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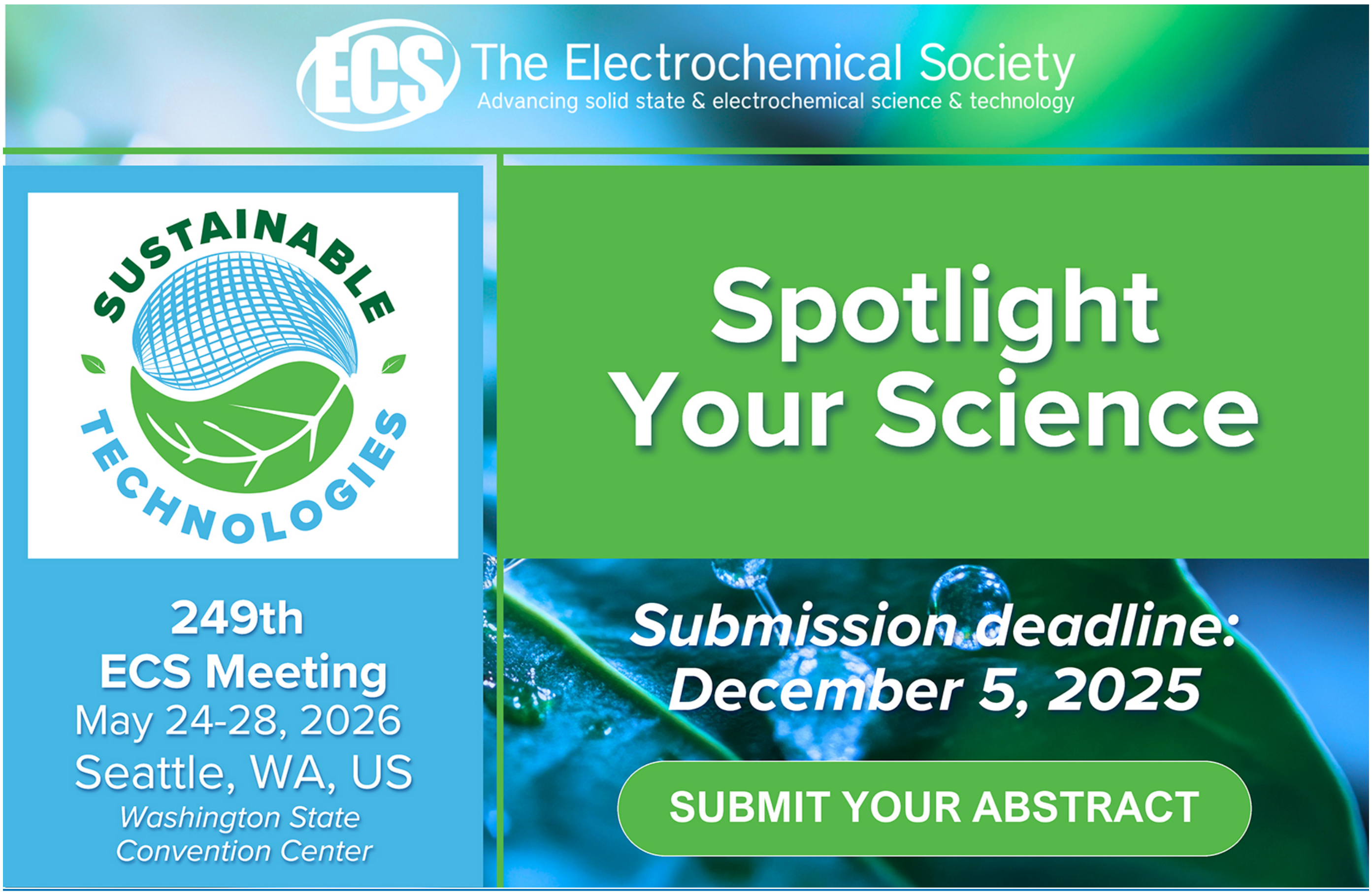

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MASS operations in port calls

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Abstract. To achieve success in the maritime industry's shift towards autonomous vessels — seeking the goals of enhanced efficiency, environmental sustainability, and improved safety — it is crucial to develop, test, and validate new procedures and technologies for autonomous ship operations, which includes management of Maritime Autonomous Surface Ships (MASS) at port. So far, the focus of autonomy in maritime has been mainly on the navigational issues, and not as much on the integration between port technology and procedures, and remote operations centre (ROC) operation. MASS will not necessarily have its bridge, cargo handling equipment, and maintenance being manned by onboard agents, but can rather be fully operated and organised by a ROC. To overcome these challenges, there are different areas of concern that must be considered such as navigation and docking, cargo handling, and maintenance, etc.

1. Introduction and Background

Maritime Autonomous Surface Ships (MASS) for cargo operations are not expected to become fully autonomous within the foreseeable future. There will be differences in the implementation depending on types of operations and challenges because of the regulations that is not in place. Yara Birkeland is still manned, so is the two ASKO ferries operating in the Oslo fjord [1,2]. There are many different concerns such as availability to digital infrastructure, and regulations for types of operations, global regulations, as well as regulations of doing autonomous operations in a port basin, local regulations, as examples. The development of technology as well as the Remote Operation Centre (ROC) role will define clear limitations for when the MASS can be in control on its own, and for when a handover to the ROC operator is required. The Seamless project [3] described four different autonomy levels as following, with reference to IMO's autonomy levels [4]:

- ***L1: Direct Control:*** *The operator has full control of the system, e.g., by levels and push buttons, and uses relatively simple automation and decision support systems.*
- ***L2: Automatic Operations:*** *The automation system performs the operations under continuous supervision by an operator. Examples are auto-docking, auto-tracking, dynamic positioning.*
- ***L3: Constrained Autonomous:*** *The automation performs the operations without continuous supervision of a human operator.*
- ***L4: Autonomous:*** *Autonomous refers to autonomy level Constrained Autonomous.*

An **operational envelope** (OE) refers to the range of conditions a system or a MASS can safely and effectively function. It's a multidimensional space that defines limits on operational parameters such as vessel speed, weather forces, traffic, stress factors, visibility, latency, communication and availability to infrastructure as examples. The OE's defines the boundaries within an autonomous system and how it can safely and reliably perform its intended tasks without human intervention, and when the technology should call for human assistance when the technology is not capable to solve the problem itself.

