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MASTER'S THESIS

Unmanned Surface Vessels as a safer and more sustainable alternative for maritime operations within the Offshore Safety Zone

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Submission Date: The 2nd of June 2021

I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 12-1.

Abstract

Offshore industry is in need for alternative shipping solutions, due to stricter environment regulations and higher fuel prices. Thanks to common advancement in technology, it is now possible to develop safer and more sustainable vessels for offshore operations. Therefore, purpose of this study is to investigate whether Unmanned Surface Vehicles (USVs) can replace conventional vessels in light Inspection, Maintenance and Repair (IMR) operations within installation`s safety zone.

For this reason, USV`s features were investigated in terms of benefits they may bring for IMR operations. Secondly, issues concerning cooperation between USV and offshore installation were identified as well as their possible solutions. In order to examine USV`s sustainability, weather window analysis for “Åsgard” platform was carried out. Based on the obtained results, it was possible to choose the most appropriate Launch and Recovery System for USV`s Remotely Operated Vehicle. Data for this study was obtained through extensive literature research of official documents, scientific journals, books and statistics.

This thesis presents benefits as well as challenges that await USV within next decade. Moreover, it can serve as a great basis for further research on other USV applications within safety zone, such as subsea constructions, supplies etc. On the other hand, concept of unmanned vessels is still new, which results in limited number of available resources, standards and regulations. Therefore, most of the thesis is based on assumptions and free interpretation of existing regulations that could apply to USVs and their employment within installation`s safety zone.

Acknowledgements

Throughout my journey with master's degree, I have received an amazing support and help from many incredible people.

First, I would like to express my very great appreciation to my supervisor, Jens Christian Lindaas, for his valuable and constructive advice throughout planning and development of this master thesis. His knowledge, experience and ingeniousness contributed greatly to the outcomes of this thesis. He always guided me in the right direction, whenever I need it. Working with him was a great experience and a pure pleasure.

I would like to offer my special thanks to "Deep Ocean" and its staff, especially to Knut Vibran Knutsen. Without his ideas, professional approach and enthusiasm, completion of this dissertation would be impossible. Moreover, provided by "Deep Ocean" materials form the basis of this thesis and gave the opportunity to draw crucial conclusions for unmanned operations at sea.

I would also like to extend my thanks to my university tutors, who introduced me to the world of maritime operations in an engaging and innovative way. No to a lesser extent, I would like to acknowledge academic personnel, namely Hilde Sandhåland and Anna Therese Nesheim Østhus, who always helped me and guided me throughout these two years at the HVL University.

Finally, I wish to thank my parents and my boyfriend for their support and continuous encouragement. This accomplishment would not be possible without them. Moreover, I could always count on my fellow classmate Sandeep Nepal, whenever I needed help or reassurance.

Thank you all.

Karolina Helmer

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List of abbreviations

Abbreviation	Meaning
AAWA	Advanced Autonomous Waterborne Applications Initiative
AI	Artificial Intelligence
ASC	Autonomous Ship Code
AUV	Autonomous Underwater Vehicle
CAGR	Compound Annual Growth Rate
COLREG	Convention on the International Regulations for Preventing Collisions at Sea, 1972.
CONOPS	Concept of Operations
DNV GL	Det Norske Veritas and Germanischer Lloyd
DP	Dynamic Positioning
ECC	Engine Control Centre
ECDIS	Electronic Chart Display and Information System
EMSA	European Maritime Safety Agency
ETA	Estimated Time to Approach
e-ROV	Electrical Remotely Operated Vehicle
FPSO	Floating Production, Storage and Offloading
GM	Metacentric Height
GNSS	Global Navigation Satellite System
GOMO	Guidelines for Offshore Marine Operations
GPS	Global Positioning System
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study

HD	High Definition
HFO	Heavy Fuel Oil
HSE	Health and Safety Executive
HSEQ	Health, Safety, Environment and Quality
IMO	International Maritime Organization
IMR	Inspection, Maintenance and Repair
IR	Infra-Red
ISO	International Organization for Standardization
ISR	Intelligence, Surveillance and Reconnaissance
IT	Information Technology
LARS	Launch and Recovery System
LIDAR	Light Detection and Ranging
LWIR	Long Wave Infra-Red
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MJ	Mega Joule
MPAs	Marine Protected Areas
MRC	Minimum Risk Condition
MRP	Marine Responsible Person
MRS	Marine Safety Forum
MT	Metric Ton
MUNIN	Maritime Unmanned Navigation through Intelligence in Networks
NCS	Norwegian Continental Shelf

Nm	Nautical miles
NTNU	Norwegian University of Science and Technology
OIM	Offshore Installation Manager
OOW	Officer of the Watch
OPEX	Operational Expenses
OSV	Offshore Service Vessel
PMS	Power Management System
RCC	Remote Control Centre
ROV	Remotely Operated Vehicle
SA	Situation Awareness
SC	Self-Controlled Function
SMS	Safety Management System
SOLAS	International Convention for the Safety of Life at Sea
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
SWIR	Short Wave Infra-Red
TCC	Total Crew Costs
UKCS	United Kingdom Continental Shelf
UNCLOS	United Nations Convention on the Law of the Sea
UPS	Uninterrupted Power Supply
USD	United States Dollar
USV	Unmanned Surface Vehicle
VHF	Very High Frequency
ZOC	Zones of Confidence

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1. Introduction

1.1. Background

"Shipping is perhaps the most international of all world's great industries- and one of the most dangerous" [1]

Since the dawn of time, man has always been aware of life fragility. Wars, diseases and everyday accidents are, whether we like it or not, an inseparable element of our life. Therefore, it is an instinct to protect and prevent ourselves from situations in which our life could be endangered. Nevertheless, history has showed that people themselves can be the biggest threat to their own lives.

Overconfidence, rushing, shortcuts, distractions are just some of the root causes of accidents that had happened in maritime industry in recent years. These behaviours are typical for environment in which time is money. Pressure, which is imposed on the captain and crew members is inversely proportional to their time off from work. On the other hand, it would be wrong to say that all accidents are caused by human actions. System or equipment failures, environmental impact, hazardous materials are just some of the other sources of danger at sea. However, if we take a closer look at the "Annual Overview on Marine Casualties and Incidents 2020" by European Maritime Safety Agency (EMSA) we can clearly see that from 1801 accidents examined during the investigation, 54% were caused by human actions and only 28% by system or equipment failure [2].

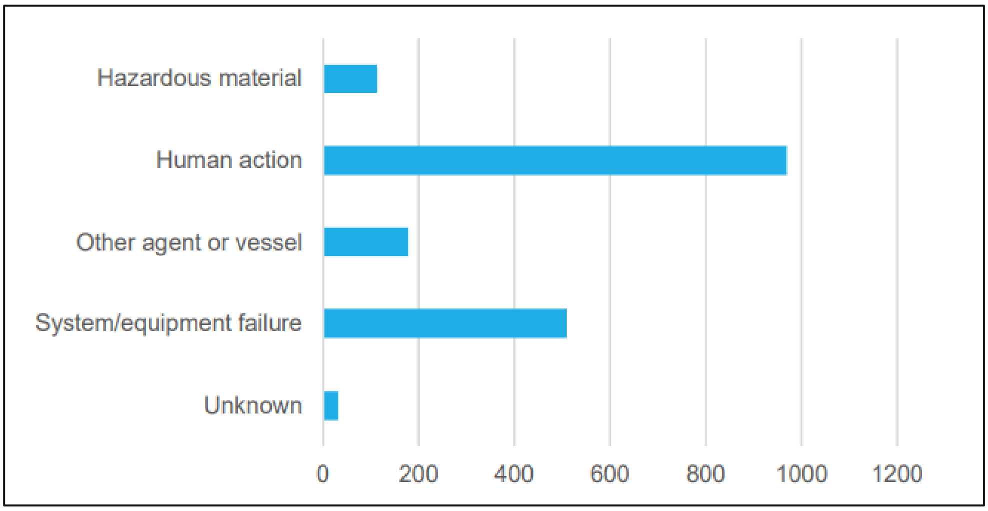

Figure 1. Distribution of accidents events for the period 2014-2019 [2]

With development of technology, ship`s crew began to decline, as more on-board tasks could be fulfilled without human intervention. This is due to common progress in automation, robotics and IT in every branch of maritime industry. Such decrease in human presence, triggered engineers and scientists to work on high-tech solutions, which could relocate people from vessels to shore-based centres. They came up with innovative concept, which would allow vessel to operate by itself or with help from operators located onshore. Such remote or autonomous vehicles would use advanced sensor technology in order to provide necessary information about the surrounding for better situation awareness. Moreover, their collision avoidance system would allow to reduce risk of collisions and to provide, as many believe safe and efficient maritime operations.

On the other hand, along with development of new shipping concept, many questions have arisen regarding its safety. Some argue that autonomous or remote vessels cannot replace officers on the bridge in situation assessment. What`s more, it is not sure whether such vehicles are able to perform complicated tasks common for i.e., offshore industry. All the above issues come down to a one decisive question: Do we make maritime operations safer, by making ships more independent from people?

At this moment, the biggest profit generator within maritime industry is offshore. Starting from the XX century, oil and gas industries expanded their exploration from lands towards seas and oceans. Oil companies, with the help of engineers and geologists began to design and construct platforms, allowing for oil extraction from the seabed. Despite appearance, it is also one of the most dangerous industries. Complex offshore operations, such as drilling, oil production and oil transportation makes the platform and area around extremely fragile. Therefore, all safety related activities associated with offshore industry have always top priority. A good example to illustrate the scale of consequences that may arise from underestimating the offshore hazards is the explosion of Deepwater Horizon platform in 2010. It caused 11 casualties and contributed to the biggest oil spill in petroleum history. It was estimated that 4.9 million barrels were discharged into the ocean during that event [3]. Even though accident was not caused by vessel`s intentional or unintentional actions, it still illustrates how dangerous offshore operations can be.

Despite many efforts from maritime organizations and shipping companies to raise safety standards in industry, accidents continue to happen. In recent years, there have been several collisions and even more near misses with offshore structures. Just between 2001-2010 on the Norwegian Continental Shelf (NCS) there have been 26 accidents involving ships and platforms [4]. Only in two of the accidents, vessels passed by outside the installation`s safety zone. In the rest of the cases, vessels were operating inside the 500 m safety zone.

Safety zone aims at protecting people who work on the platform and those in its immediate vicinity [5]. Safety zone itself does not pose a risk of collision. However, non-compliance to safety standards, insufficient training for bridge team, fast pace of operations and no breaks between shifts might increase the likelihood of an accident unprecedentedly.

All this together indicates urgent need for changes in safety management system within offshore industry. Moreover, having an enormous advantage in today`s developments, it would be a waste not to use their outcomes for high-reaching purposes, such as safety of maritime operations. Only in the last few years, there have been many studies and projects related to the Unmanned Surface Vessels, such as SEA-KIT USV project, Sounder USV System from Kongsberg group etc. Many of USVs have been already tested in real sea-going conditions and now they are used by the Navy and ocean scientists [6]. USV`s performance proved to meet expectations, which contributed to their further developments. These vessels keep getting bigger, technology advanced, and environmentally friendly. It is predicted that within some years, USVs will be used for commercial transportation and other more complicated tasks, so far reserved only for conventional vessels.

1.2. Objectives

The main aim of this research is to verify whether USVs can be considered as an alternative to conventional shipping within 500 meters safety zone. Dissertation will indicate safety aspects of unmanned operations as well as gaps in the existing regulations regarding USVs. Furthermore, economic and environmental aspects of USV employment within safety zone will be analysed as well.

Presented thesis seeks to answer the following research questions:

1. What are the features of USVs that make them safer in comparison to manned vessels?
2. How offshore installation and USV can work together to guarantee safer maritime operations within safety zone?
3. What are the economic and environmental benefits of USV employment in offshore industry?

1.3. Limitations

Following research is limited to one region of offshore operations, that is Norwegian Continental Shelf. This is due to fact that, each of the oil-producing country has their own regional guidelines for offshore operations within its territorial waters. Thus, involvement of each offshore region and its legislation could lead to generalization of the research and this in turns, to inaccurate results. Therefore, presented thesis is largely based on Det Norske Veritas Germanischer Lloyd (DNV GL) guidelines and international maritime regulations applicable to a Norwegian Continental Shelf region. Northern part of NCS i.e., Barents Sea is not considered in following thesis as weather conditions there are still too harsh for USVs operations.

Further limitation refers to the type of operations. It is assumed that USV is going to perform IMR operations, such as inspection of subsea structures using ROV. ROV will be connected with USV through a tether and deployed using most likely moonpool.

Lastly, it is essential to make a distinction between phrases appearing in the text, such as “manned” and “unmanned”, “remote” and “autonomous”. Term “manned” refers to a vessel with people living and working physically on board. It applies also to manned vessels with slight or advanced degree of automation. On the other hand, term “unmanned” relates to a vessel with no human presence on board during ship`s operations. The same phrase is also used in reference to autonomous and remote vessels in all levels of autonomy.

Furthermore, it is significant to make distinction between different levels of autonomy. According to the Lloyd Register, we can distinguish six levels of autonomy [7]:

- *"AL0-Vessel is operated manually. It has no autonomous functions.*
- *AL1- On ship decision support system.*
- *AL2- On and off decision support system.*
- *AL3- "Active" human in the loop.*
- *AL4- Human on the loop- operator/supervisory.*
- *AL5- Fully autonomous (& rarely supervised).*
- *AL6- Fully autonomous (& with no supervision)".*

In the following dissertation focus is placed on unmanned vessels with autonomy level between AL3-AL4.

1.4. Scope

Chapter 2 gives a closer look at thesis methodology and explains why chosen approach is the most suitable. It also describes in details criteria for validity and reliability in this type of dissertation. Lastly, precise explanation of data collection and data analysis are given together with ethical issues encountered during research process.

Next part of the thesis Chapter 3 "Safety Zone" familiarizes the reader with the area of USVs operations, its location and environment conditions. Moreover, it describes roles and responsibilities of people, who have the greatest influence on safety within 500 meters zone. Last subsection presents first outcomes about general suggestions for safe USV operations.

Chapter 4 "Legislation of unmanned vessels and their challenges" is dedicated to legislation issues concerning USV operations generally at sea and specifically within safety zone. International conventions and standards, such as STCW, COLREG, SOLAS, DNV GL and GOMO are analysed in terms of their application to the USV vessels in their present form.

Chapter 5 demonstrates current developments concerning USVs, their application and future developments. Moreover, detailed description of degrees of autonomy and design principles will be presented here as well, as it has direct impact on safety issues. All this together will be analysed in relation to IMR operations that can be performed by remote USVs, based on review of existing literature on the subject.

Chapter 6 “USV`s hazards and their causes within 500m safety zone” points out the most common threats, that can happen during USV operations and possible countermeasures. The emphasis is putted on unforeseeable events, as their consequences are the most damaging. Lastly, following chapter describes threats and mitigation strategy for RCC, focusing on procedural failures and human factor.

Chapter 7 “Safety of IMR operations using USV/ROV” describes different aspects of IMR operations, that have significant influence on their effectiveness and safety. Such issues like weather window, significant wave height, communication and LARS are thoroughly examined. In addition to that, advantages and disadvantages of various onboard sensors are analysed to choose the best solutions for USV operating in harsh weather conditions.

Chapter 8 “Sustainability and environmental impact of USVs” investigate possible benefits of USV employment in offshore and general in maritime industry. Capital, operational and voyage costs are estimated for USV employment and compared to conventional Offshore Service Vessels (OSV). Moreover, possible solutions for USV`s alternative propulsion system is given, that would reduce pollutions and make vessel environmentally sustainable.

In Chapter 9 “Discussion” we will find answers to three research questions posed in “Objectives”. In Chapter 10 are presented final conclusions concerning USV application within safety zone.

2. Research method

2.1.Research approach

Following dissertation has adopted mixed approach, i.e., qualitative in general with small part of quantitative analysis. Aim of the research was to establish a cause-and-effect analysis of USVs application within offshore industry, particularly when operating inside 500m safety zone.

During the whole research, it was crucial to fulfil criteria of validity and reliability, without which obtained results are worthless. Validity of the research was achieved through continual search for alternative explanations of the obtained results. Furthermore, to enhanced validity of the outcomes, experienced and skilled “moderators” have been selected. First moderator was “Deep Ocean group”. Their contribution to the thesis was not affected by *“what we want to hear”* but were genuine and neutral. Second moderator was thesis supervisor, whose experience helped in revision of bias and indicate the factual errors. By engaging in research process two moderators, it was possible to look at the USV`s safety aspect from different perspectives.

At the same time, in order to draw clear and meaningful conclusions, reliability criteria must be achieved. Below, are presented four rules that have been followed during the research process in order to make the outcomes reliable:

- *Research findings are transferable.*
  Some of the research findings can be used in a broader aspect of USV application within offshore industry. For instance, legal challenges that USVs may encounter can be treated universally, as the same rules and regulations, such as COLREG, SOLAS, STCW will apply to USVs around the world. Therefore, contents of the second chapter of the thesis are transferable, but only for USVs with autonomy level AL3-AL4 and in context of international regulations.
  When it comes to operational aspect of the remote vessels, the majority are equipped with same type of sensors and collision avoidance systems. Therefore, presented results on safety of remote operations, from technological point of view can be useful for similar type of projects.
  On the other hand, it could be problematic or even impossible to transfer research findings to another location, as diverse environmental conditions occur in different

parts of the world. This in turn, will affect ship`s motion in different manners and produce divergent conclusions on USV`s safety.

Considered in the following dissertation IMR operations, such as inspections of subsea structures cannot be used in the projects, where more complex USV`s tasks are examined.

- *Research findings are trustworthy.*

  In order to make research findings credible, various types of strategies can be adopted. In following thesis, it was chosen to use "Data Triangulation" method. Materials about each topic were collected from various sources in space, i.e., books, articles, websites and from several people, i.e., company in cooperation, co-workers, friends working in offshore industry. After that, data triangulation was saved using codes with different symbols. It allowed for easier identification of relevant segments later during the analysis. For instance,

  - "U" marked all information about USV, its features, operations, etc.,
  - "I"- stood for information on installation`s features, operations, etc.,
  - "E"- stood for economic and environment aspects of USV`s etc.

- *Research process is dependable and findings confirmable.*

  Dependability and confirmability in the following research were achieved by neutral interpretation of the data. Analysis was not influenced by personal way of thinking but based on grounded knowledge only. This allows to treat this research as a prototype model for future research and to repeat the research process with similar outcomes [8].

2.2. Data collection

As it was established in previous chapter, following thesis has mixed character. Therefore, types of data needed are written and numerical materials about:

- Rules and regulations, which apply or might apply to the USV within safety zone,
- Features of USV, that makes it safe to operate within safety zone,
- Features of effective communication between the installation and Remote Control Centre (RCC),
- Numerical data on irregular waves occurring within NCS,
- Economic and environmental aspects of USV employment within offshore industry.

Collecting method that was used during the research process is a “Document Review” of a secondary/existing data, such as conventions, standards and guidelines. All existing knowledge about the topic was identified during Internet research. Official websites and data bases of IMO, DNV GL, GOMO, were careful examined using keywords linked to the USV and installation`s safety zone. In addition to that, books and articles related to the subject of considerations were founded using HVL Library “Oria’s E-Journal System”. These materials provided a good overview on research topic. Another source of existing knowledge was “Deep Ocean” group. They supported thesis with relevant data, which enhanced and boost accuracy of the project. All the above sources were cross- examined in terms of authority, accuracy, objectivity, currency and coverage of containing information.

