# Report

## Feasibility Study for an Unmanned Deep Sea Bulk Ship and Short Sea Container Ship

**Author(s):**

Odd Erik Mørkrid, Pauline Røstum Bellingmo, Egil Wille

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**Client(s)** (pos partner):

SFI Autoship

SINTEF Ocean AS
Postal address:
Otto Nielsens veg 10
7465 Trondheim

Switchboard: +47 46415000

Enterprise /VAT No:
NO 937 357 370 MVA

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**AUTHOR(S)**
Odd Erik Mørkrid, Pauline Røstum Bellingmo, Egil Wille

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**ABSTRACT**

Autonomous ships have gone from being an odd research topic to becoming reality within cargo transport. However, so far both research and commercial projects have focused on smaller ships, with a certain route between specific ports and operating purely in national waters. This report investigates whether it is feasible to operate a large cargo ship, freely on any route, visit any port, and sail in national and international waters, just like a conventional ship. The feasibility is assessed based on technical, regulatory, and commercial (economic, environmental, and social) aspects. The conclusions are based on a traffic light model, where green means feasible today, yellow within five years, and red five years or beyond. The results show that a fully autonomous cargo ship is not feasible today. However, individual functions on the ship can be automated with economic and environmental gains. To learn which functions, you should read this report!

**PREPARED BY**
Odd Erik Mørkrid

SIGNATURE
Odd Erik Mørkrid
Odd Erik Mørkrid (Feb 7, 2023 10:03 GMT+1)

**CHECKED BY**
Håvard Nordahl

SIGNATURE
Håvard Nordahl
Håvard Nordahl (Feb 7, 2023 13:51 GMT+1)

**APPROVED BY**
Trond Johnsen

SIGNATURE
Trond Johnsen (Feb 7, 2023 22:38 GMT+1)

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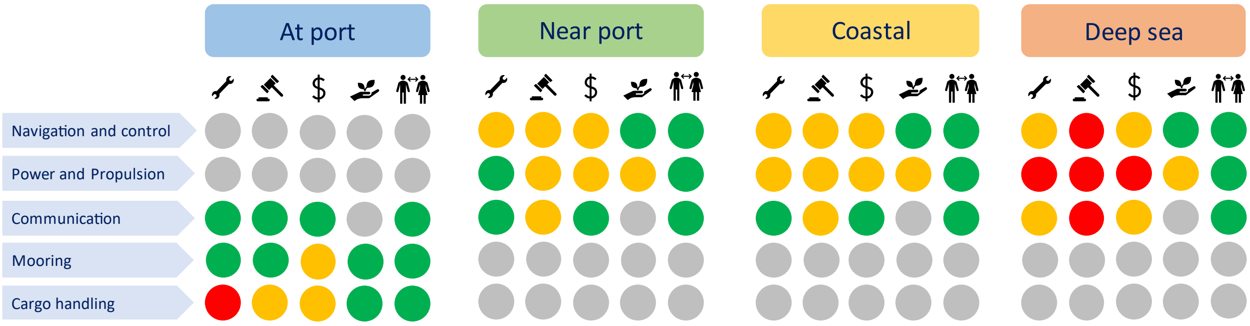
# Executive Summary

With increasing pressure to reduce the environmental footprint, increase safety, lack of seafarers, and high competition on cost, the maritime industry has started to investigate autonomous ships as an alternative to conventional ships. Automation can remove people from hazardous operations, such as mooring and cargo handling, and thus increase the safety. Moreover, autonomous ships are an enabler for energy efficiency measures, such as weather routing, which can contribute to reduce the environmental footprint. Today there is a lack of seafarers, which is expected to decrease even more in the future. Autonomy in ships can reduce the needed manning. Additionally, since crew cost accounts for about half of the operational expenditure (OPEX), a lot can be saved by reducing the manning, especially by moving well paid officers on shore. Moreover, superstructure on the ship, such as bridge and hotel areas, can be removed on unmanned ships, making the ship cheaper to build and enabling the ship to be smaller and/or transport more cargo. This will reduce the energy for transport per cargo unit. However, unmanned ships may introduce redundancy requirements that would increase the cost.

The objective of this feasibility study is to evaluate if it is feasible to operate large, unmanned cargo ships with human support from a ROC, i.e., constrained autonomy (see Section 2.1), that can operate in international waters. In this study, the term cargo ship is used to include deep sea break-bulk and short sea container ships. A prerequisite for the study is that the ship is operating in international waters and can visit any port. Additionally, it is assumed that the unmanned cargo ship is a new build and without superstructure, and Norwegian regulations are considered when discussing national regulations.

The feasibility is evaluated based on technical, regulatory, and commercial assessments. Moreover, to evaluate the feasibility of an unmanned cargo ship, the voyage is divided into different operational phases: *At port*, *near port*, *coastal* and *deep sea*. Next, the functions performed on board a cargo ship today is divided into different crew tasks: *Navigation and control*, *propulsion system*, *communication*, *cargo handling*, and *mooring*. Lastly, the feasibility of performing each task autonomously is evaluated for each operational phase. The evaluation is based on input from the project partners and other available sources.

The results of the feasibility study are summarized in Figure 1. The columns show the different phases, and the rows show the different tasks (functions). The feasibility of a constrained autonomous cargo ship is evaluated from a technical (🔧), regulatory (🔨), and commercial (economic, environmental and social $ 🌱 👫) point of view. The traffic lights indicate whether it is feasible or not to automate the given task. A green light indicates that it is feasible today, a yellow light indicates a that it is feasible within the next 5 years, while a red light indicates that it is not feasible within the next 5 years.



| | At port | | | | | Near port | | | | | Coastal | | | | | Deep sea | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 🔧 | 🔨 | $ | 🌱 | 👫 | 🔧 | 🔨 | $ | 🌱 | 👫 | 🔧 | 🔨 | $ | 🌱 | 👫 | 🔧 | 🔨 | $ | 🌱 | 👫 |
| Navigation and control | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | 🟡 | 🟡 | 🟡 | 🟢 | 🟢 | 🟡 | 🟡 | 🟡 | 🟢 | 🟢 | 🟡 | 🔴 | 🟡 | 🟢 | 🟢 |
| Power and Propulsion | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | 🟢 | 🟡 | 🟡 | 🟡 | 🟢 | 🟡 | 🟡 | 🟡 | 🟡 | 🟢 | 🔴 | 🔴 | 🔴 | 🟡 | 🟢 |
| Communication | 🟢 | 🟢 | 🟢 | ⚪ | 🟢 | 🟢 | 🟡 | 🟢 | ⚪ | 🟢 | 🟢 | 🟡 | 🟢 | ⚪ | 🟢 | 🟡 | 🔴 | 🟡 | ⚪ | 🟢 |
| Mooring | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ |
| Cargo handling | 🔴 | 🟡 | 🟡 | 🟢 | 🟢 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ |

**Figure 1: Summary of technical, regulatory, and commercial feasibility of unmanned cargo ship.**

As can been seen from Figure 1, there are some yellow and red lights, indicating that an unmanned cargo ship is not feasible today. For the *at port* phase, autonomous cargo handling is the most challenging. Automated mooring is possible and commercially available in the market today. For the *near port* phase, *navigation and control* task is the most challenging w.r.t autonomy, where object detection and classification seem to be too immature. For the *coastal* phase, the navigational challenge from *near port* remains, but also the propulsion system can be a challenge due to possible failures or maintenance needs. For *deep sea*, the main challenge is the propulsion system, which needs to be functioning without failures for the whole duration, which can be up to 1.5 months. Moreover, navigation should be easier in this phase as there is less traffic, but communication with a ROC can be limited by coverage, bandwidth, and latency. However, this depends on what is needed to be communicated to a ROC in this phase, which is not yet determined.

Taking the Norwegian regulations as an example of national regulations, the regulations are adapted to the use of unmanned ships. However, as there are no large, unmanned ships operating today, any approval of operation must be tested and evaluated for every operational concept. A test period demonstrating the performance of the system is required before any approval is given (for example, the autonomous ship Yara Birkeland is given two years of test period). Thus, to get an approval for operating unmanned is rather time consuming. However, looking at the international regulations, there are still large hurdles to overcome before a ship can operate unmanned.

From a commercial perspective it seems that the economic impacts from an unmanned cargo ship are not clear, mostly because no unmanned ship of this size has yet been built. Uncertainties are, among other things, cost savings with removal of superstructure versus more expensive and redundant technology, operational cost of a ROC, and new alternative fuels and engine types which we do not currently have experience with. Environmental and social impacts, however, have mostly been considered positive. Environmental is positive because autonomy often goes hand in hand with energy efficiency measures and to possibility to increase cargo capacity if superstructure is removed. Social impact is considered positive since the focus has been to remove people from hazardous operations and move officers on shore, as there is and will be a shortage of seafarers.

This overall conclusion from the study shows that there are still some challenges to be solved before large cargo ships can operated unmanned (under the given assumptions). However, for small and medium size vessels, unmanned operation with human support from a ROC can be feasible today or in near future within certain concept of operations (CONOPS), especially in national waters where there exist regulations for autonomous ships. To operate an unmanned ship internationally, regulatory challenges related to e.g. IMO, can be solved by bilateral agreements between the countries involved. Moreover, even for a large cargo ship, some of the individual tasks can be automated today or in the near future with economic, environmental, and/or social benefits.

# Definitions

The following terms related to autonomy are defined in the ISO/TS 23860:2022 (ISO, 2022).

**Uncrewed:** Ship with no crew onboard.
Note: Crew does not include passengers, special personnel etc.

**Unmanned:** Ship with no humans onboard.

# Abbreviations

| **Expressions and abbreviations** | **Description** |
|---|---|
| AIS | Automatic Identification System |
| ANS | Autonomous Navigation System |
| ASM | Application Specific Messages |
| CAPEX | Capital Expenditure |
| CLTE | Coastal Long-Term Evolution |
| COLREG | Convention on the International Regulations for Preventing Collisions at Sea |
| DFFAS | Designing the Future of Full Autonomous Ship consortium |
| DNV | Det Norske Veritas |
| EMSA | European Maritime Safety Agency |
| FSS Code | Fire Safety Systems Code |
| GHG | Green House Gas |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| HiNAS | Hyundai intelligent Navigation Assistant System |
| IALA | International Association of Lighthouse Authorities |
| IBC Code | International Bulk Chemical Code |
| ICG Code | International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk |
| IMDG Code | International Maritime Dangerous Goods Code |
| IMO | International Maritime Organization |
| IMSBC Code | International Maritime Solid Bulk Cargoes Code |
| IMU | Inertial Measurement Unit |
| IR | Infrared |
| ISM | Instrumentation, Scientific, and Medical bands |
| LEO | Low Earth Orbit |
| LiDAR | Light detection and ranging |
| LL Convention | International Convention on Load Lines |
| LNG | Liquefied Natural Gas |
| LOS | Line of Sight |
| MAiD | Marine Autonomous Intelligent Docking |
| MASS | Marine Autonomous Surface Ships |
| MBR | Mobile Broadband Radio |
| MGO | Marine Gas Oil |
| MRC | Minimum Risk-Condition |
| NCA | Norwegian Coastal Administration |
| NF | Near Field |
| NFAS | Norwegian Forum for Autonomous Ships |
| NMA | Norwegian Maritime Authority |

| | |
|---|---|
| OPEX | Operational Expenditure |
| ROC | Remote Operation Centre |
| RSE | Regulatory scoping exercise |
| SAR Convention | International Convention on Maritime Search and Rescue |
| SD | Standard Definition |
| SFI | Senter for Forskningsdrevet Innovasjon (Center for Research driven Innovation) |
| SOLAS | Safety Of Life At Sea |
| STCW Convention | International Convention on Standards of Training, Certification and Watchkeeping for Seafarers |
| TOE | Tonnage of Oil |
| UNCLOS | The United Nations Convention on Law of the Sea |
| VDE | VHF data exchange |
| VDES | VHF Data Exchange System |
| VHF | Very High Frequency |
| VLSFO | Very low sulfur fuel oil |
| VoiP | Voice over Internet Protocol |
| VOYEX | Voyage Expenditure |
| VSAT | Very Small Aperture Terminal Systems |
| VTS | Vessel Traffic Service |
| WP | Work Package |

## Project Background

This report is a deliverable in work package 5 "Sustainable Operations" in SFI Autoship. The main objective of SFI AutoShip is to leverage on the competencies of the complete Norwegian maritime cluster and consolidate Norway as a leading global actor within autonomous ships. The project is divided into eight work packages (WPs), as shown in Figure 2.

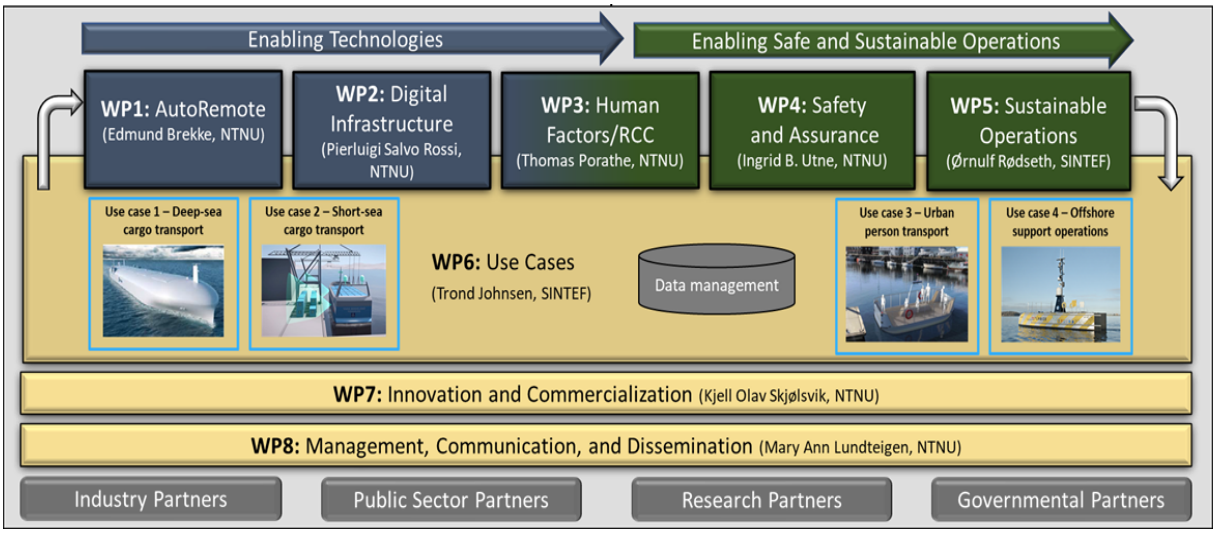


**Figure 2: SFI Autoship project structure.**

The objective of the use cases is to demonstrate the applicability and value-adding potential of research and innovation results from the center and disclose new problems for further research. There are four use cases (as seen in Figure 2), and this document will focus on use case 1: Deep sea bulk shipping and use case 2: Short sea container shipping.

# 1 Introduction

With increasing pressure to reduce the environmental footprint, increase safety, and high competition on cost, the maritime industry has started to investigate autonomous ships as an alternative to conventional ships. By automating the sailing of a ship, one can remove the difference between "bad captains", e.g. unexperienced captains sailing without taking into consideration the ship and weather, and "good captains" that optimize the route based on experience. Thus, automated navigation can reduce the environmental footprint. For ships with periodically unmanned functions (e.g. bridge) the officer on watch gets reduced workload, making it easier to comply with rest hour regulations, making time for other tasks, and can reduce the crew cost. As the crew cost constitutes about half of the operational expenditure (OPEX), a lot can be saved by reducing the manning. Moreover, for unmanned ships, crew related superstructure on the ship, such as bridge and hotel areas, can be removed, making the ship cheaper to build and enabling the ship to be smaller and/or transport more cargo. However, unmanned ships may introduce requirements on redundant systems that will increase the cost.

Autonomous cargo handling will increase the safety by removing people from the cargo handling operations. For a ship sailing autonomously, the navigation is typically less challenging due to low traffic density and reduced grounding risk in deep sea operations. The downside of autonomous deep sea operations is that land-based infrastructure, e.g. for communication and observation, is not available. For short sea operations, land-based infrastructure may be available for the whole voyage, which makes it easier to operate remotely and transmit and receive data on the ship.

Autonomous ships have been in the spotlight for a while and now there are some commercial initiatives that aims to operate autonomous ships, such as the autonomous container ship YARA Birkeland[1], ASKO's autonomous vessels[2], and the autonomous vessel Mayflower[3]. However, these ships are not operating constrained autonomously today (i.e., without humans onboard but with human assistance). A constrained autonomous ship is defined as follows (Jan Rødseth & Nordahl, 2017):

***Constrained autonomous:*** *The ship can operate fully automatic in most situations and has a predefined selection of options for solving commonly encountered problems, e.g. collision avoidance. It has defined limits to the options it can use to solve problems, e.g. maximum deviation from planned track or arrival time. It will call on human operators to intervene if the problems cannot be solved within these constraints. The SCC or bridge personnel continuously supervises the operations and will take immediate control when requested to by the system. Otherwise, the system will be expected to operate safely by itself.*

More on different levels of autonomy is described in Section 2.1. The objective of this feasibility study is to establish an understanding on whether it is feasible to introduce and operate constrained autonomous ships in the short sea and deep sea segment. Further, this study will investigate possible technical, regulatory, and commercial obstacles related to constrained autonomous short sea container ships and deep sea bulk ships. The outcome and results of this study will be used as input to further research in SFI Autoship.

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[1] https://www.yara.com/news-and-media/press-kits/yara-birkeland-press-kit/

[2] https://smartmaritimenetwork.com/2020/09/01/asko-to-build-two-autonomous-vessels-for-oslo-fjord-operations/

[3] https://mas400.com/

**Figure 3: An unmanned bulk ship. Courtesy: Kongsberg Maritime.**

## 1.1 Assumptions

1) In this report, by "cargo ship" is meant container ship and bulk ship.
2) With bulk ship is mean only break bulk ship in this report.
3) It is assumed that the cargo ship operates in international waters.
4) In this report some crew tasks related to the operation of a cargo ship are evaluated. However, the list of tasks is not complete, but limited to the tasks shown in Figure 6.
5) Safety is not directly considered in this report, but partly covered in regulatory chapter.
6) In the regulatory feasibility, the Norwegian regulations are considered when operating in national waters.
7) This report does not focus on the autonomous systems handling of sensor deviations and failures.

# 2 Background

This chapter describes the background information used in this report.

## 2.1 Levels of autonomy

When talking about autonomy on a ship level, it is useful to define what is meant my autonomy in the context of this report. Therefore, the levels of autonomy defined by NFAS serve as a relevant reference (Jan Rødseth & Nordahl, 2017):

- ***Decision support****: This corresponds to today's and tomorrow's advanced ship types with relatively advanced anti-collision radars (ARPA), electronic chart systems and common automation systems like autopilot or track pilots. The crew is still in direct command of ship operations and continuously supervises all operations. This level normally corresponds to "no autonomy".*
- ***Automatic:*** *The ship has more advanced automation systems that can complete certain demanding operations without human interaction, e.g. dynamic positioning or automatic berthing. The operation follows a pre-programmed sequence and will request human intervention if any unexpected events occur or when the operation completes. The shore control centre (SCC) or the bridge crew is always available to intervene and initiate remote or direct control when needed.*
- ***Constrained autonomous:*** *The ship can operate fully automatic in most situations and has a predefined selection of options for solving commonly encountered problems, e.g. collision avoidance. It has defined limits to the options it can use to solve problems, e.g. maximum deviation from planned track or arrival time. It will call on human operators to intervene if the problems cannot be solved within these constraints. The SCC or bridge personnel continuously supervises the operations and will take immediate control when requested to by the system. Otherwise, the system will be expected to operate safely by itself.*
- ***Fully autonomous:*** *The ship handles all situations by itself. This implies that one will not have an SCC or any bridge personnel at all. This may be a realistic alternative for operations over short distances and in very controlled environments. However, and in a shorter time perspective, this is an unlikely scenario as it implies very high complexity in ship systems and correspondingly high risks for malfunctions and loss of system.*

In these definitions the use of SCC correspond to what is called Remote Operation Center (ROC) in this report.

## 2.2 Communication Coverage

The coverage of the communication systems is divided in the categories listed in Table 1.

**Table 1: Categories of coverage for communication systems (Hagaseth & Rødseth, 2021).**

| Class | Description |
|---|---|
| NF | Near field, on the order of 1 to some 100 meters |
| LOS | Line of sight, approximately 10-20 km |
| A0 | Coverage in some coastal areas |
| A1 | General coverage in coastal areas |
| A2 | Regional sea coverage |
| A3 | Global coverage, except latitudes ±70° |
| A4 | True global coverage |

## 2.3 Autonomous Ship Initiatives

There are several ongoing projects for autonomous ships today. Below is a list with some initiatives.

- **Yara Birkeland**. Aims to be the world's first fully electric and autonomous container vessel and is developed by Yara and Kongsberg[4].
- **ASKO ferries.** ASKO Maritime has ordered 2 fully electric autonomous ro-ro (roll-on/roll-off) cargo ferries to carry truck trailers across the Oslo Fjord[5].
- **Milliampere.** Small autonomous passenger ferry that is being tested in Trondheim.
- **Zeabus**. Small autonomous passenger ferry to be used in urban areas.
- **Fugro Blue Shadow.** A small, uncrewed surface vessel for hydrographic and geophysical surveys [6].
- **Reach Remote.** Developing uncrewed surface vessel for survey, inspection, and light repair [7].
- **Ocean Infinity.** Has an uncrewed offshore ship and remote control centers, in addition to some smaller uncrewed vehicles [8].
- **DFFAS.** The MEGURI2040 project Designing the Future of Full Autonomous Ship (DFFAS) is working to develop solutions for the fully autonomous ships of the future and performed a 790km sea trial between Tokyo Bay and Ise Bay demonstrating the latest technology related to autonomous route planning, collision avoidance and remote fleet operation centre (including remote emergency response system) with the containership Suzaku in February 2022. A documentary of the effort has been released[9]. The system has been tested for offshore maneuvering, coastal navigation, and bay navigation. This included navigation in congested sea areas, for instance the ship had to pass the Tokyo Bay where roughly 500 ships pass daily (The Nippon Foundation, 2021).
- **Avikus.** Another "world's first" autonomous ship demonstration was announced recently by South Korean shipbuilder Hyundai Heavy Industries (HHI) and its autonomous navigation subsidiary Avikus[10]. The companies claim the cargo ship Prism Courage, an "ultra-large" liquid natural gas tanker operated by SK Shipping, completed the first (partly) autonomous transoceanic journey in a large merchant ship in May 2022[11]. Other efforts to develop autonomous ships for commercial use are led by Samsung Heavy Industries Co[12] and China[13].
- **Revolt**. Unmanned short sea vessel concept by DNV[14].
- **Mayflower.** Autonomous Ship developed by main partners ProMare and IBM that will use an AI captain to cross the Atlantic Ocean completely autonomously[15].