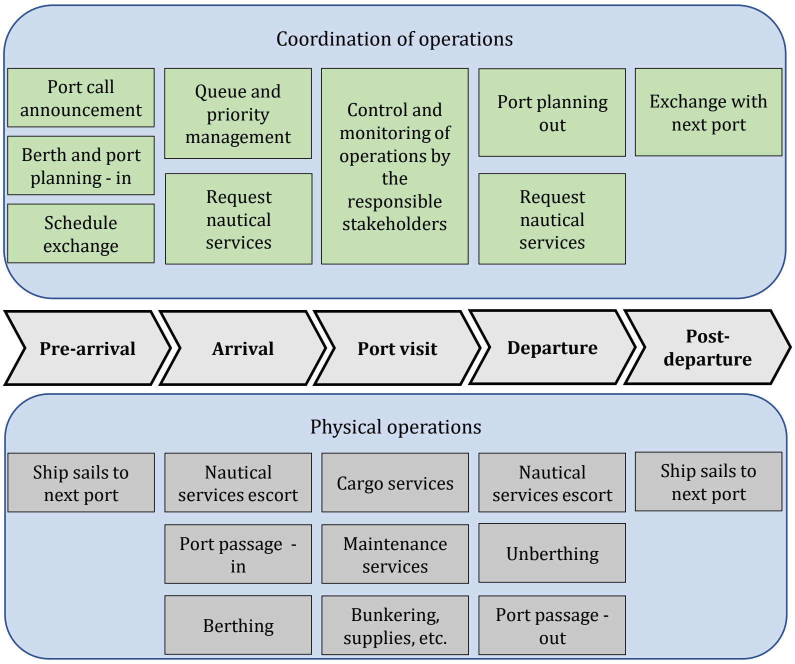
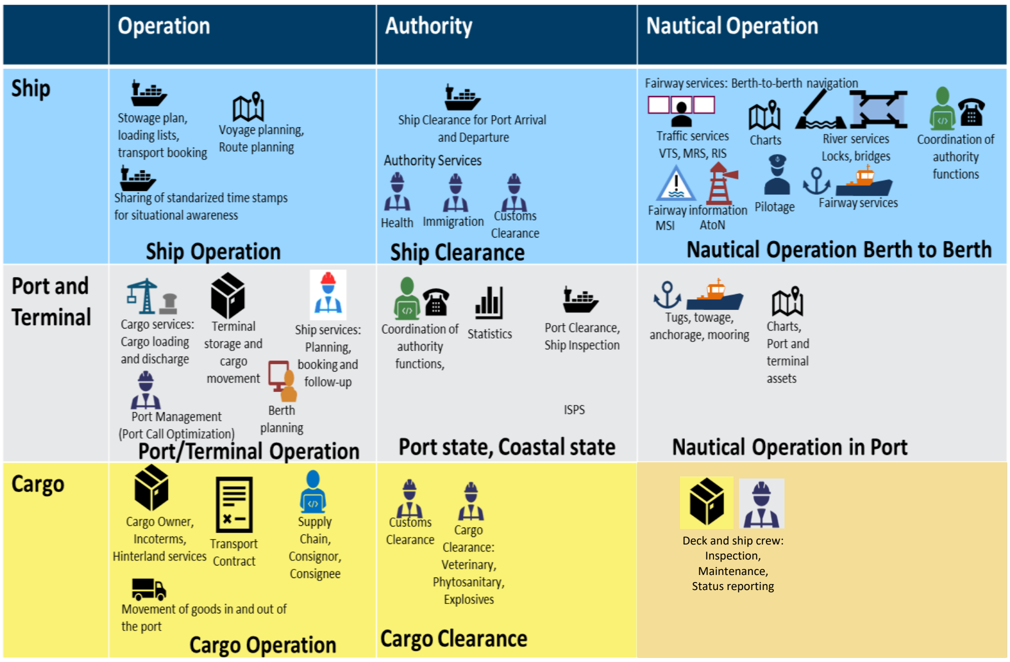


Figure 1. Conventional shipping procedures.

To ensure that autonomous ships will contribute to enhanced efficiency, environmentally sustainability, or for increased safety, it is crucial that the MASS and ROC interact and operates efficiently together. Successful implementation of autonomy requires collaboration between humans and machine. This paper will focus on how to use procedures to improve situational awareness and decision-making, it will use experiences from conventional shipping as background for developing autonomous MASS operational procedures.

Figure 1 describes a typical process for a conventional vessel, from pre-announcement of a port call, port activities, and departure from port. It describes some typical services to be in place, such as a vessel must be assisted by a pilot service where required. From the pilot's perspective on MASS — be that a local or remote pilotage —, this will require different awareness level than the usual, better understanding of the designed port passage plan, access to port sensor technologies, and the ability to give instructions which can immediately be executed directly by the MASS, or through its ROC. Furthermore, with the vessel sailing with a small to no crew, it is important to have a clear picture of whom to be in control. Figure 2 describes some stakeholders that are involved within the different operations for a conventional vessel. The integration of various technological systems — including navigation algorithms, sensor technologies, communication protocols, and decision-making processes — requires a comprehensive approach.



	Operation	Authority	Nautical Operation
Ship	Stowage plan, loading lists, transport booking Voyage planning, Route planning Sharing of standarized time stamps for situational awareness **Ship Operation**	Ship Clearance for Port Arrival and Departure Authority Services Health Immigration Customs Clearance **Ship Clearance**	Fairway services: Berth-to-berth navigation Traffic services VTS, MRS, RIS Charts River services Locks, bridges Coordination of authority functions Fairway information MSI AtoN Pilotage Fairway services **Nautical Operation Berth to Berth**
Port and Terminal	Cargo services: Cargo loading and discharge Terminal storage and cargo movement Ship services: Planning, booking and follow-up Port Management (Port Call Optimization) Berth planning **Port/Terminal Operation**	Coordination of authority functions, Statistics Port Clearance, Ship Inspection ISPS **Port state, Coastal state**	Tugs, towage, anchorage, mooring Charts, Port and terminal assets **Nautical Operation in Port**
Cargo	Cargo Owner, Incoterms, Hinterland services Transport Contract Supply Chain, Consignor, Consignee Movement of goods in and out of the port **Cargo Operation**	Customs Clearance Cargo Clearance: Veterinary, Phytosanitary, Explosives **Cargo Clearance**	Deck and ship crew: Inspection, Maintenance, Status reporting

Figure 2. Stakeholders serving a conventional vessel. Source: SINTEF Ocean

Currently under development on the EU DYNAPORT project [5] is a port operations blueprint, with the intent of bringing together the many aspects of a port call into a consistent and optimizable chain of operations. One key point is the establishment of a Port Call Coordination Centre (P3C) as a single point-of-contact for pre-port call coordination between ship and port. Taking these concepts into consideration, this paper addresses and discusses the aforementioned areas of concern for MASS operations. How can they be combined into a MASS-specific port operations blueprint, including the necessary technologies and procedures, and its connection to previous and current research and developments? Will it be possible to standardise the procedures such that same approach can be followed at the different ports?