2.3. Data analysis

Data analysis was the most important part of the research as wrong results interpretation leads to inaccurate results. Therefore, time spent on this step was longer than any other research-related activity.

Prior to data analysis, findings were properly processed. First step was to get familiar with data content by their careful reading and interpretation. At that stage, it become possible to categorize some of collected information into thematic groups. This helped to develop and establish framework for afterward analysis. It turns out to be quite manageable task, as thesis structure itself is arranged in three thematical sections: law, safety, economy/environment. These categories corelate also with research questions stated in “Objectives”. Therefore, at that moment it was possible to already find some answers for thesis research questions.

Next method “segmenting” was used to locate meaningful segments within analysed document. For this purpose, analysed data was divided into small fragments like chapters, pages, paragraphs, sentences etc. Along with that, it was essential to keep in mind supporting questions, such as: “*Do these fragments, chapters, paragraphs describe USVs, their system, technologies, equipment, vulnerabilities?”, “Do these fragments describe economical aspect of unmanned operations in offshore industry?”*, etc.

After segmenting and coding, data were thoroughly analysed using content analysis method. Content analysis is a common method for qualitative data evaluation, especially interviews transcripts. However, it also finds application in analysing big amount of various written materials. It can be conducted at any time and any place, and their procedures allow others to repeat the research schema in easy way.

3. 500 meters Safety Zone

3.1. Safety Zone features

HSE UK in document INDG189 (rev 1) defines safety zone as an area which surrounds offshore and subsea installations, such as mobile drilling rigs, production platforms, single point moorings, subsea templates and wellheads. Safety zone stretches up to 500m from central part of installation. It is prohibited to enter zone without prior arrangements with installation management. All vessels are required to respect those terms. Safety zones, which protect subsea installations are marked by light buoys, located as close as possible to the centre of such installation [5].

In addition, HSE UK indicates that safety zones are established in order to protect life of people working on the platform and in its direct vicinity. It is preserves surrounding environment by minimizing the risk of damage to the structure and protect installation from the accidents. Moreover, safety zone protects ships from collision with the installation and preserves fishermen`s gear from lost or damage caused by subsea devices. Location of safety zones can be found in Hydrographic Office Charts, radio navigation warnings and Admiralty Notices to Mariners. If vessel`s crew has dilemma whether installation is surrounded by a safety zone or not, it should be considered that it is. In this case vessel should stay away from the zone as far as possible and keep listening on channel 16 VHF [5].

In order to enter safety zone, vessel needs to fulfil all requirements imposed by international and domestic maritime authorities, i.e., United Nations Convention on the Law of the Sea (UNCLOS) and Coastal State Legislation. Moreover, only vessels which are employed for below operations can enter and stay within safety zone [5]:

- *"To lay, test, inspect, repair, alter, renew or remove a submarine cable or pipe-line.*
- *To provide services for an installation within the zone or to transport persons to or from it, or under authorisation of a government department to inspect it.*
- *If it belongs to a general lighthouse authority vessel to perform duties relating to the safety of navigation.*
- *To save life or property, owing to stress of weather or when in distress.*
- *owing to bad weather; or*
- *when in distress".*

- IMR and construction operations

In guidelines “*Marine Operations: 500m Safety Zone*” prepared by “Step Change in Safety”, we can read that during vessel`s approach to 500m safety zone, it is important to never include an installation as a waypoint. The final waypoint should be offset from the platform. Moreover, vessel should never approach the safety zone head on [9]. Before ship can enter a safety zone, master/operator needs to fulfil all pre-entry requirements (see Appendix A). They will consist of concerns relating to communication as well as determination of Marine Responsible Person (MRP) for keeping contact with the vessel [9].

In addition to that, “Step Change in Safety” guidelines indicate, that one hour before entrance, communication between vessel and platform should be switched to VHF. Moreover, description and analysis of possible evacuation routes for the vessel should be discussed here as well [9].

Furthermore, same guidelines state that further arrangements should concern vessel`s directions of approach and details of planned operations. This includes starting and ending position within the zone during the operations. Each position should be analysed in terms of hazards by the Offshore Installation Manager (OIM) and master. Vessel`s operations should be planned in a way that will minimize its presence within safety zone. Vessel should approach to the set-up position with maximal speed of 3kn. This value will vary from vessel to vessel, and it will depend on weather conditions. At set-up position, master as well as OIM/ MRP should be satisfied of onboard systems` performance. This means, that DP system is reliable, power utilization is less than 45% and vessel motion is within its operational limits [9]. Figure 2 presents 500m safety zone with an example of vessel`s approach to the installation.

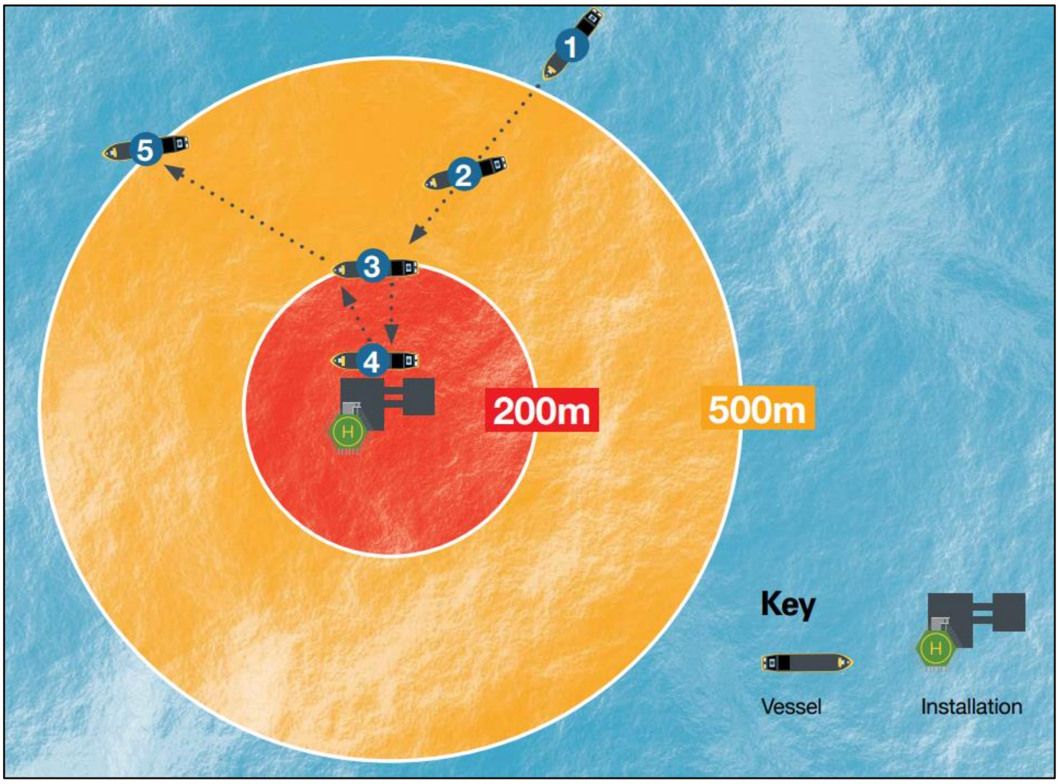

Figure 2. 500m safety zone [9]

Each offshore installation located in different part of the world will be characterized by various weather conditions. They will determine time and kind of operations, that can be performed within safety zone. Waves, visibility, wind, etc. can restrict planned operations as well as deteriorate safety of the vessel. Therefore, it is significant for the USVs safety zone employment to came up with solutions for improvement of vessel-installation cooperation.

A major issue concerning USV`s employment within safety zone is communication with installation prior to entrance to safety zone and later during operations. Many rules and regulations, such as GOMO indicate the importance of continuous and uninterrupted communication between master of the vessel and OIM/MR [10]. It is also one of the pre-entry requirements, where it is mandatory to establish communication channel, operation`s details and contingency plan (see Appendix A) [9]. However, such communication can be interfered by other vessels operating within safety zone, as well as by harsh weather conditions at NCS. Moreover, in order to possess updated on-scene data, operators would need to receive sensor`s information burdened with a small latency. All this together, have great influence on communication effectiveness and, furthermore, for safety of unmanned operations.

3.2. Roles and Responsibilities within 500m safety zone

In following chapter, a short summary of roles and responsibilities of people involved in safety zone operations is given. It is based on IMR operations, where installation cooperates with Offshore Service Vessels. Same standards of cooperation will be required from the USVs that is to maintain safety and efficient communication with the installation. Overall outcomes and recommendations about the roles and responsibilities relating to operations between USV and installation are presented in section 3.4.

So far, IMR operations conducted by conventional vessels involves several crew members working under different affiliations: vessel owner, subsea contractor and operator (mainly an oil company) [11]. This type of organization is called Operational Multiteam System (see Figure 3) [11].

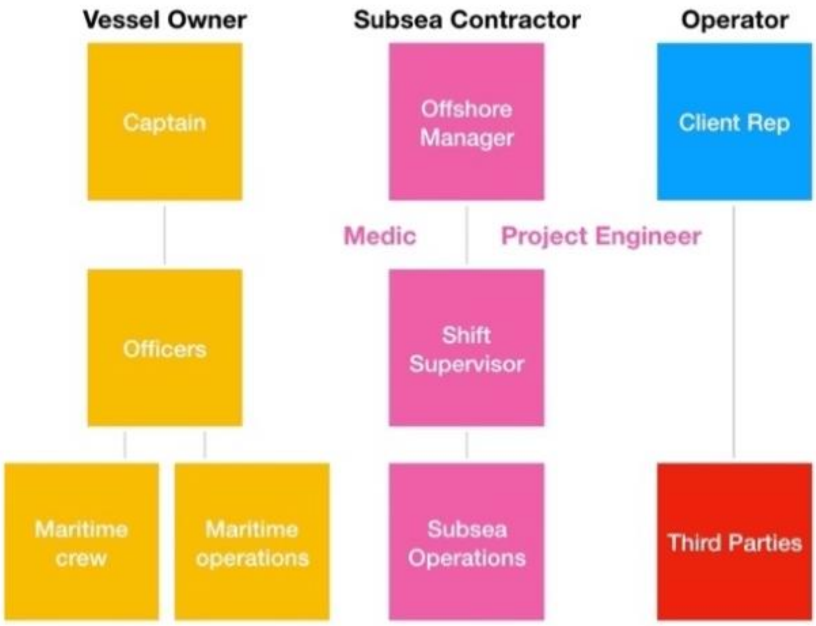

Figure 3. Organization of IRM operations on convectional vessels [11]

Such organizational management has its drawbacks, that have been revealed in research conducted by Jan R. Jonassen and I.A. Johannessen. Their studies have found that the main problem with Operational Multiteam System lays in "*unclear lines of communication and responsibilities*" as well as "*the impact of strong personalities*" [11]. It is mainly relating to collaboration between those three leaders, that can be deteriorated due to their domineering behaviours. Total number of crew members working on IMR vessel may vary between 30-100 people, depends on type of operations. Usually, they are divided into three working teams, where each has its own leader: captain, offshore manager and client rep [11].

In case of USV performing subsea inspection, matter of leadership and people involved in operations may be simplified. Numbers of crew members can be minimized to around 5-10 people located ashore in RCC. This is due to high level of vessel`s automation allowing for remote task execution. Captain, officers and chief engineer can be replaced by appropriate number of remote operators. Marine crew deck and medical staff would not be needed anymore, due to again systems automation and lack of hazards arising from working at sea. Shift Supervisor, whose task is to coordinate IMR operations can be replaced by “Timeline”, “Switchboards” and “Status” USV`s displays (see Appendix B). ROV team will remain unchanged and transferred to RCC. Offshore Manager and Client Rep presence would not be necessary in every operation, especially when most of the USV task are light interventions and inspections with low level of complexity. Beside USV`s team, the important role will play installation`s employees, such as OIM and MRP to maintain a high safety level of conducted operations.

3.2.1. Offshore Installation Manager

In report prepared by Health and Safety Executive *“The selection and training of Offshore Installation Managers for crisis management”* we can read that the most important role of OIM is to assess all possible situations, which can generate hazards for people working on the installations and its direct vicinity. The results of his/her risk analysis should be followed by immediate actions to reduce exposure to the possible dangers. In order to meet expectations, the OIM`s qualifications should include good knowledge of offshore operations, confirmed by appropriate certifications. In addition to that, the OIM should have great understanding of installation`s emergency plan and systems, as well as being able to act as an on-scene commander in case of major accidents [12].

When it comes to USV performance within safety zone, the OIM could have problem with crisis management in case of accident involving USV. In mentioned HSE report, it is stated that there should be a system for practice decision-making ability for OIMs in case of emergency situations. This issue has been derived from the interviews with installation`s employees, who concluded that in emergency situations OIM struggle to act as an on-scene coordinator [12]. Therefore, it is vital to improve training and competence standards for OIM, considering eventual employment of the unmanned vessels within installation`s safety zone.

Furthermore, in the event of accident, USV `s remote operators must rely heavily on decisions made by OIM, as he/she is physically at the scene. In emergency situations, where stress level is high, misunderstandings may arise. OIM may encounter difficulties to cooperate with the remote operators as they may not understand the OIM`s intentions or have a wrong interpretation of the obtained situation. All this together shows, that OIM training should include communication procedures between installation and remote centre in emergency situations. The OIM should feel comfortable and confident when cooperating with USV and its operators.

3.2.2. Marine Responsible Person

Marine Responsible Person is an installation worker who has long experience and good understanding of operations between installation and vessel. There are no official requirements imposing selection of such person. Nevertheless, it is proven that having designated MRP can be beneficial for effectiveness and safety of operations [9].

Marine Safety Forum (MSF) while developing a "*Marine Operations Guide for operations within 500 m Safety Zone",* realised that the guidelines cannot be effectively use without personnel with adequate marine knowledge. Therefore, MRP should have good understanding of relevant guidelines, policies and regulations, that apply for operation within 500m safety zone. In addition to that, he/she should have knowledge about different types of vessels and relation between their displacement and generated kinetic energy. This is crucial to have a notion about possible load impact on installation. [13].

Having this in mind, main MRP` tasks will include effective communication between installation and vessel. What`s more, MRP will be responsible for pre-entry checklists, observation of all vessels` movement and weather trigger points, that may affect planned operations [13].

According to guidelines developed by MSF, Marine Responsible Person should also have sufficient knowledge about [13]:

- *"understanding of basic nautical terminology.*
- *having a meaningful interaction with the vessel bridge officers (remote operators).*
- *situations which require appropriate actions, including "Stop the Job" in the event of unexpected events.*

- *ability to understand and manage a safe and effective operation.*
- *recognise safe and unsafe approach of an attending vessel in terms of course and speed.*
- *awareness of the potential consequence of collision for various energy levels"*

When it comes to MRP`s cooperation with USV, he/she should have basic knowledge about vessel`s features, systems and its behaviour during the adverse weather conditions. MRP should keep informing the operators about changes in sea conditions and other vital for safety of navigation information. That would improve the USV`s situation awareness and thus, safety.

Issues described in chapter 3.2.1., concerning cooperation between OIM and remote centres will also apply to MRP. Therefore, it is necessary for MRP to obtain additional training concerning operations with unmanned vessels and communication with Remote Control Centre.

3.2.3. Duty Holder and Master of the vessel

"Marine Operations: 500m Safety Zone" guidelines indicates that responsibilities of Duty Holder cover Collison Risk Management system, its development and implementation. Such system must be prepared for each vessel, that plans to enter a safety zone. If USV is going to perform a task within safety zone, such system should be appropriate adjusted. Collision Risk Management should also include all procedures and methods for collision risk assessment and recovery plan in case of accident. In addition to that, Duty Holder must ensure that installation is manned with qualified personnel, who will follow safety guidelines established by top-down authorities [9].

Master of the vessel is obliged to provide safety of people on board. As it was mentioned earlier, Master and OIM should keep informed each other about each step of operation. In the event of any threat, it is in Master`s responsibility to undertake actions aimed at eliminating the hazards and if necessary, to request help from authorities [9]. Within safety zone operations, he/she makes sure that vessel stays in the position using DP system. Furthermore, it is master`s final decision whether to start, continue or abort operation and leave the safety zone.

When it comes to USV, the responsibilities of the master must be transferred to the one of the remote operators. Therefore, one of the remote operators should have same or better skills than master, such as high resistance to stress, good communication skills, great decision making and sufficient knowledge on navigation and automation systems. When it comes to responsibilities imposed by the international conventions, operator must maintain proper look-out, act in accordance with COLREG regulations and proceed with safe speed, especially when navigating within safety zone [14].

3.2.4. ROV Supervisor and ROV Pilots

Execution of IMR operations using USV and Remotely Operated Vehicles will include employment of the ROV team. In the paper prepared by I.A. Johannessen et.al., ROV Supervisor would act as a leader of ROV team. He/she will be responsible for ROV pilot’s development and learning process. ROV pilots operate the ROV and take care of its maintenance. Moreover, pilots must report any difficulties or hazards to the ROV Supervisor so the appropriate countermeasures can be undertaken. The most important responsibility of ROV pilots is to perform a dive in safe and efficient manner according to HSE procedures [11].

3.3. Location at Norwegian Continental Shelf – weather aspect

Norwegian Continental Shelf is an area of 2 039 951 km^2. It covers North Sea, Norwegian Sea and Barents Sea. Since late 1960s, when first oil reservoirs “Ekofisk” have been discovered, Norway has been exporting about 1.1 million oil barrels daily [15]. The largest number of production platforms is situated within the region of North Sea. Figure 4 provides map of the Norwegian Continental Shelf with its boundaries. Green and yellow colours represent the area that are open for oil and gas extraction. It is noticeable that almost all southern part of NCS is open for petroleum activities. The further north, the less activity is expected due to hard weather conditions, Marine Protected Areas (MPAs) and fewer sedimentary rocks, that may contain oil and gas.