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[4] https://www.kongsberg.com/no/maritime/support/themes/autonomous-ship-project-key-facts-about-yara-birkeland/

[5] https://www.massterly.com/news-1

[6] https://www.fugro.com/about-fugro/our-expertise/remote-and-autonomous-solutions/remote-and-autonomous-vessels

[7] https://reachsubsea.no/reach-remote-project-update/

[8] https://oceaninfinity.com/ourtechnology/

[9] https://www.nyk.com/english/news/2022/20220425_01.html

[10] https://safety4sea.com/hhi-navigates-fully-autonomous-passenger-boat/

[11] https://www.offshore-energy.biz/hyundai-heavy-conducts-worlds-first-transoceanic-voyage-of-lng-carrier-on-autonomous-navigation/

[12] Samsung Autonomous Ship (SAS): https://www.kedglobal.com/shipping_shipbuilding/newsView/ked202110170002

[13] https://maritime-executive.com/article/china-reports-first-autonomous-containership-entered-service

[14] DNV ReVolt project website: https://www.dnv.com/technology-innovation/revolt/

[15] Mayflower Autonomous Ship Webpage: https://mas400.com/

# 3 Methodology

To evaluate the feasibility of a constrained autonomous cargo ship, the voyage is divided in different operation phases, see Section 3.1. Next, the functions performed on board a cargo ship today is divided in different crew tasks, see Section 3.2. Lastly, the feasibility to perform each task constrained autonomously is evaluated for each operation phase as described in Section 3.3. The evaluation is based on input from the project partners and other available sources.

## 3.1 Operational Phases

The different operational phases of a cargo ship are illustrated in Figure 4. There are four phases including *at port*, *near port*, *coastal*, and *deep sea*.

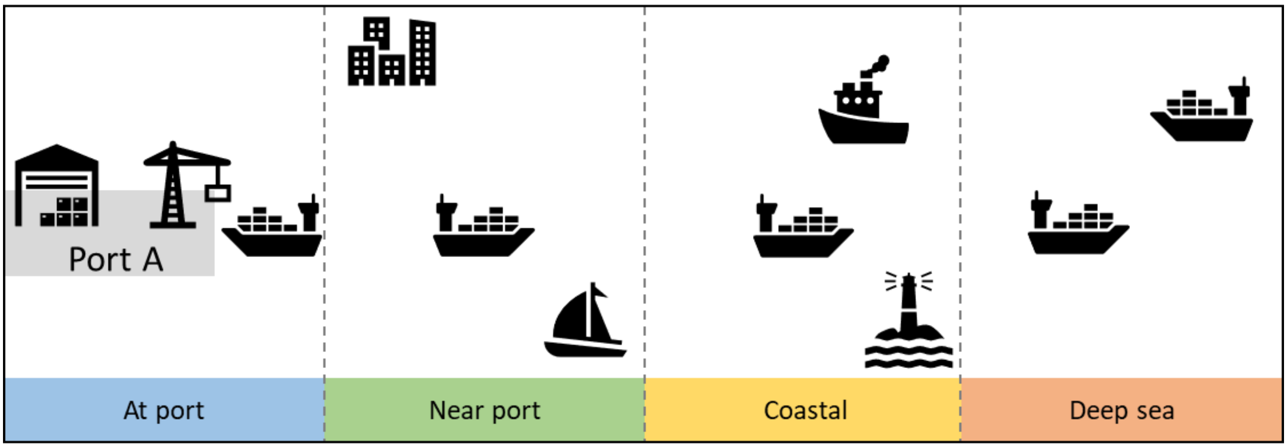


**Figure 4: Operational phases for a deep sea bulk ship.**

### At port

The *at port* operational phase is defined as the phase where the ship is stationary at a port. Typical tasks performed in this phase includes mooring of the vessel and handling the cargo. The cargo handling includes on-loading and off-loading and securing cargo.

### Near port

*Near port* is defined as the phase where the ship is approaching or leaving a port. In this phase the ship is typically moving slowly, e.g. when docking, and there may be several vessels and leisure activities in the area.

### Coastal

*Coastal* is defined as the phase where the ship is operating in a congested traffic area or confined waters. In this phase, navigating the vessel may be a challenging task.

### Deep sea

*Deep sea* is considered as the phase where a ship is operating in open sea, typically with a low traffic density and little maneuvering, as the ship typically follows a straight route.

## 3.2 Crew tasks

In order to operate a vessel unmanned, the automation must be able to do the same tasks and functions as the crew do today. To identify the obstacles for operating a vessel unmanned, we start by looking into the tasks performed by crew on board cargo ships today in addition to remote control. This includes:

1. **Navigation and control**: Navigation is the act of getting a vessel from one location to another. This is typically performed at the bridge of the vessel and includes observing the surroundings to get a situational awareness, planning the route to travel based on this situational awareness, and steering and controlling the vessel according to the desired route.
2. **Power and Propulsion**: The crew is responsible to monitor, maintain, and repair the propulsion and support systems (Nedcon Maritime, 2013). The crew is also responsible for other systems, such as power generation, steering, lighting, air conditioning, and electrical power. Maintenance: A lot of maintenance is done by the crew every day.
3. **Communication**: Today, the crew perform different types of communication at the ship. This includes ship-ship communication, i.e., communication with other ships for instance to avoid possible conflicts, and ship-shore communication, e.g, with a Vessel Traffic Service (VTS) or a port authority. In the future, more data would need to be communicated for a ship to operate safely unmanned. Communication with agents (from the port) and planning of the next port call (need to enter correct terminal and have an available berth etc), discussing timing, just-in-time, tide water, labor for cargo operations, contact with governments (customs) etc. For a constrained autonomous ship, it will need human assistance by humans in an ROC. Communication between the ship and ROC is also included in this task.
4. **Mooring:** When the ship has reached its destination, it needs to be moored before it can start off-loading the cargo. The mooring typically includes ropes and mooring lines to secure the vessel to the quay. The mooring task does not include any maneuvering to the dock (docking) and assumes that the ship is at the dock when this task starts.
5. **Cargo handling**: The cargo handling includes on-loading and off-loading (in most cases by the means of a crane), preparing dunnage, cargo monitoring, and securing cargo in the hold.
6. **Other**
   - **Safety:** This must be considered in all the other mentioned tasks as well. Examples: distress signals where the vessel must assist as required, evacuation of people and/or cargo.
   - **Firefighting:** Handling fire hoses, operating fire extinguishers (e.g. CO2 and water mists controlled by the crew), closing fire doors, mustering etc. E.g. investigating where the source of fire is and close the correct quick closing valves.
   - **Ballast & bilge:** To operate ballast, bilge, cargo and fuel pumps. Ballasting is mainly done at the terminal, during cargo handling. Ballast exchange at sea is only done if there is a problem with the Ballast Water Treatment System due to a technical failure or unfavorable environmental conditions (e.g., dirty ballast water). The ballast water is not allowed to be discharged if the water is untreated or does not contain the same local fauna (e.g. when going from San Diego to Los Angeles).
   - **Maintenance:** Maintenance is not only performed related to the propulsion system, but to the whole ship. E.g., hull, hatch covers, deck, cranes, lights for navigation, various electrical systems, and safety equipment.
   - **Access to the ship:** Crew must be able to board the ship to perform different tasks, such as cargo handling. To board the ship, a gangway or other equipment must be set up safely.
   - **Administrative:** Bill of lading, legal responsibility for cargo, customs/security/ISPS
   - Other tasks are also performed related to the operation of a cargo ship but is not included here.

In this study, the tasks under "other" will not be evaluated to limit the scope. The evaluation will include tasks 1-5 as illustrated in Figure 5. However, a brief discussion of the "other" task will be included.

**Figure 5: Illustration of crew tasks.**

## 3.3 Assessments

The feasibility of a constrained autonomous cargo ship is evaluated from a technical (🔧), regulatory (🔨) , and commercial ( $ 🌱 👫) viewpoint. Moreover, each of the crew tasks are evaluated for each of the operational phases that are applicable. For instance, the mooring task is only applicable for "at port" operation phase. To do the assessment, a traffic light model is used, where each color indicates the feasibility the tasks for each operation phase. The different colors are defined as follows:

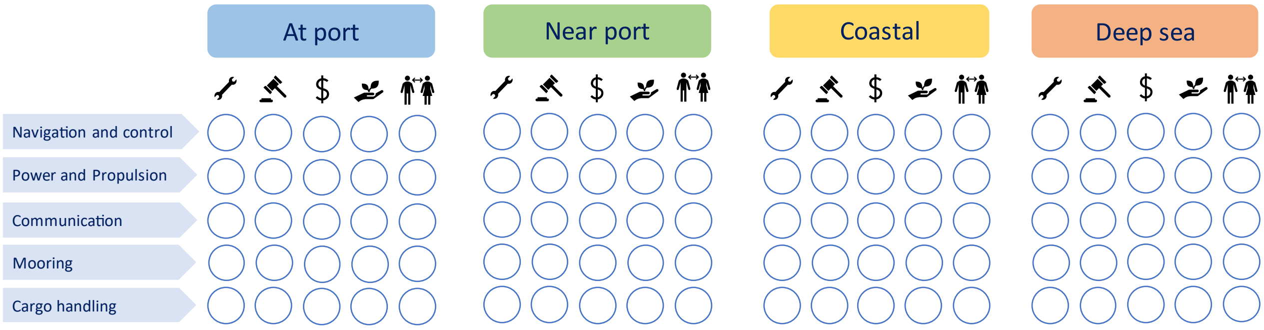
🟢 Feasible today

🟡 Not feasible today, but within the next 5 years

🔴 Not feasible or unrealistic, in the next 5 years

⚪ Not applicable

More specific definitions for the traffic lights are defined for technical (Chapter 5), regulatory (Chapter 6), and commercial (Chapter 7). The feasibility will be summarized as illustrated in Figure 6, but here without colors.



| | At port | | | | | Near port | | | | | Coastal | | | | | Deep sea | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 🔧 | 🔨 | $ | 🌱 | 👫 | 🔧 | 🔨 | $ | 🌱 | 👫 | 🔧 | 🔨 | $ | 🌱 | 👫 | 🔧 | 🔨 | $ | 🌱 | 👫 |
| Navigation and control | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Power and Propulsion | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Communication | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Mooring | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Cargo handling | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

**Figure 6: Example figure illustrating a summary of the technical, regulatory, and commercial feasibility.**

# 4 Use Cases

This report covers the two use cases "deep sea bulk ship" and "short sea container ship". This chapter describes the prerequisites for these use cases.

## 4.1 Deep sea Bulk Ship Operations

Before starting the feasibility study on unmanned deep sea bulk shipping, it is paramount to understand how the ships are operated.

**Figure 7: Star Lysefjord. Courtesy: Wolfgang Plapp.**

In this study we use the Grieg Star bulk ship *Star Lysefjord* as an example case, see Figure 7. This is an L-class break bulk ship with the following characteristics[16]:

- Deadweight: 50 728 mt
- LOA: 204.4 m
- Beam: 32.26 m
- Draft: 12,7 m
- Gross reg. tons: 37 447 mt
- Cranes: 4 x 75 mt Jib, combinable to 150 mt

One typical trade for Grieg Star bulk ships is from Europe to the USA. This trade uses a couple of days between ports in Europe, about two weeks to cross the Atlantic, and a few days between ports in the USA. Another trade is from Chile to China, which takes one and a half month. In the south of Chile conventional satellite communication has bad coverage and availability. In this trade the bulk ship operates several days in areas where communication availability and bandwidth are limited.

### 4.1.1 Propulsion

The use case bulk ship is equipped with a main propeller in addition to a bow thruster and a flap rudder. A deep sea bulk ship typically uses a diesel engine for propulsion with very low sulfur fuel oil (VLSFO) where the regulations require maximum 0.5% Sulphur content, while the cleaner fuel Marine Gas Oil (MGO) is used where maximum 0.1% Sulphur is required. Each ship can experience about two outages annually. The most common maintenance performed on these ships are caused by clogged separators and filters. With the use of VLSFO as fuel, maintenance must be performed every 4th-8th hour in worst case. With other cleaner fuel, there is less clogging and thus less maintenance that needs to be performed.

### 4.1.2 Docking, mooring and cargo handling

These bulk ships can have up to four cranes on board the vessel. Each crane can carry up to 75 mt with an outreach of 26 m. Mooring typically takes 1-2 hours. The ships mainly use tugboats to assist when docking today, but has bow thruster and flap rudder to reduce the amount of tugs needed.

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[16] https://griegstar.com/vessels/

## 4.2 Short sea Container Ship

Before starting the feasibility study on unmanned short sea container ship, it is paramount to understand how the ships are operated.

In this study we use the container ship NCL Averøy as an example case, see Figure 8. The ship has the following characteristics[17]:

- Deadweight: 11206 mt
- LOA: 134.4 m
- Beam: 22.74 m
- Draft: 8.8 m
- Gross tons: 9990 mt
- Cranes: 2 x 45 mt
- Capacity: 886 TEU

**Figure 8: NCL Averøy. Courtesy: NCL.**

The NCL container ships mostly have trades out from Rotterdam, Hamburg and Bremerhaven and along the Norwegian coastline up to Finnsnes (sometimes Tromsø). A roundtrip from Rotterdam to Orkanger takes about one week and similarly for Finnsnes (Tromsø) it takes about two weeks. These numbers include time spent on cargo handling. In these trades the ships operate in the *coastal* and *deep sea* phases and cross Norwegian, Dutch, German, and international waters. The ships mainly dock by themselves without the use of tugboats but may need docking assistance when the weather is rough. All the ships have certified pilots, but an external pilot is required in the Port of Rotterdam.

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[17] https://griegstar.com/vessels/

# 5 Technical Feasibility

This chapter will establish if constrained autonomy is technically feasible for a deep sea break bulk ship and a short sea container ship (see Section 2.1 for levels of autonomy). The technical feasibility will be evaluated for each of the tasks "navigation and control", "propulsion system", "cargo handling", "mooring", "communication", and "ROC" (see Section 3.2). Moreover, each task is evaluated for each of the defined operation phases "at port", "near port", "coastal", and "deep sea" (see Section Operational Phases3.1). For each task we have defined different high level acceptance criteria to evaluate whether it is technically feasible or not. If not specified otherwise, the acceptance criteria are the same for both the bulk ship and the container ship use cases. The definition of the traffic lights for the technical feasibility is described in Table 2. The content of this chapter is based on inputs from different partners in the SFI Autoship including Grieg Star, Maritime Robotics, Massterly, SINTEF Ocean, and SINTEF Digital.

**Table 2: Definition of traffic lights for technical feasibility.**

| | |
|---|---|
| 🟢 | Satisfies all acceptance criteria today |
| 🟡 | Some acceptance criteria are not satisfied today but expected within 5 years. |
| 🔴 | Most acceptance criteria are not satisfied today and is not expected within the next 5 years. |
| ⚪ | Not applicable |

## 5.1 Navigation and Control

To navigate a vessel, one needs to gain situational awareness, i.e., observe, detect, and classify objects in the surroundings of the vessel, plan the path depending on these surroundings and according to the maritime rules, and steer the vessel according to the planned route while ensuring the safety of the ship, crew, and cargo. To gain situational awareness one needs to observe and detect the surroundings of the vessel. This includes to observe and detect objects surrounding the vessel, e.g. other vessels, kayaks, and shore. Additionally, the weather conditions should be observed to gain a complete situational awareness. Historically, a situational awareness around the vessel has been gained by one or more people looking at the surroundings. Today, many vessels are equipped with several sensors used to observe and detect the surroundings and the motions of its own vessel. This may include Global Navigation Satellite System (GNSS), radar, lidar, compass, IMU, camera, speed log, echo sounder, and weather sensors. A path planner should not only try to avoid collisions but also try to find the optimal path for the ship. The path to be sailed must be planned based on the gained situational awareness and according to maritime rules considering the maneuverability of the vessel.

**Existing solutions**

There exist several solutions for automated navigation and control today, see examples below:

- Sea Machines. Sea Machines offers the autonomous self-piloting system SM300 that fuses data from radar, differential GPS, AIS, camera, and depth sounder (Sea Machines, 2022). The SM300 includes obstacle detection and classification and predicts their course and uses this to reroute the vessel if needed while complying with the Convention on the International Regulations for Preventing Collisions at Sea (COLREG). The SM300 has been tested on a tugboat sailing around Denmark where 97% of the 1000+ mile journey was sailed constrained autonomously including 31 collision avoidance and traffic separation maneuvers[18]. The tugboat was remotely commanded from Boston where they had access to the state of the vessel, situational awareness of the surroundings, real-time vessel-borne audio, and video from many streaming cameras.

- Avikus. Avikus develops the navigation assistant system Hyundai intelligent Navigation Assistant System (HiNAS) (Avikus, 2022). HiNAS fuses data from radar, ais and camera and uses AI to automatically detects objects. The fused sensor data helps the captain gain situational awareness. The solution also includes algorithms for collision avoidance and grounding alarms to assist the navigation. Avikus has conducted a transoceanic voyage of a large 300 m LNG carrier using HiNAS[19].
- DFFAS[20]. The autonomous navigation is based on cameras and 3 types of radars capturing 3 different frequency bands, including mm-wave radar to detect small targets. The collision detection and avoidance are performed by the Advanced Routing Simulation and Planning unit that bases the decision-making on a *Preference model* that captures the navigational preferences of the ship's captains in an attempt to generate the most appropriate manoeuvre for each situation based on extensive data of past voyages[9]. The navigation system has been tested on a 95 m container ship for 800 km in coastal areas of Japan.
- Orca AI. Orca AI has developed a collision avoidance system using high resolution and thermal cameras (Orca AI, 2022). The collision avoidance system can also integrate other existing sensors on the vessel.
- Kongsberg. Kongsberg can detect, classify, and observe objects, obstacles, vessels, and shoreline[21]. For instance, the navigation and autonomous operations of YARA Birkeland is delivered by Kongsberg and will be supported by several proximity sensors, including a radar, a light detection and ranging (LIDAR) device, an automatic identification system (AIS), a camera system and an infrared (IR) camera[22]. The systems also include object detection and collision avoidance.
- Captain AI. Another example is Captain AI that has developed a navigation system that can plan paths in real-time and steer the vessel accordingly. The situational awareness is based on object detection and classification from fusing radar, camera, GPS, sonar, and AIS. This has been tested with a patrol vessel in the Port of Rotterdam[23].

A general note for all these solutions is that details of what they include and their performance is lacking. The autonomous navigation systems are summarized in Table 3.

**Table 3: Autonomous navigation systems.**

| **Solution** | **Data** | **Algorithm** | **Tested (ship, area)** |
|---|---|---|---|
| Sea Machines | Radar, differential GPS, AIS, camera, and depth sounder. | Obstacle detection and classification, path planning. | Tugboat, coastal area. |
| Avikus | Radar, ais, and camera. | Object detection, collision avoidance and grounding alarms | Large tanker, deep sea. |

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[18] https://gcaptain.com/tug-completes-1000-nautical-mile-autonomous-voyage-around-denmark/

[19] https://www.prnewswire.com/news-releases/hd-hyundais-avikus-successfully-conducts-the-worlds-first-transoceanic-voyage-of-a-large-merchant-ship-relying-on-autonomous-navigation-technologies-301559937.html

[20] DFFAS = Designing the Future of Full Autonomous Ship consortium.

[21] https://www.kongsberg.com/no/maritime/products/situational-awareness/

[22] https://www.kongsberg.com/no/maritime/support/themes/autonomous-ship-project-key-facts-about-yara-birkeland/

[23] https://www.captainai.com/news/captain-ais-autopilot-successfully-tested-in-the-port-of-rotterdam/

|  |  |  |  |
|---|---|---|---|
| DFFAS | Cameras and 3 types of radars capturing 3 different frequency bands, including mm-wave radar to detect small targets. | Object detection, collision detection and avoidance, path planning | Container ship, coastal. |
| Orca AI | Cameras | Collision avoidance | Unknown |
| Kongsberg | Cameras, radar, lidar, AIS, GNSS. | Object detections and classification, collision avoidance | Container ship and ferries, coastal |
| Captain AI | Radar, camera, GPS, sonar, and AIS | Path planning | Patrol vessel, near port. |

The following subsections will investigate the feasibility of constrained autonomous navigation during the operation phases defined in Chapter 3, i.e., near port, coastal, and deep sea. Notice that the phase "*at port*" is not relevant for the navigation and control task. For the navigation and control task, the challenges related to handling the navigation for deep sea bulk ships and short sea container ships are assumed to be similar, since the use case bulk and container ships are both large vessels that sail slowly (see Chapter 4). When bulk and container ships are evaluated together, the term cargo ship is used to referrer to both. However, for the docking operation, there is a large difference between the two ships, as the deep sea bulk ship typically needs to be assisted with tugboats to perform the docking, while the short sea container ship typically docks by itself.

### 5.1.1 Near Port

**Acceptance Criteria:**

1) The vessel can handle navigation in a congested area with ships and leisure activities but might need human assistance if the traffic picture is too complex or in case of unforeseen events.
2) The vessel can dock by itself without assistance from tugboats.

Table 3 shows that there exist several solutions in the market for autonomous navigation that include situational awareness and path planning, where some of these have been tested for large cargo ships. However, based on the information available from the system providers, it is unclear if the solutions satisfy Acceptance Criteria 1, i.e., complex navigation near port. Based on interviews with technical partners in the project, the biggest challenge for autonomous navigation is the object classification. For instance, when an object is detected, it is vital for the navigation system to know what the object is (e.g. a bulk ship, kayak or tugboat) and how the object is moving. In order to get accurate object classification, a lot of data is needed to train the machine learning algorithms. Today, there is a lack of enough quality data to develop highly accurate object detection algorithms. Thus, Acceptance Criteria 1 is not fully satisfied for both uses cases (bulk and container ship).