2. Methodology

Operational support from the ROC is needed to handle MASS operations. For safe operations, the ROC operator needs a clear picture of the ship status and the surroundings, relevant to the ongoing operation, based on the intelligent analysis of available information. It is important that ROC have the fully control, as well as the juridical responsibilities in case of an accident or unwanted situation. VTSs, pilots and ports normally give advice, while the captains onboard a conventional vessel have the responsibility to execute. The captain role will be the duties of the ROC.

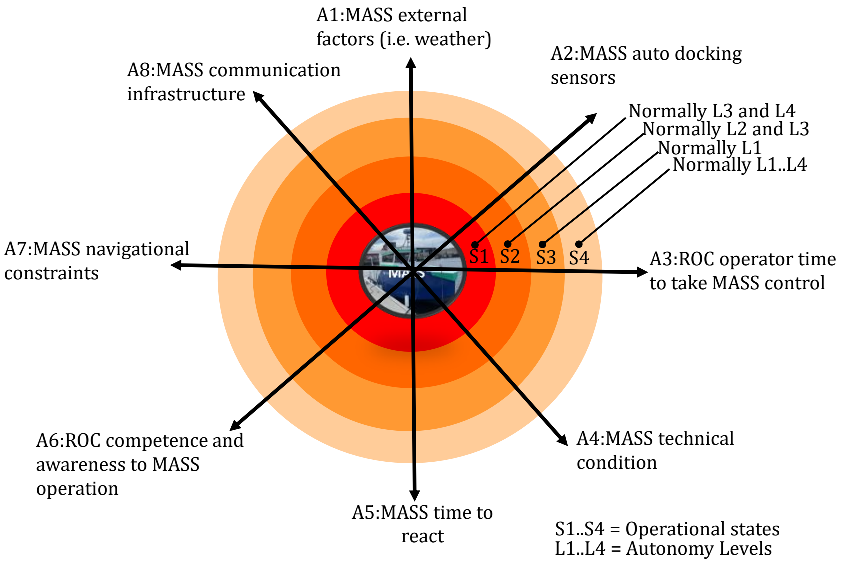


Figure 3. States (S's), Autonomy level (L's) and operation levels (A's) for MASS

Figure 3 illustrates various operational states a MASS can transition through, labelled from S1 to S4, from a normal to a fall-back condition depending on the MASS operational condition. There will be different operations in use (A1 .. An) depending on the MASS place of operation (departure, sailing, cargo operation, etc). Each of the A's will have different measure values, such as for external factors, A3 = wind + current + fog + rain, etc. Each circle in the figure indicates state and autonomy level. It is normal that an operation will change state up and down, depending on changes of measured values that is explained below. The four states in the figure are:

- **S1** represents the normal operation, (normally L3 and L4, constrained or autonomous constrained), while
- **S2** is a first warning of a change based on new values, (ICT request assistance from ROC, L2 and L3)
- **S3** is a state where the condition escalates to be worse, and a pre-state before a safe state (Call for direct control, L1)
- **S4** indicates a fall-back condition, that a MASS goes to a safe state. Normally the Maximum Response Time (TMR) and Response Deadline (TDL) values have passed, or the ROC capabilities to take control is not possible.

If one of the values in the A's gives a higher value than max value set, it triggers a change of state. For example, if the wind increases in the operational condition in A3, to a higher wind force that is categorised as max value in S1, this might trigger a change of state where for example a warning sent to the ROC operator is done, and thereby moving to S2. Within each state there will be different formulas or calculations, such as for the A3, MASS external factors, where the formula can be:

- **S1**=[A3((wind < 10 knots) + (fog < (visibility > 3 NM)) + (current < 5 knots) + (TMR<20 sec) + (TDL<30 sec))+A4(..)+An(..)],
- **S2**=[(wind < 8 knots) + (fog < (visibility > 2 NM)) + (current < 4 knots) + (TMR<15 sec) + (TDL<25 sec) ...].

When changing from one state to another, a change of autonomy level is likely to happen, from autonomous operation to direct control by the ROC as for above, L4 to L1, as example. The handover process between automated systems and human operators requires a time buffer—referred to as the **Maximum Response Time (TMR)**—which spans from the moment the automation signals the need for human intervention to when the operator can deliver an appropriate response [6]. This interval depends on the operational procedures in place on both the vessel and at the Remote Operations Center (ROC), as well as the operator's initial state when action is required. Another critical time parameter is the **Response Deadline (TDL)**. This represents the worst-case scenario; the shortest possible time between the automation detecting a potential issue and the point at which it must initiate a fall-back procedure to transition into a safe state (illustrated as S4). Different operations will have varying TDL and TMR values, which are defined in the Operational Envelope (OE), illustrated as A's in the examples above.

3. Scenario Descriptions and State of the Art

3.1 State of the art

The advent of Maritime Autonomous Surface Ships (MASS) is redefining the landscape of global shipping, promising enhanced efficiency, reduced operational costs, and new paradigms in safety management. The International Maritime Organization (IMO) defines a MASS as "a ship which, to varying degrees, can operate independently of human interaction" [7]. This definition encompasses a continuum of vessels, from those equipped with advanced decision-support systems to fully autonomous ships capable of navigating and operating without any crew on board. The IMO's regulatory scoping exercise, completed in 2021, systematically reviewed the applicability of existing international conventions to MASS and highlighted the need for new or adapted frameworks to ensure that safety, security, and environmental protection standards are upheld [8]. A pivotal component in the operation of higher-degree MASS is the Remote Operations Centre (ROC). As defined by the IMO, a ROC is a shore-based facility that can monitor, supervise, and, when necessary, directly control one or more MASS, and on ISO/TS 23860:2021 as "remote control centre (RCC)", being a "site remote from the ship that can control some or all of the autonomous ship system processes". The ROC is central to the safe deployment of autonomous vessels, acting as both a supervisory node and a point of human intervention in exceptional circumstances. Operational support from the ROC is needed to handle daily operations, with mission planning to handle complex navigational situations. For safe operations, the ROC operator needs a clear picture of the ship status and the surroundings, relevant to the ongoing operation. The forthcoming IMO MASS Code [8], expected to become mandatory by 2028, will set out detailed requirements for ROC infrastructure, including operator qualifications, communication protocols, and procedures for transferring control between ROCs, especially when advancing to fit the legal framework of the United Nations Convention on the Law of the Sea (UNCLOS). Notably, the Code will reinforce the principle that a designated human master must always be responsible for a MASS, whether onboard or at a ROC, thereby maintaining a clear chain of accountability—a critical consideration for safety and liability [8].