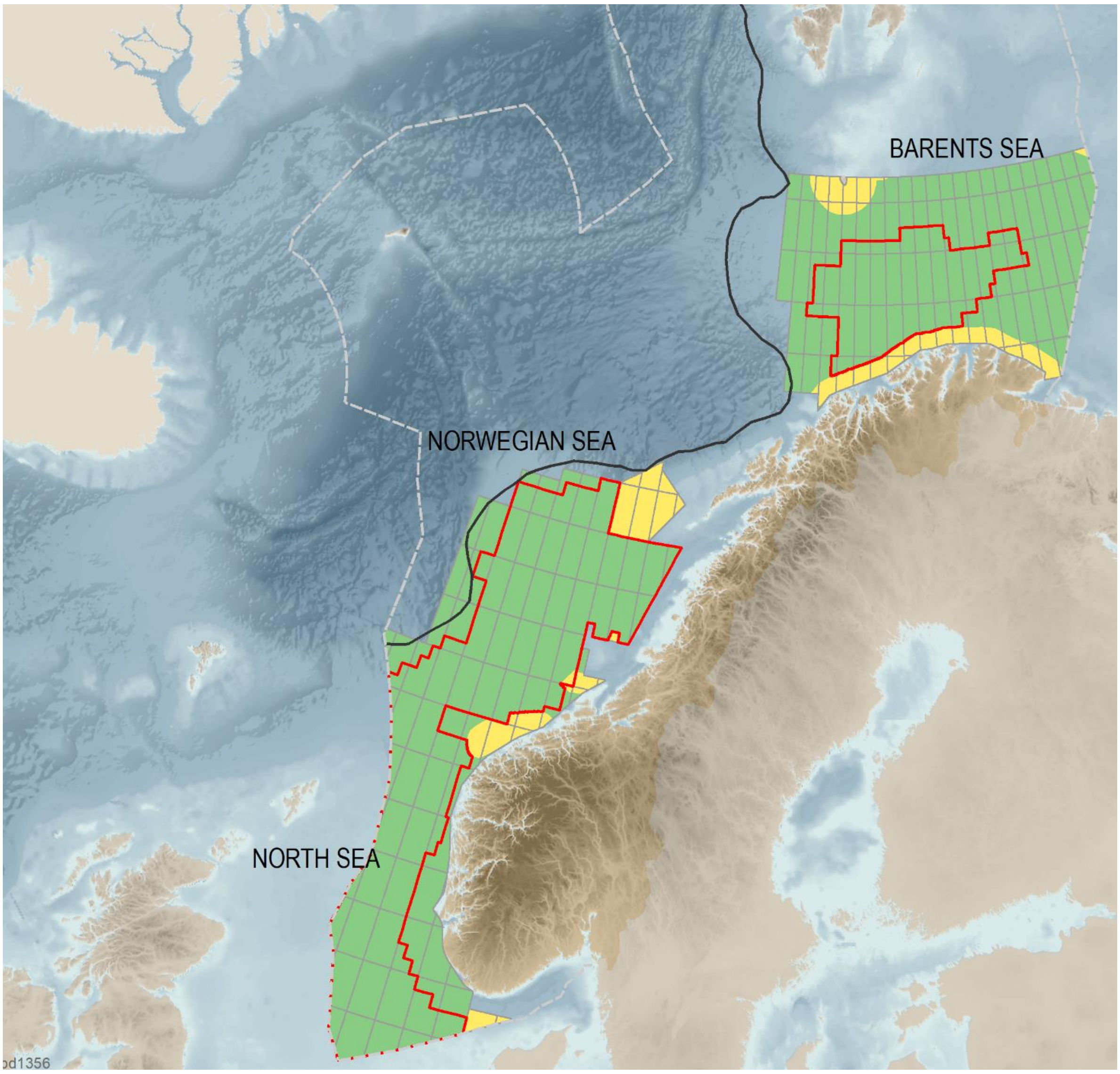

Figure 4. Area overview of Norwegian Continental Shelf (Status for 2020) [16]

The biggest issue concerning offshore operations within mentioned above areas is unpredictability of the weather conditions. In northern parts of NCS, weather is much more extreme, as heavy snowfalls, polar laws and icing occurs more often than in other parts of the Shelf. In addition to that, Barents Sea is not supplied with enough amount of monitoring stations, towards accurate weather forecasting. Therefore, maritime operations within Barents Sea will be associated with greater risk, than in the other parts of the NCS. Therefore, we will consider USV`s application for North and Norwegian Sea only.

Most of the activities within NCS will have a weather-sensitive character. Planning of such operations will vary from company to company, as some of their weather guidelines are more detailed than others [17]. Nevertheless, environmental conditions will pose a great risk to the safety of operations around the platform, making them a major threat. Thus, it is extremely important for safety of offshore operations to continuously monitor and collect meteorological data.

Report prepared by PAFA Consulting Engineers "*Weather-sensitive offshore operations and Metocean data*" mentions weather triggers that can significantly influence operations within installation`s safety zone. The most significant ones are wind speed and its direction, strong currents and sea state. They must be considered while planning the IMR operations together with ROV. For instance, mean wind speed with value of 20-25kn, should oblige operator and OIM to conduct risk assessment before any operation can begin. The emphasis should be putted on vessel`s motions and possible damage to carried cargo, such as ROV [17].

Furthermore, report states that sea states and visibility are other triggers, which should be taken into consideration at NCS. When significant wave height is between 3-4m, vessel should not enter safety zone without risk assessment regarding its position within the zone. What`s more, when visibility around the installation is less than 250m, vessels should stay out of the zone and maintain continuous radar observation [17].

Before USV can enter 500m safety zone, operator in remote centre would have to fill in pre-entry checklist concerning weather condition assessment (see Appendix A). This might turn out to be challenging for operators located in RCC. Beside USV`s sensor technology and weather forecasts received in remote centres, it will be still hard to estimate the real conditions at sea and whether they are going to deteriorate. Therefore, such weather assessment to a large extent will depend on provided by installation measurements. However, such weather assessment will not always reflect the conditions near the sea surface that are relevant to the vessel. According to PAFA Consulting Engineers, installation`s wind sensors are usually located on the top of the structure, which is hundreds of meters above the sea level. This will make such measures inaccurate for USVs weather assessment. Moreover, installation`s weather stations might not be properly maintained, as there are no official regulations which would require to fulfil such obligations [17].

During adverse weather conditions it is not enough to rely on onboard meteorological sensors only. Installation`s weather station may not provide accurate meteorological data either. PAFA Consulting Engineers indicates few reasons. First of all, there are no official regulations regarding installation`s weather sensors, their maintenance and surveys. They are considered only as an extra feature to the rest of the platform's equipment. This in turns, can lead to bad maintenance and inaccurate measures. Moreover, on many occasions person who is responsible for interpretation of weather forecasts has no relevant meteorological education [17].

Lastly, PAFA Consulting Engineers in their report point out that pauses between each weather forecast can be too long in order to detect and react on sudden weather changes. Therefore, additional meteorological equipment and measures should be considered, as only complete and precise weather forecast can assist the master in decisions regarding planned operations. Many captains claim, that only if they had more detailed information about weather conditions, they could avoid many accidents. Solutions such as wave rider buoys, current meters, employment of additional meteorological personnel to complete on-board weather forecast, meteorological information from nearby platforms etc. are just some of those suggested by the experienced captains. These devices would allow for local distribution of meteorological information, as the data is transmitted through satellite to the attending vessels and the installation [17].

Adverse weather conditions at NCS will have great impact on planning and duration of USV`s operations. Considered here inspections and light interventions using ROVs will demand detailed weather forecast for several hours. Such operations cannot be performed and finished in short period of time, as it involves pulling the ROV back out of the seabed, often when strong current occurs. Even though inspections are low-invasive operations, they should be planned more precisely as weather conditions can drastically change during their execution. In this case, operators should be provided with the best meteorological information available and discuss it with the OIM. It could be a solution to equip safety zone with mentioned wave raiders, that could measure weather conditions on the sea surface. Such data would be automatically transferred to remote centres and will help to boost the accuracy of operator’s weather assessment.

4. Legal challenges and prospects of unmanned operations.

This chapter will be devoted to closer investigation of the most important conventions and standards, which are meant for conventional shipping. Nevertheless, it will be discussed how COLREG, STCW, SOLAS, GOMO and DNV GL can apply to unmanned vessels and what legal challenges they may encounter.

One of the thesis objectives is to find out to what degree unmanned vessels can operate remotely and at the same time safely. In order to do that, relationship between legislation and technology need to be well understood. On the other hand, such issue may be not easy to deal with as various challenges may arise from different levels of ship`s autonomy.

Concept of unmanned vessels is quite new, which make it difficult to obtain relevant literature for the throughout analysis. In addition to that, such concept has not been yet tested for any of the operations within installation`s safety zone. This means, that there is no regulatory framework developed specifically for unmanned vessels within the safety zone. Because of that, following chapter is developed only on the basis of existing international rules and regulations, such as SOLAS, COLREG, STCW etc., which USV must comply with anyway.

4.1. DNV GL

DNV GL is an international classification society established in 2013. DNV GL provides services to many different industries such as shipping, Oil & Gas, renewable energy, i.e., around the world.

When it comes to unmanned shipping, DNV GL is currently working on a set of standards, that will help the new concepts and technologies meet safety requirements. DNV GL is also involved in research projects about autonomous shipping and autonomous control system, such as “ReVolt” and Advanced Autonomous Waterborne Applications Initiative (AAWA). Every year DNV GL invests 5 % of its total revenue on research and developments [18]. Research outcomes help DNV GL to assess risk for autonomous operations and to set up new autonomous standards. Experimental scale model of autonomous ship is now in use by Norwegian University of Science and Technology (NTNU), in order to conduct more trials, vital for the future progress of autonomous shipping [19].

One of the documents prepared by DNV is “Autonomous and remotely-operated ships Class Guidelines”, which estimates safety level of unmanned operations. It states that unmanned vessels should maintain safety, that is *“(...) equivalent or better compared to a conventional vessel where navigation is performed by navigators on board”* [20].

Above guideline is divided into “Process Guidelines” and “Technology Guidelines”. “Process Guidelines” explains how concept of autonomous and remote vessels is developed and later approved by the flag state. It also describes technology approval process intended for autonomous and remote vessels. The second part “Technology Guidelines” will provide guidance on autonomous/remote vessels` design and their supporting systems, such as navigational, engineering and communication system [20]. Those guidelines will be the basis for USVs safety considerations described in Chapter 5.

The most important document under DNV GL development is Autonomous Ship Code (ASC), which could be the first regulatory framework for unmanned operations mandated by SOLAS. B.J. Vartdal et.al suggests, that ASC must be first amendment by existing codes and conventions, which probably will take some time. As technology progression of unmanned vessels is developing rapidly, it would be unwise to formulate specific requirements for sensors, data fusion, algorithms at IMO level. Therefore, such task should be assigned to the classification societies. Classification societies would also need to establish standards to which autonomous and remoted vessels must comply [21]. Figure 5 demonstrates structure of ASC suggested by DNV. Tier V refers to manufacturers and industries, whose regulations and standards would also be a part of ASC.

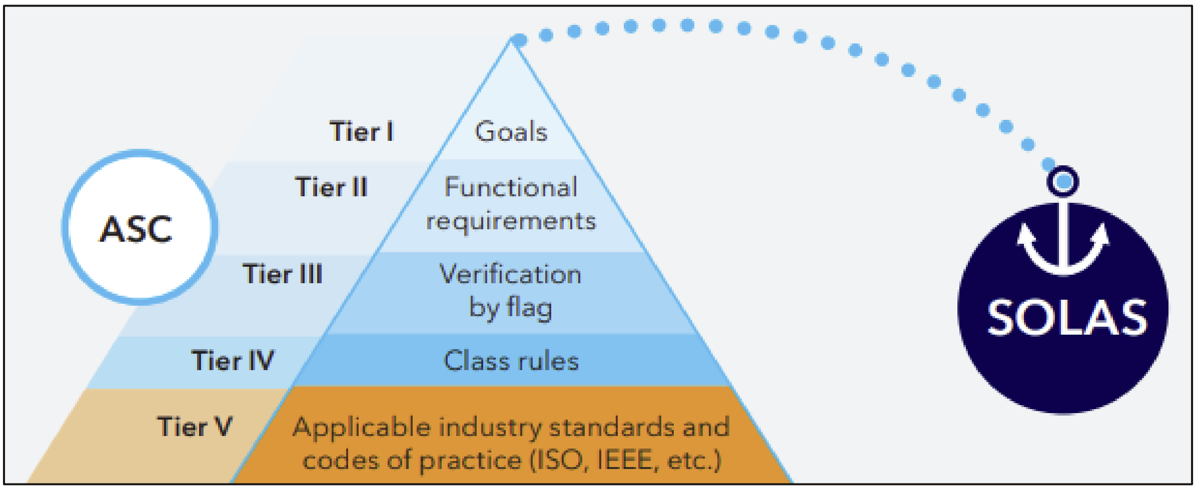

Figure 5. Suggested by DNV GL structure of Autonomous Ship Code [21]

We can conclude, that DNV GL is so far the only authority that took up the issues of unmanned vessels and develop guidance based on throughout research. Therefore, their procedures will be the only one, that are enough reliable to use them as a groundwork for the following thesis. Rest of the guidelines and conventions, such as SOLAS, STCW, COLREG and GOMO will be analysed in terms of legislation gaps and challenges towards unmanned vessels. Therefore, investigation below is based on identification of fragments that can be interpreted in favour of remotely operated vessels.

4.2. GOMO

International Guidelines for Offshore Marine Operations (GOMO) are set of guidance which applies to operations within 500m safety zones. GOMO was published in United Kingdom on 11th of November 2013 and in Norway on 1st of June 2014 [22]. It contains fourteen chapters and appendices in which all the aspects of offshore operations are described. Some of the other countries may also need to include their local regulations in order to complete basic guidelines proposed by GOMO. Examples of a regional supplements are “United Kingdom Continental Shelf Supplement” and “Norwegian Guidelines”.

Norwegian Guidelines include “Operasjonsmanual for Offshore Servicefartøyer på Norsk Sokkel” and other, developed by offshore companies, such as Equinor, Aker BP, Lundin Norway AS, Neptune Energy, etc. Those documents consist of guidelines and standards relating to offshore operations, however in more specific manner than those described in GOMO. Many of the guidelines, which are developed by companies refers to a particular installation, considering its design, type of operations and environmental conditions at the location. Therefore, GOMO should be treated only as a basis for other, more distinct local guidelines for offshore operations.

GOMO does not include the possible employment of autonomous or remote vessels within installation`s safety zone. Therefore, following description will indicate GOMO`s most highlighted matters when it comes to offshore operations and how those issues may apply to future USV`s operations.

First of all, GOMO put special emphasis on certification, training, competency and manning of installation`s employees and vessel`s crew members. Competency of people is illustrated by the acronym “KATE”, which means knowledge, ability, training and experience. These qualities are the most desirable and valued in working environment of offshore operations [23]. Importance of manning is also demonstrated in SOLAS and STCW, as a determinant of safety of life at sea. As GOMO is based on international conventions, therefore further issues concerning manning of remote centres will be investigated in sections 4.4. and 4.5.

Furthermore, GOMO distinguish three operational levels. Each of them is characterized by the level of operational complexity and each will require different qualifications from the involved people. Operational levels are assigned after determining types of operations, that are going to be performed during contract period. These levels refer only to the vessel`s crew [23].

In Chapter 5 of GOMO regulations we can read that IMR operation together with ROV would require "Operational Level B" of medium complexity. For conventional vessels that would mean specific requirements relating to bridge and engine manning. Bridge should be covered by two STCW certified Officers. If vessel operates with dynamic positioning, then one of them should have basic DP Induction course. When it comes to engine room, the watch keeping engineer should actively monitor machinery from close vicinity [23]. Interpreting this requirement in relation to USV, we would have two RCC operators, one of which having DP operator certification. At this level of autonomy, monitoring of engine room can be performed remotely from Engine Control Centre (ECC), where chief engineer can operate one or many vessels. Such solution was proposed by DNV GL while developing the "ROMAS" project [24].

4.3. COLREG

COLREG (Convention on the International Regulations for Preventing Collisions at Sea, 1972) is an updated version of "Collision Regulation" of 1960. The following new rules were added: "Safe speed", "Risk of collision" and "Vessel`s operations within or close to the traffic separations schemes" [14].

Rule 1 states that all COLREG`s regulations apply to all type of ships navigating within high seas and other waters connected to them [25]. Second rule specifies roles and responsibilities of master, his crew and owner of the vessel. Rule 3 describes vessel as a *"(...) every description of watercraft, including non-displacement craft, WIG craft and seaplanes, used or capable of being used as a means of transportation on water"* [25]. So far, there is no indications that autonomous or remote vessels would have problem to comply with COLREG.

Rule 5 states, that *"Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision"* [25]. This means, that that rule applies to "*Every vessel (...)*", which includes autonomous/remote vessels, as there is no indication whether crew must be on board or not [26]. Therefore, if rules and regulations are fulfilled in a satisfactory manner, captain and crew`s responsibilities can be transferred to the operators in remote centres. It is also supported by the fact, that technology at USV`s disposal allows for a much better performance of look-out activities, such as advanced laser scanners and thermal cameras [19].

Another issue relates to the words *"proper"* and *"by all available means"*. Here, it is important to examine whether use of onboard sensors can replace Officer of the Watch (OOW) in performing a look-out and still be considered as a *"proper"* and *"by all available means"* [26]. COLREG states, that look-out should be performed using senses of hearing and seeing. O.L. Fastvold indicates that it is not specifically said, that hearing and seeing cannot be performed via technology, such as high- quality sensors. Such technology, however, must give the same sense of impression as the OOW was on the board. It is vital for making unmistakable and thoughtful decisions. Furthermore, it is not expressed where the look-out should take place. Therefore, OOW can be located physically on the bridge or in another place, as long as look-out is performed in *"proper"* manners [26].

This in turn, indicates another issue, namely whether look-out performed from the remote centres is as *"proper"* as look-out on the bridge. The statement *"(...) proper look-out by sight and hearing (...)"* and *"as well as by all available means"* indicates that the look-out performed only via hearing and seeing is not enough to fulfil the requirement of *"proper"* [26]. Therefore, additional look-out using radar, radio and other devices is required here as well. If such technology is available in the remote centres and perform their function in the same manners as traditional onboard devices, then unmanned vessels would also comply with this requirement [26].

We can conclude, that look-out can be transferred to remote centres and still comply with the COLREG. Maritime Unmanned Navigation through Intelligence in Network (MUNIN) and AAWA projects, proven that technology installed on their unmanned vessels provides more accurate and effective look-out than traditional one [27]. Moreover, O.L. Fastvold points out that big advantage of remote look-out is reduction of OOW fatigue and distraction which improves safety of navigation. This means, that unmanned vessels can be as safe as conventional one or even safer, when it comes to look-out function [26].

However, such compliance with COLREG is only possible, as it uses very general wording, leaving big room for interpretation. Moreover, technological progress requires reinterpretation of this rule, as the look-out can be performed in more advanced way and still meet the *"proper"* and *"by all available means"* obligations [28]. O.L. Fastvold indicates that with increase of unmanned vessels appearance on the waters, the greater will be the need for specific regulations concerning safety of autonomous and remoted vessels. Thus, a new annex to COLREG regulations dedicated only to the unmanned vessels could be a solution for non-compliance [26].

When we look at the whole perspective of compliance with COLREG, it is more possible for remotely operated vessels to meet COLREG requirements as human is still active in the loop. Furthermore, remotely operated vessels can comply with the COLREG only if the installed technology will allow operators for satisfactory situation awareness [26].

4.4. STCW

STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers) was adopted on 7th of July 1978. The Convention sets the minimum standard for training, certificating and watchkeeping, which must be obliged. Before the STCW entered into force, each company or country had their own standards when it comes to training of their seafarers. This led to diversity in the training of the seafarers and therefore in safety at sea. Unified rules set the minimum level for the knowledge of people working at sea, making them at the same time easier to be supervised [29].

STCW applies to vessel`s crew, who physically serves on board. The Article III "Application" states that "*The Convention shall apply to seafarers serving on board seagoing ships entitle to fly the flag of the Party (...)"* [30]. This indicates that the STCW cannot be applied to remote crew of the unmanned vessel as they are not serving physically on board [26]. However, it is also mentioned in Article I "General obligations under the Convention", that the aim of STCW is "*to ensure that, from the point of view of safety of life and property at sea and the protection of the marine environment, seafarers on board ships are qualified and fit for their duties"* [30]. The unmanned vessels are designed for different maritime operations, where still safety of human beings, protection of the cargo and environment are top priorities. Therefore, the STCW application might be extend to the vessel`s crew in remote control centre, as it is to a large extent, their responsibility to avoid hazards on the sea [26].