When a vessel approaches a port, it must perform docking, i.e., sails from the fairway area to a dock where it stops. Un-docking is performed when the vessel sails from the dock to the fairway. To satisfy Acceptance Criteria 2, the ship must dock autonomously. Autonomous docking has been demonstrated by some actors. For instance, MAiD (Marine Autonomous Intelligent Docking) Systems claims to have developed and tested an autonomous docking system for marine vessels that can accurately control the velocity of the vessel and calculate a safe path to the selected docking location (MAiD Systems, 2022). According to MAiD, the autodocking system can be used for a variety of vessels, including cargo and container ships, but there is no information regarding actual usage of this system. Additionally, the DFFAS (Designing the Future of Full Autonomous Ship) has performed autonomous docking maneuvering for a 95 m container ship (NYK Line, 2022). Another provider is Kongsberg Maritime that offers automatic docking for ferries (Kongsberg Maritime, 2022). This system is used on the Bastø Fosen ferry today. However, there is limited information on the performance of these docking systems, which makes it uncertain if there are operational limits to the docking systems, e.g., weather limitations.

**Short sea container ship**

For a container ship, the docking is typically done without assistance from tugboats, meaning that the ship has sufficient actuation to perform docking on its own. However, due to the uncertainty of the performance of the autodocking systems, Acceptance Criteria 2 is not fully satisfied. Since both Acceptance Criteria 1 and Acceptance Criteria 2 are not fully satisfied today for short sea container ship, but expected to be satisfied within the 5 years, a yellow light is given.

**Deep sea bulk ship**

As described in Section 4.1, the use case bulk ship is normally assisted by tugboats to perform docking today. However, a newbuild ship can be designed to be fully actuated, making it easier to dock by itself. Nevertheless, a new ship with full actuation will come with an additional cost compared to using an existing ship. As mentioned for short sea container ship, the performance of today's autodocking systems are uncertain. To fully satisfy Acceptance Criteria 2, the ship must be able to dock by itself at any port in the world, which is not guaranteed for today's autodocking systems. Since both Acceptance Criteria 1 and Acceptance Criteria 2 are not fully satisfied for a deep sea bulk ship in near port, but expected to be satisfied within the 5 years, a yellow light is given.

### 5.1.2 Coastal

**Acceptance Criteria**

3) The vessel can handle navigation in a congested traffic area but might need human assistance if the traffic picture is too complex or in case of unforeseen events. For instance, if the traffic picture is complex, a human operator may need to communicate with nearby vessels and decide on who is doing what.
4) Can navigate in confined waters without physical pilotage on board.
    a. Avoid groundings and keep a safe distance from land.

As mentioned at the beginning of Section 5.1, navigating the use case bulk and container ships are assumed similar since they are both large and slow vessels. Thus, for the coastal operational phase, both use cases are evaluated together.

In the coastal operational phase, the navigation system must be able to handle navigation in a congested traffic area where the COLREGs are unambiguous to satisfy Acceptance Criteria 4. As for the near port navigation, the challenge is to have accurate object classifications, which is not in place today. Thus, Acceptance Criteria 4 is not fully satisfied.

To safely guide a vessel into or out of a port or navigating in a hazardous area, a pilot with local knowledge is used (International Maritime Organization, 2022). The pilot has local knowledge and can effectively communicate with shore. Today, this requires a person to board the vessel to guide it. As outlined in (Porathe, 2022), this becomes an issue for unmanned vessels, as the pilot has nowhere to go. Porathe suggest a MASS routing service based on an automatic local information center currently researched in the IMAT project[24] as a possible solution to this issue. In other words, a digital pilotage service providing this

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[24] https://www.sintef.no/projectweb/imat/

local knowledge and expertise. However, to the authors knowledge, solutions to handle the pilotage for autonomous ships has not been demonstrated yet. For a constrained autonomous ship, the ship can have human assistance from an operator in an ROC. Assuming that the ROC operator is a certified pilot for the area in question, Acceptance Criteria 5 can be satisfied. However, this is a topic for further research.

For the coastal operation phase, Acceptance Criteria 5 can be satisfied (under the given assumptions), but Acceptance Criteria 4 is not fully satisfied today due to the object classification challenge. Thus, orange light is given in the traffic light model.

### 5.1.3 Deep Sea

**Acceptance Criteria**

5) Can navigate in open sea with low traffic density without human support for a long period of time.

As mentioned, navigating the use case bulk and container ships are assumed similar since they are both large and slow vessels. Thus, for the deep sea operational phase, both use cases are evaluated together.

In deep sea, the communication coverage and availability are typically poor. Additionally, if communication is available, the performance (e.g. bandwidth and latency) is often limited. This means that the ship needs to operate without human support for some periods of time, depending on the availability. As the deep sea operational phase is characterized by little traffic and open sea, the navigational challenge should be easier. As for the other operational phases, accurate object classification is a challenge to gain situational awareness. However, since there are less objects to detect deep sea, this challenge might not be so predominant for this phase. Assuming that the object classification is correct, planning the route and steering the vessel should in this phase be a feasible task. In conclusion, Acceptance Criteria 6 for deep sea is not fully satisfied due to the limitation of today's object classification. Hence, a yellow light is given for deep sea for both bulk ship and short sea container ship (see Figure 9).

### 5.1.4 Conclusion

Figure 9 shows the conclusions of the technical feasibility of constrained autonomous navigation and control for deep sea bulk ships and short sea container ships. Navigation and control is not applicable when the ship is at port, but a yellow light for the other phases due to the limitations of today's object detection and automated docking.

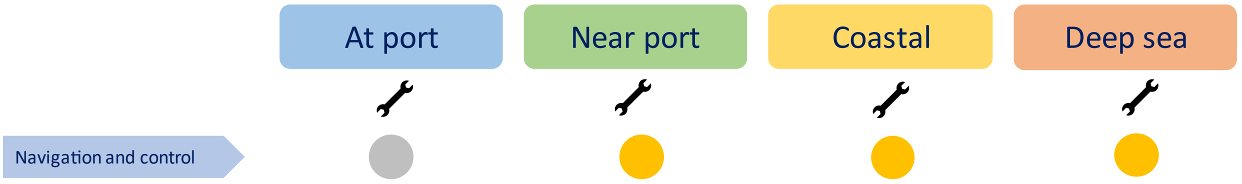

**Figure 9: Technical feasibility for navigation and control for an unmanned cargo ship.**

## 5.2 Power and Propulsion

Assuming that the ship is moored while at port, this operational phase is not applicable for this task.

**Acceptance Criteria**

1) Condition monitoring and fault prediction is possible.

Acceptance Criteria 1 is considered independent of the different operational phases. Regarding Acceptance Criteria 1, there exists solutions for condition monitoring e.g., Kongsberg Maritime' condition monitoring solution[25] for engines, generators, compressors, thrusters, and pumps. Additionally, there are some solutions for fault prediction and research on this subject. For instance, Kongsberg's Health Management service[26] that claims to reduce unplanned maintenance and avoid disruption, using the information available from the condition monitoring solution. However, there is a lack of information on the performance of the condition monitoring and fault prediction systems. Another example of this, is the DFFAS' trial simulating a fully autonomous operation of a container ship, where the fleet operation center had functions for engine-abnormality prediction to support the operation of a fully autonomous ship from shore (NYK Line, 2022). However, as stated by Mitsubishi Heavy Industry[27],

> "One of the biggest issues of a fully automated vessel is fault prediction, and enhanced engine monitoring technologies that monitor motor conditions are being developed and tested as well".

Moreover, the existing condition monitoring systems focus on the larger components, while smaller sub systems connected to the propulsion system, such as a leakage on a pipe, are not covered by these systems. As such, condition monitoring and fault prediction has some solutions, but as the performance and coverage of systems is uncertain, Acceptance Criteria 1 partially satisfied today.

In addition to being able to monitor and predict faults for the propulsion system (Acceptance Criteria 1), the propulsion system must be able to operate without downtime or need for maintenance if the task is going to be performed without human intervention. If a ship can operate without downtime or maintenance depends on the sailing time for the ship between ports. To evaluate if this is feasible, we define different acceptance criteria depending on the expected operational time windows for the different phases.

### 5.2.1 Near Port

**Acceptance Criteria**

2) Can operate without downtime or need for maintenance for up 2 hours.

As described in Section 4.1, deep sea bulk ships are typically equipped with a diesel engine using VLSFO. Using this propulsion system and fuel, the ships typically experience two outages annually, but need maintenance performed about every 4-8th hour due to clogged separators and filters at the worst. Since the worst-case maintenance need is less frequent than 2 hours, Acceptance Criteria 2 is satisfied, giving a green light (see Figure 10).

### 5.2.2 Coastal

**Acceptance Criteria**

3) Can operate without downtime or need for maintenance for less than a week.

As mentioned in the "near port" phase, maintenance is needed every 4-8th hour in worst case using typical propulsion system for a large cargo ship today. This means that Acceptance Criteria 3 is not satisfied today, as the ship cannot operate without intervention for a week. However, this is a conservative evaluation based on current propulsion systems and the economic fuel VSLFO which has higher need for maintenance compared to cleaner fuels which are more expensive. The need for a propulsion system without downtime on a voyage, in addition to the focus on more environmentally friendly ships, creates a need to look at other

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[25] https://www.kongsberg.com/no/maritime/products/engines-engine-room-and-automation-systems/condition-monitoring/

[26] https://www.kongsberg.com/maritime/services/kongsberg-remote-services/health-management/

[27] https://www.marinelink.com/news/worlds-first-fully-autonomous-ship-493576

propulsion systems and energy sources. To the authors knowledge, there is not an easily available overview of uptime and maintenance needs for the different propulsion systems and energy sources. For some shorter voyages in the coastal phase, batteries may be used as the energy source, which is expected to operate without much downtime or need for maintenance. Considering the expected development of alternative propulsion systems and energy sources in near future, a yellow light is given for the task propulsion system in the coastal phase (see Figure 10). Different propulsion systems and energy sources will be further discussed in the commercial feasibility, see Chapter 7.

### 5.2.3 Deep Sea

**Acceptance Criteria**

4) Can operate without downtime or need for maintenance for more than a week.

Like the other operation phases, considering a large cargo ship that uses a diesel engine running on VSLFO, maintenance may be needed every 4-8th hour. This means that Acceptance Criteria 4 is not satisfied with the propulsion system and fuel typically used today, as the system would be required to operate for more than a week without intervention. As mentioned in Section 5.2.2, an overview of expected uptime and maintenance related to different propulsion systems and energy sources are not easily available today (to the authors knowledge). In the future, Acceptance Criteria 4 may be satisfied using other propulsion systems and energy sources, but this is not expected to happen in the next five years. As such, a red light is given to the task propulsion system for the deep sea phase (see Figure 10).

### 5.2.4 Conclusion

Figure 10 shows the conclusions for technical feasibility of constrained autonomous propulsion system for the different operational phases.

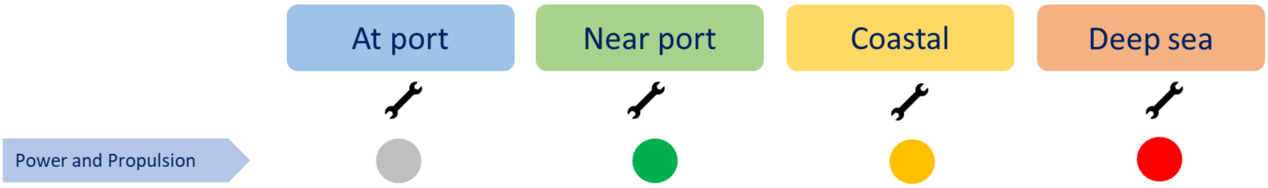

**Figure 10: Technical feasibility of propulsion system for an unmanned cargo ship.**

Based on this, the feasibility for the use case ships, i.e., deep sea bulk ships and short sea container ships, are evaluated in the following subsections.

#### *5.2.4.1 Deep sea bulk ship*

As described in Section 4.1, a deep sea bulk ship operates different routes and can have sailing times up to 1.5 months. This means that a constrained autonomous bulk ship must be able to operate for 1.5 months without failures that cause downtime. Assuming that all voyages of a deep sea bulk ship involve the operational phase "deep sea", which has been given a yellow light (see Figure 11), unmanned propulsion system is not feasible for a deep sea bulk ship today.

#### *5.2.4.2 Short sea container ship*

A short sea container ship can operate many different routes with varying length and sailing time. As described in see Section 4.2, the use case container ship can have voyages up to two days sailing time between ports operating in the "coastal" phase. For short sea container ships with voyages up to two weeks, unmanned propulsion system is not feasible today as "deep sea" is given a red light (see Figure 11). However, for shorter voyages of less than a week (coastal), this is considered feasible within the next five years.

## 5.3 Communication

A ship must communicate with other vessel (ship-ship communication) and with ports, authorities (ship-shore communication). Additionally, a constrained autonomous ship (see Section 2.1 for definition) may need human assistance either from crew onboard or from an ROC. Since human assistance from crew onboard is the convention today, this will not be covered in this section. However, advances in autonomous system can enable reduced manning onboard the ship, which will require new technologies and solutions. This is discussed in Section 5.6. Human assistance from an ROC on the other hand, is currently under development for some autonomous ship initiatives, where there are still some challenges that needs to be investigated. Although many systems and technologies are required to operate a ROC, this section will focus on the communication requirements for a ROC.

Communication with other ships, ports and authorities is typically performed using voice communication system such as Very High Frequency (VHF) radio. It is possible to digitalize the VHF communication, e.g. by using Voice over Internet Protocol (VoIP), but this still requires a human operator to be ready to answer at all times, e.g. in an ROC. Sometimes, ships communicate with each other by voice communication to resolve traffic challenges and the operators agree on who takes what action. This can be solved by always having an ROC operator ready to communicate and take control of the unmanned vessel. Another alternative is to exchange the route between ships. However, this requires that route exchange systems are installed on all ships, not only the autonomous ships. Furthermore, for this to work without further voice communication, the COLREGs needs to be explicit on how to behave in any situation and not include room for interpretation. Some actors are looking into route exchange, but this is not expected to be on alle vessel in the near future. Thus, a human operator, either on the bridge or in an ROC must be present to handle voice communication for an autonomous ship. For an unmanned vessel, the voice communication must be transferred from the vessel to an ROC where humans can respond.

For remote operation of a vessel, lots of data needs to be transferred from the vessel to the ROC. For instance, this may include sensor data from the vessel (both internal and external), such as radar, camera, and status of engines and mechanical parts in addition to control commands need to be sent to the vessel in order to remotely control the vessel and voice communication. Exactly what data needs to be communicated between an autonomous vessel and an ROC are not certain at the moment. However, what is certain is that remote operation requires a reliable and safe communication system with sufficient bandwidth and latency.

Communication performance differs depending on where the ship is. The need for human assistance can also differ based on the operational phase of the ship. For instance, near port operation may require more human assistance due to the navigational challenges compared to deep sea operation. Table 4 gives a summary of some common digital communication systems that can be used for maritime operations. This includes VHF Digital Exchange Systems (VDES) (IALA, 2018), Mobile Data Services (HBR radiofrequency technologies, 2022; Ho et al., 2018), Very Small Aperture Terminal Systems (VSAT) (Rodseth et al., 2015), Low Earth Orbit (LEO) Systems (Space Explored, 2022; Spaceflight 101, 2022), Local Real-Time Communication Systems (Kongsberg, 2019; Lee et al., 2021). The coverage of the communication systems is defined in Section 2.2.

**Table 4: Comparison of digital communication technologies.**

| **Communication technology** | **Bandwidth [Mbps]** | **Coverage** | **Latency [mean ms]** | **Available** |
|---|---|---|---|---|
| Mobile Data Services | | | | |
| 4G | 60-350 | A0 | 50 | Now |

|  |  |  |  |  |
|---|---|---|---|---|
| CLTE | 10-100 | A1 | 50 | Now |
| 5G | 1000 – 20 000 | A0 | 1 | Now |
| Satellite Systems |  |  |  |  |
| VSAT | 0.1-100 | A2 | 350 | Now |
| Iridium | 1.5 | A4 | 200 | Now |
| Starlink | 300 | A3-A4 | 99 | 2023 |
| Local Real-Time Communication Systems |  |  |  |  |
| 5G private network | 100 – 20 000 | LOS | 1 | Now |
| ISM | 1 | NF | 1 | Now |
| MBR | 0.7-17 | LOS | 1 | Now |

*CLTE = Coastal Long-Term Evolution. *ISM = Instrumentation, Scientific, and Medical bands. *MBR = Maritime Broadband Radio. *LOS = Line of Sight.

What communication system is best suited will depend on the operational phase, i.e., port area, coastal, or deep sea. Requirements for autonomous ship and ROC communication are not easily available. The requirements depend on what needs to be communicated. For instance, if video needs to be communicated to the ROC, the bandwidth required depends on the video quality. For high resolution video HD 1080p, 5 Mbps may be needed, while for low resolution video SD 360p only 0.7 Mbps may be needed[28].

Nevertheless, the ROC will use all the bandwidth that is available and need to prioritize on what is communicated depending on the bandwidth limitations. It is assumed that the ship enters a minimum risk condition state if the communication is lost in a challenging situation.

### 5.3.1 At Port

At port the ship needs to be moored and the cargo needs to be handled. If the cargo handling is operated remotely, there are certain criteria that needs to apply. Today, the requirements to do the cargo handling remotely are not yet defined.

**Acceptance Criteria**

1) Near Field (NF) communication coverage is required.
2) Gain situational awareness to remotely operate deck cranes during cargo handling from an ROC.
3) Remote control deck cranes during cargo handling from an ROC.
4) Must be able to communicate with other vessels, authorities, and ports in real-time.

When the ship is at port, all the communication systems listed in Table 4 have a coverage of at least near field. Thus, Acceptance Criteria 1 is satisfied if one of these systems are used. To satisfy Acceptance Criteria 2, the communication system must have high bandwidth and low latency. To get sufficient situational awareness in an ROC to remotely operate deck cranes, we assume that HD 1080p video of needs to be transferred, giving a minimum bandwidth requirement of 5 Mbps. Additionally, other data may need to be transferred to the ROC to get situational awareness. MBR and 5G private network have sufficient bandwidth and low latency (1 ms) and can satisfy Acceptance Criteria 2 and 3.  Since communication between the ship and the ROC is available, Acceptance Criteria 4 can be satisfied by transferring voice communication (e.g. from VHF radio) to and from a ROC where an operator handles the communication. As all the acceptance criteria are satisfied, a green light is given for communication at port (see Figure 11).

### 5.3.2 Near Port

In this phase the ship needs to be docked and navigate between other vessels and leisure activities.

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[28] https://www.vdocipher.com/blog/video-bandwidth-explanation

**Acceptance Criteria**

5) LOS communication coverage is required.
6) Gain situational awareness around the autonomous ship at all times.
7) Possible to remotely control a ship when docking and maneuvering on demand.
8) Must be able to communicate with other vessels, authorities, and ports in real-time.

Many of the communication systems have coverage that satisfy Acceptance Criteria 5. Data from several sensors may be needed to gain a situational awareness at the ROC, e.g., camera, radar, and lidar. Exactly which sensor data is needed at an ROC is not certain at this moment, and the requirements for the bandwidth and latency will depend on the sensor data being transferred. Assuming that SD video (1080p) needs to be transferred to the ROC to gain situational awareness, this requires about 0.7 Mpbs. Other sensor data required will add to the required bandwidth. To remotely control a ship near port, low latency is important. 5G and MBR both have LOS communication coverage and low latency, but 5G has significantly more bandwidth than MBR. This means that 5G and maybe MBR (depending on the bandwidth) satisfy Acceptance Criteria 5-7. Since communication between the ship and a ROC is available, Acceptance Criteria 8 can be satisfied by transferring voice communication to and from a ROC where an operator handles the communication. This means that all the acceptance criteria are satisfied, giving a green light for communication near port (see Figure 11).

### 5.3.3 Coastal

In this operation phase the ship can have a challenging navigation task with many vessels and possible groundings.

**Acceptance Criteria**

9) The communication coverage requirement is A2 (regional sea coverage, according to Table 1).
10) Gain situational awareness around the autonomous ship at all times.
11) Possible to remotely control a ship when traffic picture is too complex or in case of unforeseen events. For instance, if the traffic picture is complex, a human operator may need to communicate with nearby vessels and decide on who is doing what.
12) Must be able to communicate with other vessels, authorities, and ports in real-time.

In a coastal operation, the vessel is close to the shoreline and may have terrestrial communication systems available, thus the communication coverage requirements would be A1 or A2 depending on the operational area. To cover most coastal areas, A2 is set as the acceptance criteria. This means that satellite communication is required to satisfy Acceptance Criteria 9, assuming that the satellites systems are available. As described in the near port operational phase, the sensor data required to gain situational awareness in an ROC are not certain at the moment. VSAT has A2 communication coverage and can have up to 100 Mpbs of bandwidth, but a latency of 350 ms. However, a cargo ship typically moves slowly, a latency below half a second is assumed satisfactory for remote control. Thus, under the given assumptions, Acceptance Criteria 10 and 11 are satisfied for the coastal operational phase. Since communication between the ship and a ROC is available, Acceptance Criteria 12 can be satisfied by transferring voice communication to and from a ROC where an operator handles the communication. This means that all the acceptance criteria are satisfied, giving a green light for communication near port (see Figure 11).

The satellite communication system Starlink is still commissioning but aims to be able to communicate with a low latency and high bandwidth and is an option when it is fully up and running.

### 5.3.4 Deep Sea

**Acceptance Criteria**

13) The communication coverage requirement is A3 (global coverage, except latitudes ±70°, according to Table 1).
14) Gain situational awareness around the autonomous ship on demand.
15) Possible to remotely control a ship on demand.
16) Must be able to communicate with other vessels, authorities, and ports in real-time.

For deep sea operations, terrestrial communication is not available. Thus, satellite communication is needed. Iridium has a global coverage (A3), bandwidth of 1.5 Mpbs, and a latency of 200 ms. Using Iridium, Acceptance Criteria 13 is satisfied. As mentioned in the other phases, what sensor data is required to gain situational awareness in an ROC is not certain at the moment. Since the bandwidth of Iridium is limited, the sensor data that can be transferred is also limited. However, 1.5 Mpbs is enough to send a SD video (0.7 Mpbs) and some other data. However, it might not be enough bandwidth to gain a full situational awareness at the ROC. To take remote control of the vessel, low latency is important. In deep sea, a cargo ship moves slowly and thus a latency of 200 ms is assumed acceptable. With the currently available satellite system Iridium, Acceptance Criteria 13 and 15 are satisfied, but Acceptance Criteria 14 may be harder to satisfy with this system due to the limited bandwidth. Communicating with authorities, vessels and ports is assumed to require limited bandwidth and Acceptance Criteria 16 should thus be satisfied using the currently available communication system. In near future, Starlink will be up and running and can provide a global coverage with high bandwidth and low latency and is assumed to satisfy all the acceptance criteria. This gives a yellow light for communication in deep sea, as this is expected to be feasible within the next five years (see Figure 11).

