	Check	Disengage
Illuminate	Pressurize	Stow	Confirm	Don
Increase	Prevent	Test	Depower	Engage
Initialize	Proceed	Transmit	Ensure	Fly
Initiate	Program	Trim	Examine	Input
Inspect	Provide	Tune	Hold	Inventory
Intercept	Read	Turn	Inform	Jettison
Interrogation	Record	Unfasten	Insure	Land
Isolate	Recover	Unload	Notify	Level
Load	Remove	Unsecure	Power	Lower
Maintain	Repeat	Update	Release	Output
Modify	Report	Verify		Park
Monitor	Request			Raise
Manuevuer	Reset			Retract
				Rotate
				Taxi

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