Legislation gap for remote operators and their compliance with STCW, can be also found in Article IX where is clearly stated that "*The Convention shall not prevent an Administration from retaining or adopting other educational and training arrangements, including those involving seagoing service and shipboard organization especially adapted to technical developments and to special types of ships and trades, provided that the level of seagoing service, knowledge and efficiency as regards navigational and technical handling of ship and cargo ensures a degree of safety at sea and has a preventive effects as regards pollution at least equivalent to the requirements of the Convention"* [30].

O.L. Fastvold points out that it is only a temporary solution, as the remote operator in their training needs to include not only navigational knowledge, but also advanced technical skills. The STCW offers only standards for navigational part of the ship`s operations. Nevertheless, it is safer to use (at least) the STCW and other regional regulations like DNV GL and GOMO, as a "quick fix" until necessary content will be added to the STCW. Then, the Convention could apply to remote operators as well [26].

One of the most important issues, when it comes to unmanned vessels is their ability to reflect situation in which vessel is at the moment. On board sensors must replace human`s eyes and ears, as if the operators were physically on board. This issue leads to another challenge for remote operators and their compliance with STCW, namely the watchkeeping. Convention dedicates all VIII Chapter to the watchkeeping activities, making it clear that it has a great importance. Chapter VIII applies to vessel`s master, officer of the watch, officer of the engine room and radio operators, whose keep their watch physically on board [28]. The emphasis is placed on the officer of the watch and engineer officer: "*officers in charge of the navigational watch are responsible for navigating the ship safely during their periods of duty, when they shall be physically present on the navigating bridge (…) at all the times", "officers in charge of an engineering watch, (…), shall be immediately available an on call to attend the machinery spaces and, when required shall be physically present in the machinery space (…)"* [30]. It is difficult to translate the above statements in favour of USVs. Therefore, regulations concerning watchkeeping must be rewritten, so that remote vessels can comply with them. It is also important to remember that technology used on unmanned vessels can replace current methods of keeping the watch. This should in some degree change man`s view on unmanned vessels as a more vulnerable than conventional ones [26].

O.L. Fastvold claims that remote operations seem to be far from compliance with the STCW watchkeeping regulations. The content of the Convention is entirely based on human presence, that connects all ship-related activities on board. Moreover, during 99` session of Maritime Safety Committee, it was concluded that the unmanned vessels cannot comply with the STCW and recommends new training standards for shore- based crew [26].

O.L. Fastvold suggests that solution to non-compliance with STCW could be a new convention, that is applicable only to the unmanned vessels and their operators. Such approach has been already used for fishing vessels, which resulted in the creation of STCW-F. Another alternative would be to amend current STCW and remove requirement concerning on board presence, as the word "on board" is the main obstacle for unmanned vessels to comply with this Convention. However, as it was mentioned before, seafarers` qualities are characterized by different working conditions created by the sea. Whole STCW convention was developed for such circumstances and not another, therefore replacing a few words might not change anything [26].

4.5. SOLAS

International Convention of Life at Sea oblige all contractors to ensure safety of life at sea by setting minimum standards when it comes to construction, seaworthiness and safe manning [31].

Safe manning of vessel is one of the main issues, that SOLAS is trying to manage. Each vessel is obliged to obtain a Minimum Safe Manning Certificate, stating that vessel have been "*sufficiently and efficiently manned"* [32]. Such document is issued by the flag state and it is valid for five years. SOLAS do not clearly indicate how many people should be on the bridge and whether they need to be on board for safe navigation. It only articulates that crew number should satisfy *"contracting government"* [32] and *"ensuring that, from the point of view of safety of life at sea, all ships shall be sufficiently and efficiently manned"* [32]. This means, that if remote centres are sufficiently manned and operators perform their duties efficiently, they can comply with the Convention. What`s more Annex 2 to IMO Resolution A. 1047(27) about "Principles of Safe Manning" states that *"The minimum safe manning of a ship should be established taking into account all relevant factors, including the following: (...), level of ship automation, (...)"* [33]. This indicates that crew on board may lose their relevance for the sake of improvements of ship`s automation. Following thesis consider USVs with level of automation AL3-AL4, that will still require constant control and supervision from the operators on shore [7]. This means that such vessel may be “unmanned”, but at the same time “attended”, performing its operations in a safe and efficient manner [26].

Another concern related to USV compliance to SOLAS is transferability of master duties. It is master`s responsibility, in the light of maritime law, to maintain at all the time safety standards and to protect environment against inadvertent pollution [32]. Location at NCS and nature of USV`s operations within safety zone, making it even more necessary to find a solution for duties handover from captain to operator in remote centre. According to Convention, in order to provide safety at sea, competent muster should stay in charge of the vessel [32]. O.L. Fastvold states that it does not mean, that he/she should stay physically on board. Such legislation gap of manning requirements might allow remote operators to become a master of the vessel only if they have adequate education and experience. On the other hand, it is uncertain if such transfer of duties will not have a negative impact on safety, which is the main determinant of SOLAS requirements [26].

It is important to notice, that due to new developments of onboard devices, some of the crew`s duties, including captain`s, are performed by automated systems. According to O.L. Fastvold, master`s responsibilities will not significantly differ from those fulfilled by the remote operator. On the contrary, operator may perform captain`s tasks even better, as his equipment is more advanced, his technical knowledge about the vessel is greater and fatigue/distraction is smaller. Moreover, new technologies proved to have beneficial influence on vessel`s safety, as human factor is appropriate reduced [26]. On the other hand, there is a bigger risk of system and equipment malfunction, as vessel is getting technological advanced. The most critical one is loss of communication with the ship. In this case, master is no longer “attending” the vessel, however he/she is still in charge. Therefore, it is operator who will be held accountable for any accidents involving commanded vessel [26].

To sum up, duties of the master are possible to transferred to the remote operator under certain conditions. O.L. Fastvold suggests that such operator should have knowledge and experience as great as master`s. Moreover, it is necessary for operator to obtain additional education in USV automation, construction, limitations and emergencies. Document of competency should be kept in digital form in order to prove that remote centre is manned in accordance with SOLAS. This in turn, will make the vessel seaworthy [26].

In addition to that, Maritime Safety Committee`s 99th session specified, that unmanned but remotely operated vessels can comply with SOLAS regulations in reference to safe manning, unlikely autonomous vessels [26]. However, flag state as a “contracting government” can create barriers for such vessels, as it is up to them to decide whether ship is manned in a safe and efficient manner [26].

From the above examples, we can conclude that remotely operated vessels, such as USVs fit to maritime authorities’ definition of the “vessel” [26]. However, if we consider different levels of autonomy, some of the regulations in their present form will not apply to all unmanned vessels. Therefore, existing legislation will apply to the USVs to a greater extent than to autonomous vessels, as there is still human in loop during remote operations [26].

So far, unmanned maritime operations are considered to happen within territorial waters. It is still new shipping concept and some of the tasks seems to be too complex at this stage of development. Therefore, A. Tommi et.al. states there is no need to create whole new conventions for unmanned vessels. It would be enough to add necessary parts to the existing documents or rewrite some of the sections, concerning for example a transferability of master`s responsibilities to the onshore operator. However, when unmanned vessels will prove that their operations are safe and efficient, then it will be wise to begin to work on a set of rules and regulations applicable only for them, such as Autonomous Ship Code [19].

While developing a new set of regulations for the unmanned vessels it is important to consider their autonomy level and location of operations. Each level of autonomy will be characterized by different risk and hazards, that the ship may encounter during the operations. In following thesis, we consider an USV with level of autonomy between LA3-LA4. This means, that operations conducted by vessel will to a large extent depend on decisions made by operators in remote centres [7]. The same will apply to location of the unmanned operations. NCS is characterized by adverse weather conditions, which can have strong influence on communication with the vessel, as well as on performance of the operation. Therefore, new regulations should be not as strict as in case of autonomous vessels, however still more rigorous than existing ones for conventional shipping [28].

5. Unmanned Surface Vessels as a new operational concept

Term "safety" has been a priority in the maritime industry for several decades. Therefore, it will determine direction of future maritime developments, i.e., ship`s design and its purpose. If the company have decided to replace conventional vessels with USVs, then they should fulfil requirement of "equivalent safety". This means, that USVs should be as safe as traditional vessels or even safer [20]. Besides that, new shipping concept of unmanned operations will require to consider safety issues from the very start. For this purpose, it is important to consider how the unmanned vessels will relate to safety right from the very beginning of the design process. Following chapter describes current USV developments. It will be explained how USV concept is developed, bearing in mind type of operations (IMR) and their location (installation`s safety zone at NCS).

5.1.Current USV developments

Demand for unmanned vessels is increasing fast, as more benefits of their usage have been discovered within a few years. Conventional vessels are not in line with changes, that await maritime industry in next decade. Such issues as climate change, national security, new requirements concerning personnel, etc. have forced companies to think about new shipping concept, that will meet requirements of the upcoming years [34]. Therefore, maritime and offshore industry heads towards innovative solutions, such as unmanned vessels.

The Unmanned Surface Vessels can be defined as *"(...) water-borne vessels that are capable of operating on the surface of the water without any onboard human operators"* [35] We can also meet other USV terms, such as "Autonomous Surface Vehicles" (ASVs), "Autonomous Surface Crafts (ASCs) as well as "semi-autonomous" or "fully autonomous" vessels. In following thesis, term "remote" is in use interchangeably for term "semi-autonomous".

USV concept consists of following segments: USV`s type, application, operations, endurance, system, hull type and size. However, we will take a closer look only at those segments that have the greatest impact on safety. Based on operation, USV concept is divided into autonomous surface vessels and remote surface vessels. According to "Global Unmanned Surface Vehicle (USV) Market- Industry Trends and Forecast to 2027": *"In 2020, remote operated surface vehicle segment has been accounted for the largest market share in* *operation segment as it is more convenient to use remotely from a base station"* [36]. Such prediction is dictated by unclear international rules concerning autonomous shipping. As it was concluded in Chapter 2, the autonomous surface vessels are not a subject to most of the maritime rules and regulations. However, when it comes to remote operated vessels, there have been identified many loopholes that allow them for compliance. Therefore, they are considered as easier and safer alternative for the current industry situation.

Before moving to more complex issues concerning USVs automation and system, it is important to have a general overview on the USV`s architecture, components and potential application (see Figure 6 and Figure 7).

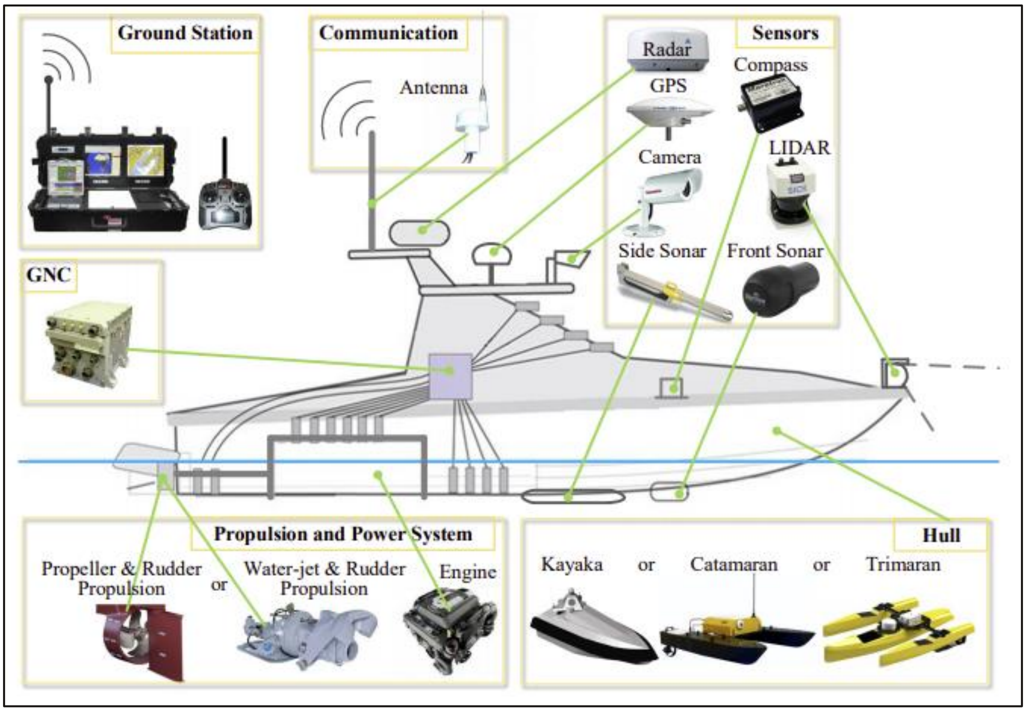

Figure 6. Typical components of USVs systems [34]

So far, USVs prove to provide a wide range of applications, such as military use, ocean surveys, scientific research, offshore industry etc. Their employment brings many benefits, such as lower operational costs, flexibility, reliability of collected data and improved safety.

Types	Application
Military use	➢ Port, harbour and coastal surveillance, patrolling, reconnaissance. ➢ Search and rescue. ➢ Mine's countermeasures. ➢ Target drone boats;
Scientific research	➢ Ocean activities research. ➢ Bathymetric survey. ➢ Ocean biological phenomena, migration and changes in major ecosystems. ➢ An experimental platform for the purpose of testing hull designs, communication and sensor equipment, propulsion and operating system;
Ocean resource exploration	➢ Oil, gas and mines exploration. ➢ **Offshore platform and pipeline construction and maintenance (IMR operations);**
Environmental mission	➢ Environmental monitoring, sampling and assessment. ➢ Disaster aided prediction, management and emergency response. ➢ Pollution measurements and clean-up;
Other applications	➢ Transportation. ➢ Refuelling platform for USVs, AUVs, UUVs and other manned vessels.

Figure 7. Possible applications of USVs [34]

With development of technology, it become possible to employ USVs in more complex operations. In paper prepared by Justin E. Manley called *"Unmanned Surface Vehicles, 15 Years of Development"* we can read, that Navy has started examining their USVs for mobile navigation references. It means that USVs could be used as an air-sea radio frequency and acoustic transmitter. Such application, according to Navy is vital for recognition of networked battlespace [6]. Example of such USVs can be seen in Figure 8. Moreover, USVs have been considered for harbour security and for mines sweeping.

Figure 8. MIT `kayak` USVs [37] [6]

On the other hand, USVs that are used for scientific purpose have simpler operational requirements. Figure 9 demonstrates survey USV developed by CEE Hydro Systems. The company aim was to create a simple design USV, in order to minimize demands for the specific system expertise and to obtain high quality data. The CEE`s USV is equipped with single beam echosounder and single data module to present data in simpler and more usable way [38].

Another vehicle, USV “Sounder” developed by Kongsberg group is a multipurpose vessel, that is characterized by high endurance and manoeuvrability. In its product sheet we can read, that USV “Sounder” is equipped with three rudders, slim bow and stabilizing roll and pitch fins. USV “Sounder” is fitted with the first class of sounders, in order to provide hydrographic surveys, fish detection and seismic support [39].

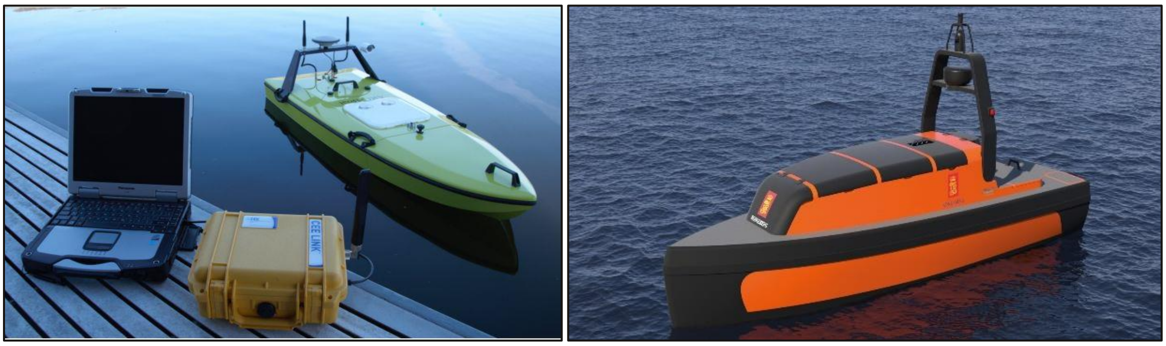

Figure 9. CEE- USV Remotely Operated Hydrographic Survey Boat and Sounder Unmanned Surface Vehicle developed by Kongsberg Group [38] [39]

Recent developments lean towards renewable energy, such as wind, solar and wave energy. An example is “Unmanned Ocean Vehicles, Inc.”, which has rigid sails equipped with solar panels for electric power [6]. This allows for long-lasting endurance which is perfect for demanding scientific applications. Furthermore, utilization of wave energy led engineers to development of another type of USVs, namely wave gliders. Wave gliders are designed to generate propulsion power from the wave motions. Such vessel has been tested in real sea conditions, covering an impressive 2500 Nm in 142 days [6]. This proves, that USVs are on the right track not only for the short-range voyages, but also for longer operations on the open sea.

5.2. Current developments on USV`s IMR operations.

In following thesis, it is considered that USV is going to perform IMR operations, such as subsea inspections within installation`s safety zone. In order to execute such task, it is necessary to prove that USV can be as safe and efficient as conventional OSVs. Therefore, we will focus on design and technological solutions, that make those vessels a better alternative for IMR operations within installation`s safety zone.

Before anything else, some of the current developments concerning USV/ROV operations will be shortly described. First example of subsea inspections performed by USV is research project developed by “TOTAL” and “TechnipFMC”. The aim of research was to find a new solution for IMR operations, in order to save money and simultaneously maintain high safety standards. In 2018, they successful carried out light subsea inspection using ROV deployed from the USV “INSPECTOR” (see Figure 10) [40].

According to ECA GROUP, remote control of ROV was possible via wireless communication link. The ROV and USV was controlled by the onshore operators. The ROV was able to perform repetitive actions with the subsea structure. During the test, TechnipFMC and Total were able to gather enough data to validate the project and *“(...) evaluate the effect of video quality and latency over the ROV operability”* [40]. Furthermore, it allowed them to examine skills of the onshore operators performing IMR operations using USV/ROV [40].