### 5.3.5 Conclusion

There exist communication systems that have coverage for all the operational phases. The challenge for all the phases, is how much data is needed to gain situational awareness at the ROC and the requirements this puts on the bandwidth. For the phases *at port* and *near port*, communication systems with high bandwidth and low latency are available, enabling large amounts of data that can be transferred to gain situational awareness and remote control. For *coastal*, high bandwidth is also available, but with some latency. However, as a large cargo ships typically move slowly, the latency is relatively low for this use case. In the *deep sea* phase, limited bandwidth is available today with a global coverage, meaning that full situational awareness might be a challenge. The technical feasibility for remote operation for the different operational phases is summarized in Figure 11.

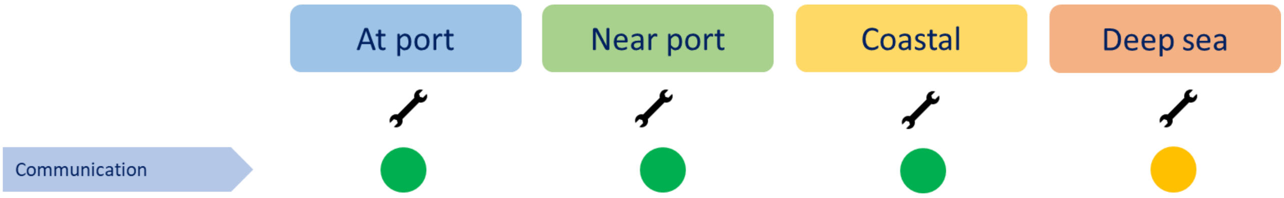

**Figure 11: Technical feasibility for communication for an unmanned cargo ship.**

## 5.4 Cargo Handling

**Acceptance Criteria**

1) The crane must be able to connect to and release the specific cargo.
2) The crane must be able to move the cargo from quay side to cargo hold.
3) The cargo must be adequately secured without human support.
4) The cargo must be kept secured during the voyage.

A gap analysis for automated cargo handling operations (Mørkrid et al., 2022) was conducted as a part of the SFI Autoship. This analysis was done for both break-bulk and containers as indicated by the title. The main findings are summarized in this section.

Onshore (terminal) cranes were not part of the scope of the mentioned report, but the same challenge applies here as well, the lack of automation of connection and release of the cargo. The cranes themselves are in many cases automated and remotely controlled. However, the same conclusion goes as for deck cranes, the operations cannot be performed without personnel due to the hooking of the cargo. This is especially true for break-bulk, whereas there are solutions available for containers, related to automatic twist-locks.

For break-bulk, the main finding is that these operations are hard to automate, especially the connection (hooking) of the cargo. The main reason for this is the vast diversity of commodities (up to 15-20 per voyage) and packaging which makes automation challenging. As of today, there is no fully automated connection (hooking) for any commodity (maybe except from e.g. steel pipes where magnets can be used), and the report suggests separate research projects for the matter. Remote control of the cargo handling operations has been suggested as a first step towards automation, and there are plans in WP5 to perform research activities related to remote control of shipboard cranes. There are semi-autonomous solutions in the market, and for some commodities there are potentials for autonomous hooking, as per the findings from the gap analysis for automated cargo handling operations (Mørkrid et al., 2022).

Another important issue related to autonomous cargo handling is the securing of the cargo units. For containers this is an issue when these are being stacked above deck. There is currently no solution available for automation of the lashing operations. Cell guides have been suggested as a solution to this, but for bigger containers ships like the NCL fleet, these are not feasible due to the height of the container stacks.

The technical feasibility of constrained autonomous cargo handling for a cargo ship is summarized in Figure 12.

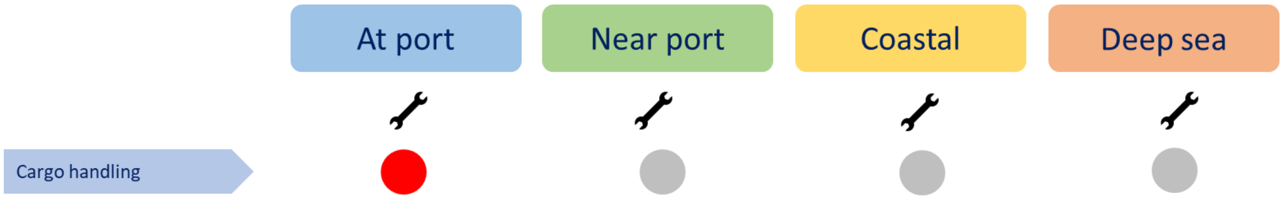

**Figure 12: Technical feasibility of cargo handling for a cargo ship.**

## 5.5 Mooring

**Acceptance Criteria**

1) The mooring system must automatically moor and unmoor the ship.
2) The mooring system must be able to handle draft and tidal changes.
3) The mooring system must be able to handle rolling motions induced by cargo handling.

In this study, mooring is only considered when the ship is at port, so the other operational phases are not applicable. A ship can also be moored at sea, for instance to another ship. However, this is not considered in this study. As both use cases, i.e. deep sea bulk ships and short sea container ships, are large cargo ships, they are evaluated together for the mooring task.

A gap analysis on automated mooring systems have been made as a part of the SFI Autoship project (Bellingmo & Jørgensen, 2022). This section summarizes the outcomes from that report. Today, there exist three different types of automated mooring, that is, vacuum pads or magnetic pads attaching to the hull of the ship, and robot arm used to attach the mooring lines from the ship on bollards on the quay. AutoMooring Solutions (AMS) [29], Trelleborg[30], and Cavotec[31] are providers of vacuum based mooring systems. AMS is the only provider of the magnetic mooring system. These systems are in general flexible as to how big vessels they can serve, it is rather a question about cost. There seem to be few limitations regarding operation, if the installed system (with several pads) is designed to meet the weather conditions in the area. In general, vacuum pads are preferred over magnets, as magnet pads require a completely flat surface to withhold the holding force. From a technical point of view, vacuum pads seem to be the most versatile and promising solution, however it is an expensive investment for ports around the world, aspects which will be discussed in chapter 7 (commercial feasibility). For the robot arm systems, two systems are available, that is, the lasso robotic arm from MacGregor, which is installed on Yara Birkeland[32], and the rope picker robot from AutoMooring Solutions (AMS)[33]. A challenge with the large ships is the height differences that occur due to tidewaters and differences in draught. The total height difference can be up to 11 meters according to Grieg Star. The robotic arm is said to have a range of 21 meters, but further investigation is needed to conclude whether this is adequate for these kinds of vessels.

Among these automated mooring systems, the vacuum-based system has been tested the most. The robotic arm mooring system are in the testing phase and has not been thoroughly tested in normal operation yet. Thus, the real performance of the robot arm systems is not certain. For cargo ship, assuming that the ships operate between ports where automatic vacuum mooring systems are available, the mooring system can automatically moor the vessel, handle large draft and tidal changes and roll motions induced by cargo handling. This means that all the acceptance criteria are satisfied, and by that a green light is given indicating that automated mooring is technically feasible today for both deep sea bulk ships and short sea container ships, see Figure 13.

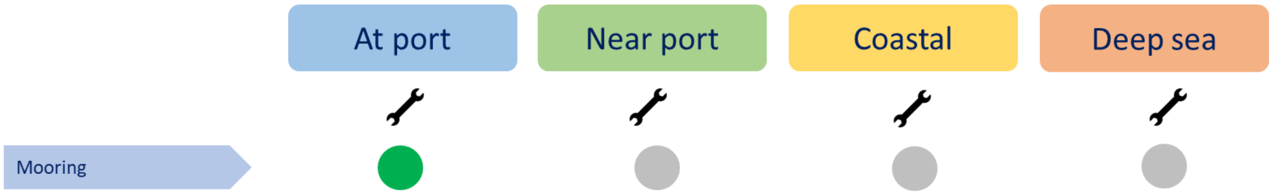

**Figure 13: Technical feasibility of automated mooring for an unmanned cargo ship.**

## 5.6 Discussion

In order to limit the scope of this study, several topics have not been discussed in the main section but will be briefly discussed in the following. One such topic is safety. Safety is essential to have trust in autonomous systems and must be incorporated in all the technical systems to maintain a safe operation. For instance,

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[29] https://automooringsolutions.com/

[30] https://www.trelleborg.com/en/marine-and-infrastructure/products-solutions-and-services/marine/docking-and-mooring/automated-mooring-systems/automoor

[31] https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring

[32] https://www.macgregor.com/intelligent-solutions/automated-mooring-system/

[33] https://automooringsolutions.com/

when transmitting and receiving data, e.g., between an autonomous ship and a ROC, the cyber security is crucial. An ROC operator must have the correct information from the autonomous ship to correctly determine what should be done. If not, it can lead to a dangerous situation. Even conventional vessels are subject to cyber-attacks, such as jamming and spoofing. For an autonomous ship being monitored from a ROC, more data needs to be transferred, making it even more vulnerable.

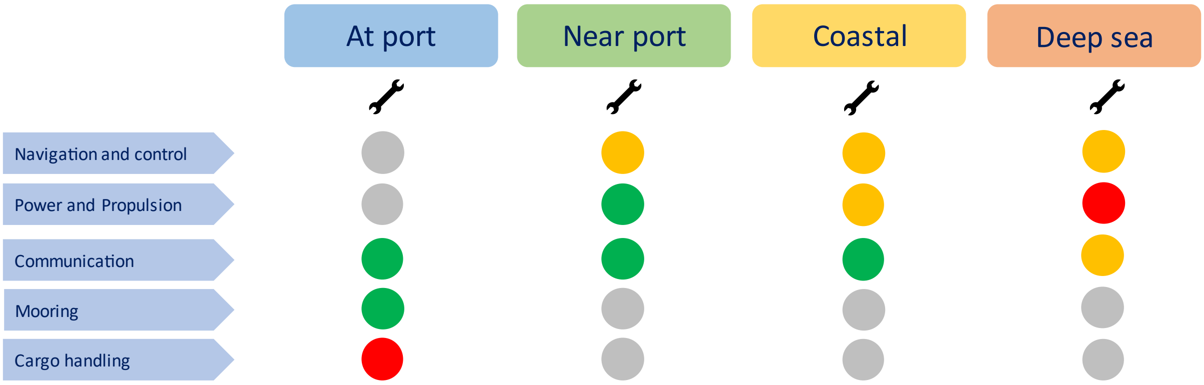
More than just making sure that data is received, one must ensure the quality of the data used for the autonomous systems. A deviation or failure in data can impact the performance of the whole operation. This can lead to downtime for the autonomous system, which can be critical for an unmanned ship. Thus, it is vital to ensure the uptime of the autonomous systems. Even though a technological solution exists to automate a function, e.g., automated mooring, the autonomous systems must be operational at all times to avoid downtime. This has not been included in the acceptance criteria for the different tasks, as some of the systems are still under development and the performance is not certain. If an autonomous system has limited performance in terms of uptime or a decision is based on the wrong input data, redundant systems may need to be considered to ensure continuous operation. However, with redundancy comes an additional cost. The matter of redundance will be further discussed in Chapter 7.

In case of a failure, the unmanned ship must enter a minimum risk condition state which must be predefined. This has not been included in the acceptance criteria in this chapter but must be in place to safely operate an unmanned ship. Additionally, to be operated from a ROC, the navigation system must know its own limitations and when human assistance is needed.

The results from this study show that an unmanned deep sea bulk ship is not possible with the technology available today. However, as this study considers a constrained autonomous ship, where human support can be offered from an ROC or by crew onboard, constrained autonomy might still be achieved for some tasks by human assistance from crew onboard. Depending on the technological feasibility, the manning related to some tasks may be reduced. Reduced manning due to increased autonomy can enable some tasks to be operated periodically unmanned. Periodically unmanned tasks introduce new challenges, such as when to alert the operator and if the system has sufficient situational awareness to know when human assistance is needed. This is particularly relevant for the deep sea phase, where the traffic is limited and thus the navigation should be easier. For propulsion systems, reducing the manning depends on the performance and uptime. With the engines and fuels typically used today, reduced manning may only be possible for short voyages. The need for maintenance and downtime for alternative propulsion systems needs to be further investigated. Using automated mooring is possible today and would liberate the crew related to this task today. Regarding automated cargo handling, if this can be fully automated, manning can be reduced. However, as this is not technically feasible in the near future, reduced crew in this task is also a future potential. Moreover, to reduce the overall manning, one must look at all the different tasks the crew are involved in on bulk ships, as one person typically performs multiple tasks that are vital for the operation. The topic of reduced manning and periodically manning should be further investigated in this SFI.

## 5.7 Technical Conclusion

Figure 14 summarizes the technical feasibility of an unmanned constrained autonomous cargo ship. The different tasks have been given a color indicating the feasibility for each operation phase. The definition of the traffic lights for the technical feasibility is described in Table 2.



| | At port | Near port | Coastal | Deep sea |
|---|---|---|---|---|
| Navigation and control | ⚪ | 🟡 | 🟡 | 🟡 |
| Power and Propulsion | ⚪ | 🟢 | 🟡 | 🔴 |
| Communication | 🟢 | 🟢 | 🟢 | 🟡 |
| Mooring | 🟢 | ⚪ | ⚪ | ⚪ |
| Cargo handling | 🔴 | ⚪ | ⚪ | ⚪ |

**Figure 14: Technical feasibility for an unmanned cargo ship.**

As can been seen from Figure 14, there are some yellow and red lights, indicating that an unmanned cargo ship is not feasible today. For the *at port* operational phase, the biggest challenge might be the autonomous cargo handling. Automated mooring is possible and commercially available in the market today. For the *near port* phase, the biggest challenge for autonomy is the *navigation and control* task, where object detection and classification need further development. For the *coastal* phase, the navigational challenge from *near port* remains, but also the *power and propulsion system* can be a challenge due to possible failures or maintenance needed. For *deep sea*, the main challenge is the *power and propulsion*, that needs to be functioning without failures for the whole duration of the phase, which can be up to 1.5 months. Moreover, navigation should be easier in this phase as there is less traffic, but communication with a ROC can be limited by coverage, bandwidth, and latency. However, this depends on what is needed to be communicated to a ROC in this phase, which is not yet determined.

# 6 Regulatory feasibility

The overall objective of this chapter is to understand if a deep-sea bulk ship or a short-sea container ship can operate unmanned with autonomy level *constrained autonomy,* seen from a regulatory perspective. There will be a separation between international regulations and national, where Norway is chosen specifically, with input from the Norwegian Maritime Authority (NMA) and the Norwegian Coastal Administration (NCA) among others. The assessments will be concluded with traffic lights as indicated in Table 5.

**Table 5: Colours and descriptions for regulatory assessment.**

| | |
|---|---|
| 🟢 | Compliance with applicable regulations is expected to require moderate concept qualification efforts. However, might not necessarily been proven commercially yet. Testing and verification period expected (with people on board during this period). |
| 🟡 | Compliance with applicable regulations demands extensive processes for concept development and qualification. |
| 🔴 | Not possible (or incredibly challenging) to achieve unmanned operation which satisfies applicable regulations |
| ⚪ | Not applicable |

## 6.1 Relevant regulations

It has been decided to split the assessment into international and national regulations, where Norway is used as national reference in this report.

### 6.1.1 International Regulations

The most relevant international authorities to be included as part of the regulator feasibility for international operation are:

- **The International Maritime Organization (IMO)**
- The International Labour Organisation
- The International Tele Union
- European Maritime Safety Agency (EMSA)

Whereas the most relevant conventions are:

- The Safety of Life at Sea Convention (SOLAS)
- The International Convention for the Prevention of Pollution from Ships
- The International Search and Rescue Convention (SAR)
- The Convention on Standard of Training, Certification and Watchkeeping for seafarers (STCW)
- The Maritime Labour Convention
- The Load Lines Convention
- **The Convention on International Regulations for Preventing Collisions at Sea (COLREG)**
- The International Convention on Tonnage Measurement of Shipsu
- **The United Nations Convention on Law of the Sea (UNCLOS)**

It has been necessary to limit the scope of this international regulatory feasibility assessment and hence the focus in this report is limited to IMO, COLREG and UNCLOS, and DNV is included as classification society.

### 6.1.1.1 *The International Maritime Organization (IMO) regulatory scoping exercise*

IMO completed a regulatory scoping exercise (RSE) for the use of maritime autonomous surface ships (MASS) in 2021 (IMO, 2021). The aim of this RSE was to determine how safe, secure, and environmental sound MASS operations might be addressed by IMO instruments. IMO did some assumptions during the RSE which are summarized as follows:

- Autonomy level four means no crew on board
- Passenger transport without seafarers on board cannot be performed
- Determination of whether remote operator is a seafarer and whether it encompasses all personnel working on board of a ship or those individuals capable of operational control of the ship, are outside of the remit of RSE
- For autonomy level three and four persons may stay on board during berthing, cargo handling and anchoring
- MASS of level one is considered a conventional ship with some additional functions to support human decision-making.
- The Safety Management of MASS relates to functions which are autonomous

High-priority issues stemming from the RSE (IMO, 2021):

- Meaning of the terms master, crew, or responsible person
- Remote control station/centre
- Remote operator as seafarer
- Terminology

Further potential gaps and topics (IMO, 2021):

- Manual operations and alarms on the bridge
- Actions by personnel (e.g. firefighting, cargoes stowage and securing and maintenance)
- Watchkeeping
- Implications for search and rescue
- Information required to be on board for safe operation

The goal of IMO is to develop a MASS Code. An IMO road-map for development of IMO instruments for MASS aims at developing a goal-based instrument in the form of a non-mandatory Code, which is planned to be adopted in 2024. A mandatory Code will be developed and enter into force in 2028, based on the experience from the non-mandatory Code[34]. This MASS Code will include goals, functional requirements, and corresponding regulations, suitable for all degrees of autonomy, and at the same time address important gaps and topics identified by the RSE.

Based on the discussions above, second half of 2024 will be the earliest occasion where an IMO Mass Code will be available. Before such a MASS Code is in place, it is not likely that unmanned ships will be allowed to operate internationally, unless the "involved" countries make a bilateral agreement permitting a specific ship to sail unmanned. Such bilateral agreements could potentially enable certain international voyages for an unmanned vessel, but a "free sailing" unmanned cargo ship is not realistic in the absence of a MASS Code.

### 6.1.1.2 *The Convention on International Regulations for Preventing Collisions at Sea (COLREG)*

Whether or not MASS can be feasible from a COLREG perspective is an interesting and challenging issue to address, as there are various contexts and perspectives to consider. One of which is the fact that MASS will have to coexist and interact with conventional manned vessels in the foreseeable future.

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[34] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Autonomous-shipping.aspx

"*As long as MASS will interact with humans on manned ships there has to be a limited number of common and easy to understand rules known to, and obeyed by, all vessels at sea. One can dream up other rules, but what we got, and need to adhere to, is the COLREGs. Having said that, one might consider if extensions or revisions may be needed*" (Porathe, 2019).

Porathe further explains that the COLREGs are written in a general manner in order to be applicable in a wide range of situations, such that the precise interpretation of the rules generally requires context-based considerations where "the ordinary practice of seamen" is applied in addition to knowledge of the rules.

The challenges related to interpretation of COLREGs for autonomous navigation systems (ANS) are further emphasized from a legal perspective, in the following contribution by the doctorate at The Faculty of Law in Oslo (University of Oslo):
*"Autonomous navigation must contend with the problem of collision avoidance, an aspect regulated by the ColRegs (i.e., Convention on the International Regulations for Preventing Collisions at Sea, 1972).*

*A number of rules are built around the assumption that human senses and perception will be used. It is uncertain so far, from a legal perspective, whether technical solutions which emulates human characteristics can constitute an acceptable equivalent means of compliance with these aspects of the COLREGs. Moreover, to increase the chances that MASS will be operating within the same legal framework of conduct as regular vessels, it is crucial to consider how the conduct-oriented rules will be incorporated into the algorithms of their autonomous navigation systems (ANS). However, the COLREGs display the conventional quirks of any legal instrument written in natural language, such as vagueness and generality, which conflicts with the precision and clarity that algorithms often require. Establishing a baseline of good conduct that can serve as a standard for the development of COLREGs-compliant ANS assumes that the normative content of each rule is well understood, which naturally entails legal interpretation. But legal interpretation tends to be case-specific, carried in the light of factual information which helps guide the analysis of the rules. This is fundamentally different from the extrapolative exercise of programming ANS, which necessitates that the algorithms represent a 'timeless' understanding of the rules which would theoretically allow MASS to tackle in a legally acceptable manner future and unforeseen circumstances.*

*The current COLREGs certainly complicates the task, but it is not certain they represent an absolute obstacle to MASS either, as for example the regulatory challenge will significantly vary from one rule to another. Though amendments to the ColRegs may be sensible, MASS-specific amendments are perhaps not ideal due to the difficulty of proposing in advance general solutions to problems that will depend on the features of continuously evolving proposed technical solutions."*

Figure 15 shows a screenshot from marinetraffic.com, situated outside of the Netherlands, with Rotterdam in the bottom left corner. This figure is included to show the complexity of the maritime traffic in congested areas internationally. The COLREG algorithms will have to deal with a lot of conflicting collision avoidance situations in this area.