The ISO ISO/TS 23860:2022 [9] standard also introduces terms for operator control modes, such as monitoring, strategic control, and tactical control, to describe the division of responsibilities between humans and automated systems in various operational scenarios. RODSET et al. [10] argue that, in place of considering degrees of autonomy, the concept of autonomy should be seed as binary: existing or not. Which changes the perspective towards considering nested operational domains — Operational envelope (OE), Operational Design

Domain (ODD), Constrained Autonomy Domain (CAD) and a fall-back space — and cooperation modes between human and automation — Operator exclusive; Operator Assisted and Constrained Autonomous. Furthermore, they mention that the resulting definitions are largely associated with the sailing operations and that, a level of automation of several auxiliary systems is crucial for proper understanding of the MASS capabilities under its OE. This nuanced classification is essential for safety, as it clarifies the roles of human operators and automation and sets requirements for system fall-back and handover procedures in the event of failures or emergencies.

Safety remains a paramount concern at all levels, as the transition from human-operated to autonomous systems introduces new risks related but not limited to system reliability, cyber threats, and the potential for reduced situational awareness among remote operators [6, 11]. The readiness of port infrastructure to accommodate MASS is a critical factor for the successful integration of autonomous vessels into the maritime domain. Modern ports are increasingly investing in digitalization and smart technologies, such as high-precision GNSS, LIDAR, radar arrays, IoT sensors, and 5G/6G communication networks, to support real-time data exchange, situational awareness, and remote supervision [12, 13].

Artificial Intelligence (AI), Digital Twins (DT) and Machine Learning (ML) research in the autonomous ship domain:

Some research related to Remote Operation Centre (ROC) and MASS has focused on AIS (Automatic Identification System) data as an input to training AI models to improve situational awareness by predictions [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36]. The VesselAI-project delivered trained, high-quality interpretable machine learning and deep learning models for classification, analysis and forecasting by using AIS historical and live data, also for detection of anomalies in traffic, as well as for prediction of possible routes. The follow-up project TwinShip, will utilize the platform developed in VesselAI to create ship digital twins based on AI and Machine Learning-driven analysis. In the HEU AUTOSHIP and AEGIS, work was done to present an overview of the most relevant applications of AI for autonomous ships and their limitations in the context of approval. The RCN (Research Council of Norway)-project Proxima focused on data processing of image data from radars and cameras to detect and track safety-critical objects around the ship. Machine learning algorithms were used for detection and classification of objects, and the extracted detections were then used to track objects on the sea surface to contribute to situational awareness. The high-level expert group on AI published an ethics guideline for trustworthy AI [37].

Situational awareness research for the ROC operator:

The EU project MUNIN [38] suggested that one ROC operator has the capacity to operate six ships at the most. Since then, many projects [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36], e.g., AEGIS and HEU AUTOSHIP have proposed mechanisms to delegate the responsibility between the ship and a ROC and have focused on a closer collaboration between technology and humans in control, e.g. through the use of Operational Envelopes. The Norwegian project "Smartere Transport" analysed the impact and effect of increased level of automation on the distribution of roles between onboard crew and ROC. The project IMAT focused on how to bring awareness to a ROC operator through development and testing of land-based sensors, communication systems and control systems, while the project MARMAN focuses on building knowledge regarding governance, management and work practice for maritime transport systems. Research port test beds, such as those in Bremerhaven, have demonstrated the use of distributed optical sensors and sensor fusion frameworks for ad hoc situational awareness, enabling online detection of relevant situations and reliable remote communication between onshore and offshore participants [12]. However, the heterogeneity of port infrastructure and the lack of harmonized standards for sensor integration and data exchange remain significant barriers. Safety is a recurring concern; failures in critical sensors or communication links could compromise the safe navigation and berthing of MASS, underscoring the need for robust redundancy, fail-safe mechanisms, and continuous monitoring.

Operational Envelope, Remote operation and human-machine interaction research:
Work on definition of the operational envelope for maritime, autonomous transport systems has been performed in several projects [14], including MUNIN, HEU AUTOSHIP, AEGIS for autonomous transport systems, and Autoflex and Seamless for operation of autonomous barges on inland waterways. The AutoTeaming project focuses on supporting human-machine teaming, enabling meaningful human control, i.e., ensuring sufficient systems and time to avoid accidents and incidents and for safe and scalable operations. LOAS investigated land-based supervision of autonomous ships. SFI Autoship is a Norwegian research-based innovation centre with the focus on enabling technologies like situational awareness, artificial intelligence, autonomous control and digital infrastructure, in addition to new business models and operational concepts, and methods and models for risk monitoring.

Research work on International standards and information exchange:
Work to support standardized information exchange between ship and shore have been proposed by many projects, such as the ISTS-project and in the ongoing DYNAPORT-project. Ongoing work to digitalize ports and assets is done in Digital Havn and AutoPort which aims to improve the efficiency of small-sized ports by using AI and Operational Research methods to automate and optimize cargo handling processes. OpenBridge and OpenRemote have focused on how to integrate different systems and equipment, how to provide interoperability regarding bridge equipment through standardized interfaces and protocols and human-machine interfaces, including AI as a method for developing new applications. The CySIMS project [14] investigated a public key infrastructure for the maritime domain to protect critical communication against cyber-attacks.

4. Discussion

To aid the discussion of the topics, the port call will be seen as missions of a MASS. These missions follow, in part, the proposed mission model of [39], with some rearrangements and simplifications. Figure 4 shows a high-level scheme of the chaining of the proposed missions, with a sub-set of the actors involved on the execution of these tasks. The main aspect of this scheme is to highlight the intricate web of collaboration between actors — namely the ship and the nautical services — and the movement between locations. The main locations being the Pilot Boarding Place (PBP) — where the incoming vessel usually meets with the assigned pilot and tugboats —, the berth, and the base of the nautical resources. For conventional operations, the arrows imply the physical movement of these actors in between the highlighted areas, while for MASS operations, it depends on the degree of automation employed by the MASS vessel and the port. For example, if the pilotage is completely remote, the arrows leaving from the Pilot imply a connection established between the MASS and ROC, and the pilot. For tugboats, although they could eventually be remotely operated or even autonomous, it still implies physical movement of assets.