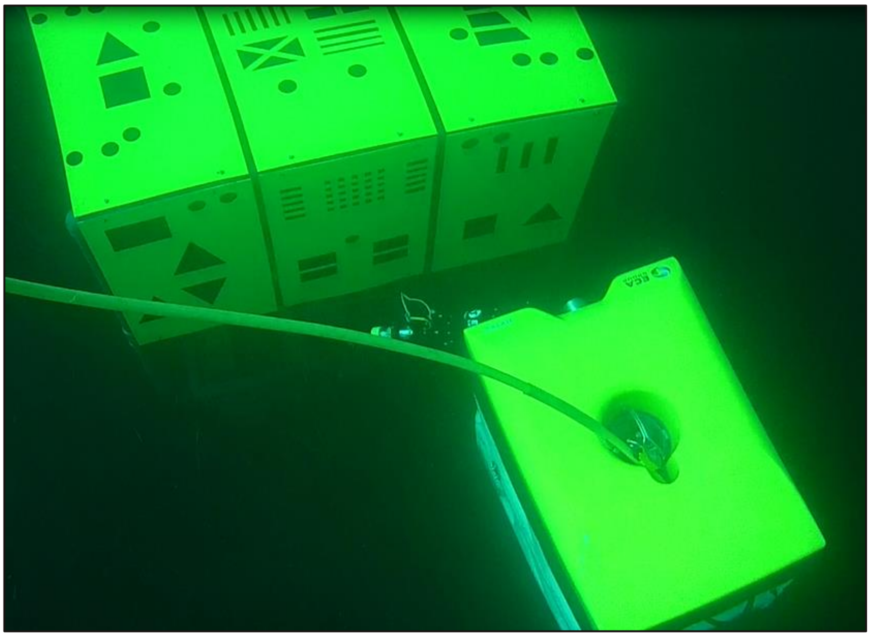

Figure 10. USV/ROV developments [40]

In article “*Subsea Technology and the New Routes to Residency”* we can read about another USV concept developed by “Fugro”. Their new electric e-ROV called “Fugro Blue Volta” would be deployed from 12 meters long USV “Fugro Blue Essence” (see Figure 11). Their aim is similar to one presented by “TOTAL” and “TechnipFMC”, which is to provide unmanned subsea inspections using USV and ROV. E-ROV will be able to conduct inspection tasks at depths of 450m. What is interesting, is that even bigger 24m vessel is under their development, allowing for subsea inspection at 2.500m [41].

According to Fugro`s flyer, main features of “Fugro Blue Essence” include large gondola with multi beam echosounder and extensive amount of equipment for situation awareness: dual radar, weather station, 360 degrees cameras. Additionally, vessel will have long lasting up to 30 days endurance for Autonomous Underwater Vehicle (AUV) operations and up to 10 days ROV inspections. In order to avoid collisions, USV will be equipped with AI collision avoidance system and radar repeater. In addition to that, real-time data transfer from e-ROV to RCC would allow to make right decisions in time, thus reducing the risk of accident [42].

Furthermore, “Fugro” assures that utilization of USV can reduce up to 95% fuel consumption in comparison to conventional vessels. This, as well as optimised Geo-data acquisition make the “Fugro Blue Essence” operations more sustainable and efficient [42].

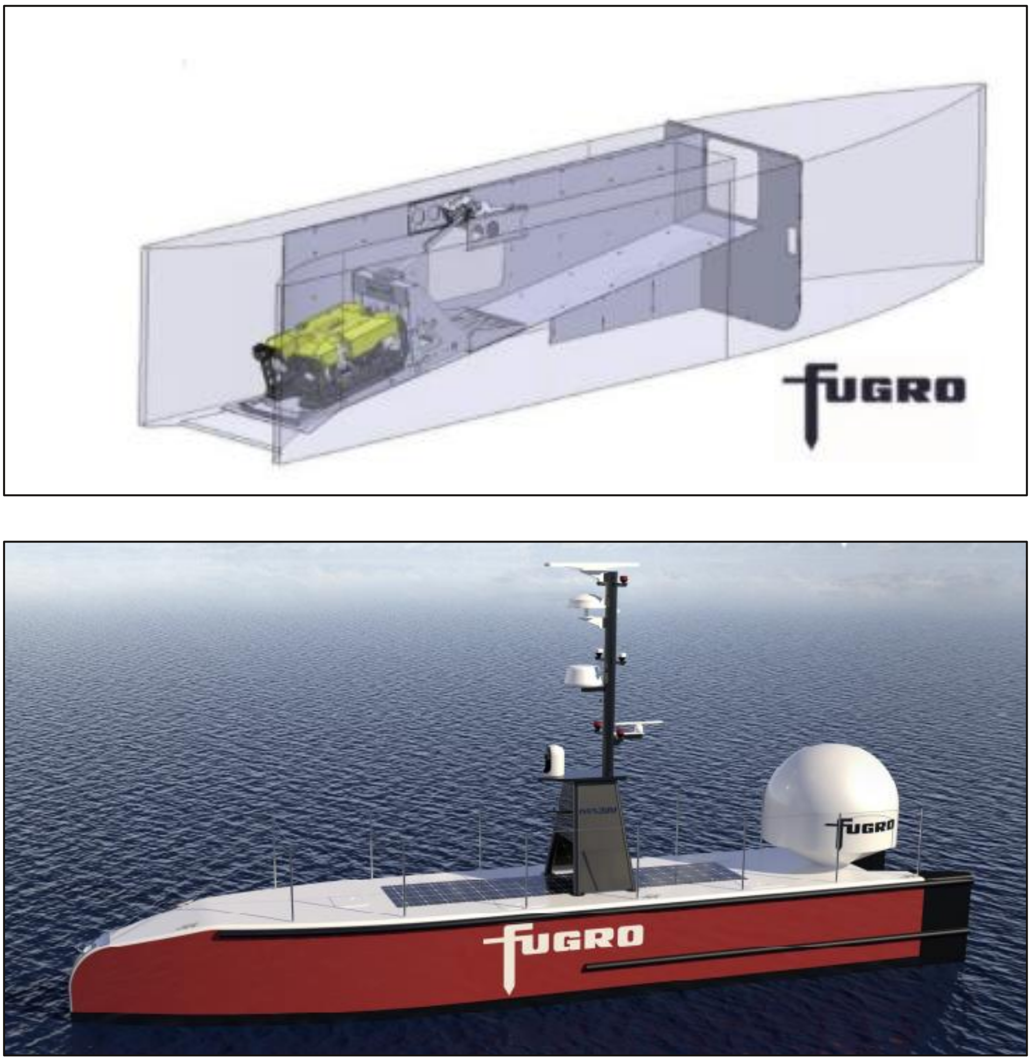

Figure 11. Illustration of USV “Fugro Blue Essence” and ROV “Fugro Blue Volta” [41]

So far, IMR operations have been conducted using OSVs with around 30-100 people onboard. According to guidelines "*Marine Operations: 500m Safety Zone*" such amount of people makes the Health, Safety, Environment and Quality (HSEQ) policy complex and strict. What`s more, in the event of collision involving approximately 85 meters long OSV with displacement up to 15.000t, the impact load would be enormous. For instance, OSV with displacement of 5.000t drifting out of control with a speed 4kn would collide with the platform with impact of 11MJ (Bow/Stern on collision). Furthermore, vessel with displacement of 10.000t drifting out of control with the same speed of 4kn would collide with the installation with doubled amount of energy, i.e., 22MJ. Above numbers are derived from the probable velocity obtained from the assumptions, that OSV is drifting out of control in a significant wave height of 4m with speed 3.9kn [9].

Furthermore, in the same guidelines it is stated that the acceptable collision energy value for fixed platform is 14MJ, which is a strong impact. However, it would not cause the platform to collapse. It is a traditionally accepted value, as installation`s design standards, such as BS EN ISO 19902 does not include accidental energy impacts. Nevertheless, OSVs are growing in size and displacement, making their accidents much more destructive. On the contrary, offshore operations performed by USVs would require much simpler HSEQ policy, as no human are directly involved in operations. What`s more, considered here 15-20m USVs will generate much lower load impact in case of the accident [9].

To sum up, previous as well as current USV developments have a great impact on the future improvements of shipping industry. USV`s benefits have been acknowledged, which have increased demand for those vessels. If USVs were too dangerous and impractical, then no further research would be undertaken. Yet, it is quite opposite.

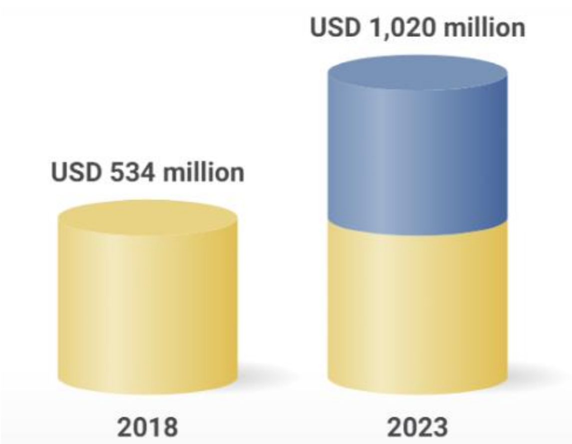

Figure 12. The USVs Market forecast for 2023 [43]

According to *"Unmanned Surface Vehicle Market"* from 2018, it is expected that USV market will grow from USD 534 million in 2018 to USD 1.020 million in 2023 (see Figure 12). This is due to urgent demand for military and commercial operations, such as Intelligence, Surveillance and Reconnaissance (ISR), maritime security, oceanography and oil & gas exploration. New technology advancements, such as high-quality sensors and auto remote systems drawn attention of future clients, convincing them to invest in USV market [43].

5.3. USV`s concept of operations

At the design level, an important step is to decide which of the USV`s functions will be remotely controlled, and which become automated. Such decision will be dictated by the type of operations that USV is going to perform, as well as their location.

USV`s Concept of Operations "CONOPS" is of particular importance. CONOPS is known as a common framework for description of proposed system from the perspective of a future user [44]. Such framework is vital for standardization process of autonomous and remote systems, which makes unmanned vessels easier to implement within the industry. CONOPS has been already used by companies developing unmanned vessels. Properly completed CONOPS contains data of all USV operational aspects [45]. Therefore, throughout the thesis the emphasis will be placed on those aspects included in CONOPS, that have the greatest impact on safety of the unmanned vessels. Those are *"Functions and operations-degree of automation", "External supporting system- sensors and positioning systems", "Physical characteristics of the ship- hull, propulsion and navigation systems"* and *"Recover, incident and emergency preparedness"* [45].

5.3.1. USV`s design standards

To ensure, that USV is going to meet safety standards, it must be designed based on several principles. At any time when failure occurs, vessel to some extend should deal with the problem on its own using appropriate systems installed onboard. These system arrangements are defined by the DNVGL-CG-0264 as self-contained and self-diagnostic capabilities. In most cases, onboard systems on conventional vessels will operate until they fail. This in turns, can cause long unavailability of the vessel due to sudden requirements for new equipment, parts or even vessel. Consequently, the USVs with non-stop self-contained and self-diagnostic systems will have an advantage over conventional vessels [20].

In addition to that, some of the design principles should receive special emphasis for IMR operations at NCS. Those are *"Physical characteristics of the ship-hull, propulsion and navigation systems"* required by CONOPS. Thus, USV should have following hull features [46]:

- hull design should provide better ship stability.
- some parts of the hull should be strengthened, as not all the obstacles may be detected by the sensors and cameras.
- due to NCS harsh and adverse weather conditions, USV`s hull should be designed in a way to improve slash and wash suppression and overall stability.
- Broaching "*is the sudden and uncontrollable turning of a ship to a beam on orientation to the sea. If the sea is big enough and has sufficient wave slope, there is then a high risk of capsize*" [47]. Such phenomenon should be avoided, as USV can lose its course and RCC control over the vessel. It is especially important for safety zone operations, where ability to maintain own position is necessary to avoid accidents.
- Due to lack of the crew on board, some design improvements may be introduced, such as the omission of sea sickness criteria. Vessel can be stiff in roll, which give room for other design solutions, such as low load distribution favourable for ship`s stability.

When it comes to ship`s propulsion design, the main emphasis should be putted on following issues [46]:

- USV, as an unmanned vessel do not need to consider noise and vibration levels on board. Therefore, more efficient propulsion systems with high pressure pulses and noises can be installed onboard. Such solution would not have application in MPAs, where vibrations and noises are harmful for ocean`s fauna. Nevertheless, considered in thesis southern and central parts of the NCS are not located within any MPAs.
- Propulsion system should be highly redundant, which results in having at least two independent propulsors, with their own power generator and transmission.

In brief, in order to make USVs safe in their operations they should not pose threat to themselves, other vessels, offshore structures or to the marine environment. Therefore, USVs should be able to [48]:

- Retain their seaworthiness continuously during conducted operations and voyage at different sea states.
- Rearrange operations accordingly to changes in prevailing conditions, such as adverse weather conditions or other abnormal situations.
- Handle crisis situations, such as fire onboard, system failures, etc at sea.

When it comes to USV design and its onboard system, it must be arranged in a way to achieve good quality and high availability. In other words, ship`s and RCC equipment should be of high quality, high degree of redundancy and fault tolerance [20]. Moreover, IMR equipment should be designed in a way to allow easy maintenance and replacement of used parts when it is in harbour.

5.3.2. Degrees of autonomy

For the following considerations, it is necessary to discuss USV`s degrees of autonomy and how they will affect the safety of navigation in the safety zone. Article *"Defining Ship Autonomy by Characteristic Factors*" written by Ø.J. Rødseth suggests that in order to make USV operate within safety zone, its autonomous functions should be introduced to the vessel gradually and with balance. This means, that new USV concepts should have lower level of autonomy, staying largely under human control. In addition to that, three more factors should be taken into consideration when deciding on USV`s level of autonomy. Those are operator presence, degree of automation and complexity of operations [49].

Ø. J. Rødseth in his article indicates that operations complexity can be estimated using the ODD (Operational Design Domain). The ODD helps to create vessel`s operational framework for its onboard systems. Moreover, the environmental conditions, ship`s manoeuvrability and human contribution are defined here as well [49].

Furthermore, Ø.J. Rødseth states, that ODD includes potential failures and threats that must be mitigated by USV and its systems. ODD can be defined over vessel`s time t and position p, as a O (t, p). "O" is a multi-dimensional state-space, that contains all system states. The "O_{AC}" will refer to actions controlled by the automation system and "O_{OE}" actions controlled by the operator only. In addition to that, it is important to define fallback space F

when “O” is outpaced. Fallback strategies will vary for different parts of the voyage. It will also depend on the prevailing weather conditions, as keeping the position or turning back can be difficult in hard weather conditions. Therefore, strategies should be readjusted accordingly to situation [49]. The complexity of unmanned vessel`s operations using ODD is presented in Figure 13.

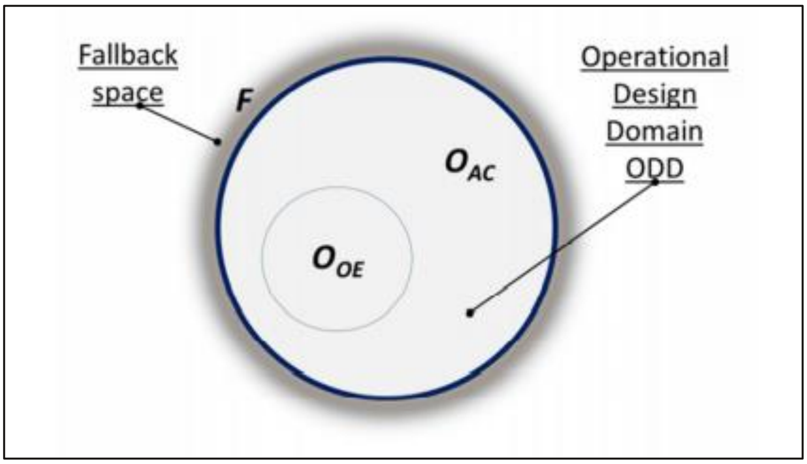

Figure 13. Complexity of the operations for the unmanned vessel [49]

ODD should include following constraints: geographic constraints, meteorological conditions, presence of other vessels/installations, USV features/limitations, operation`s features, communication system, safety requirements [49]. All of them must be taken into consideration when developing new USV/ROV concept, as the ODD is a part of the CONOPS [49]. Figure 14 illustrates IMR operations complexity proposed by NORSOK for conventional vessels:

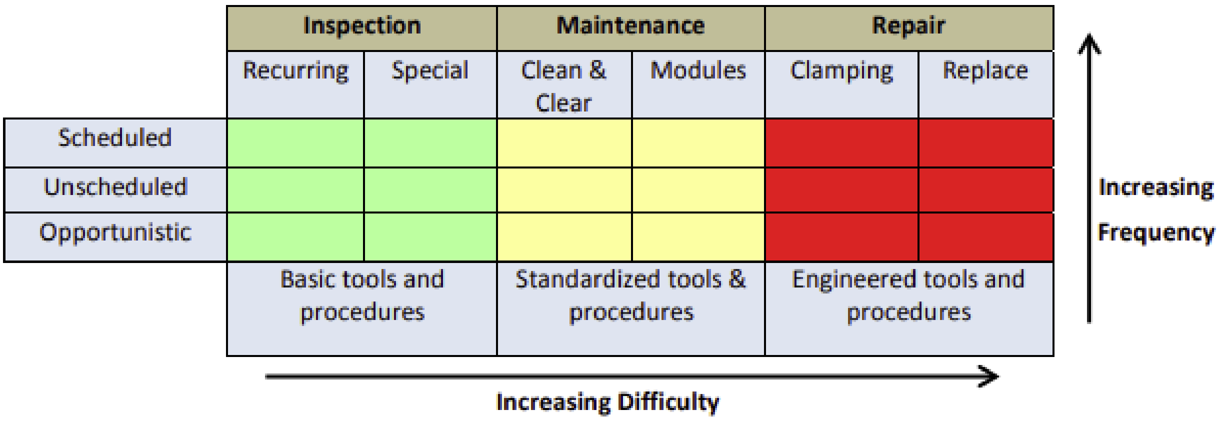

Figure 14. IMR operation complexity [50]

In his master thesis S.S. Honorat indicates, that inspections will have a low level of complexity as they are highly standardized and quite common. The maintenance will require much more equipment than subsea inspections. Furthermore, maintenance and repair activities will highly depend on weather conditions as heavy equipment is often lifted. Thus, those operations will require much longer operational time [50].

Even though, inspections have low level of complexity when conducted by conventional vessels, it may not necessary be the same for unmanned vessels. Inspections are not a common task for USVs, neither maintenance nor repair. USV is still new shipping concept, that would need more time to prove its usefulness for IMR operations.

Ø.J. Rødseth explains that it is impossible for unmanned vessel to stay within the limits established in ODD, as it operates in dynamic environment. Therefore, DST (Dynamic Ship Task) should be defined here as well. DST defines tasks that are perform by the vessel`s systems and RCC during the voyage. Those are: object detection, object classification, anti-collision systems and sensor systems [49].

Furthermore, he indicates, that DST is divided in a same way as OOD, which is: tasks that can be done by automation system (Automatic DST) and those that are performed by the operator (Operator Exclusive DST). DST must have defined fallback space *f*, in order to bring the vessel back into safe state if the failure/accident occurred. However, different failures and hazards may require more than one fallback. The DNV GL distinguish two degrees of fallbacks, i.e., MRC and Last Resort (LR) [49].

MRC (Minimum Risk Condition) is a state where ship can automatically regenerate itself and still be operational [49]. According to DNVGL-CG-0264, USV should manage to retain within Minimum Risk Condition (MRC) at all the time during conducted operations (see Figure 15). This means, that none of the incidents should throw the ship and RCC out of MRC, nor should it be the cause of the serious accidents [20]. This principle is especially important when USV is conducting inspection operations using ROV. Any failure of USV system or equipment should not cause serious harm to the ongoing subsea operations. Examples of potential MRCs can be founded in the Appendix C.

DNVGL-CG-0264 states that, if system or equipment failure will throw the USV off the MRC, then hazards should be mitigated by alternative control techniques and by usage of redundancies. If more than one sensor or device fail at the same time, it may cause chain reaction, ending in an accident. Therefore, USV should be equipped with i.e., two steering systems and additional positioning systems [20]. What is important, is to make the redundant systems independent from each other and place them in separate onboard locations in case of fire or flooding.