Thomas Porathe (Porathe, 2019) concludes that "*It is of great importance that the maneuvers of autonomous ships are predictable to human operators on manual ships. The AI onboard has a potential to become "smarter" than humans, and to be able to extrapolate further into the future and thereby behave in a way that might surprise people ("automation surprise"). Instead the software should focus on behaving in a humanlike manner."*

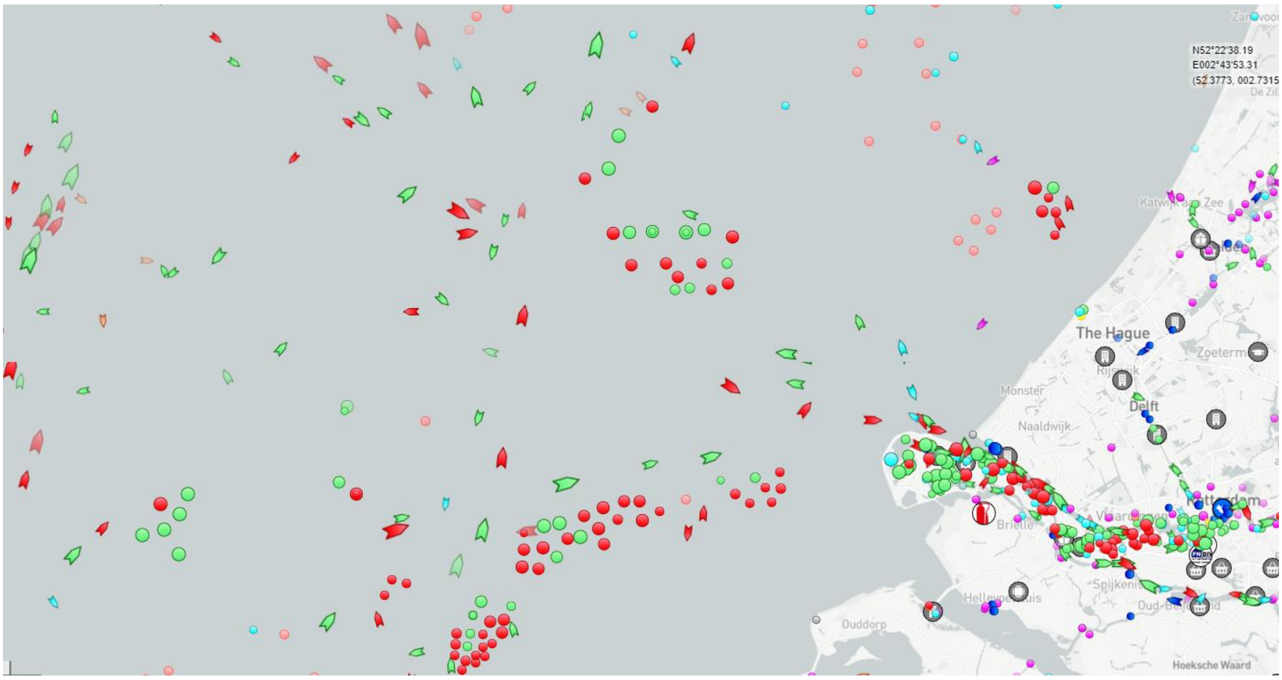

**Figure 15: Marine traffic around Rotterdam and the coast of the Netherlands, source: MarineTraffic.com (screenshot 27.09.2022 12:41).**

WP4 in SFI Autoship has a particular focus on COLREGs through the doctorate at The Faculty of Law in Oslo (University of Oslo). The research is aimed at discussing the challenges presented by MASS from various angles. The research does not only ask how the current COLREGs could be an obstacle to achieving fully unmanned autonomous ships but is similarly interested in the different ways the introduction of new technology can challenge long established understandings of existing legal concepts. The existing legal norms are supposed to guide human behavior. When the regulated conduct is no longer being carried out by humans, our usual methods for assessing and verifying compliance are also challenged. If compliance with COLREGs must be proven before MASS are allowed to operate, then asking these questions are paramount. It is too early at this stage to conclude whether MASS are going to be obstructed by the current COLREGs, especially when many of the technical aspects remain unresolved and in the development stage. Any conclusion at this stage will have to remain highly speculative, but the overall impression is that the traffic light is yellow as seen from a COLREG perspective, since extensive processes for concept development and qualification will be necessary to identify and address difficult cases.

#### *6.1.1.3 The United Nations Convention on Law of the Sea (UNCLOS)*

*"The United Nations Convention on the Law of the Sea was adopted in 1982. It lays down a comprehensive regime of law and order in the world's oceans and seas establishing rules governing all uses of the oceans and their resources. It embodies in one instrument traditional rules for the uses of the oceans and at the same time introduces new legal concepts and regimes and addresses new concerns. The Convention also provides the framework for further development of specific areas of the law of the sea."*[35]

It has been underlined by NMA that UNCLOS might have some hurdles to overcome for autonomous vessels. More specifically Article 91, 94 and 98 and a general question whether a MASS can be categorized as a ship. Challenges related to the specific articles are listed as follows:

- Article 91: Nationality of ships

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[35] https://www.imo.org/en/OurWork/Legal/Pages/UnitedNationsConventionOnTheLawOfTheSea.aspx

  - This article is about the genuine link between a ship and a flag state. So, a question arises: Can a flag state exercise control of a vessel that is operated by an ROC outside of the flag state's territory?
  - In Norway jurisdiction is directed towards the ship owner and not the ship
- Article 94: Duties of the flag states
  - Related to the definitions of master and crew and how the state flag can exercise jurisdiction when the master/crew is situated in another country, and what will be the role of a remote operator
- Article 98: Duty to render assistance
  - The more autonomous the ship becomes, the more it will struggle to render assistance. However, it is the master of the ship who is responsible when it comes to rendering assistance.

Some of the challenges listed above can be covered by the coming IMO MASS Code, but not all, so UNCLOS must be considered specifically when assessing whether a ship can operate freely internationally.

#### *6.1.1.4 Conclusion*

The (mandatory) IMO MASS Code will not be ready until 2028, and some of the UNCLOS articles have not been covered yet for unmanned ships. COLREGs is also considered challenging, as there are still various challenges to be addressed and solutions to be developed. Hence, the conclusive color of the traffic light is red, meaning that it is not currently possible to comply with applicable regulations for an unmanned ship operating in international waters.

Possible "exceptions" to this conclusion are cases where bilateral agreements between countries enable unmanned operation in a specific routes. Such operation, however, is greatly limited and differs substantially from the use cases described in chapter 4. Furthermore, unmanned operation based on bilateral agreements requires extensive qualification and development processes with relevant authorities.

### 6.1.2 National regulations in Norway

In Norway, the responsibility of maritime safety is divided between the Norwegian Maritime Authority (NMA) and the Norwegian Coastal Administration (NCA). The NMA is responsible for the safety of life, health, environment, and materials on vessel with Norwegian flag and foreign vessels in Norwegian waters (Norwegian Maritime Authority, 2022), while the NCA is responsible for safe and efficient passage in fairways along the coast and into ports, and national emergency preparedness against acute pollution (The Norwegian Coastal Administration, 2022).

#### *6.1.2.1 The Norwegian Maritime Authority (NMA)*

Today there are no existing national regulations specific for approval of autonomous vessels. Due to the ongoing projects on autonomous ships (see Section 2.3), a circular (Rundskriv-Serie V. RSV 12-2020) has been developed by the NMA (Norwegian Maritime Authority, 2020a). The circular describes the documentation requirements and principles for ships with autonomous functions. To ensure that autonomous or remotely operated ships are as safe as conventional ships, and that risks that come from remote control or autonomy are identified, NMA bases their procedures on the *IMO guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments*, known as Circ.1455 (International Maritime Organization, 2013). Temporary assessment and final acceptance of new technology and solutions based on this circular is done by NMA. An autonomous or remotely controlled ship which NMA accepts based on the circular, might get a certificate or approval to operate in domestic service. This is the case even if the ship is built according to a classification society's guidelines and class rules (Norwegian Maritime Authority, 2020a).

The legislations applicable to the ship type in question (cargo ship, passenger ship, fishing vessel etc.) are referred to as a basis in the NMA circular, along with the general philosophy that autonomous or remotely operated ships should have the same safety levels as conventional ships. Furthermore, the following regulations are referred to in section 3 of the NMA circular:

i. Ship Safety and Security Act

ii. Reg. n°.1072 on construction of ships

iii. Reg. n°.666 on the manning of Norwegian ships (manning Reg. 09) (“bemanningsforskriften”)

iv. Reg. n°.537 on watchkeeping on passenger and cargo ships (“Vaktholdforskriften”)

v. Reg. n°. 75 on collision avoidance at sea ("Sjøveisreglene")

Documentation requirements based on the IMO Circ.1455 are linked to:

1. Preliminary design
    I. Concept of operation (CONOPS)
    II. Pre-HAZID
    III. Safety philosophy
    IV. Design philosophy
    V. Operation and maintenance philosophy
2. Analysis of preliminary design
    I. Updated Pre-HAZID with corresponding
    II. Risk analysis/assessments
    III. Gap analysis
    IV. HAZID and risk assessments
3. Analysis of final design
    I. HAZID and risk assessments
4. Performance approval tests & analyses
    I. Failure Mode and Effect Analysis (FMEA)
    II. Test requirements

A flow chart for the certification process for conventional vs non-conventional ships is shown in Figure 16 (in Norwegian). Note the particular focus on third party verification for the alternative design process related to the non-conventional part. This alternative design process is closely related to the list of documentation requirements above.

The conclusion on regulatory feasibility for domestic service is positive based on the NMA processes described above.

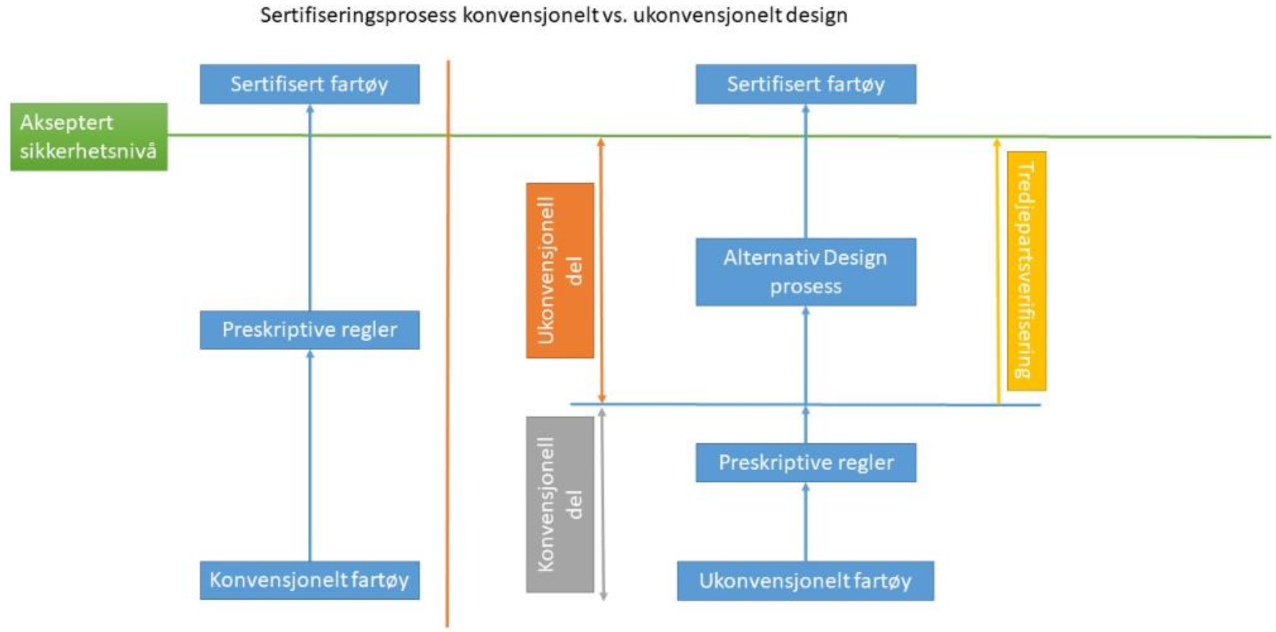

**Figure 16: Flow chart for certification process for conventional vs non-conventional ship, source: NMA Rundskriv-Serie V. RSV 12-2020 (Norwegian Maritime Authority, 2020b).**

#### *6.1.2.2 The Norwegian Coastal Administration (NCA)*

After getting the approval to operate autonomously from the NMA, one still needs to get approval to operate in the Norwegian waters. This is the mandate of the NCA. As for conventional ships, an autonomous ship should not negatively affect the maritime security or the traffic flow. The NCA exercises authority under the following regulations: The Harbour Act, the Pilotage Act, the Pollution Control Act, the Svalbard Environmental Protection Act and the Planning and Building Act (The Norwegian Coastal Administration, 2022). The Pilotage Act is now a part of the Harbour act. Ships with a length longer than 70 m or width over 20 m are required to have pilotage in applicable waters (Lovdata, 2015). As described in Sections 4.1 and 4.2, the use case bulk ship and use case container ship are more than 80 m long, meaning that pilotage is required. For a cargo ship operating autonomously in Norwegian waters, the Harbour Act describes how a ship owner can sail without pilotage by applying to get approval from the NCA for "autonom kystseilas" (meaning autonomous coastal sailing) (Lovdata, 2018). As this law ("autonom kystseilas") has not been applied for yet, it describes the application steps in general terms. The terms include

a) *Surveys and step-by-step testing,*
b) *Requirements for the vessel's navigation and maneuvering system,*
c) *Sailing restrictions, and*
d) *Requirements for competence of the local waters for personnel associated with the testing and operation of autonomous coastal sailing and requirements for pilots to be consulted.*

As long as the ship owner can satisfy the requirements for "autonom kystseilas", a bulk ship or container ship can operate without a pilot on board from a regulatory standpoint (Lovdata, 2018).

### 6.1.3 Classification society requirements

EMSA defines classification societies as "*organisations which develop and apply technical standards for the design, construction and survey of ships and which carry out surveys and inspections on board ships. Flag* *states can authorise classification societies to act on their behalf to carry out statutory survey and certification work of their ships."*[36]

While this feasibility study focuses on DNV when it comes to classification society requirements, there are various other initiatives related to autonomous ships among the other classification societies. One such example is the Japanese classification society ClassNK, which granted Approval in Principle (AiP) for a fully autonomous ship framework for NYK and MTI in 2022[37]. The so-called APExS-auto is covering automation of a series of necessary processes, including information gathering, analysis, planning, approval, and execution. This framework has been used in conjunction with the DFFAS project.

### *6.1.3.1 Classification society requirements: Det Norske Veritas (DNV)*

The focus in this report will be on DNV as a classification society, mainly because DNV is a partner in SFI Autoship. DNV has not yet provided rules for autonomous or remotely controlled unmanned ships, but rather issued a risk-based guideline, which is supported by functional and detailed technical guidance. The following subsection will elaborate on the content and proposed use of this guideline.

#### 6.1.3.1.1 Class guideline for autonomous and remotely operated ships (DNV)

The objective of DNV's class guideline (DNV-CG-0264) for autonomous and remotely operated ships (DNV, 2021), is to provide guidance for:
"*1) Safe implementation of novel technologies in the application of autonomous and/or remotely controlled vessel functions, 2) recommended work process to obtain approval of novel concepts challenging existing statutory regulations and/or classification rules*"

The guideline covers four types of operational concepts:

- *Decision support navigational watch*
    - The officer in charge of the navigational watch is on board the ship but gets support from enhanced decision support systems for navigation and control of the ship.
- *Remote navigational watch*
    - The officer in charge of the navigational watch is located in an ROC, with no people on board to support the ROC in navigation and control of the ship and the radio communication as defined in the STCW code
- *Remote engineering watch assisted by personnel on board*
    - The officer in charge of the engineering watch is located in an ROC, with crew on board to perform certain tasks and support the ROC when needed
- *Remote engineering watch*
    - The officer in charge of the engineering watch is located in an ROC, with no crew on board to support the ROC in performing the engineering functions.

The listed four concepts can be linked to autonomy levels, and DNV has chosen the definitions from the IMO RSE (IMO, 2021). In this report the NFAS definitions is being used, and more specifically *constrained autonomy*. This autonomy definition covers the operational concepts *"Remote navigational watch"*and *"Remote engineering watch"*, which in turn can be linked to the tasks *"navigation and control"* and *"propulsion system"* in this report.

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[36] https://www.emsa.europa.eu/inspections/90-classification-societies.html

[37] https://smartmaritimenetwork.com/2022/03/15/fully-autonomous-ship-framework-gets-classnk-approval/

DNV lists some main principles which are important for assessment of autonomous and remotely controlled ships in Table 6.

**Table 6: DNV's main principles for assessment of autonomous and remotely controlled ships.**

| Principle | Description |
|---|---|
| Equivalent safety | Autonomous ships shall be as safe or safer than conventional ships (life, property, and environment). |
| Risk-based approach | Risk analysis covering the operation of the vessel, design and implementation of novel technology and remote supervision and control of a ship from an ROC |
| Operational focus | Operational modes and scenarios must be thoroughly analyzed, and all potential hazards identified. It must be ensured that the technology will be able to deal with foreseeable events. |
| Minimum risk conditions (MRC) | An MRC is a state the ship should enter when it comes in situations outside of normal operation, but is expected to deal with it. This is to be considered as a safe state for the vessel and is part of a contingency plan. |
| Functional focus | The design methodology should address all functions of the ship and ROC. The key functions are listed in Table 7. |
| Degrees of automation ad human involvement per function | The guideline uses different categorizations for the degree of automation for respectively the navigation and engineering functions. |
| System engineering and integration | There is a need for a high focus on system engineering and integration activities, and an organization must take on the role as system integrator. |
| Design principles | Six design principles should govern the design of an autonomous or remotely controlled ship:<br>1. Maintain a safe state<br>2. Maintain normal operation<br>3. Redundancy and alternative control<br>4. Independent barriers<br>5. Self-controlled capabilities on board<br>6. Self-diagnostics and supervision |
| Software engineering and testing | *"It is required that the software is being developed and configured according to established processes, and that a verification and validation strategy which puts emphasis on elaborate, multi-faceted testing of the software is established."* (DNV, 2021) |
| Cyber security | The design of all systems involved in the autonomous or remotely controlled ship should explicitly focus on cyber security. |

These principles are also addressed in NMA's note "RSV 12-2020" (Norwegian Maritime Authority, 2020b), (see section 6.1.2.1) and are generally key topics in most initiatives and discussions related to MASS.

In their class guideline, DNV defines the *autoremote*[38] *infrastructure* as the "whole set of vessel(s), systems, communication-link(s), remote control centre and all other systems that together fulfils all the requirements and intentions of a safe operation of an autonomous or remotely operated vessel", and highlights some of its most important functions. The highlighted functions, termed *key functions*, are presented in Table 7. These key functions are necessary to achieve the objective of equivalent safety (the autonomous ship must be at least as safe as a conventional ship), which lays the foundation for the approval process. Some of these functions are traditional ship-functions, while others are related to automatic and remote operation.

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[38] Autoremote is a DNV term from DNV-CG-0264: Common wording for equipment/technology providing remote- and autonomous control

Table 7: Key functions of the Autoremote infrastructure (DNV).

| **Key function** | **Comment** | **Category/reference (in this document)** |
|---|---|---|
| Remote control and supervision | A fundamentally important task in the context of these use cases, since fully autonomous solutions (without remote assistance from humans) for deep sea bulk or short sea container shipping are not considered realistic at present. | 6.2 Navigation and control<br>6.3 Power and Propulsion<br>6.4 Communication |
| Communication | Fundamentally important, as it is a prerequisite for interaction with RCC and other stakeholders | 6.4 Communication |
| Navigation and maneuvering | Essential function, necessary for both conventional and unmanned operation | 6.2 Navigation and control |
| Propulsion | Essential function, necessary for both conventional and unmanned operation | 6.3 Power and Propulsion |
| Steering | Essential function, necessary for both conventional and unmanned operation | 6.3 Power and Propulsion |
| Electrical power supply | Necessary for most/all functions on board. | 6.3 Power and Propulsion |
| Control and monitoring | Fundamental function, for both conventional and unmanned operation. | 6.2 Navigation and control<br>6.3 Power and Propulsion |
| Watertight integrity | Essential for operation, but not explicitly addressed in this study. Assumed to be relatively easy to maintain autonomously | - |
| Fire safety | Important in all contexts. 2 main differences for unmanned operation compared to conventional operation:<br>• No crew safety to maintain<br>• No crew available to assist/ contribute | - |
| Ballasting | Mainly relevant during loading and unloading. Not addressed explicitly in this study. | - |
| Drainage and bilge pumping | Essential for operation, but not explicitly addressed in this study. Assumed to be relatively easy to maintain autonomously | - |
| Anchoring | Not considered relevant for this use case, except perhaps as a last resort MRC in certain emergency situations | - |
| Cargo handling | Prerequisite for all shipping operation, both manned and unmanned | 6 Cargo handling |
| Maintenance | Essential for all electromechanical systems designed for long duration use, such as deep sea shipping. Especially important for unmanned systems which may operate for weeks without local human assistance | 6.3 Power and Propulsion |

## 6.2 Navigation and control

The navigation and control task has been covered by the sections above and can be recognized as one or more of the key functions in Table 7. However, the most relevant parts of navigation are situational awareness and object detection, these are linked to the general rules on "proper lookout" and "determination of own position". The specific detection range requirements should be decided per concept qualification project and will depend on ship type, size, maneuverability, and speed. Another part of the navigation is the route planning, and if the ship concept is based on handing over the action planning task to a remote operator in complex situations, this operator should receive sensor data providing the necessary situational awareness to perform the task with an equivalent level of safety when compared to manual route planning.

As stated in DNV-CG-0264, *"It should be part of the concept process to evaluate capabilities of the technology and to ensure a sufficient situational awareness for the remote navigator according to the tasks."*

One of the key challenges related to navigation for bulk ships and container ships is the requirement for pilotage, which might be seen as a regulatory hurdle. However, NCA has addressed this topic and opened for "autonom kystseilas" (autonomous coastal sailing), following steps from sub section 6.2.2.

From a regulatory perspective, nationally in Norway, it is deemed feasible to navigate and control an unmanned ship, however due to the nature of the COLREGs it must be concluded that it is not currently feasible without specific actions. As such, the proposed traffic light color for regulatory feasibility is yellow for national (near port and coastal) and red for international (due to IMO, UNCLOS and COLREGs, see section 6.1.1.4). Figure 17 summarizes the regulatory feasibility for navigation and control at different operational phases.

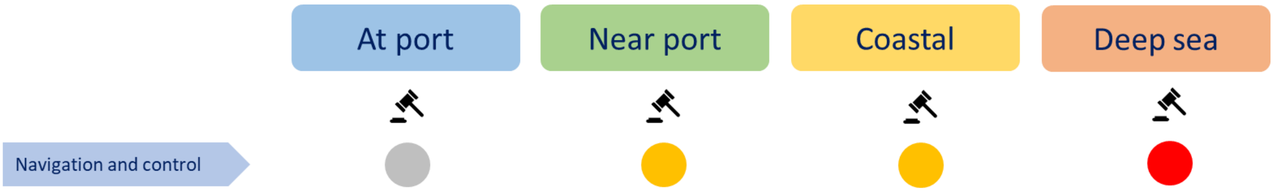


**Figure 17: Regulatory feasibility for navigation and control for an unmanned cargo ship. All phases except deep sea are regarded as domestic/national.**

## 6.3 Power and Propulsion

Main relevant functions are propulsion, power generation, steering (and relevant systems supporting these), where DNV (DNV-CG-0264, section 5, heading 4.2) has the following definition: "*The terms propulsion system and steering system should be understood to include necessary auxiliary systems such as fuel, cooling, power, control systems*."