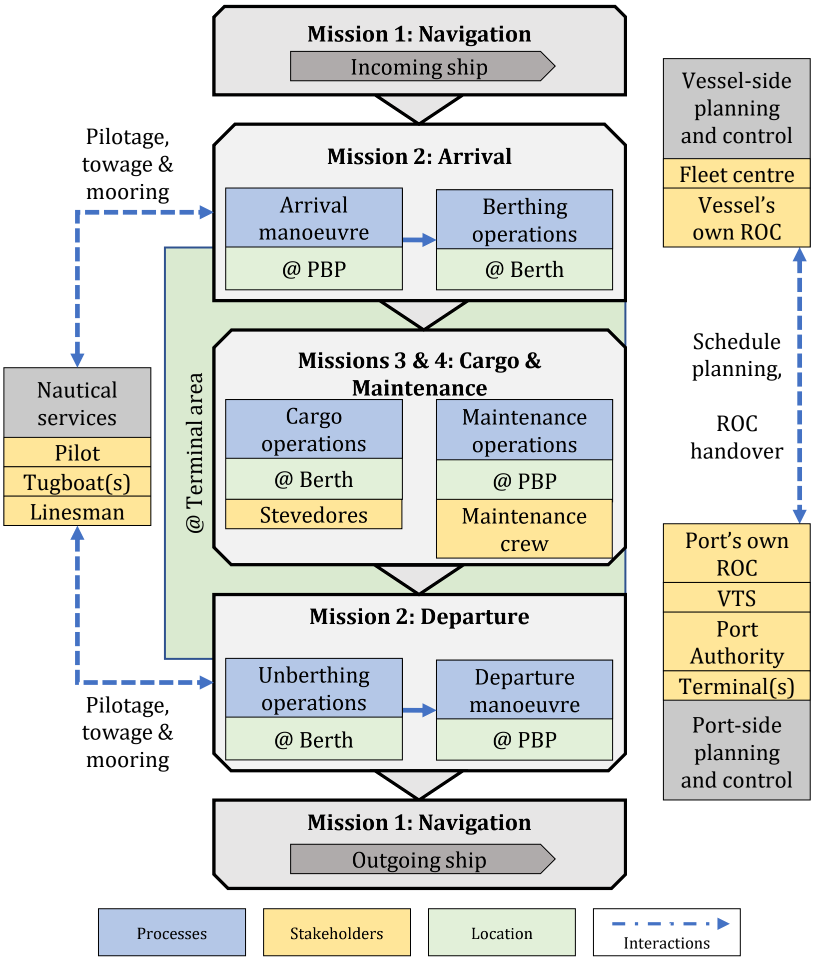


Figure 4. Order of missions

During normal operations (S1), MASS vessels can maintain constrained autonomous operation (L3-L4) while executing pre-programmed approach procedures, but environmental factors such as wind exceeding 10 knots or visibility dropping below 3 nautical miles trigger state transitions to S2 or beyond, requiring ROC operator assistance and potentially shifting to direct control (L1). The critical nature of these manoeuvres, taking place in confined port waters with high traffic density, means that the TMR values must be minimized to ensure rapid intervention when automated systems encounter unexpected situations or equipment failures. The following missions will explore in further detail the peculiarities of the operations carried within them, correlating to these and other important aspects.

4.1 Mission 1 : Navigation between ports

This mission deals with the open waters' navigation between two ports. In the scheme presented in Figure 4, this mission ends with the arrival of the ship to the port and starts again after the departure. Ocean navigation in conventional shipping relies heavily on human expertise and experience, with navigation officers maintaining continuous watch duties to ensure safe passage. Watch-keeping procedures require crew members to monitor navigation equipment, maintain situational awareness, and respond to changing weather conditions or traffic situations. Traditional navigation employs established protocols for position fixing, chart correction, and navigation equipment maintenance, with crew members required to be familiar with GPS, radar, ECDIS, and compass systems. Human decision-making remains paramount for route adjustments, weather routing, and collision avoidance, particularly when encountering unexpected situations or equipment failures. The experience and interpretation of the situation done by navigators on the spot is an essential aspect to provide safe operations, especially when combined with the application of maritime laws and regulations, such as for COLREGs [40]. A key aspect for this process to work is the communication between the several members of the crew while operations are carried. For autonomous systems, these operational concerns of conventional shipping remain, but with parts of the monitoring and decision-making capabilities being shifted from direct human assessment and intervention to automatized situational awareness and control systems, with shore-based intervention as support when the systems exceed the reach of their operational parameters. MASS depends on sophisticated sensor fusion, along with the processing of multiple data streams (such as from onboard MASS sensors on ship status, AIS, weather, satellites and the ROCs themselves) to provide these capabilities.

Essential for this operation are the ROCs being employed to support the MASS. Handover between ROCs along the route are expected due to operational and legal constraints, as contemplated by the high-level functional requirement FR16.2.12 [41]. The legal framework behind MASS operations is not yet fully developed [42], requiring intermediate interpretations to correlate with and follow, as best as possible, existing conventional shipping law. For example, while technically a ROC situated in one country might be able to control the MASS when sailing into another country's maritime domain, the responsibility of control might be required to be passed onto a ROC located at this next country, local presence. This might be repeated multiple times during the navigation between ports and within a port basin, but it will depend on the implementation of said ROCs along the usual shipping routes and coastlines, much like the VTS. Such infrastructure can also aid the situational awareness of environmental and traffic scenarios to be faced by the MASS while in transit, by having more precise local data and support available. The compatibility of these systems also comes into play. Such ROCs might be equipped with a wider range of systems to operate different technologies, which might only fulfil parts of the full capabilities of the MASS-own ROC. The suitability of the routes is to be assessed during voyage planning and monitored during the operation, as done on conventional operations.

Environmental constraints significantly impact the departure and navigation operational envelope. Weather conditions including wind speed, wave height, visibility, and precipitation directly affect vessel's performance. The operational envelope for ocean navigation encompasses several critical phases: following planned track, collision avoidance, and weather routing, each with specific state transitions based on environmental and traffic conditions [6]. The planned route should also be exchanged with VTSs and with other traffic.