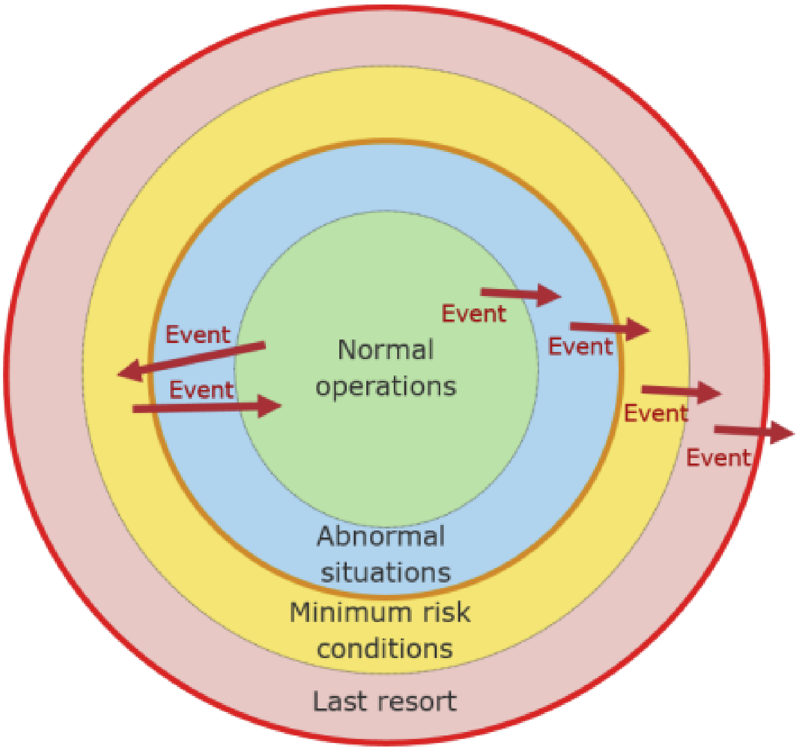

Figure 15. Concept of normal operations, abnormal situations, MRC and Last resort [20]

The Last Resort MRC is a state in which vessel can remain until outside help will arrive. In this case, system cannot regenerate itself automatically. Thus, operator should perform some easy countermeasures such as drop the anchor or shut down the engine [49].

Another factor that describes autonomy level is location and presence of the operator. Here we can distinguish additional scale for operator`s presence in unmanned operations [49]:

- *"L0R0- Fully autonomous vessel.*
- *L0R1- Monitored autonomous vessel.*
- *L0R2- Constrained autonomous vessel.*
- *L1R2- Supervised vessel/unmanned RCC.*
- *L1R0- Temporarily unmanned RCC.*
- *L0R3- Unmanned vessel, fully remote controlled".*

As the IMR operations can vary from low to high level of complexity, operators should be present at all the times in RCC. Despite the efforts from the companies to increase ship`s autonomy levels and thus cut the costs of having the operators, in case of IMR operations safety must always come first [49].

Those levels will have both benefits and drawbacks. Ø.J. Rødseth indicates that the biggest drawback of having a remote controlled USV is command latency. Autonomous control systems automatically transit vessel to MRC state, whenever operator failed to do so. Moreover, system will keep the vessel in MRC state as long as operator will earn good situation awareness and plan the necessary actions. If vessel is fully remote, operator must be careful enough to notice that ODD has been exceeded and then put vessel in one of the MRCs [49].

According to DNVGL-CG-0264 guidelines "Autonomous and remotely operated ships", it is extremely important to categorize the degrees of autonomy for the specific type of vessels and not lump them together. Therefore, each ship`s type should have their own autonomy scales, as different tasks are burdened with different risk. Such distinction should be also made between navigational and mechanical functions of the ship. This is because, ship`s engine room and mechanical functions are already to some extent automatic. Their performance is however, supervised by the onboard engineers. Examples of ship`s mechanicals functions are propulsion, electrical power supply, watertight integrity, ballasting, drainage and bilge pumps. On the other hand, ship`s navigational functions depend on human activity onboard. Those functions are navigation, manoeuvring, control, monitoring, communication [20].

Furthermore, DNVGL-CG-0264 guidelines indicates that each of the above navigational functions can be further divided into sub-functions with different levels of autonomy. As Figure 16 indicates, each navigational function can be classified into one of the four groups: detection, analysis, planning and action. Each group can be performed either by the operator, system or combination of both [20].

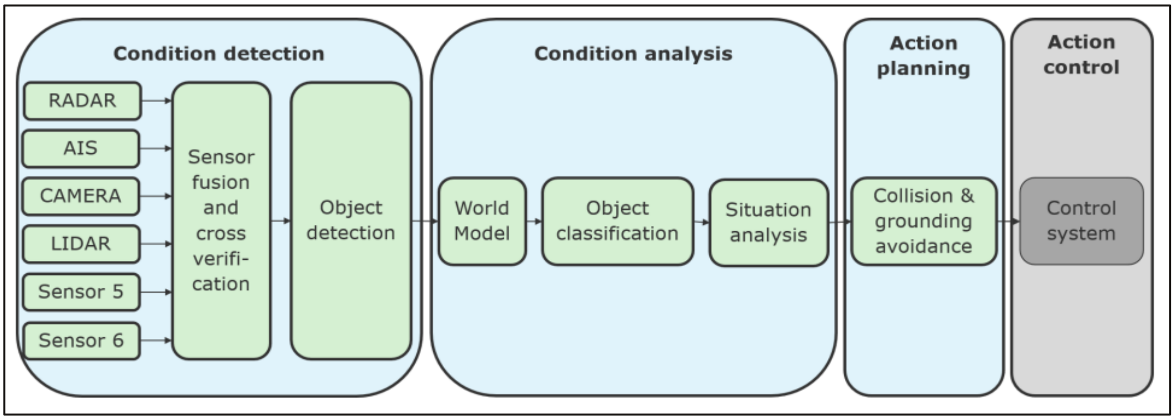

Figure 16. Classification of unmanned vessel`s navigational functions [20]

To understand how the above distribution works, let us take an example. We are considering an USVs that is partially remotely controlled and partly autonomous. It is decided, that look-out is performed by system using various onboard sensors. Secondly, condition detection part is done by the system. Thirdly, condition analysis is performed by the operators in the remote centres based on data obtained from the sensors. Action planning is executed by the system, which can recalculate new passage plan. Lastly, control of the planned actions is performed through control system and its actuators. Such control system will be based on existing technologies used on conventional vessels [20].

Moreover, DNVGL-CG-0264 guidelines specify that each of the USV`s navigational and mechanical functions should be performed at the safety level equal to or better than conventional vessels. Therefore, condition detection using sensors should be better performed than human look-out on board. Secondly, condition analysis will be accomplished with a success if sensor data will fully reflect the prevailing conditions around the vessel. Finally, action planning must be conducted in accordance with COLREG regulations and in safer manners than navigator onboard [20].

Discussed redundancies, may turn out to be insufficient for USV to become as safe as conventional vessel. Therefore, DNVGL-CG-0264 recommends independent ship`s supervision beside supervision executed by decision support system. Independent supervision should always take place in situations when probability of the failure is higher. Designated person for such supervision must have an appropriate knowledge about operational safety and functioning of the support system. His/her task is to analyse ship`s functions and evaluate their performance. This should be done independently of what support system has indicated.

Moreover, such analysis should be based on data provided by independent sensors, as Figure 17 indicates [20].

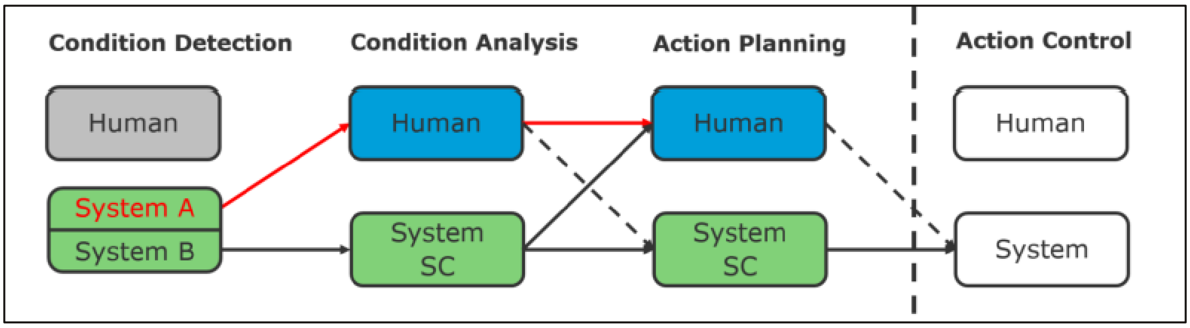

Figure 17. Independent supervision [20]

Furthermore, DNVGL-CG-0264 suggests that independent supervision should always be performed, when vessel is encountering abnormal circumstances, such as adverse and harsh weather conditions. In this case, weather can affect proper functioning of the sensors and thus, automated decision support systems [20].

To sum up, if USV is properly designed and remotely operated, probability of failure will be decreased. Degree of autonomy will depend on the type of operations that ship will perform. According to DNVGL-CG-0264 guidelines, safety of these operations will be influenced by the choice of the ship`s functions that will be remotely or autonomously controlled. This in turns, will depend on operational aspects of the vessel, which include operational area, jurisdiction and regulations, vessel`s features, weather and sea states limitations, roles and responsibilities of involved people, remote control centre`s features and wireless communication characteristics [20]. Wherever human is involved in decision making process, his/her location should be precisely stated, i.e., onboard, remote control centre or both [49].

6. USV`s hazards and their causes within 500m safety zone

6.1. Types of USV`s failures

According to DNVGL-CG-0264 class guideline, we can distinguish two categories of failures i.e., foreseeable and unforeseeable, which can occur during the lifetime of USV. Foreseeable failures are those that are expected to happen due design flaws, manufacturing errors, excessive mechanical loads etc. Such failures should not interrupt USV`s operations. Usually, they are mitigated by redundancy systems onboard. On the other hand, unforeseeable failures can make the vessel stop to operate or limit its certain functions. They can be caused by external and environmental factors. They are less probable than foreseeable failures, but they can still occur. An USV that experienced such failure should remain in a safe state or access the Minimum Risk Condition. Both types of failures should be considered during development of USV`s operational concept [20].

There are two basic preventive measures that are used on any type of the vessels: failure detection, response systems and redundancies. DNVGL-CG-0264 guidelines suggests that unmanned vessel should have redundancy type R0, which means *"(…) continuously availability, unless justified otherwise".* Installed redundant unit should perform independently, which means it has its own power source. Moreover, it should perform its functions in a same manner as faulty one [20].

On conventional vessels appropriate safety level is obtained using failure detection systems and crew`s activities aimed at maintaining a safe state. DNVGL-CG-0264 indicates that in case of unmanned vessels, there is no possibility for physical or hand-operated actions. Therefore, more redundancy of critical systems, better automations, advanced diagnostic and monitoring systems should be a priority when planning and designing the USV. All the solutions mentioned above should provide USV with fail-to-safe respond to failures [20].

When it comes to most common failures for unmanned vessels, they are mostly the same as for conventional ships. Those are [20]:

- Fire
    - Considered as an unforeseeable failure.
- Flooding
    - Considered as an unforeseeable failure.

- Collision
  - Considered as an unforeseeable failure.
- Electrical failures
  - Considered as foreseeable failures:
    - Failure of power converter
    - Faults in electrical equipment and cables (short circuits)
    - Failure of Uninterrupted Power Supply (UPS)
    - Failure of power generators
    - Failure of power generated controls
    - Failure of power management systems
- Control/Safety Systems failures
  - Considered as foreseeable failure:
    - Wire break
    - Loose connections
    - Occasional software failure
    - Communication errors
    - Failure in electronic components
- Communication System failures
  - Considered as foreseeable failure:
    - Wire break
    - Loss of power
    - Connection faults
- Machinery/Equipment failures
  - Considered as foreseeable failure.
  - Considered as unforeseeable failure if:
    - Component is thoroughly proved to be healthy.
- Cyber threats
  - Considered as an unforeseeable failure.
- Environmental factors
  - Considered as an unforeseeable failure.
- Human factor
  - Considered as an unforeseeable failure.

All the above failures must be considered in a ship`s risk assessment [20]. Moreover, knowledge about ship`s failures and whether they are predictable or unpredictable can greatly contribute to overall ship`s safety. Designers, knowing the potential threats that unmanned vessel may encounter, can focus on those ship`s systems and segments that might be the most exposed and fragile. Special attention should be given to those threats that are impossible or hard to predict. It is especially important for operational location where weather is a major determinant of the success of the operation. For instance, NCS is an area where harsh and adverse weather conditions can pose a great hazard to the vessel.

As we can see from the above list, most types of the ship`s failures are unforeseeable. However, it does not mean that they will happen most often. Probability of collision, flooding or fire on board is much lower than in case of equipment malfunction. On the other hand, in case of unforeseeable failures their consequences can be much more fatal. Therefore, considering USV operations within installation`s exclusion zone, where the greatest hazard is a collision with the platform, the company should focus on eliminating the unforeseeable failures in the first place. As a result, in following hazard analysis (see Appendix D) are considered only those threats/accidents that are unforeseeable.

What is also important to mention, is that ship`s automation will introduce new type of failures. Thus, before allowing USV to operate within safety zone, in-depth testing of all vessel’s functions should be undertaken. Moreover, DNVGL-CD-0264 recommends that testing conditions should reflect as much as possible those prevailing at NCS. Each new failure should be included in a ship`s risk assessment and appropriate countermeasures adapted [20]. In the following chapters it will be proved that the advanced technology used on unmanned vessels allow for better failure detection and ship`s condition monitoring.

6.2. Hazard analysis for safety zone operations

In "Appendix D: Hazard analysis for safety zone operations", we can find a table which consists of possible hazards for USV when operating within installation`s safety zone. Following subchapters include description and conclusions for each of the hazard analysed in this table.

6.2.1. Fire onboard

One of the most dangerous hazards on vessel is fire. Lack of direct proximity of the firefighting vessels and the unmanned nature of the USV makes fire safety one of the top priorities. In "Hazards Analysis Process for Autonomous Vessels" prepared be O.A. Valdez Banda et.al., we can read, that lack of knowledge and overlook can greatly contribute to deterioration of fire safety onboard. When it comes to organizational factor, it will reveal poor planning of extinguishing system features, its distribution onboard and type. This may be due to lack of sufficient economic funds for the advanced fire detection and extinguishing system or as a result of hasty decisions. Moreover, rare maintenance schedules, that are prepared by maintenance department of the organization, can be responsible for fire equipment malfunction or its overheating [51].

In comparison to manned vessels, USV may turn out to be less vulnerable to fire. This is due to fact, that in many cases fire onboard is caused by crew members, who ignore fire safety precautions and regulation. What`s more, USV would not have any flammable materials onboard, such as furniture and textiles as there is no living quarters for crewmembers anymore. However, when it comes to poor maintenance and fire equipment failures, the unmanned vessels can be exposed to a same extent as conventional vessels [52].

O.A. Valdez Banda et.al. explain that USV can become a fire-safe vessel if the emphasis will be placed on exhaustive planning of electrical devices and wiring. Each electrical component should be thoughtful, in terms of USV`s purpose and tested. Maintenance should cover preventive activities, such as cleaning and inspection of the wire's connections. Moreover, technical solutions for electrical systems i.e., heating/cooling will prevent condensation on electrical devices and overheating. In order to detect and extinguish fire in a fast and effective way, information about the fire should be received by remote centres without delay. Furthermore, automatic extinguish systems would be the best solutions for the unmanned vessels, as it does not need human intervention for initiation. Moreover, proximity to the installation structure or other vessels carrying crude oil, requires an immediate and effective response to the fire [51].

It seems that the amount of the above requirements will entail great costs for the company. Nothing further from the truth. O.A. Valdez Banda et.al. indicates that cost of mitigation strategy for firefighting on unmanned vessels are lower than for traditional vessel. In comparison to flooding or collision avoidance countermeasures, where changes or improvements affects ship`s structure, costs of fire protection are quite low. Moreover, as there are no passengers on USVs, there is no need for having additional fire alarms, fire extinguishers and video surveillance systems in passenger spaces. All these together shows that there are many solutions for the fire safety of unmanned vessels [51].

6.2.2. Danger of sinkage/capsizing

Another hazard identified for USV and its operation within safety zone is danger of sinkage/capsizing. The first cause of such threat is flooding. This may be due to a penetration of the ship`s hull, heavy rains or residual water from the firefighting.

Within installation safety zone, there may be underwater and surface structures and buoys, that pose a potential threat to the ship`s hull. This may be due to fail obstacle detection or delay in data transmission, preventing operator from acting on time. Bearing this in mind, USV that is intended for operations within safety zone should have a double hull and compartmented structure. If the company has restricted economic resources, USV should have at least strengthened parts of the hull that are most vulnerable and exposed [51].

Flooding can also appear from the onboard piping system that is leaking. O.A. Valdez Banda et.al., suggests that it can be caused by vibrations and pressure shocks that affects metal pipes or by complex piping system that has many connections. Such issues result from the poor planning, poor installation and lack of knowledge from the client`s side. That is why, it is so important to ensure that the piping system is planned in a precise and thoughtful way. This would assure that system is reliable and easy to maintain. Moreover, effective bilge pumps could remove water from the leakage and keep the vessel on the surface [51].

As the weather conditions at the NCS are often very harsh with high sea state and heavy rains, good drainage system is a necessity. For USVs not exceeding 20 meters in size, even a small amount of seawater on deck may affect ship`s stability. Also, it is important to consider cold temperatures during winter at NCS, when drainage system can be blocked by ice. Therefore, heating system should be installed as well [51]. USV can lose its stability due to large amount of water after firefighting as well. Thus, extinguishing system used in USVs should use small amount of water or replace it by foam. Moreover, water used in firefighting can cause damage to electricity systems onboard or other equipment, resulting in huge financial loss for the company [51].

Article “*Towards the assessment of potential impact of unmanned vessels on maritime transportation safety”* by K. Wrobel et.al. indicates that USVs and manned vessels will share the same root causes of flooding, such as poor design and corroded pipelines. Only in one case, the USVs may turn out to be safer when it comes to flooding threat. This is when crew of conventional vessel is not enough familiar with onboard equipment and their potential faults, such as clogged drainage system, leaking piping system etc [52]. When it comes to cargo shifting, the only problem may be related to proper securing of the ROV on USV`s board, so the risk of its dislocation is minimized to zero.

6.2.3. Collision with fixed object

However, the most dangerous situation that can take place within the safety zone is collision with the installation and collision with another ship. When it comes to object detection sensors, the emphasis should be placed on their appropriate selection. Performance of many onboard sensors will be affected by the weather conditions, like rain, ice and dirt. Solution for such issues is vital, as conditions at NCS are often harsh and demanding.

O.A. Valdez Banda et.al. recommend that USV should be equipped with heating, cooling and cleaning system to allow object detection sensors work properly. Moreover, company should develop maintenance plan, that would cover all vital onboard systems and allow them to function continuously and effective. It should be conducted by the qualified personnel, that would take their time to perform their maintenance [51].