DNV-CG-0264 includes reference to SOLAS in relation with propulsion system, and more specifically Ch. II, Part C:

- *"Means shall be provided whereby normal operation of the propulsion machinery can be sustained or restored even though one of the essential auxiliaries becomes inoperative. Special consideration should be given to the malfunction of systems and components subject to anticipated failure. (Interpretation of SOLAS Ch.II-1 Reg. 26.3)."*
- *"Systems and components supporting the propulsion function shall be arranged with redundancy and capacity sufficient to ensure that the vessel can maintain a navigable speed in case of potential failures of single systems and components. (Interpretation of SOLAS Ch.II-1 Reg. 26.2).*"

### 6.3.1 E0 – Periodically unattended machinery space

The E0 class notation has existed for quite some years already and allows for periodically unattended machinery spaces. An important prerequisite for the E0 notation is that relevant alarms are forwarded from engine control room to the responsible officer's cabin, and subsequently to the bridge (which is always attended) if the responsible officer fails to respond. ABB has looked into whether B0 (periodically unattended bridge) could be a solution to reduce fatigue for the crew on the bridge and increase safety in terms of added technology and situational awareness (Lehtovaara, n.d.).

However, for domestic voyages it is still anticipated that the NMA circular (Norwegian Maritime Authority, 2020b) and the use of DNV-CG-0264 (DNV, 2021) are covering also propulsion system and unattended machinery space and bridge, not only periodically. The challenges are related to making sure that a remote operator gets the satisfactory situational awareness, not only for navigation, but also for the machinery on board. All relevant alarms and monitoring signals from the machinery must be forwarded to the ROC in some way, either being all or an overall status signal which indicates the state of the machinery.

General redundancy requirements for conventional vessels are that the loss of a main function must be restored within 10 minutes, and that the loss of essential functions propulsion and steering must be restored within 30 seconds. For unmanned vessels, however, the redundancy needs may vary depending on the intended operations of the vessel, and the terms "main function" and "essential function" become less clear. The term "key function" is therefore often used instead of main and essential functions. Fault tolerance for systems supporting key functions needs to be addressed in the conceptual design process, and a CONOPS document needs to define MRCs for each operational mode. If, during any part of a voyage, the vessel has a last resort MRC which requires propulsion capability, the propulsion system should be designed in such a way that this last resort MRC can be maintained under all potential failure conditions.

For unmanned concepts like use case 1 and use case 2, it is not possible to perform any local or manual actions by humans to re-establish vessel functions, so key functions should be arranged with redundancy and robustness to eliminate or reduce the need for local (human) support in the event of failures and incidents. To compensate for the lack of manual and local intervention by humans, the design should include increased redundancy, more automation, improved HMI and alert management and more rigid definitions of safe states, when compared to conventional vessels. Furthermore, the types of failures to be considered should be extended and systems should have more sophisticated diagnostic and monitoring functions to detect evolving problems.

Potential failures which may impair key functions should be included in risk assessments, which may in turn lead to design adjustments. Potential failures should not remove the vessel's ability to enter and maintain MRCs.

Risk assessments for potential failures should cover at least the following incidents and failures:

- Fire and flooding
- Failures in rotating machinery and other mechanical components
- Electrical failures
- Failure of control systems and safety systems and data communication networks/links
- Cyber security incidents
- Human errors and external events

It is in general important that standby or backup functions are regularly tested to detect "hidden" failures which may not be detectable during "normal operation". This is especially important for unmanned operation, since there will not be humans on board who can perform local troubleshooting. According to DNV-CG-0264 (section 6, heading 5.5), remotely operated systems should be subject to such function tests prior to every voyage. It should also be possible to perform such a function test throughout the voyage, e.g. before entering critical operation phases.

Existing requirements for unattended machinery spaces should be observed, and it will be important to compensate for the lack of "human sensing" with appropriate sensing equipment such as cameras (regular and/or infrared), microphones and vibration sensors to achieve equivalent ability to detect abnormal conditions. Furthermore, the remote operator may need state-of-the-art communication solutions (e.g., with augmented reality) to efficiently interpret such sensor data.

Unmanned cargo vessels on international voyages may not rely on application "local processes" for concept approval of propulsion related systems (e.g. based on the NMA circular) and are subject to IMO regulations, which have various gaps/hurdles regarding MASS operation, as described in section 6.1.1.1. Gaps related to maintenance are particularly relevant for propulsion related systems.

### 6.3.2 Conclusion

By applying NMA circular and DNV-CG-0264, the national (Norwegian) regulatory feasibility for propulsion system is expected to be yellow in the sense of traffic light color, as it will not be straight forward to enable a cargo ship to operate freely. For international waters the picture gets even more complex and there are hurdles related to IMO instruments. Hence, for international, it is currently red, but soon to become yellow. Figure 18 summarizes the regulatory feasibility for propulsion related systems at different operational phases.

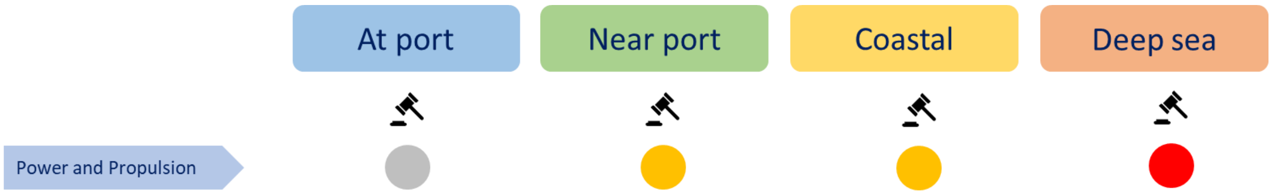


**Figure 18: Regulatory feasibility for propulsion related systems for an unmanned cargo ship. All phases except deep sea are regarded as domestic/national.**

## 6.4 Communication

For a remote operator to have equivalent object detection capability (when compared to a manned bridge), the video and audio feed must meet strict requirements to enable such equivalence. These strict requirements may not apply for the entire voyage but are likely to apply during certain phases of the voyage, such as docking operations. During deep sea sailing legs with limited internet connection, the navigational tasks will probably have to be solved by onboard systems, with occasional help from an ROC operator. When the vessel is at port, communication is less critical (as navigation and propulsion related systems are "inactive"), and the ROC link is more reliable (assuming good communication infrastructure at the port), which makes communication related challenges much more manageable.

### 6.4.1 Class society requirements

According to DNV-CG-0264, the risk analysis of the communication systems should include at least the following incidents and failures:

- unauthorized persons gaining access to the communication link
- jamming of wireless communication links

- interception of data traffic by 3rd party
- spoofing of data by 3rd party
- malware entering the systems
- failure of electronic components in the communication links
- less than ideal radio-coverage for wireless links
- error in transmission of data (also known as bit-faults)
- lack of acknowledgement of command(s)
- wrong configuration of communication functions
- unexpected reduction of available bandwidth during operations
- unexpected increase of latency during operations
- unstable data-links over time
- network storms
- loss of power

To avoid loss of data, it should be possible to transfer real time logs to a database on shore. All nodes in the autoremote infrastructure should be synchronized, to enable a uniform time tagging of alerts and log data. DNV-CG-0264 also states that requirements for bandwidth (based on worst-case scenario) and latency should be calculated and documented, and that the communication link should be fault tolerant such that it can operate at full capacity despite single component failure.

For control and monitoring in general, DNV-CG-0264 states that the ROC operator should achieve situational awareness sufficient to perform remote operation in a safe way equivalent to local operation on a crewed vessel. Available functions for automatic support and control should be taken into account when considering the required level of situational awareness for the remote operator. In general, "*The situation awareness necessary for the remote operator will depend on the level of automation and decision support functionalities supporting the control of the function. The nature and criticality of the function under control will also influence the required situational awareness*" (DNV, 2021).

For deep sea sailing, and perhaps for coastal sailing in rural areas, it is likely that the stability and bandwidth of available ROC connections will be limited, which in turn may limit the ROC operator's situational awareness (as video and audio streams cannot be transferred reliably). When high-definition CCTV is challenging to transmit reliably to an ROC, it may be necessary to employ other systems which provide good situational awareness without the need for high data flow. Also, as indicated in DNV-CG-0264, a high level of automation can compensate for limited bandwidth and situational awareness, as it gives onboard systems a higher degree of autonomy such that the need for remote decision making and control is reduced. Since both use cases are likely to encounter connectivity issues, the use case vessels must have a sufficient level of automation to endure periods of limited or no ROC connection.

For an unmanned vessel, the autoremote infrastructure has to be able to communicate with external stakeholders to the ship, either directly/autonomously or with help from ROC. The following communication tasks must be handled by automatic systems onboard and/or by ROC:

- Communication with other vessels, VTS, tugs, pilot station, etc (typically via VHF hardware on board the vessel)
- Transmission of emergency messages from the vessel
- Relaying of received emergency messages
- Replying to messages received from other vessels
- Interpreting sound and light signals around the vessel and recognizing day shapes and navigation lights

- Voice communication with crew and passengers on board the vessel (if applicable)
- Voice communication with humans near the vessel

ROC personnel should be able to conduct some of these communication tasks without depending on the communication link between ROC and the vessel.

Requirements for alerts are similar to those for conventional vessels, the main difference being that the responsible operator to receive and respond to alerts will be a remote operator. For automatically operated functions it should not be necessary to perform human action to maintain operation (or safe state). For such functions, alerts requiring human intervention should not exist unless warranted by special circumstances such as emergency conditions. Manual emergency operation from ROC should be possible, but not necessary, to enter and maintain safe state.
Although manual actions should not be needed to enter or maintain safe state, it should be possible to respond to failures with manual actions from ROC (e.g. to reset/restart systems).

Unmanned cargo vessels on international voyages may not rely on application "local processes" for approval of communication related functions/tasks (e.g. based on the NMA circular) and are subject to IMO regulations, which have various gaps/hurdles regarding MASS operation, as described in section 6.1.1.1. Gaps related to requirements regarding people on board are particularly relevant for communication systems.

### 6.4.2 Conclusion

Communication can be split into two overall topics: Voice communication over radio and connectivity related to an ROC. Voice communication is expected to be relayed from ship to ROC and as such it can be covered by an ROC operator. However, neither voice communication nor ROC connectivity issues have been tested or verified in real operation yet. The regulatory aspect is not a hurdle per se for national operation in Norwegian waters (following the NMA circular), but internationally there are still issues, as long as the IMO MASS Code is not yet ready. For the at port phase, the light is green since the vessel is stationary and reliable connections are readily available. For the "sailing phases", the conclusion is yellow light for national and red for international. Figure 19 summarizes the regulatory feasibility for communication functions/-systems at different operational phases.

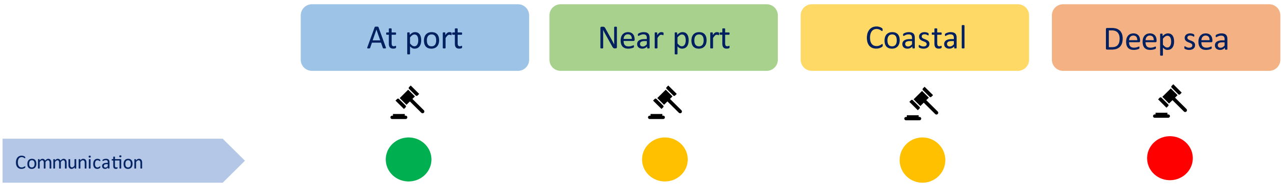


**Figure 19: Regulatory feasibility for communication systems for an unmanned cargo ship. All phases except deep sea are regarded as domestic/national.**

## 6.5 Cargo handling

### 6.5.1 Class society requirements

We have not gone into details on the cargo handling in this report, partly because it has already been concluded from a technical perspective that autonomous deck cranes are not feasible yet. The following rules and standards from DNV might be worth looking at:

- DNV-RU-SHIP Pt.5 Ch.1 Bulk carriers and dry cargo ships
- DNV-RU-SHIP Pt.6 Ch.4 Cargo operations
- DNVGL-ST-0377 Standard for shipboard lifting appliances

However, it seems that none of the above have specific requirements related to unmanned or autonomous cargo handling. Due to the nature of the immaturity of remote and autonomous cranes, the conclusion is a yellow light for cargo handling, from a regulatory perspective. Figure 20 summarizes the regulatory feasibility for cargo handling systems at different operational phases.

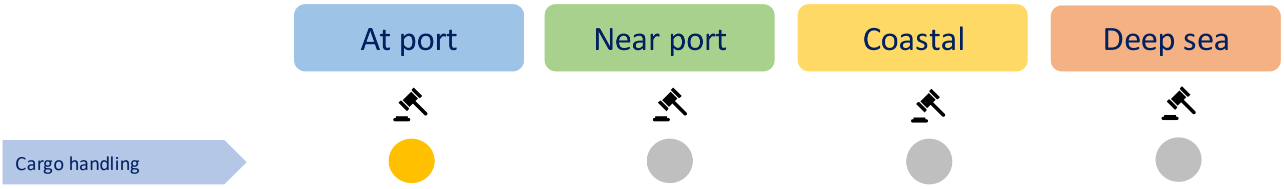


**Figure 20: Regulatory feasibility for cargo handling systems for an unmanned cargo ship.**

## 6.6 Mooring

Unmanned mooring will require specific equipment on board and/or at port. If extensive infrastructure additions at ports are necessary, this is probably not feasible, since the use case cargo ships operate between various ports and terminals within the ports.

The following tasks shall also be supported (according to DNV-CG-0264) to provide the necessary situational awareness:

- Supervision of docking operations
- Monitoring of vessel's heading, rudder angle, propeller RPM, propeller pitch (if relevant) and thrusters (if relevant)
- Release of sound signals
- Monitoring the relevant mooring operations by having orders effected
- Effect two-way communication with mooring stations on board and ashore
- Effect two-way communication with other parts of the vessel organization when required

However, it is not expected that there will be regulatory hurdles for autonomous mooring, at least none which are not covered by DNV-CG-0264 and NMA's circular. Hence, it is concluded with a green light from a regulatory perspective. Figure 21 summarizes the regulatory feasibility for mooring systems at different operational phases.

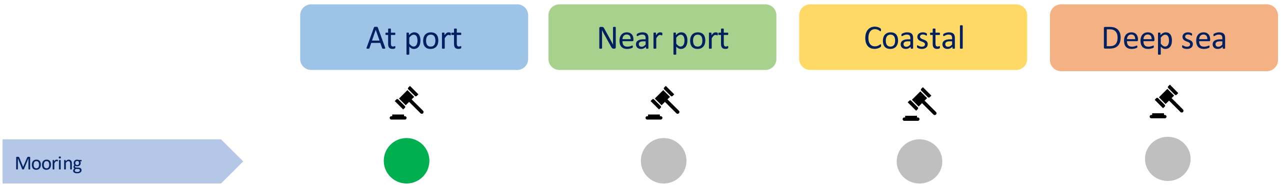


**Figure 21: Regulatory feasibility for mooring systems for an unmanned cargo ship.**

## 6.7 Discussion

Present initiatives for unmanned vessels still follow a case-by-case approach, and it is difficult to get specific answers/requirements that apply to all applications/implementations of a vessel type, since they can operate in different contexts, each requiring specific considerations. Approval based on management of risks associated with the specific CONOPS is still necessary, but as the collective autonomy experience grows, we may see more and more requirements which apply more widely among autonomous vessels, reducing the amount of the case-specific considerations in the approval process.

The process of introducing new technologies to solve crew tasks has been ongoing for decades, and there are already many tasks which are handled by automation today which were manual (and required more crew) in the past. Autonomy can be seen as the "final destination" of the already ongoing evolution from manual to automated operation, but the distinguishing challenges arise when approaching the transition from manned to unmanned ships.

Autonomy concepts today are defined by a very specific CONOPS, typically with vessels operating between a limited number of locations with specific infrastructure which is developed/tailored for a given operation. These tailor-made solutions make unmanned/autonomous vessels a lot less flexible than crewed vessels, limiting their operation to a select few ports. Standardizing port infrastructure for autonomous systems is challenging since the technologies developed to take over human tasks have limited ability to apply judgement and solve nuanced or unexpected problems.

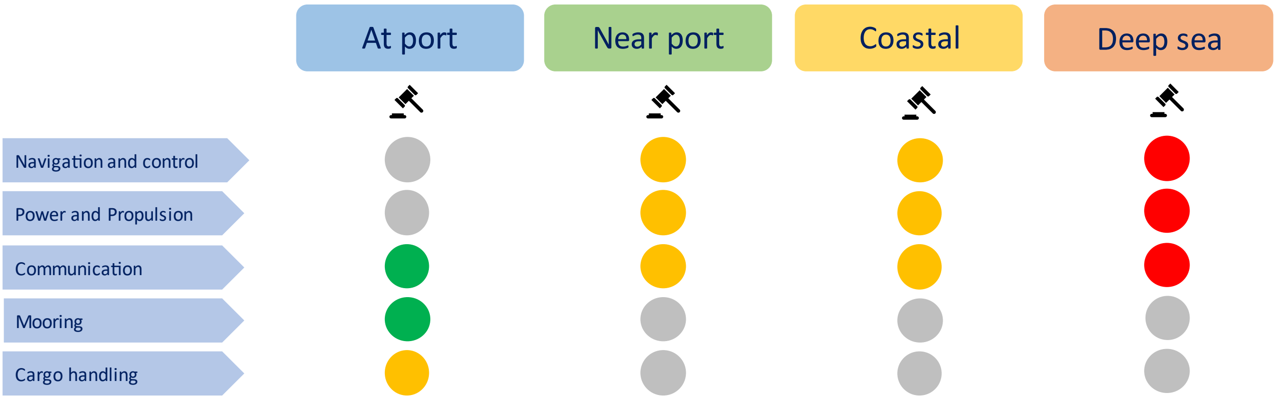
Unmanned vessels will constitute a very small part of the global fleet and must therefore be able to coexist and interact with conventional vessels (except in areas which are reserved for unmanned operation). One question which is still unanswered is whether unmanned vessels should have a minimum ability to support other vessels and seafarers. In a future scenario with widespread operation of unmanned and autonomous vessels, the coexistence with conventional vessels may prove particularly challenging. It may be necessary to not only adapt new solutions to existing rules, but also to adapt existing rules (e.g. SOLAS, COLREG) to new technologies. One of the main "high priority items" identified in the RSE is to consider the development of a new instrument (e.g. a MASS Code), to limit the confusion and inconsistencies which may be caused by amending existing instruments to properly address MASS concepts.

## 6.8 Conclusion

Based on the proposed approach to evaluate new concepts in cooperation with relevant authorities, and today's state-of-the-art technology, it seems that most (or all) the identified regulatory challenges should be manageable, by iterating the concept until all considerations are properly addressed. In that sense, it should be feasible from a regulatory perspective to perform unmanned cargo shipping nationally (at least in Norway). For international cargo shipping, unmanned concepts are presently not regarded as feasible.

Figure 22 summarizes the feasibility of unmanned/remote controlled operation of key functions from a regulatory perspective. Defining clear "feasibility categories" is difficult given the speculative (and somewhat subjective) nature of this assessment, however the assessment is done based on the color definitions in the introduction of this chapter.

In some cases, the different kinds of feasibility (technical, regulatory and commercial) are strongly linked, and should therefore be viewed in the context of each other.



| | At port | Near port | Coastal | Deep sea |
|---|---|---|---|---|
| Navigation and control | ⚪ | 🟡 | 🟡 | 🔴 |
| Power and Propulsion | ⚪ | 🟡 | 🟡 | 🔴 |
| Communication | 🟢 | 🟡 | 🟡 | 🔴 |
| Mooring | 🟢 | ⚪ | ⚪ | ⚪ |
| Cargo handling | 🟡 | ⚪ | ⚪ | ⚪ |

**Figure 22: Regulatory feasibility. All phases except deep sea are regarded as domestic/national, whereas deep sea is regarded as international operation.**

# 7 Commercial Feasibility

The overall objective with the commercial feasibility study is to establish an understanding of the commercial potential and viability for an unmanned deep sea bulk ship, independent of technical and regulatory feasibility. However, the choices and outcome from the technical and regulatory studies will be subject to commercial viability in this chapter.

Kretschmann et.al. (Kretschmann et al., 2017) states that autonomous vessels are expected to contribute within the following dimensions of sustainability:

"

1. *Economic sustainability by keeping operational expenses low, especially crew-related costs, to facilitate efficient international trade*
2. *Ecological sustainability by enabling new and innovative ways to reduce overall fuel consumption e.g. due to the absence of life-support systems on board*
3. *Social sustainability by increasing safety due to moving trivial operational tasks from fatigue crew to on board automation and by enabling shore-based and family friendly monitoring jobs for nautical personnel ashore.*

"

An example of a yearly operational profile for a bulk carrier is presented in the same paper (Kretschmann et al., 2017) and is expected to be quite descriptive also for the deep-sea bulk ship this report deals with:

- Ship at berth/waiting: 120 days (corresponds to *At port*)
- Ship maneuvering: 29 days (corresponds to *Near port* or *Coastal*)
- Ship in sea passage: 216 days (corresponds to *Deep sea*)

The assessments in this chapter are based on a new-build (autonomous equivalents of the ships presented in section 4.1 and 4.2) and further key assumptions are:

1. An autonomous ship is expected to be unmanned with no bridge superstructure (or modular superstructure which can be removed when the vessel is ready to be unmanned)
2. An autonomous ship is expected to sail with lower speed
3. An autonomous ship is expected to be more digitalized than today's conventional ships
4. An autonomous ship is expected to use green energy (e.g. methanol, ammonia, hydrogen)

As for the rest of the report, traffic lights are used to conclude on commercial feasibility:

**Table 8: Traffic light definitions for commercial feasibility.**

| **Colour** | **$ Economic** | **Environmental** | **Social** |
|---|---|---|---|
| 🟢 | Economic effects positive | Positive environmental effects | Positive effects on society/people |
| 🟡 | Economic effects unclear | Unclear environmental effects | Unclear effects on society/people |
| 🔴 | Economic effects negative | Negative environmental effects | Negative effects on society/people |
| ⚪ | Not applicable | Not applicable | Not applicable |

## 7.1 Overall Key Performance Indicators (KPIs)

KPIs which will serve as a foundation for the cost-benefit analyses and are defined as part of the work on logistics system cost-benefit analyses in work package 5. These KPIs are categorized into three main categories: *economic* (section 71), *environmental* (section 72) and *social* (section 73).

### 7.1.1 Economic KPIs

The economic KPIs are divided into the categories *costs* and *time*.

#### *7.1.1.1 Costs*

The overall costs categories assessed in this chapter is:

- **CAPEX.** Capital costs are all expenses related to new-build or purchase of a vessel, which includes new building price, cost of financing and the sales amount when selling the vessel. For a ship owner typically up-front investment, interest, and depreciation.
- **OPEX.** Operating costs varies for different ships, but can be defined as crew costs, stores & consumables, maintenance and repair, insurance, general costs and periodic maintenance (Kretschmann et al., 2017).
- **VOYEX.** Voyage costs are mainly fuel and port charges.