Navigation between ports requires careful management of transitions between different operational envelopes as vessels move through various maritime domains. Here, the operational envelope defines interaction and states between automation systems and human operators, with clear protocols for handover between ROCs, or ROC operators, due to operational requirements, or when vessels cross jurisdictional boundaries. Only a single ROC must be responsible for a MASS at any one time, though multiple ROCs may be responsible sequentially during a single voyage under certain conditions [42]. Future development must address conditions allowing handover of responsibility between ROCs and issues arising when ROCs are located outside the flag state of a MASS. These considerations are essential for safe and efficient MASS operations across international waters while maintaining regulatory compliance and operational safety standards.

Navigation between ports represents the operational phase where MASS vessels can maintain the highest degree of autonomy, typically operating in S1 state for extended periods while processing multiple data streams from AIS, weather systems, and satellites. However, the handover process between different ROCs along international shipping routes requires careful management of operational envelope transitions, particularly when vessels cross jurisdictional boundaries or areas with high traffic, and must adapt to different communication protocols and regulatory requirements. The sensor fusion capabilities required for this mission directly support the A1-A8 parameter monitoring framework, where external factors (A3) such as wind, current, fog, and rain are continuously assessed against predetermined thresholds. Mission 2's complex operational requirements—encompassing ROC handovers across international waters, sensor fusion capabilities, and multi-jurisdictional coordination—cannot be effectively managed without robust standardized frameworks that ensure seamless interoperability between autonomous vessels and diverse port infrastructure systems.

4.2 Mission 2 : Departure and Arrival operations

Arrival and departure manoeuvres are two of the most complex and safety-critical processes of conventional shipping, requiring coordination between multiple systems and stakeholders. Following the scheme presented in Figure 4, this mission will deal with both arrival and departure manoeuvres as both share the main points of discussion fitting the scope of this paper. Vessels must navigate confined port waters, coordinate with vessel traffic services (VTS), and transition between port-confined and open-water navigation modes. For MASS operations, these characteristics remain present, now with the added complexity of a multitude of automatic and even autonomous systems to perform the same tasks. A major shift is the use of digital pilotage, where the Remote Operating Center (ROC) will digitally exchange information with the pilotage services for executing navigational commands and maintaining communication with traffic and port services.

In MASS operations, the ROC acts as the primary contact point for traffic and port services, managing permissions, communication, and integration with port infrastructure. Digital data exchange between the ROC and port—including berth coordinates and resource allocation—must be approved before execution. Service providers must adapt to MASS-specific procedures, such as tug line handling and line release timing. Cargo and maintenance information must be digitally coordinated for safe and efficient operations. Structured port call procedures are vital in supporting the operational envelope by standardizing communication, coordination, and data exchange between vessels, port authorities, and service providers. For MASS, such procedures enable seamless integration of digital data exchanges—such as berth coordinates, resource allocation, and cargo handling plans—ensuring that all stakeholders have synchronized and approved information before execution. This standardization enhances safety, operational efficiency, and regulatory compliance by providing clear protocols for data exchange, stakeholder coordination, and emergency response across different ports and operational phases. Moreover, the transition between operations —such as from port to open sea or between control centres—requires robust, standardized handover protocols. In MASS, this may involve a ROC-ROC handover or a switch from autonomous to manual control in critical situations. Structured port call procedures and digital integration are essential to ensure safe, efficient, and compliant operations throughout these transitions. Furthermore, autonomous ships must comply with the International Regulations for Preventing Collisions at Sea (COLREGs), which provide rules applicable to all vessels upon the high seas [43]. MASS navigation systems integrate multiple sensor technologies including positioning sensors, radar, sonar, Automatic Identification System (AIS) receivers, cameras, lidar, and microphone arrays to maintain comprehensive situational awareness [44]. The evolution from conventional to MASS operations in arrival and departure manoeuvres is characterized by a shift from manual, crew-based processes to digital, automated, and remotely managed workflows. The operational envelope for this mission is defined by environmental, technical, and regulatory parameters, all of which are increasingly managed through structured, standardized digital procedures that enhance safety, efficiency, and interoperability.

4.3 Mission 3 : Cargo-Handling Operations

This mission is established as a sub-process of the on-berth activities, shown in Figure 4. This allows us to focus on the most relevant parameters for cargo handling, avoiding much of the complexity of the overall system capabilities. Traditional cargo handling operations require extensive coordination between the ship's crew, the stevedores at the quay, and the terminal. Cargo handling operations for MASS vessels require sophisticated systems capable of managing loading, stowage, and unloading procedures. These can be implemented to multiple degrees of required human overseeing and interaction. Two main considerations emerge for MASS cargo operations: the compatibility with the port-own cargo-handling equipment, and the capability to perform the same monitoring and corrective tasks as the crew would be responsible for, respecting the operational envelope on which these operations are designed to be carried out.

For both conventional and MASS, the port call is not to be performed if the ship and the berth — regarding both physical limitations and operational capabilities — are not compatible. Additionally for MASS, the complexity of mixing MASS-own and port-own systems, ranging from L1 to L4, also comes into play for cargo handling. For instance, the vessel might have its own cranes, which can have automation built into it, or be remotely operated by either the ship's or the port's ROC. A similar situation might also be in place when using the terminal's equipment. Autonomous grab ship unloaders, implemented in Hamburg and Rotterdam ports, represent significant advances in automation for bulk cargo operations, using real-time 3D LiDAR scanners and GPS positioning systems to achieve the task [45]. In the context of developments on MASS pushing the autonomous capabilities of port processes, it is reasonable to assume that these future vessel's operations will be integrated with port-own future cargo handling solutions.

The MASS own operational envelope for cargo operations encompasses several critical components such as vessel stability and weight limitations, cargo type constraints and weather limitations. Additionally, the same list can be used to describe the operational envelope of the cargo handling systems themselves, which must also be considered for the planning of operations under this mission. Traditional stability assessment relies on the knowledge of the ship's stability, digital systems and calculations by qualified crew members, while MASS operations require these tasks to be carried by automated systems that can interpret stability data and make real-time adjustments. Further considerations regarding different cargo type require a deeper dive into each trade. For this, case studies based on the different trades have been proposed that extensively cover the aspects of MASS functions with port operations [43n].