Furthermore, O.A. Valdez Banda et.al. indicates that company should set a correct operational limit for unmanned vessels operating at NCS. Those limits can be established basing on USV`s manoeuvre abilities, its features and operational area, i.e., safety zone. It is important that they are not set too hight only because the company is under pressure from the outside or is intentionally taking a risk. Appropriate operational limits will assure that USV`s operations are interrupted before ship`s safety and others in its vicinity is compromised [51].

In order to make USV operate safely in demanding weather conditions, constant weather monitoring should be performed. Operator in remote centres should not only rely on one source of weather forecast, i.e., installation`s weather station, general weather forecasts, due to their inaccuracy and sometimes usefulness for USVs. As it was described in Chapter 3.4., vessel needs to obtain weather and sea state data locally and close to the sea surface [17]. Therefore, USV should be equipped with sea condition detection sensors installed on their board, that would give an accurate and valuable results. Moreover, such sensors would allow to predict sudden changes in conditions, that are common for the NCS [51].

When conducting operations with ROV, it is crucial for remote operators to have a good knowledge on local currents. Moreover, construction of ROV must withstand and keep the position in the high currents in order to reach the work site [53]. Especially in the installation`s safety zone, ROV operations should be planned with accuracy, taking always into account local currents. When it comes to USV, it must be equipped with high speed ROV winch system that would allow for fast ROV recovery in case of emergency situations [53]. It should be also mentioned that strong ocean currents can affect vessel as well. A.J.L. Solem points out that USVs with smaller propulsion system can face difficulties to keep their position, especially when ROV is deployed into the sea. This can lead to loss of control over the ship`s steering and damage to ROV and subsea structures [54]. Therefore, if the company wants the USV to operate safely within safety zone, continuous weather observation should be carried out.

6.2.4. Collision with moving object

Another cause of potential USV collision with installation or moving objects is technical failure of equipment or system. According to O.A. Valdez Banda et.al., such issue could be solved by redundancy of the critical systems as well as thorough planning and testing of all USV technical systems. This task should be a teamwork carried out by engineers, buyers, manufacturers and legal side. In order to prevent technical failures, operators ashore should be able to constantly monitor and detect faults in technical systems. It is incredibly important, as early error detection can contribute to its quick repair and thus, avoiding accident and off-hires [51].

Journal article prepared by K. Wrobel et.al. specify that most of the collisions involving conventional vessels is caused by poor look-out, performed by the crew members. Therefore, during USV design process emphasis should be placed on detection systems and their capabilities to detect all type of dangers. Use of radar as a detection tool is not enough, especially when USV is navigating in restricted visibility. Thus, use of other detection devices, such as infra-red cameras should be considered [52].

As it was described in chapter 3.3 weather conditions at NCS will pose great risk to USV`s operations. Wave heights will be one of the most important as well as most dangerous factor in IMR operations, as it can affect functioning of ROV devices and vessel itself. Further environmental analysis will take place in “Chapter 7” while estimating weather window for IMR operations using USV.

6.2.5. Outcomes

What conclusion can be drawn from all that? USV can pose many hazards but not as many as conventional vessels. Unlike them, USVs have easier and cheaper mitigation strategy. Technological solutions used on USV allow for threat/failure detection in time, only if they have been carefully selected and maintained. Moreover, the root causes of identified hazards may result not from equipment or system defect, but from the omissions at the organizational level, i.e., poor planning, lack of knowledge, lack of competence, poor documentation and communication, unclear responsibilities/organization [51].

The biggest benefit of USV employment would be elimination of crewmembers’ injuries and potential fatalities, as no person is directly exposed to the risk of the above hazards. However, when it comes to consequences of unmanned vessel`s accidents, they are more severe than in case of conventional vessels [52]. The distribution of probability and consequences of unmanned vs manned vessel`s accident illustrates Figure 18.

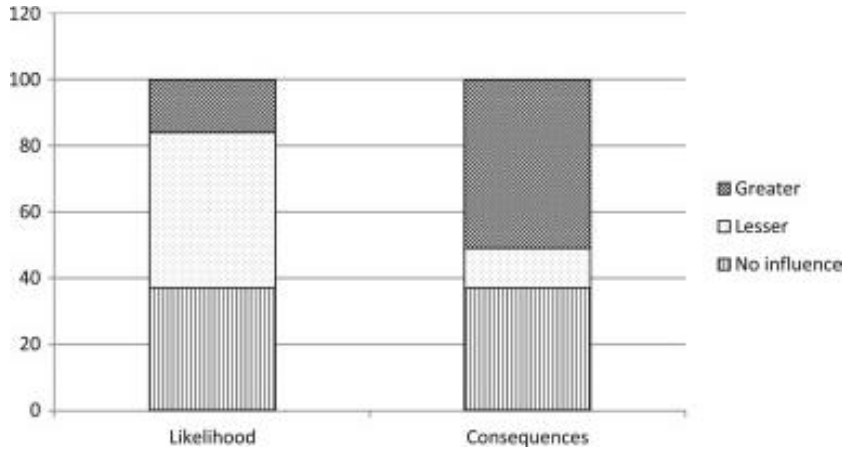

Figure 18. Likelihood and consequences of unmanned vessel`s accident compared with conventional one [52].

Such values for unmanned vessel can be explained by lack of immediate assistance from the ship`s crew. For instance, K. Wrobel et.al. point out that in case of collision with manned vessel, USV would have restricted capabilities to pick up the survivors from the water. What`s more, in case of flooding, damages to the unmanned vessel`s asset would be much greater. This is due to late discover of faults, usually after failure of all sensors [52].

6.3. RCC and Human Factor

RCC as an integral part of unmanned vessel`s infrastructure will have a great impact on safety of the operations. Therefore, hazard identifications and development of mitigation strategies for RCC will be critical for safety. The DNVGL-CG-0264 guidelines for autonomous and remotely operated vessels has identified relevant threats for RCCs, such as [20]:

- *“RCC fire and evacuation.*
- *Cyber-attacks.*
- *Communication failures and delays.*
- *Handover of the duties from one operator to another.*
- *Illegitimate person accessing the RCC or vessel.*
- *External power grid blackout”.*

Most of the above threats are unforeseeable. Thus, according to DNVGL-CG-0264 all RCC equipment should be organised and designed with appropriate failure tolerance, allowing vessel to enter one of MRCs or maintain a safe state. As there is no crew onboard, mitigation strategy should be as effective as for the conventional vessel or better. Moreover, special attention should be given to power supply failures in RCC, especially when we are considering remotely and not autonomous USV. Loss of control of such vessel, which is almost entirely at the operator`s discretion, can result in a serious accident, such as collision with platform or another vessel. Therefore, it is important that RCC can return to normal functioning within seconds after the failure occurred. The RCC`s hazards and thus, the vessel can be solved by installing redundancies of internal and external power supply system, UPS, RCC`s lightening, etc [20].

Safety of unmanned vessels, including USVs will depend on design and technology that is going to be applied on the vessel. However, it can turn out to be not enough to reduce risk of accident. RCCs and vessel`s automation will contribute to different types of human errors, such as issues with operator`s situation awareness (see Figure 19). Therefore, human factor should still be considered as a one of the main challenges in development of unmanned vessels [55].

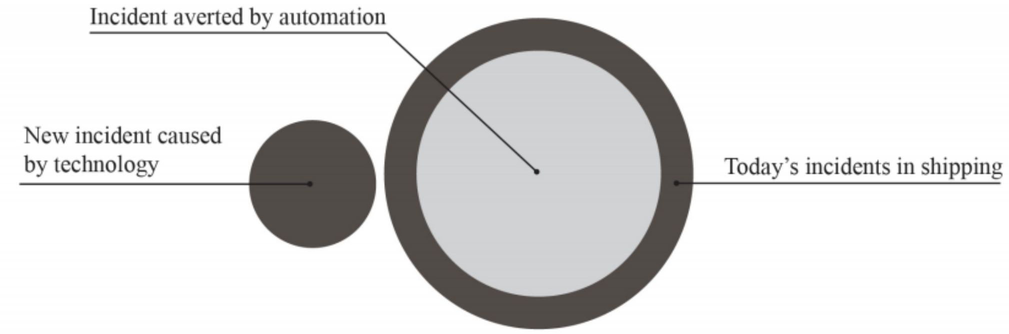

Figure 19. Human factor accidents after employment of unmanned vessels [55]

The cooperation between automation system and human may not always be exemplary. Therefore, following issues may occur [48]:

1) Lack of situation awareness
2) Skill degradation
3) Information overload
4) Level of trust in automation – Automation awareness
5) Boredom and lack of vigilance
6) Command latency

Besides that, the biggest challenge will be to design the RCC in a way to ensure good situation awareness for the operators. In C. Kristoffersen paper "Unmanned autonomous vessels and the necessity of human-centred design." we can find five design rules that can help to arrange RCC (here SCC- Shore Control Centre) for better situation awareness. Those are [55]:

- *"The SCC should be designed to keep operator in the loop.*
  SCC`s design should ensure, that operator actively participates in decision making and is more involved in automation. Passive attitude can lead to out-of-the-loop syndrome.
- *The SCC should be designed to replace sensory information that is no longer available for the operator.*

Due to remote operation, there will be no physical sense of ship rocking or general ship sense. Therefore, sensory information should be provided by SCC in a way, that operators would feel like being physically on the ship. To reflect shipboard conditions in the SCC, the engagement of masters and officers in design process may be helpful.

- *The SCC should provide enough information for the operator to obtain SA-without being overwhelmed.*

  Amount of the sensor information may negatively affect the operator’s performance, causing confusion and thus, deteriorating situation awareness. Therefore, SCC should be designed to display only this sensor information that is relevant for the operator. So called sensor fusion, that would display several sources of data in a one indication could solve this issue. Still, such system should be tested by the operator to check if he/she obtain situation awareness. In addition to that, SCC should only support operator`s situation awareness and not making decision for him/her. Operator should be still able to see more than one solution, often different than those proposed by the system.
- *The SCC should provide automation transparency.*

  The SCC should be designed in a simply and organised way. Operator should not feel confused and surprised, on the contrary he/she should obtain a good automation awareness. Operator should understand current and future steps of automated system. This can be achieved by visualization of system`s future actions, for instance expected routes on the map without information overload.
- *The SCC should indicate which level of autonomy the unmanned operates on at all the time.*

  The level of autonomy should be displayed for the operators at all the time, as it can change during the voyage. The operator can make a mistake, by thinking that he or she oversees the vessel, but it turns out it was a system”.

In addition to that, when considering remotely operated vessel, operator should also be able to maintain automation awareness. This is due to great impact of automation on situation awareness of the operators, causing “out-of-the-loop” syndrome [55].

According to C. Kristoffersen, “Out-of-the-loop” is a syndrome that links operator`s performance and implementation of the automation. It appears, when operator is not keeping up with the situation presented by the automated system or when he/she is distracted by other tasks. It causes deterioration of situation awareness, as operator try to get on track with the current situation using plenty of time. The occurrence of “out-of-the-loop” syndrome is not only induced by operator`s inattention, but also by poor automation system design. Failed design can lead to misinterpretation of displayed data or to overlook of the vital information. If system is designed in an appropriate manner, then operator can multitask and thus, stays in the loop [55].

Field of unmanned vessels and RCCs is still new, which means that there has not been yet many investigations on operators’ performance in RCCs. However, some of the publications, such as [56] indicates that there is a clear link between ship`s automation and operator’s situation awareness. Automation brings the greatest benefits when is designed in harmony with human`s cognitive limits. Thus, engagement of operators in design process should reduce human error in unmanned operations [56].

Other issues concerning human factor, like boredom and skill shortage should also be considered during remote operations. Article written by K. Raheleh et.al., suggests that boredom can cause lack of vigilance and thus, increased risk of accident. When it comes to skills deterioration, the remote operator who greatly rely on automation will have problem to maintain skills that are necessary to handle various maritime actions. The more experienced crewmember and his knowledge about vessel, the more effective will be his countermeasures in case of hazardous situations. In case of unmanned vessels, the most certified and experienced experts in RCCs may have problem to assess the situation and to undertake proper actions due to insufficient amount of data [57].

7. Safety of IMR operations using USV/ROV.

7.1. Voyage and operation planning

When it comes to voyage planning, there are many issues that need to be considered by the operator before USV`s departure. The most important one will be weather forecast for the voyage and specifically at the location of operation. Having in mind adverse and hush weather conditions of the NCS, this factor will have a special importance.

AAWA`s Position Paper "Remote and Autonomous Ships- The next step" indicates that route planning for short and long distances will differ from each other. For short range missions, voyage can be planned by the operators who manually places the waypoints. However, when USV is going to operate in high seas and within complex area such as installation`s safety zone, manual planning of each waypoint can be too complicated. This is due to increased number of waypoints as voyage distance increases. Moreover, the longer legs between the waypoints the more difficult is to check the route in terms of safety. In addition to that, voyage planning for longer distances away from the shoreline will include communication issues between vessel and RCC [58]. An example of remote navigation to set up waypoint illustrates Figure 20.

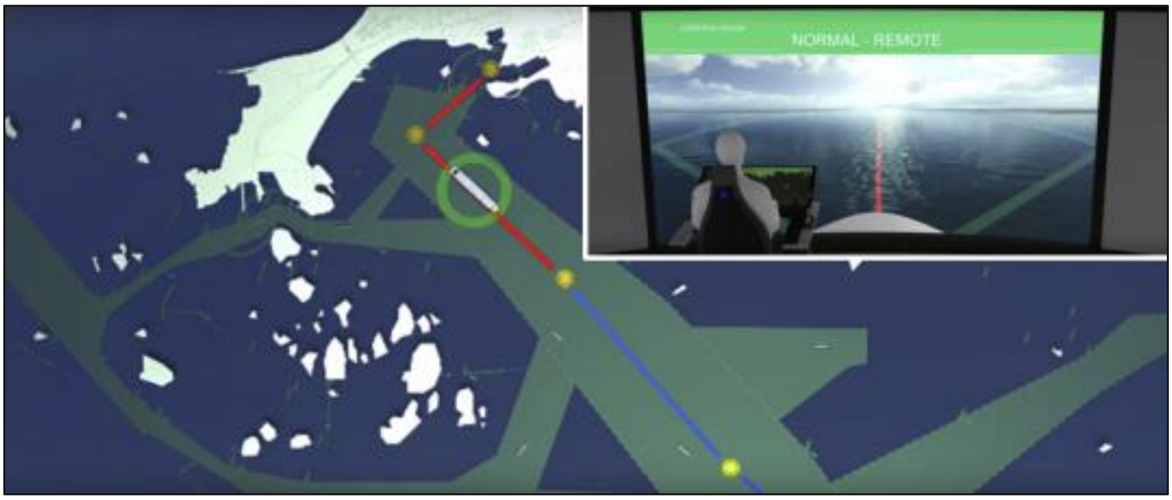

Figure 20. Remote navigation to set up waypoints [58]

AAWA`s Position Paper indicates also that manual control over the vessel will be required when approaching and operating within safety zone as well as while navigating in narrow channels. On the open sea, where vessels trafficking is not so heavy, the operators may allow for more autonomous navigation, still under constant supervision. Furthermore, data transmission is limited to the minimum. These includes vessel`s position, course, speed, Estimated Time to Approach (ETA) to the next waypoint, information on critical ship`s systems and other information vital for situation awareness [58].

According to B.J. Vartdal el al., nautical charts will have a great impact on safety of voyage, especially their accuracy. The accuracy of nautical charts is described by ZOC (Zones of Confidence) as in the Figure 21. ZOC function should be activated on Electronic Chart Display and Information System (ECDIS) during voyage planning. However, it should be turned off during the passage to avoid data overload affecting remote operator`s situation awareness. ZOC help to maintain levels of risk during the voyage, by indication of position accuracy, seafloor coverage and depth accuracy. It will help operators on the watch to better understand the position. Seafloor coverage gives the better reliability of bathymetric data [21].

Zone of Confidence (ECDIS symbol)		Position accuracy	Depth accuracy
A1	* * * * * *	5 metres	0.5 metres + 1% depth
A2	* * * * *	20 metres	1.0 metres + 2% depth
B	* * * *	50 metres	1.0 metres + 2% depth
C	* * *	500 metres	2.0 metres + 5% depth
D	* *	More than 500 metres	More than 2.0 metres + 5% depth
U	U	Not assessed	Not assessed

Figure 21. Zones of Confidence [21]

When preparing a passage plan, vessel`s route should be kept within A1-B triangles away from areas C, D and U. The ZOC should be a compulsory part of voyage planning for USV, as it greatly enhances safety of planned route [21].

7.2. Environmental Analysis

The phenomena that can greatly influence IMR operations performed by USV or any conventional vessel will be waves, wind, ice and current. However, the most important factor is significant wave height “Hs”. Significant wave height is defined as the average height of the highest one-third waves in a wave spectrum [59].

Let us have a look on wave height statistics for Platform “Ekofisk” and “Gullfaks C” obtained from website windfinder.com. Average wave height for “Ekofisk” varies from 1m between May and August to 2-3m for autumn and winter seasons (see Figure 22) [60]. The average wave height is circa equal to 2/3rd (64%) the value of significant wave height [59]. Therefore, for summer average wave height of 1m the significant wave height will be around 1.6m. For winter seasons, where average wave is 3m high the significant wave height will be equal to 4.7m.

When it comes to “Gullfaks C”, which is located north from the “Ekofisk” the average wave height is higher. 1m wave height may occur only in month June, where during the remaining months, the average wave height is between 2-3m (see Figure 22) [61]. The more north, the wind and thus waves will be bigger. It is not advisable for conventional vessels to enter safety zone when significant wave heights vary from 3-4m [17]. These recommendations are for traditional OSV vessels, the size of which is several times larger than USV.

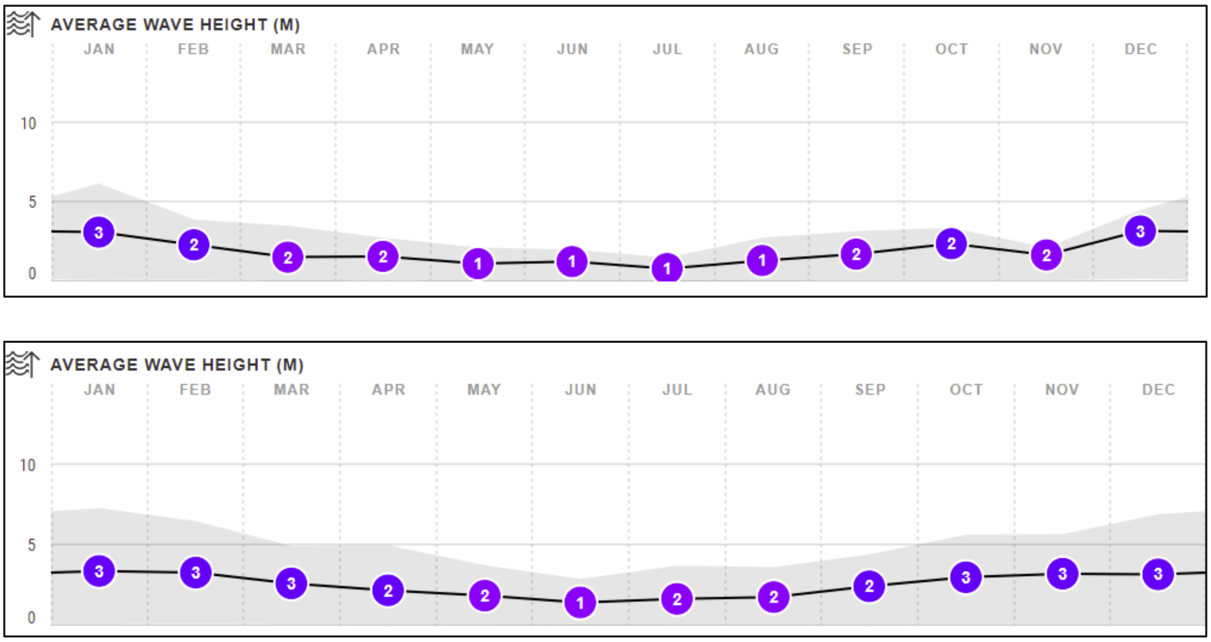

Figure 22. Annual average wave height for Platform "Ekofisk" and “Gullfaks C” [60] [61]

Significant wave height will influence USV motion, namely roll, heave and pitch. If vessel is proceeding with a slow speed at higher significant wave height, then heave motion will be larger. Furthermore, vessel will have larger pitch angle at lower speed and higher significant wave height. This can cause draft changes and thus, making the navigation safety endangered. This issue should be seriously taken into account when considering USV operations at safety zone, where vessel`s speed should be less than 3kn [9].