An overview of costs (CAPEX, OPEX, VOYEX) for a reference bulker (Panamax bulk carrier) is shown in Table 9 (Kretschmann et al., 2017). As can be seen, OPEX is about 20 %, VOYEX 53 % and CAPEX 34 % for this specific reference vessel.

**Table 9: An overview of costs for a Panamax bulk carrier.**

| Cost category | Specific costs | Percentage | mUSD |
|---|---|---|---|
| OPEX | Crew costs | 7.8 % | 10 |
| | Other costs | 12.4 % | 16 |
| VOYEX | Fuel | 41.1 % | 53 |
| | Port charges | 12.4 % | 16 |
| CAPEX | Capital costs | 26.3 % | 34 |

The numbers in Table 9 can be used to understand the potential for cost savings and where to focus the efforts. It is worth noting that crew costs only stand for 7.8 % of the total cost. It is obvious from the figures that CAPEX and fuel costs are the main cost drivers.

##### 7.1.1.1.1 Crew cost

Average salary per month ($) for bulk carrier crew (2021) is listed below, based on an article on www.nauticjobs.com[39], divided in three departments: *Deck*, *engine,* and steward (*hotel)*:

**Table 10: Average salary / month ($) for crew on bulk carriers (2021).**

| Department | Rank | Average salary / month ($) |
|---|---|---|
| Deck | Captain / Master | 10.500 |
| | Chief Officer / Chief Mate | 7.750 |
| | Second Officer | 3.200 |

---

[39] https://www.nauticjobs.com/blog/2020/10/22/bulk-carrier-crew-salary-guide-2021/

| | | |
|---|---|---|
| | Third Officer | 2.900 |
| | Boatswain / Bosun | 1.800 |
| | Able Seaman | 1.350 |
| | Ordinary Seaman | 1.060 |
| Engine | Chief Engineer | 10.000 |
| | Second Engineer | 8.100 |
| | Third Engineer | 3.350 |
| | Fourth Engineer (Junior) | 2.700 |
| | Electrical Officer (ETO) | 4.800 |
| | Oiler | 1.390 |
| | Fitter / Welder (Engine) | 2.050 |
| Steward (Hotel) | Chief Cook | 2.000 |
| | Chief Steward | 1.300 |
| | Steward Assistant (Messman) | 1.000 |

As can be seen from Table 10, deck officers have significantly higher salaries than bosuns and seamen etc. Bringing some officers on shore could as such have an impact on OPEX. However, in the figures presented in Table 9, costs related to ROC operation is not included.

For a 90 m long container ship, (Gribkovskaia et al., 2019) estimates that manning can be reduced from 7 to 2 people for a ship with high level of autonomy.

#### 7.1.1.1.2 Energy cost

For a deep sea bulk ship and short sea container ship, it is not realistic with batteries or hydrogen fuel cells in near future, hence combustion engines will probably be the most realistic choice of machinery. Then there are some fuel alternatives, where hydrogen, ammonia and methanol are the ones that can have zero emissions of $CO_2$ (well-to-wake) if they are produced with zero emission. Obviously, it must be distinguished between grey and green productions of the mentioned fuels. Prices and $CO_2$ emissions from different fuel types are discussed in the paper *Assessment of Alternative Fuels and Engine technologies to reduce GHG* (Lindstad et al., 2021) and summarized in Table 11.

**Table 11: Fuel cost (Lindstad et al., 2021).**

| **Fuel** | **Grey [USD/TOE]** | **Green [USD/TOE]** |
|---|---|---|
| Hydrogen | 1.100 | 1.100 - 1.750 |
| Ammonia | 1.100 | 1.100 - 1.750 |
| Methanol | 800 | 1.360 - 3.235 |
| VLSFO | 440 | - |
| MGO | 500 | - |

It is clear from the fuel prices in Table 11 that hydrogen, ammonia, and methanol are significantly more expensive than VLSFO or MGO, even for the grey options.

As discussed in the technical feasibility section (see Section 5.2), the power and propulsion system must operate without need for maintenance or failures during a voyage in order to be unmanned. The need for maintenance depends on the propulsion system and the energy source. An overview of the needed maintenance for the different fuels and energy sources are not readily available today. However, based on the experiences from the operation with VLSFO (or MGO), the current fuels require frequent maintenance (daily), meaning that cleaner fuels or other energy source must be investigated for an unmanned cargo ship, to reduce the maintenance need.

#### *7.1.1.2 Time*

The following KPIs under the *Time* category are discussed in this sub section: *Loading time, Sailing time, Unloading time,* and *Waiting time prior to berth.* All of which are expected to be affected by the different choices of automation. If a longer sailing time could be accepted, the steaming speed could be reduced and hence the overall energy consumption could be significantly reduced. This fits very well with unmanned shipping, as speed would not have any effect on a crew which is not there. Waiting time prior to the berth can potentially be removed if necessary digitalization measures are implemented (e.g. message and information exchange between ship and port) and steaming speed is lowered to secure just in time arrival.

### 7.1.2 Environmental KPIs

The environmental studies in this report consider $CO_2$ emissions (leaving out $SO_x$, $NO_x$, and particulate matter among others).

### 7.1.3 Social KPIs

The social KPIs are considering safety and risk to personnel and work-life balance and competence/training.

#### *7.1.3.1 Safety and risk to personnel*

Shipping has a poor safety record. According to Wärtsilä Smart Autonomy report (Wartsila, 2021), the safety record for the maritime industry is about 20 times worse than the average onshore worker. Within the maritime industry, the worst-performing segments were general cargo and passenger ships. Furthermore, from a total of 4.104 accident events (in the period 2011 – 2018), 65.8 % were attributed to human actions. In the same period, it was reported 7.694 persons injured and 696 fatalities.

#### *7.1.3.2 Work-life balance and competence/training*

This sub section is linked to the third sustainability dimensions presented in the very beginning of this chapter:

- *Social sustainability by increasing safety due to moving trivial operational tasks from fatigue crew to on board automation and by enabling shore-based and family friendly monitoring jobs for nautical personnel ashore.*

It is expected that on shore maritime jobs will be more attractive for the coming generations, especially given the shortage of officers in the coming years. The needed competence will be different, as there is a fundamental difference in being on board a ship or located in an ROC. This will also affect training and schooling of officers. For ordinary crew there will be different roles in the ROC than on board, and as such there will probably be an increasing need for people with higher education.

## 7.2 Navigation and control

The task navigation and control is to be understood as the system consisting of control algorithms to navigate and control the ship under different circumstances, asking for human assistance when necessary. The commercial assessment of this task does not distinguish between the phases but leaving out the *at port* phase.

### 7.2.1 Economic impact

For an autonomous cargo ship, CAPEX is expected to increase with 8 % annually (of the total capital costs for the ship, not only navigation and control) from higher system complexity and new technology, e.g. autonomous navigation system, according to (Gribkovskaia et al., 2019). On the other hand, the CAPEX *can* be reduced due to removal of the superstructure and all safety equipment related to manning, such as lifeboats. Since the technology for an autonomous ship is still developing, it is uncertain at this point if the CAPEX will be increased, due to new technology, or decreased, due to removal of superstructure. However, as the CAPEX accounts for 26 % of the total cost of a Panamax bulk ship (see Table 9), an increase or decrease of the CAPEX will have a large impact on the total cost.

Other benefits of removing the superstructure are that the cargo capacity can be increased and thus decrease the cost per transported unit. Alternatively, if superstructure is removed, the ship can be slenderized while maintaining the cargo capacity. A slender body will reduce the energy cost due to lower resistance and reduced CAPEX (smaller ship to build). Studies presented in *Autonomous ships for coastal and short sea shipping* (Gribkovskaia et al., 2019) show that the cargo capacity can be increased from 190 TEU to 208 for a 90 m container ship, if removing the superstructure. Additionally, this paper shows that slender ship bodies will significantly reduce the energy consumption and thus the energy cost.

If the navigation and control task is automated, the bridge can be unmanned, which reduces the crew cost. However, for an unmanned constrained autonomous ship, a ROC is required to ensure human assistance when needed. The operators in the ROC will increase the crew cost. In order to ensure economic benefits of an unmanned ship, the ROC needs to operate multiple ships at once, to reduce the crew cost per ship. Nevertheless, the total crew cost only accounts for about 8 % of the total cost (see Table 9).

There is little or no literature available related to costs with a ROC, but the MUNIN project suggested that an ROC can monitor 90 vessels at a time (Kretschmann et al., 2017). According to the project, overall yearly personal costs of the remote operations center are USD 10.400.000, which equals USD 116.000 per vessel. In addition, there will be investment and operating costs with an ROC, summing up to USD 2.100.000 and USD 875.000 respectively (these numbers are total for the fleet of vessels monitored by the ROC). Average crew wages savings if the ship is unmanned is calculated to USD 945.000 per year (Kretschmann et al., 2017).

A much larger expense is the fuel cost, which accounts for about 40 % of the total cost for a bulk ship. By using weather routing and better and more consistent use of machinery, fuel consumption is expected to be reduced by 10 % or more (Wartsila, 2021). This means that the total cost can be reduced by more than 4 %. Additionally, as the ship is operating unmanned, the speed can be reduced without impacting the crew. Lower speed can reduce the overall fuel consumption, and thus the overall cost of the ship.

Due to the complexity and unclear cost picture of all the topics discussed above, it has been concluded with a yellow traffic light for the economic effects of this task.

### 7.2.2 Environmental impact

Environmental impact from autonomous navigation and control is mainly expected from weather routing and better and more consistent use of machinery. Expected fuel savings from these solutions are 10 % or more (Wartsila, 2021), which will reduce the emissions and thus the environmental impact. Additionally, autonomous navigation may increase the safety at sea by avoiding collisions, groundings, and reducing the number of evasive maneuvers. Evasive maneuvers cost energy as the ship needs to deviate from the planned route, and thus reducing this can reduce the energy consumption. Moreover, collisions and groundings can cause major damage to the environment and the ocean, e.g. plastic pollution[40]. Thus, if autonomy can reduce the number of collisions and groundings, this will have positive impact on the environment.

Moreover, (Wartsila, 2021) concludes that if docking time can be decreased by autonomous means, it can save two to three percent fuel per minute saved on a two-hour voyage.

From an environmental point of view it has been concluded with green lights for all the three phases in question, because it is assumed reduced energy consumption and thus emissions, as well as assumed reduction of evasive maneuvers.

### 7.2.3 Social impact

Some cargo ships, such as deep sea bulk ships, can be sailing more than a month before calling the next port, meaning that the crew must be away from their homes for a long period of time. Additionally, some tasks, such as navigation, are less challenging in open waters, leaving most of the work to the autopilot and thus boring the navigators. Bringing the same officers to a remote operations center instead is likely to be more attractive, especially for younger people.

According to Allianz Global Corporate & Specialty, Safety & Shipping[41], it is estimated that 75 – 90% of marine accidents involves human error. Human errors are primary factors in 75 % of the value of all claims related to liability insurance, in the period between 2011 and 2016. Of course, the numbers tell nothing about how many accidents which were averted by humans. Anyhow, it is assumed that situational awareness technology with high quality object detection and classification could replace the officer on watch, eliminating (or reducing) the need for human outlook. In this way the mentioned officer can either get more resting time or free up time to other tasks such as administrative.

The *Seafarer Workforce* Report from BIMCO and the International Chamber of Shipping states that the industry has to take immediate action to avoid serious shortage of officers in 2026[42]. There will be a need for additional 89.510 officers by 2026. Today the shortfall is already 26.240 officers.

Introducing the concept of ROC and moving one or more officers/operators on shore surely has effects on the social lives of the officers/operators. With the predicted shortage of seafarers this effect is considered positive.

As a result of the discussions in this sub section it has been concluded with a green light for the social impact from this task.

### 7.2.4 Conclusion

The commercial implications from autonomy in navigation and control are summed up in Figure 23. The *at port* phase is considered not applicable and hence with grey lights. The economic impacts from automation of this task are not clear with the limited study done in this report, and hence concluded to be yellow. It is assumed that some or all the deck officers are moved on shore, and the navigation system uses intelligent route planning and execution, being consistent at all times (meaning no variations due to different captains).

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[40] https://www.theguardian.com/environment/2022/jan/25/nurdles-are-everywhere-how-plastic-pellets-ravaged-a-sri-lankan-paradise

[41] https://www.agcs.allianz.com/news-and-insights/expert-risk-articles/human-error-shipping-safety.html

[42] https://www.ics-shipping.org/press-release/new-bimco-ics-seafarer-workforce-report-warns-of-serious-potential-officer-shortage/

Social implications have also been assumed to be positive as balancing work – private life is easier when located at a ROC, rather than onboard a ship.

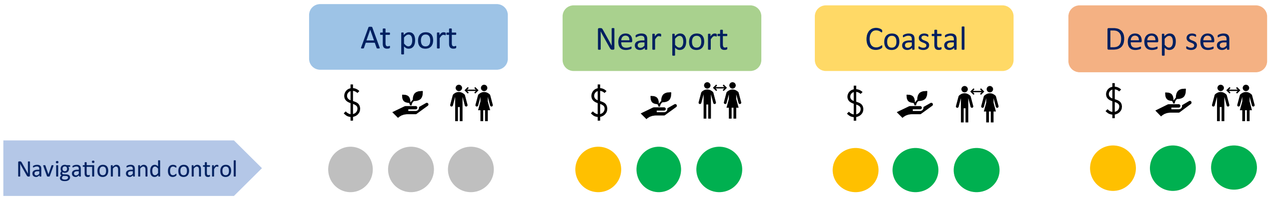

**Figure 23: Navigation and control commercial feasibility.**

## 7.3 Power and Propulsion

When considering the propulsion system from an autonomous point of view, the focus is on challenges related to the lack of crew on board to follow up on e.g. failure situations. If this crew is moved on shore, new needs arise. The following KPIs (linked to propulsion system) were reported by the project partners during the SFI days in 2021:

- No equipment failure
- Time to/from nearest break
- Failures report from automation systems
- Redundancy

Based on the KPIs above, seen from a commercial perspective, there are mainly two important topics:

1. The need for and follow-up of maintenance of the propulsion system
2. The required and expected operational up-time, which is linked to redundancy (and safety)

Hence, these will be central in the commercial discussions in this section. In addition, it must be related to use of alternative fuels and new types of engines and energy sources. This part is mainly discussed in the environmental sub section (7.3.2). The assessment of the power and propulsion system is left out for *at port* phase (indicated with grey lights in Figure 24), and the *near port* and *coastal* phases have been considered similar with respect to the power and propulsion system assessments.

### 7.3.1 Economic impact

A typical large cargo ship does not have much redundancy, and in most cases only one propeller and rudder. This results in a vulnerable ship in case of any failure to machinery or propeller/rudder. Given the long sailings distances, it is likely that failures will emerge, and the only way out might be to enter an MRC (minimum risk condition) state, which might be challenging to follow up if the ship is far from shore. Hence, from an economic perspective, there are three main factors to be considered:

- The extra CAPEX for new propulsion systems and redundancy in equipment, and higher automation cost related to condition monitoring and remote control possibilities: Uptime requirements
- The maintenance cost for different kinds of machinery and added cost due to alternative energy sources (compared to conventional fuel)
- Salary of seafarers versus service personnel cost at the terminals

The demand for a high uptime introduces the need for higher redundancy in equipment and a more complex condition monitoring system, which clearly will increase the CAPEX significantly. Moreover, the need for high uptime and low maintenance of power and propulsion system means that alternative systems and energy sources must be used. As seen from Table 11, the fuel costs for alternative fuels are higher than the conventional fuels, which will increase the VOYEX.

The costs of having crew on board to do maintenance of the power and propulsion system is likely to be lower than hiring service people at the different terminals. Studies done as part of the MUNIN project[43] suggest that a boarding crew of nine engineers and technicians is needed to carry out maintenance while at berth (120 days per year). In 2017, the costs for the boarding crew were estimated to be USD 135.000 (+15 % additional cost) per vessel yearly (Kretschmann et al., 2017). However, this estimate is considered to be much higher today (2022). It is assumed that this crew is hired from the port. Another perspective here is the fact that the on board crew also has other tasks on the ship, and it is linked to tasks like cargo handling and mooring operations. Hence, there might be a dependency between the three (maintenance, mooring, and cargo handling).

### 7.3.2 Environmental impact

Autonomy does not have much impact on environment seen from a propulsion system perspective, but autonomy is often linked to greener fuels and power systems due to the need for low maintenance. The reduction in GHG emissions, and specifically $CO_2$, can be significant if green fuels (considered from well to wake) are used. Annual $CO_2$ equivalents reduction (compared to a conventional MGO engine) are estimated to 2.280 for hydrogen, 2.147 for ammonia and 2.257 for methanol (Lindstad et al., 2021). Whereas these numbers are dramatically changed if the alternative fuels are considered grey (produced from natural gas) from well to wake: An **increase** of 1.508 for hydrogen, 902 for ammonia and 270 for methanol. All numbers are relative to MGO as reference (0 reduction). VLSFO has an increase of 33 $CO_2$ equivalents compared to MGO. In conclusion, assuming that the greener power and propulsion system can satisfy the uptime requirements for an unmanned cargo ship, autonomy will have a positive effect on environment. However, it is of utmost importance that the fuel is green, since grey fuels actually have higher $CO_2$ emissions than VLSFO or MGO.

### 7.3.3 Social impact

The social impact related to automation in power and propulsion systems needs to be linked to maintenance and the shift from highly mechanical to electrical installations. As the crew is removed from the ship, the maintenance must be done at the terminals, as indicated in sub section 7.3.1. With the increasing lack of available seafarers, it is clearly an advantage to automate on board and reduce the need for maintenance work while sailing. There will however be a need for more competent service personnel at the terminals (who is more educated in automation and electrical systems than pure mechanical). Hence, there will be a shift in competence needed, while this is considered positive as the jobs become less physical and more challenging, which might attract younger people in years to come.

### 7.3.4 Conclusion

The commercial feasibility for propulsion system automation is shown in Figure 24. Environmental (if green fuels) and social effects are considered positive for both near port, coastal and deep sea, while as the economic effects are a bit unclear for *near port* and *coastal*, and clearly negative for deep sea. The latter because the salary of the crew doing maintenance is low, and it is unlikely that a deep sea bulk ship can sail up to one month without any breakdown or maintenance needs. The cost of redundancy and automation to ensure enough uptime is considered too high for the bulk segment. The resulting environmental color is yellow due to uncertainties related to fuel type and the well to wake considerations.

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[43] http://www.unmanned-ship.org/munin/

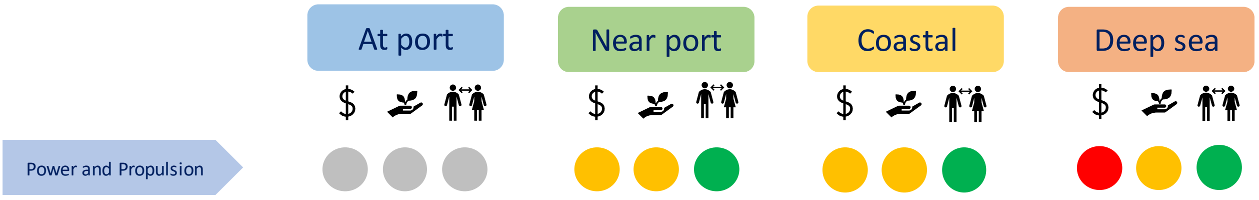

**Figure 24: Propulsion system commercial feasibility.**

## 7.4 Communication

The communication includes the traditional voice communication used for ship-ship communication and ship-shore communication. Additionally, this task includes the communication needed to operate the unmanned ship from a ROC (since we are considering a constrained autonomous ship). In the commercial evaluation of feasibility, it is assumed that the voice communication can be handled from a ROC as long as there is communication between the ship and the ROC. Thus, the focus in this section will be on communication with the ROC.

### 7.4.1 Economic impact

In order to have an ROC, investment in technology and communication systems are needed to monitor and operate the unmanned ship. When a ship is operated from an ROC, safe and reliable communication is critical, hence there is also a need for redundant communication systems. The added cost of having a reliable communication with high bandwidth and low latency is significant and linked to a higher OPEX.

#### *7.4.1.1 At port and near port*

In these phases it is assumed that there will be coverage by 4G, 5G, MBR, WiFi, or similar which is considered adequate and there should not be necessary with satellite communication. It is further assumed that the costs of these systems are lower than for satellite (this has not been verified as part of this study). Therefore, the traffic light is set to green, due to the overall consideration related to communication cost and the crew being on shore, in a ROC, as operators responsible for several ships.

#### *7.4.1.2 Coastal and deep sea*

When operating in the coastal or deep sea phases, satellite communication is needed. Satellite communication is expensive, and especially when transferring more data and requiring high bandwidth and low latency.

However, it is hard to estimate these costs of ROC communication as it is not yet clear exactly what data or that needs to be transferred and thus the needed bandwidth and latency. This is a topic in itself which will not be investigated in this report. Because of these considerations the traffic light is yellow for these phases.

### 7.4.2 Environmental impact

Commercial feasibility related to environment for communication is considered not applicable, as the focus is on connectivity and the communication itself. It has been concluded that introduction of connectivity with a ROC does not affect the environment.

### 7.4.3 Social impact

There are mainly two topics of interest when considering the social impact from communication relate to an unmanned cargo ship:

1. The positive effect on the crew/operators because of digital information exchange, which eases administration and monitoring
2. Communication with other ships might be relayed to a ROC, in combination with more complex situational awareness, as an operator will have the responsibility of several ships simultaneously

For topic 2 above it is assumed that there will be a need for somewhat different competence, as it will be fundamentally different to control several ships than one individual. It is also a separate research question in itself, how the operator gets "enough" situational awareness and what "enough" is. The overall conclusion is anyhow that the social impact from communication is positive and hence green.

### 7.4.4 Conclusion

Figure 25 shows the conclusions on commercial feasibility related to communication for an unmanned cargo ship. Note that it assumed that both costs and people will see positive effects from this, while the cost picture is somewhat unclear, and possibly negative for deep sea. For communication it has been distinguished between the phases *at port*/*near port* where satellite is not needed and *coastal* (at least parts of this phase) and *deep sea* where the cost of satellite communication (more data transfer and added bandwidth and latency requirements) might be very high. The overall economic assessment of communication is linked to the connectivity with the ROC and as such the effects of moving crew on shore must be included in the traffic light. The overall economic impact is considered positive as a result of this assumption. It has been considered challenging or not applicable to assess the environmental impact from the communication and connectivity, and as such the traffic light is grey (further research should be done to be able to perform this assessment, outside of the scope of this report). The social effects are hard to assess for the communication task, but the conclusion from sub section 7.4.3 is still positive and green.