Effective means of communication must be established between MASS ROC operators and cargo terminal representatives, remaining effective throughout cargo operations. Furthermore, reliable means to perform an emergency stop on operations must be in place and accessible for all actors involved, along with the backing legal limits and implications of such systems, yet to be fully developed. Here, the TMR must also be minimized, as cargo operations can pose a serious risk for operators and equipment.

The successful implementation of MASS cargo handling operations depends on coordinated development of vessel technologies, port infrastructure, and standardized communication protocols that enable seamless integration across different automation levels and operational scenarios. The transition to standardized port call operations will likely provide much of the necessary capability for port call planning and coordination between terminals and the MASS.

4.4 Mission 4 : Maintenance Operations While in Port

Traditional maintenance operations rely on experienced crew members who perform routine inspections, preventive maintenance, and emergency repairs using their technical knowledge and experience. Maintenance scheduling depends on crew availability and experience, with repairs often requiring improvisation and adaptation using available resources. Many of these operations are carried out while other main tasks are being performed, leveraging the multi-skilled nature of maritime crew members. This mission will focus on maintenance tasks carried out on port.

For MASS, this on-the-spot manual maintenance capability is either very limited or not build into the system, from having a small crew to being a fully un-manned vessel. Moreover, maintenance at sea is to be limited to inspections, software updates and minor repairs [39]. Instead, MASS relies on onshore maintenance during port calls, which might raise the cost and length of onshore operations [46]. To limit this impact, the scheduling of maintenance operations must be integrated with the planning of port calls and the time to be spent on berth. This brings two concerns: having the right assessment of what maintenance tasks must be performed, and the availability of the required minimal conditions for it to be performed.

The planning of maintenance operations is crucial to predict the extent and length of operations. Condition-based maintenance (CBM) represents a fundamental shift from scheduled maintenance to predictive interventions based on actual system conditions [11]. For MASS operations, CBM relies on remote maintenance systems to operate autonomously, identifying potential failures and reporting them for the scheduling of maintenance to be conducted, on top of scheduled periodic inspections and maintenances. The responsibility of organising these operations remains on the ship operator, however, the planning must be considered and communicated since the first steps into planning a port call.

The planning for maintenance activities happens under constraints, such as equipment availability, specialist technician access, and regulatory compliance. The first two points can be addressed while fitting the port to receive MASS operations and follows the same compatibility concerns as on mission 3. Thus, the solution to this matter lies in establishing a safety net of potential or even preferred stops for maintenance, along with on-board systems capable of detecting potential dangers in sufficient enough advance for this safety net to be effective. Moreover, to more effectively support the integration with MASS maintenance operations, ports might be persuaded to provide auxiliary specialized infrastructure for these operations. MASS-specific berths to allow such vessels to spend extended periods performing maintenance tasks, while not blocking an active quay, can become a solution. Economic viability of such berths, however, depends on in-depth business case studies, yet to be formulated. The operational envelope includes predictive accuracy requirements, maintenance resource availability, and emergency repair capabilities. A transition to standardized port call operations blueprints would likely facilitate the integration of MASS maintenance systems into port call planning and coordination. Real-time performance monitoring enables proactive maintenance planning compared to periodic assessment systems in traditional operations, which might help the MASS operator to decide, with time in advance, when and where to perform maintenance. Nonetheless, the successful implementation of MASS maintenance operations depends on coordinated development of vessel technologies, port infrastructure, and standardized communication protocols that enable seamless integration across different automation levels and operational scenarios.

4.5 Summary of missions

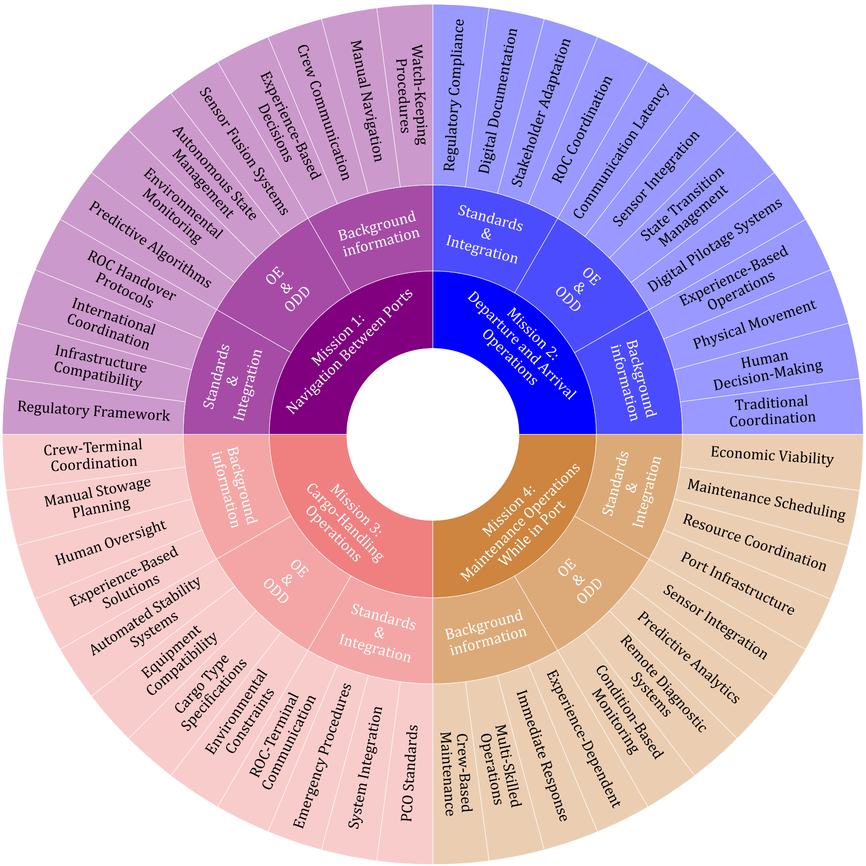


Figure 5. MASS Missions framework

The doughnut graph in Figure 5 consists of three concentric rings representing different levels of operational detail. The inner ring contains the four primary MASS missions, the middle ring divides each mission into three analytical categories, and the outer ring provides four specific sub-topics for each category, creating a total of 48 distinct operational elements. The analysis reveals varying complexity levels across missions, with departure/arrival operations presenting the highest integration challenges due to confined water navigation and intensive stakeholder coordination. Navigation operations, while technically sophisticated, benefit from extended autonomous operation periods. Cargo handling and maintenance operations present moderate complexity with significant standardization opportunities. All missions demonstrate the critical importance of sensor fusion, communication protocols, and automated decision-making systems. However, each mission requires specialized technological adaptations: real-time collision avoidance for navigation, stability monitoring for cargo operations, and predictive analytics for maintenance. The analysis consistently identifies standardization as a critical success factor across all missions. ROC coordination protocols, digital documentation systems, and regulatory compliance frameworks emerge as common requirements that must be addressed through industry-wide standardization efforts. Each mission demonstrates the evolution from human-centred to technology-centred operations while maintaining human oversight capabilities. The TMR/TDL parameter framework provides the critical bridge between autonomous operation and human intervention across all operational scenarios.