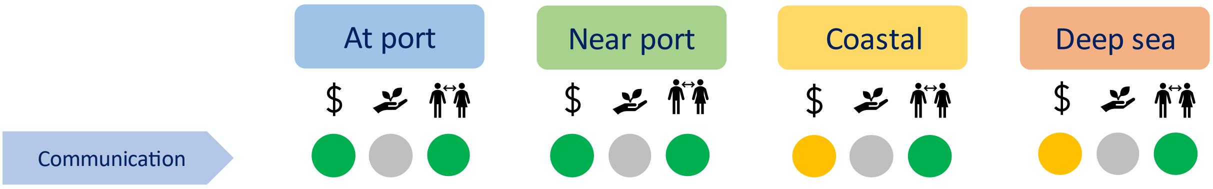

**Figure 25: Communication commercial feasibility of a cargo ship.**

## 7.5 Cargo Handling

A fully unmanned ship would ultimately also need autonomous cargo handling systems to be installed either on the ship or at the terminal. This section will focus on the commercial effects (economic, environmental and social) from automation of the cargo handling operations, for geared vessels (the cranes in on board the ship). The following subsections present some qualitative thoughts around the topic. The assessment of the cargo handling is conducted for the at port phase only, since the other phases are considered not applicable (which is reflected with grey lights in Figure 26).

### 7.5.1 Economic Impact

To assess the economic impact of cargo handling automation is challenging and complex. Seen from the ship's perspective, it is automation of the crane which might make a difference. An autonomous crane, when available, would be more expensive (higher CAPEX) than a conventional crane, but operational expenses (OPEX) might be lower, due to manning cost savings and less maintenance due to electrical drives instead of hydraulics. Introducing and enabling remote control of cranes come with a higher CAPEX because of more complex technology and added sensors. Efficiency might also be affected, as remote control in many cases will be more complex than manual crane control, at least in the transition period from manual to remote control.

MacGregor states that electric solutions in cranes cause lower CAPEX and OPEX[44]. Lower CAPEX is achieved if electric cranes are considered in the design phase, and the size of the generator can be smaller and hence the total vessel cost will be lower. Maintenance and service costs will be lower, MacGregor has calculated that the average service cost for electric cranes over 15 years will be 22 % lower than for conventional cranes. At the same time, loading and unloading of bulk and containers can be more efficient as electric cranes operate at higher speeds and precision.

### 7.5.2 Environmental impact

It is challenging to assess the environmental impact of automation of cargo handling related to bulk operations. Automation of the cranes will probably not affect the GHG emissions to a high extent, since there is limited efficiency improvement potential, however if automation goes hand-in-hand with electric cranes, then there is a huge potential. Electric cranes[44] typically consumes 50 % less energy than hydraulic cranes, mostly because there is no loss of energy due to energy transfer. In addition, the potential for oil spills are eliminated. There will also not be any oil change needed, which eliminates the waste oil.

### 7.5.3 Social impact

Several social impacts from automation of cargo handling operations have been identified, whereas the most important are:

- Eliminate human exposure to risk related to heavy lifts, related to near misses and (fatal) accidents. This goes for both crew on board and stevedores at the terminals.
- Overcome the issue of lack of experienced crane operators, as well as better working conditions. Crane operators can be located in an ROC or similar, and as such control cranes on several ships
- Noise related to cargo handling operations in terminals close to residential areas, which will be reduced with electrical cranes and lifting equipment in general.

The conclusion on social impact from automation of cargo handling operations is positive, as exposure to risk is eliminated, crane operators get better working conditions and noise from cargo handling operations will be reduced (positive for people living in the surroundings of the terminal).

### 7.5.4 Conclusion

Based on the discussions above on economic, environmental and social effects on commercial feasibility, it can be concluded as shown in Figure 26. The economic effects are a bit unclear as CAPEX will be higher, but it is expected that OPEX will be reduced. Concrete numbers, however, are not included in this report.

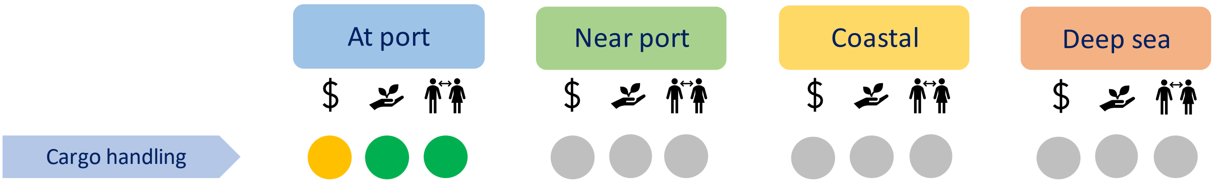

**Figure 26: Cargo handling feasibility.**

## 7.6 Mooring

Automated mooring will be an important part of an unmanned ship, and the economic, environmental and social effects are assessed in the following sub sections. The assessment of the mooring is conducted for the at port phase only, since the other phases are considered not applicable (which is reflected with grey lights in Figure 27).

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[44] https://www.macgregor.com/news-insights/news-articles/2021/more-sustainability-for-50-less-energy/

### 7.6.1 Economic impact

It is expected that CAPEX will be high for installation of automated mooring solutions, both for shipside and quayside systems. Hence, CAPEX must be seen in connection with the OPEX. Another important perspective is who takes the cost and how to make business from it. To invest in vacuum pads at the quayside is challenging for small and medium ports, where cargo volumes might be limited. However, for the bigger ports it is a different picture, and it is merely a question of business model, how to include the mooring cost as part of the port charges as an example. From a ship owner's perspective, it is probably hard to defend an investment in automated mooring system on the ship, as the CAPEX will be too high compared to savings in OPEX. However, if mooring was the only operational task for parts of the crew, this crew cost could be eliminated by reducing the crew, also reducing the need for support from the terminal operator. However, the main reason for investing in shipside mooring system would be flexibility as the ship can enter any quay (only limited by the size of the quay, as would also be the case with conventional mooring). If the ship only visits a given set of ports, and does not need the flexibility, then probably the CAPEX is too high. There is another perspective though, the fact that energy consumption can be reduced, as seen in the following subsection.

Some auto mooring manufacturers have started offering what is called mooring-as-a-service[45], where the owner pays per mooring, a business model that might work in the case where such a system is the only viable mooring solution, and the CAPEX would be too high. The mooring cost could be forwarded to the ship owner/manager as portion of the port charges.

### 7.6.2 Environmental impact

The environmental impact from automation of mooring is substantial. According to (Díaz-Ruiz-Navamuel et al., 2021), the $CO_2$ emissions from mooring operations (the handling of mooring lines) can be reduced with up to 98 % at ports where automated vacuum pads are installed. The main reason for this it the time spent to moor the ship, which can be reduced from around half an hour to 25-30 seconds if using vacuum pads installed on the quayside. However, it must be noted that this is just a part of the total mooring operation.

### 7.6.3 Social impact

The social impact from automatic mooring is connected to two main factors:

1. Reduction of human exposure to risk
2. Removal of humans as part of mooring operation

Factor 1 above is one of the main drivers for automation of mooring (besides the fact that mooring must be automated if the ship is unmanned). Mooring operation has always been an operation that exposes stevedores and ship crew to risks. According to DNV[46], statistics from the European Harbour Master's Committee indicate that 95 percent of mooring injuries are caused by ropes and wires. Over 220 mooring related incidents were reported the Australian Maritime Safety Authority between 2010 and 2014 (22 percent resulted in injuries). Autonomous mooring will eliminate human exposure to risk related to mooring operations.

Factor 2 is in many cases an argument against automation, as people lose an important work task, which ultimately will lead to less jobs in traditional ship related operations. However, this picture is complex, because the crew responsible for mooring also has other tasks. Anyhow, there is a lot of resistance with

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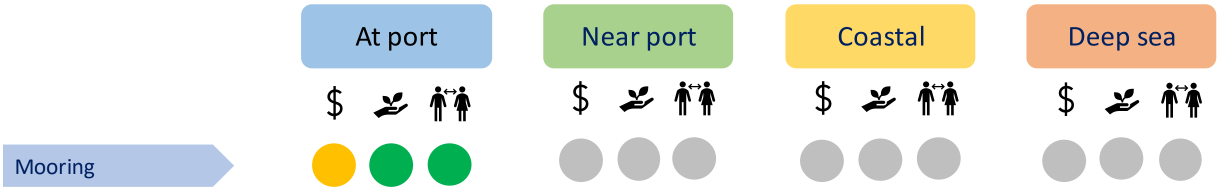
[45] https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring

[46] https://www.dnv.com/expert-story/maritime-impact/A-new-look-at-safe-mooring.html

automation in many labour unions around the world, and especially in the US[47]. At the same time there is a lack of workers in many ports, the Port of Rotterdam had 8.000 job openings in June 2022[48] and were losing ~10 % of their turnover. It is expected that this challenge will increase in the coming years.

### 7.6.4 Conclusion

Figure 27 shows the conclusions for commercial feasibility of unmanned mooring operations. Cost has a yellow colour due to highly increased CAPEX costs if ship installs automatic mooring solutions. If the ports invest in such solutions, the VOYEX costs are expected to increase, however not the CAPEX of the ship. One aspect that has not been considered in this case is insurance and liability related to automation of mooring operations, which might have unclear consequences on the cost picture. It is expected that this kind of automation will have a positive effect on the environment, as the time spent on handling ropes and wires will be reduced significantly. The social effects have been considered positive due to elimination of human risk and the shortage of workers.

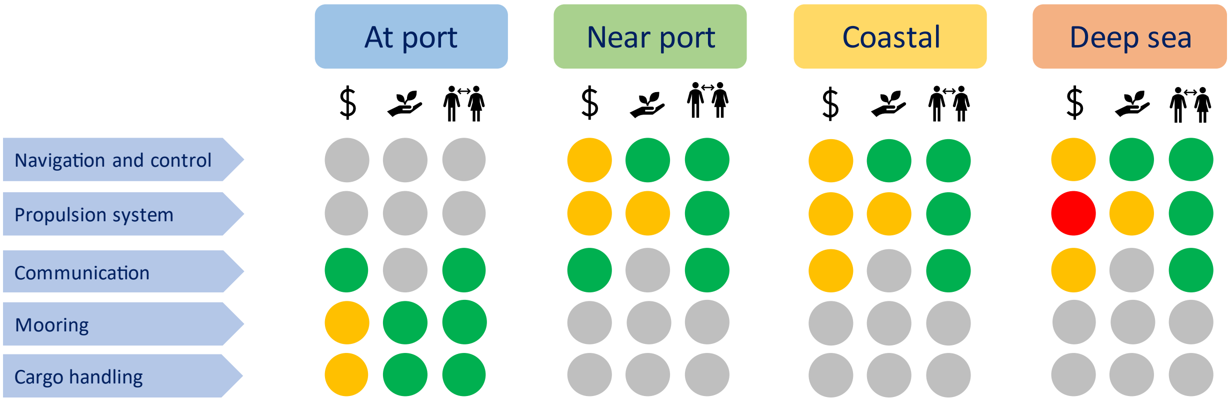


| | At port | | | Near port | | | Coastal | | | Deep sea | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $ | 🌱 | 👥 | $ | 🌱 | 👥 | $ | 🌱 | 👥 | $ | 🌱 | 👥 |
| Mooring | 🟡 | 🟢 | 🟢 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ |

**Figure 27: Mooring commercial feasibility.**

## 7.7 Commercial Conclusion

The conclusion on the commercial feasibility is shown in Figure 28. The economic impacts for an unmanned cargo ship are mostly considered yellow, mostly because there are several uncertain factors playing a role in the assessments. Environmental and social impacts are in most cases considered positive, which is linked to several reasons, which are explained in the different sections of this chapter.



| | At port | | | Near port | | | Coastal | | | Deep sea | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $ | 🌱 | 👥 | $ | 🌱 | 👥 | $ | 🌱 | 👥 | $ | 🌱 | 👥 |
| Navigation and control | ⚪ | ⚪ | ⚪ | 🟡 | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 |
| Propulsion system | ⚪ | ⚪ | ⚪ | 🟡 | 🟡 | 🟢 | 🟡 | 🟡 | 🟢 | 🔴 | 🟡 | 🟢 |
| Communication | 🟢 | ⚪ | 🟢 | 🟢 | ⚪ | 🟢 | 🟡 | ⚪ | 🟢 | 🟡 | ⚪ | 🟢 |
| Mooring | 🟡 | 🟢 | 🟢 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ |
| Cargo handling | 🟡 | 🟢 | 🟢 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ |

**Figure 28: Conclusion on commercial feasibility of an unmanned cargo ship.**

The overall conclusion is that an unmanned cargo ship under the assumption herein (ref. section 1.1) is commercially feasible with certain prerequisites, such as alternative fuels not necessarily being a requirement for an autonomous ship. This has been included mainly because of today's maintenance scheme, where daily maintenance is required and hence hard to follow up without crew on board. Further, it is a question related to redundancy and actuation of the ship, what will be required to stay as safe as a

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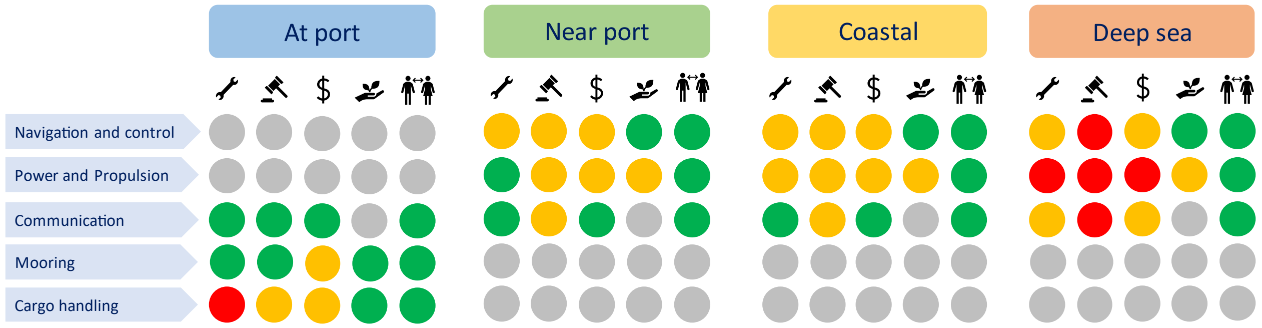
[47] https://www.dw.com/en/us-labor-dispute-dock-workers-say-no-to-port-automation/a-62973261

[48] https://nltimes.nl/2022/06/19/companies-port-rotterdam-lose-millions-due-staff-shortages

conventional ship. Most of the yellow lights in Figure 28 are linked to uncertainties because these ships have not yet been built (e.g. ships with no superstructure). However, since the cost picture might as well end up positive, and the fact that environmental and social impacts are positive, the overall commercial impact ends up positive.

# 8 Conclusion

This study has investigated whether it is possible to operate a large cargo ship unmanned, i.e., over 100 m long. In this context, the term cargo ship is used to denote either a break-bulk ship or a container ship. It is assumed that the ship is constrained autonomous, meaning that the ship can operate autonomously in most situations, but may need human assistance from a remote operations center (ROC). A prerequisite for the study is that the ship is operating in international waters and can visit any port. Additionally, it is assumed that the unmanned cargo ship is a new build and without superstructure, and that by national regulations are meant the Norwegian. The results of the feasibility study are summarized in Figure 29. The columns show the different phases and the rows show the different tasks. The traffic lights indicate whether it is feasible or not to automate the given task. A green light indicates that it is feasible today, a yellow light indicates a that it is feasible within the next 5 years, while a red light indicates that it is not feasible within the next 5 years.



| | At port | | | | | Near port | | | | | Coastal | | | | | Deep sea | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 🔧 | ⚖ | $ | 🌱 | 👫 | 🔧 | ⚖ | $ | 🌱 | 👫 | 🔧 | ⚖ | $ | 🌱 | 👫 | 🔧 | ⚖ | $ | 🌱 | 👫 |
| Navigation and control | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | 🟡 | 🟡 | 🟡 | 🟢 | 🟢 | 🟡 | 🟡 | 🟡 | 🟢 | 🟢 | 🟡 | 🔴 | 🟡 | 🟢 | 🟢 |
| Power and Propulsion | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | 🟢 | 🟡 | 🟡 | 🟡 | 🟢 | 🟡 | 🟡 | 🟡 | 🟡 | 🟢 | 🔴 | 🔴 | 🔴 | 🟡 | 🟢 |
| Communication | 🟢 | 🟢 | 🟢 | ⚪ | 🟢 | 🟢 | 🟡 | 🟢 | ⚪ | 🟢 | 🟢 | 🟡 | 🟢 | ⚪ | 🟢 | 🟡 | 🔴 | 🟡 | ⚪ | 🟢 |
| Mooring | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ |
| Cargo handling | 🔴 | 🟡 | 🟡 | 🟢 | 🟢 | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ | ⚪ |

**Figure 29: Technical, regulatory, and commercial feasibility.**

Figure 29 shows that there are still some challenges to be solved before large cargo ships can operate unmanned (under the given assumptions). However, for small and medium size vessels, unmanned operation with human support from a ROC can be feasible today or near future within certain concept of operations (CONOPS), especially in national waters where there exist regulations for autonomous ships. To operate an unmanned ship internationally, bilateral agreements between the countries involved can be a solution to solve the regulatory challenges.

Moreover, even for a large cargo ship, some of the individual tasks can be automated today or in near future with economic, environmental, and/or social benefits. This will be discussed in section 8.1.

For the task *navigation and control*, a big challenge is the technical aspects of autonomous navigation for instance due to the performance of the object detection and classification. This is especially a challenge in the *near port* phase where there are a lot of vessels and other objects and obstacles. In the *deep sea* phase, there are less objects, making the navigation easier. However, in *deep sea*, the international regulations apply, which are not ready for large, unmanned cargo ships today, while in *near port* and *coastal* (assuming Norwegian waters) there exist regulations that can make this possible after a trial period. On the bright side, there are both economic, environmental, and social benefits from automating the navigation and control task for all phases.

Regarding the task *power and propulsion*, the main technical challenge is the maintenance. Today, large cargo ships typically operate with a simple power and propulsion system and the cheapest fuel possible. This requires frequent maintenance, which makes it difficult to operate unmanned, especially when considering long voyages which is typical for largo cargo ships (e.g. a week). New and cleaner energy sources and power systems may require less maintenance and should be considered for an autonomous ship. However, the cost of cleaner energy sources is expected to be higher than conventional fuel.

For the *communication* task, which includes both traditional ship-ship and ship-shore communication in addition to the communication and connectivity needed to operate the ship from a ROC, the largest challenges are in the *deep sea* phase since this would require satellite communication. Satellite communication has varying coverage, lower bandwidth, higher latency, and is more expensive. However, the bandwidth and latency requirements depend on what is needed to be communicated to a ROC, which is not yet determined. The communication is considered not regulatory feasible in *deep sea* since it is not defined how to perform ship-ship communication for an unmanned ship and there is yet no IMO Mass Code for defining the relationship between the ship and the ROC.

The last two tasks, *cargo handling* and *mooring*, are applicable during the *at port* phase. Automated mooring is possible and commercially available in the market today. However, automated cargo handling is a challenge for the cargo ships in the discussed use cases, i.e. break bulk ships and container ships.
For break-bulk, the main challenge is the connection (hooking) of the cargo due to the vast diversity of commodities and packaging which makes automation challenging. For container ships the main challenge is the securing of the containers which involves lashing, an operation proven hard to automate.

The overall commercial impact for an unmanned cargo ship is positive under certain prerequisites, such as alternative fuels not necessarily being a requirement for an autonomous ship. This has been included mainly because of today's maintenance scheme, where daily maintenance is required and hence hard to follow up without crew on board. Further, it is a question related to redundancy and actuation of the ship, what will be required to stay as safe as a conventional ship (which is also linked to how much human intervention from a ROC that can be accepted). Still the environmental and social impacts are expected to be positive.

## 8.1 Recommendations

The results from this study showed that a large, unmanned cargo ship is not feasible today or the near future. However, there are still tasks that can be automated for a manned ship with economic, environmental or social benefits today. Below is a list of recommended actions.

- **Unmanned bridge in deep sea**. As can be seen from Figure 29, there are environmental and social benefits from automating the navigation and control in all operational phases. The economic impact in deep sea is uncertain (yellow light). In the deep sea phase, this can be seen as a low hanging fruit, as it is technical less challenging. However, there are some challenges in the international regulations that apply in the deep sea phase. This brings the idea of an unmanned bridge or periodically manned, which may be more feasible from a regulatory viewpoint.
- **Energy efficient navigation**. What has been seen from the commercial feasibility is that the fuel cost is a large part of the total cost. Thus, navigating more energy efficient will have a positive impact on both the environment and the wallet. It would be in our interest if the navigation would take other factors into considerations – such as the vessel’s movements and external conditions – to ensure that the ship gets from A to B the most efficient way (i.e. produce the lowest emissions, and ensure the cargo arrives in good condition).
- **Automatic mooring.** There are commercial products that enable automatic mooring of large cargo ships today. Using automatic mooring increases the safety (by moving away people) and can reduce the energy consumption. A downside here is the high investment cost.

## 8.2 Further Work

As discussed in Chapter 7, there are large benefits of having a fully unmanned ship. With an unmanned ship, superstructure is removed, enable more cargo to be transported per unit. To enable a large, unmanned cargo ship operating under constrained autonomy, there is still work that remains. Below is list of some actions points that should be performed.

- **Safety and redundancy for power and propulsion.** Today's commercial ships like Yara Birkeland and the ASKO ferries are over-engineered since they are first movers. This makes the investment cost for the ships very high, and it might be that this is not needed to stay as safe as conventional ships.
- **Automatic docking.** The docking of large cargo ships is mostly using tugboats today, and it is unclear how this will be done for an unmanned ship. Automated docking is being researched in the SFI and there might be possibilities for testing and demonstration as part of the project.
- **Cargo handling.** Through the cargo automation gap analysis it was recommended to look at remote control before entering into autonomous control. This seems to be the natural first step for further automation of deck cranes.
- **ROC.** Today it is not clear what data needs to be communicated between an unmanned ship and a ROC. This should be further investigated to find out if the communication systems satisfy the needs.
- **Assessment of the coming MASS code and its implications**.
- **COLREGs.** The COLREGs are not ready for autonomous navigation today and must be revised.
- **Commercial impact.** More studies on the commercial impact of autonomous ship are needed. With autonomous ships being tested today, more details of potential cost of autonomous ships can be estimated.

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