6. Conclusion and Outlook

The creation of a port call operations blueprint is one of the main tasks of the Dynaport project, with goals to facilitate port call optimisation, promote standardisation of procedures and enable just-in-time arrival of vessels. Beyond operational gains, these goals also converge to reduce emissions of operations, by allowing vessels to eco-sail towards the next port and reduce the lenght of unecessary stays at anchorage waiting for service. The blueprint is mainly divided into three layers, represented as complimentary in Figure 6. The Physical Operations Layer serves as the foundational component of the standardized port call blueprint, addressing the physical operations occurring both aboard vessels and within port facilities. This layer specifically focuses on the movement of ships, equipment, and personnel while integrating proposed solutions into specific operational contexts through analysis of coordination flows between stakeholders.

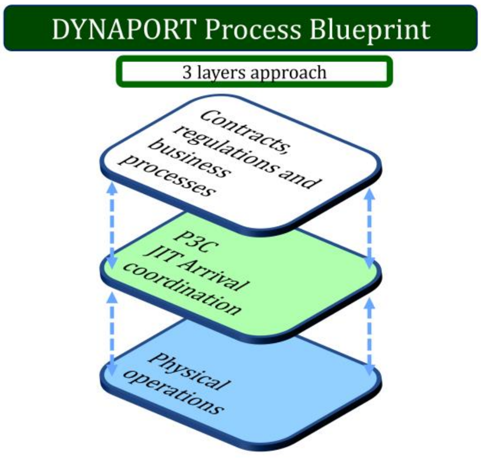


Figure 6. Dynaport blueprint

The blueprint adopts a generic approach applicable across different ports and trade scenarios, requiring the layer to accommodate operational variations while providing stable foundations for subsequent layers. The P3C (Port Call Coordination Centre) – JIT Arrival Coordination Layer represents the intermediate communication layer ensuring coordinated operations, that are essential for just-in-time arrivals.

The P3C concept introduces a centralized port coordination center to streamline communication between ships and ports, enabling efficient just-in-time arrival processes. This port-operated coordination center maintains responsibility for contacting incoming vessels and providing continuous operational support while serving as the central contact point for port stakeholders to coordinate their schedules efficiently. The top layer addresses contracts, regulations, and business processes governing proposed solutions. This layer analyses regulatory factors and proposes necessary modifications to enable effective JIT arrival coordination. For MASS operations, this layer incorporates the operational envelope management and state transitions based on information from both autonomous vessels and port infrastructure.

This blueprint, along with several other port call initiatives, leads into the direction of standardised port call procedures to be adopted widely in the industry. Coming into shape, acceptance, and, eventually, into force, it will also impact MASS operations. The discussions of this paper are meant to contribute with the bridging of this gap, by identifying, by the view of a port call, the most relevant parameters to consider when expanding to MASS operations. Using missions as examples of typical MASS operations, and have highlighted the differences between conventional and autonomous vessels. Use of operational envelopes, as well as how to change states based on information both from the MASS as well as from the infrastructure as has been pointed as important.

Conventional contracts regulate transportation through speed and service specifications, which can be adapted for MASS operations at different scales. Contract for MASS must also include the approvals to operate into port, with control from a remote location that might be in a different country. Contracts are also crucial to service providers to the MASS, for example to maintenance crew or terminal workers in a port. Permission and obligation to exchange information between ship and P3C includes the ability to get access to ICT systems and sensors in a port, that will be essential to build awareness to a ROC for MASS operation. The business processes with four mission examples are described in this paper, to give an understanding how MASS can operate, where conventional shipping and results from Dynaport has been the building blocks.

For MASS operations there are some important take-aways for success full implementation of autonomous vessels, gaps identified of relevance to port calls and operations

1. The clarification of **general terms and definitions** within the DYNAPORT project is fundamental importance as it lays the base for accurate communication and a thorough understanding of the various concepts in the project. This is highly relevant also for MASS, that needs some extra terms and definitions, that must be standardized.
2. **ICT architecture** standards have a crucial role in optimising and increasing the efficiency of port call processes, as they provide the technical basis for communication and integration between various systems and stakeholders involved in port operations. Applying these standards ensures that all systems involved can seamlessly interact with each other. This counts both for conventional as well as for autonomous operations. Without an open ICT architecture, it will be hard to build awareness and for the autonomous technology to operate.
3. **Undefined tasks, roles and responsibilities of a ROC operator:** Ambiguity in roles and procedures can lead to inconsistent decisions and inefficient operations, especially when a MASS are entering a port or when executing port operations such as unloading and loading.

4. **Undetermined automation requirements:** Unclear requirements for MASS operation in port areas, a ROC's legality to remote control and operate, and unclear procedures to allow integration with port infrastructure.
5. **Undefined approval processes and regulatory changes:** There is a lack of clarity around the approval of MASS operation to ports. Does a MASS operator have to document the systems AI-based training sets? Additionally, guidelines for trustworthiness, system development, minimum viable product criteria, and distinctions between DSS and AI systems are not well defined and not standardised. An example is that task allocation lacks clear criteria for ROC operator skills and workload, and OE for how to do handovers—both between humans and automation, and across ROCs. This also addresses the use of OE, and how to set values such as for TDL and TMR.
6. **Lack of clear communication protocols/messages/standards between ROC, MASS, port infrastructure, and service providers to MASS:** There are no standardized protocols for sharing safety procedures, emergency responses, or operational updates, which may compromise MASS safety. OE's is also proprietary solutions that are not standardised. Additionally, the role of digital assistance tools in fostering trust and awareness are poorly understood. Explainable AI should be the norm. Documented requirements and formal processes for resource allocation to MASS operations in ports are also missing.

As port call optimisation and standardisation is further developed, and the development of the MASS environment continues, both are on track to be fully integrated in the near future.

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