Having this in mind, it is vital to consider what type of deployment system for ROV would be the most appropriate for operations at NCS and within safety zone. Traditional LARS system with A-frame may turn out to be too risky and simply inefficient, due to following reasons [62]:

- Heavy wind and wave may cause ROV cage to swing and thus, hit the vessel. When ROV is recovered from the sea using this type of solution, shorten umbilical and absence of dumping will cause swinging motion to speed up. This in turns, will make the ROV recovery difficult or impossible. If LARS is not equipped with "Guide Wires" or "Guide Rails" such operations would need to be prolonged as long as better weather conditions will come. Furthermore, speed up swing motion can cause large side loading on A-frame which can lead to frame failures.
- When operating within safety zone USV would use DP system which uses thrusters, instead of anchors. If LARS system is in close vicinity to those thrusters, then it is big probability that ROV may be destroyed during deployment and recovery.

Beside the above issues, Prof. R.B. Laughlin suggests, that the attention should be also paid to ROV umbilical, as heavy currents and waves may cause frequent bending of the cable in different angles and finally break down. The repair of umbilical can be performed only onshore, which leads to downtimes and great costs [62]. If USV is considered to operate in NCS weather conditions, the heavy weather launch system should be installed on its board. Therefore, in order to choose the best possible solution for deployment of ROV from USV, it is necessary to conduct closer investigation of sea state conditions prevailing around the offshore platform.

7.2.1. Weather window analysis

We can distinguish weather restricted and unrestricted IMR operations. Weather restricted operations are those that last less than 72 hours and are based on weather forecasting [63]. Most of current IMR operations are weather restricted [11]. In following chapter, we will analyse weather window for USV that is going to perform IMR operations within safety zone of Åsgard Platform at North Sea. USV is going to carry out subsea inspection using ROV. In order to estimate duration of favourable weather conditions for such operations we need to establish acceptance criteria and environmental limiting criteria.

First of all, it is important to calculate duration of IMR operation. According to DNV-OS-H101 guidelines, duration of whole operation should include planned operation duration T_{POP} and maximum contingency time in case of emergencies (see Figure 23). T_{POP} is established based on operation`s schedule. DNV-OS-H101 guidelines called it operation reference period T_R or “safe-to-safe” duration. The operation reference period should be also as realistic as possible. Further, guidelines recommend that the T_R should be at least doubled than T_{POP} and T_C should last not less than six hours [64].

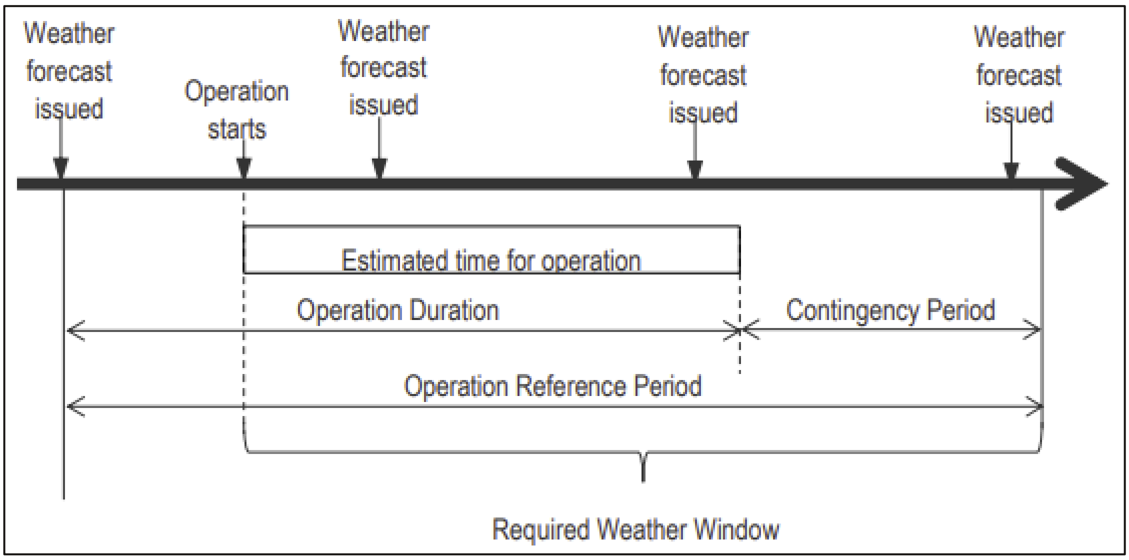

Figure 23. Operation durations [63]

DNV guidelines gives following formula for these calculations [64]:

$$T_R = T_{POP} + T_C$$

T_R – operation reference period [h]

T_{POP} – planned operation duration [h]

T_c – estimated maximum contingency time [h]

While planning Operation Reference Period for unmanned vessel, it is extremely important to precisely estimate contingencies due to [63]:

- *“technical delays, caused by fragility and failures of critical equipment (sensors, ROV, communication system).*
- *inaccuracy in weather forecasting, especially for the areas of adverse weather conditions, such as NCS.*
- *Inaccuracy in operation schedule, as some operations can be conducted faster or slower depends on operators experience in similar work”.*

Therefore, in following analysis, we are considering IMR operations, namely subsea inspections that will last:

- Case 1: T_{POP} = 12 hours and T_C = 12 hours
  Thus, T_R = 12 hours + 12 hours= **24 hours**
- Case 2: T_{POP} = 24 hours and T_C = 24 hours
  Thus, T_R = 24 hours + 24 hours= **48 hours**

Next step is to establish environmental limiting criteria $OP_{LIM.}$ According to DNV-OS-H101 guidelines those limits should always be less, than [64]:

- *“Equipment specified restrictions* (i.e., sensors` fragility to weather conditions).
- *The environment design criteria* (i.e., significant wave height).
- *Limiting conditions for positioning keeping systems* (i.e., bandwidth limitations).
- *Maximum wind and waves for safe working.*
- *Any limitations defined in HAZID/HAZOP.*
- *Limiting weather conditions for carrying out identified contingency plan”.*

In this analysis we will consider significant wave height H_S being an environmental limiting criterion, as it is the most common factor affecting vessel`s performance [50]. Thus, environmental analysis will investigate probability of favourable weather windows in different H_S and in individual months. We assumed that nine different significant wave heights are going to be environmental limits for subsea inspections, as it can be seen in table 25. This means, that above those heights there is problems with i.e., ROV deployment and recovery. However, it is important to take into consideration inaccuracy in weather forecasting when operating in the area of adverse weather conditions, such as NCS. Thus, we need to take a correction for uncertainty in weather forecast, called alpha factor.

DNV-OS-H101 guidelines have distinguished three categories of maritime operations depending on their fragility to weather: category A, B or C [64]. The IMR operations are classified into category B. Therefore, for following analysis we will use alpha factors from the table below (Figure 24), where weather forecast is obtained from *"at least two recognised and pre-defined sources (...)"* [64]. Meteorologist is not required on site; however, weather forecast intervals should not be longer than 12 hours [63].

Table 4-2 α-factor for waves, Level B highest forecast

Operational Period [h]	*Design Wave Height [m]*						
	$H_s = 1$	$1 < H_s < 2$	$H_s = 2$	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 12$	0.68	Linear Interpolation	0.80	Linear Interpolation	0.83	Linear Interpolation	0.84
$T_{POP} \leq 24$	0.66		0.77		0.80		0.82
$T_{POP} \leq 36$	0.65		0.75		0.77		0.80
$T_{POP} \leq 48$	0.63		0.71		0.75		0.78
$T_{POP} \leq 72$	0.58		0.66		0.71		0.76

Figure 24. Alpha Factors for category B of maritime operations [64]

To calculate alpha factors for H_S in range between 2-4m, we used linear interpolation described by the formula [50]:

$$p(x) = f(X_0) + \frac{f(x_1) - f(x_0) \times (x - x_0)}{x_1 - x_0} \qquad [-]$$

Results of alpha factor calculations are presented in Figure 25.

Alpha Factor	**Design Wave Height [m]**								
Operational Period [h]	**2**	**2.25**	**2.5**	**2.75**	**3**	**3.25**	**3.5**	**3.75**	**4**
$T_{POP}\leq 12$	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83
$T_{POP}\leq 24$	0.77	0.77	0.78	0.78	0.79	0.79	0.79	0.80	0.80

Figure 25. Linear interpolation of alpha factors for Hs between 2-4 m.
Source: Own study

D. Bonvik-Stone in his article *"Get the Alpha Factor: Waves, Work & Wider Weather Windows Offshore"* indicates that alpha factor reflects the fragility of curtain operations to weather conditions as well as sensitivity of onboard environmental sensors. Moreover, it considers whether there is an environmental monitoring at the location of operations or not. Alpha factors for operations without environmental monitoring will be smaller and thus, the design limits will be lower. If there is active weather monitoring such as monitoring equipment onboard, then alpha factors are bigger as well as the design limits. Therefore, one of the solutions to increase USV`s design limits could be equipping vessel with reliable environment monitoring system. Moreover, it could inform the operators, whether the significant wave height limit is exceeded, and it is time to manage associated risk [65].

Importance of having environment monitoring system onboard is also dictated by wave peak period influence on vessel`s operability limits [50]. According to DNVGL-CG-0130 wave peak period is described as a *"wave or the period of another response like vertical bending moment, in s, with the most energy in the wave or response spectrum, i.e., the most probable maximum wave or response in a short-term sea state"* [66]. For some operations, vessel will have limit of H_S =2.5m and period of 4.5s. However, when wave period will increase to 5,5s, then the limit H_S can drastically change to 1,5m and so on. Weather forecast, that the operators would receive will not always give a hundred percent accuracy results, as the wave periods are given to the closest second [65]. However, it is not sure that the period will be 5s, 5.5s or 6s. Such small differences will have an enormous impact on vessel`s design limits. Thus, having onboard sensors can allow for continuous monitoring of H_S and wave period increasing safety.

Back to alpha factor, it is necessary to calculate the operational limiting criteria for weather window estimation. Operational limiting criteria can be determined as follow [64]:

$$OP_{WF} = OP_{LIM} \times \alpha \qquad [m]$$

OP_{WF} – Operational limiting criteria

OP_{LIM} – Operational environmental limiting criteria

α- alpha factor

$T_{POP} \leq$ 12h	**Design Wave Height [m]= OP_{LIM}**								
OP_{LIM}	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
α	0.80	0.80	0.81	0.81	0.82	0.82	0.82	0.83	0.83
OP_{WF}	**1.60***	**1.81**	**2.02**	**2.23**	**2.45**	**2.66**	**2.88**	**3.10**	**3.32**

$T_{POP} \leq$ 24h	**Design Wave Height [m]= OP_{LIM}**								
OP_{LIM}	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
α	0.77	0.77	0.78	0.78	0.79	0.79	0.79	0.80	0.80
OP_{WF}	**1.54***	**1.74**	**1.94**	**2.15**	**2.36**	**2.56**	**2.77**	**2.99**	**3.20**

* Red marked numbers are not included in analysis, as data from Åsgard Platform relates to H_S >2m.

Figure 26. Operational limiting criteria for 12hours and 24hours planned operations.

Source: Own study

Having calculated OP_{WF} (see Figure 26) and knowing significant wave height, it is possible to move to last stages of weather window estimation. First step is calculations of average weather window duration for each month (see Table 43 and Table 46 in Appendix F). In order to do that, data from Åsgard Platform, gathered between 1955-1995 every six hours are needed (see Appendix E). It consists of statistics describing hourly durations of H_S being below the specified value [50].

Having calculated that, it was possible to estimate the probability of weather window large enough for 24- and 48-hours operations for different operational limits (see Table 44 and Table 47 in Appendix F). Below is given exponential distribution, which was used to calculate probability of the weather window large enough for 24- and 48-hours operations [50]:

$$P(x) = exp\left[-\frac{T_R}{T_{AVG}}\right], d_{avg} > 0 \quad [-]$$

Where:

P(x) – Probability of the weather window being larger than operation time [-]

T_R- Operation reference period [h]

T_{AVG} – Average time when significant wave height is smaller than OP_{WF}.

Before analysing obtained results, it is important to mention maximum wave height H_{MAX}. Maximum wave height can be twice the height of a significant wave height. It is common to expect H_{MAX} about three times in 24hours or 1 in every 3000 waves [67]. Therefore, operators while planning and executing USV operations should not only focus on significant wave heights but also on H_{MAX}. The maximum wave height can be calculated using formula below [64]:

$$H_{MAX} = STF \times H_S \quad [m]$$

Where:

H_{MAX} – Maximum wave height for weather restricted operations [m]

H_S – Significant wave height [m]

STF – Short term response [-]

STF= 2.0 for all reference periods

H_S [m]	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4
H_{MAX} [m]	4	4.5	5	5.5	6	6.5	7	7.5	8

Figure 27. Calculated maximum wave height for each Hs.

Source: Own study.

7.2.2. Analysis of the results

First dependency that can be noticed is that longer operations will be burdened with greater uncertainty and thus, lower operational limits (see Figure 26). For both cases, alpha factor has reduced operational limit by ≈ 20%, i.e., H_S = 2.5m to H_S = 2.02m. It is a big, yet necessary margin, as we cannot be sure if weather forecast will be still reliable in 24 hours or 48 hours' time. Alpha factors include these doubts, which making them so important for marine operation planning.

For "Case 1" values shows that, the longest weather windows occur in spring and summer seasons (average >100 hours) (see Table 43 in Appendix F). The length of the weather windows will increase with larger operating limits. For instance, for H_S = 2.02m the weather window duration of more than 100 hours will occur from May to August. For H_S = 3.32m 100 hours` weather window will spread from February to September. Same dependency can be seen for "Case 2" (see Table 46 in Appendix F). However, for longer operations such as 48 hours, the operating limits are smaller thus, durations of weather windows will become shorter.

When it comes to probability distribution, 24 hours operations will have larger possibilities to be finished within planned operation time. Moreover, the larger operational time the probability will be higher. Green numbers in Table 44 (see Appendix F) represents probability of favourable weather window occurrence for 24 hours operations that is larger than 70%. Within this range vessel has the biggest possibility to perform and finish planned operations.

Same green colour was used to mark probabilities larger than 70% in Table 47 (see Appendix F). However, in this case we can notice that the amount of such values is much lower than in case of 24 hours operations. For H_S = 2.15m, the most probable months for finishing operations within 48 hours are June, July and August. In rest of the months the probability is smaller than 70%. For the highest calculated operational limit of H_S= 3.2m, the 48 hours operations are the most probable to happen from April to September. It is much shorter period than for 24 hours operations. But as we mentioned before longer operations will be burdened with higher risk due to weather forecast uncertainty [65]. Therefore, the biggest probability for USV to perform its tasks for H_S ≈ 2- 3m would be:

- For 24 hours operations: April- September
- For 48 hours operations: June- August

In order to raise operational limits for USV, the appropriate launch and recovery system for ROV must be installed. Firs of all, it is important to consider the unmanned nature of the vessel. L.O. Nordmark in thesis *"Design of ROV Launch and Recovery System"* indicates that LARS system must be easy enough to become fully automated so there is no need of human presence. Thus, the moonpool system is the most optimistic to use for USV operating in the North Sea. Moonpool is an opening in vessel`s hull, which allows for lowering ROV and other tools into the sea. Moonpool is commonly placed as close to the vessel`s roll and pitch axis as possible to minimize angular motions during lifting operations. The ROV hall is located inside the boat, which prevents also from external conditions. From A-frame through ROV hall all the way down to the keel run guide rails. This would allow for smaller ROV pendulum and thus, safer and more efficient launching and recovery operations. Moreover, ROV would be stabilised by cursor frame, which is horizontally guided by guide rails [68].

However, E.G. Pedro in her research indicates that there is still risk that ROV would slam into cursor frame. It may also get stuck when entering the moonpool. Having in mind size of USV such system needs to be also easy to install and compact. Using moonpool as a launch and recovery solution may cause also flooding of deck, as water can enter through the water plugs of the moonpool. This can happen when the water plugs will enter resonance conditions leading to oscillation amplitude 3-4 times the wave height [69].

The biggest risk relating to ROV deployment through the moonpool is the splash zone. Splash zone is an area where ROV is first time touching the water surface and where the largest vertical hydrodynamic loads occur [70]. Moreover, as the cage with ROV is connected with the vessel by umbilical, the cage heave will be the same as the vessel`s heave, if it is not compensated [68].

Solution here could be usage of cursor frame, which would stabilize the ROV throughout the deployment (see Figure 28). On conventional vessels, cursor frame and umbilical winch are hydraulically operated. E.G. Pedro indicates, that typically, when using hydraulic winches, the velocity of lowering or recovering the ROV is around 1.40 m/s. However, in case of electric winches this speed can be higher, i.e., 2.50 m/s. Therefore, electric winches would be a better solution for USV as the adverse weather conditions in NCS often require rapid interruption of operations and recovery of ROV. Moreover, E.G. Pedro points out that electric winches are easier to operate by automated systems and could be powered by hybrid engine set up (if fitted onboard) [69]. The example of typical moonpool cursor frame system is illustrated in Figure 28.

Figure 28. Moonpool Cursor [71] [62]

Furthermore, launch and recovery of ROV on conventional vessels is supervised by the operator. It is his/her task to adjust velocity of deployment depending on the sea state conditions and ROV`s behaviour. In case of USV something must replace the operator in monitoring of launch and recovery operations as well as ROV`s weather tolerance. E.G. Pedro in her thesis suggested that monitoring performed by operator can be replaced by cameras located inside the ROV`s hangar aiming at the splash zone. In addition to that, sensors that would measure velocity and acceleration at the winches and cursor should be considered here as well [69]. When it comes to ROV`s weather tolerance, it will mainly refer to significant wave height at which it is safe to deploy the robot. ROV`s weather tolerance will depend on type of LARS that is installed onboard, namely whether it has cursor frame or not [68].

Figure 29 represents ROV`s weather tolerance when using LARS guiding system and with no guiding. Even though the ROV is deployed from the oil rig where the heave is smaller than on the vessels (vessel has larger surface area), it will still illustrate differences in significant wave height limits [68].

In case where no cursor system is installed the allowable significant wave height is 5 meters for safe ROV deployment (see Figure 30) [68]. If the significant wave height is higher than 5 meters, then launch operation must be postponed until favourable weather window appears.

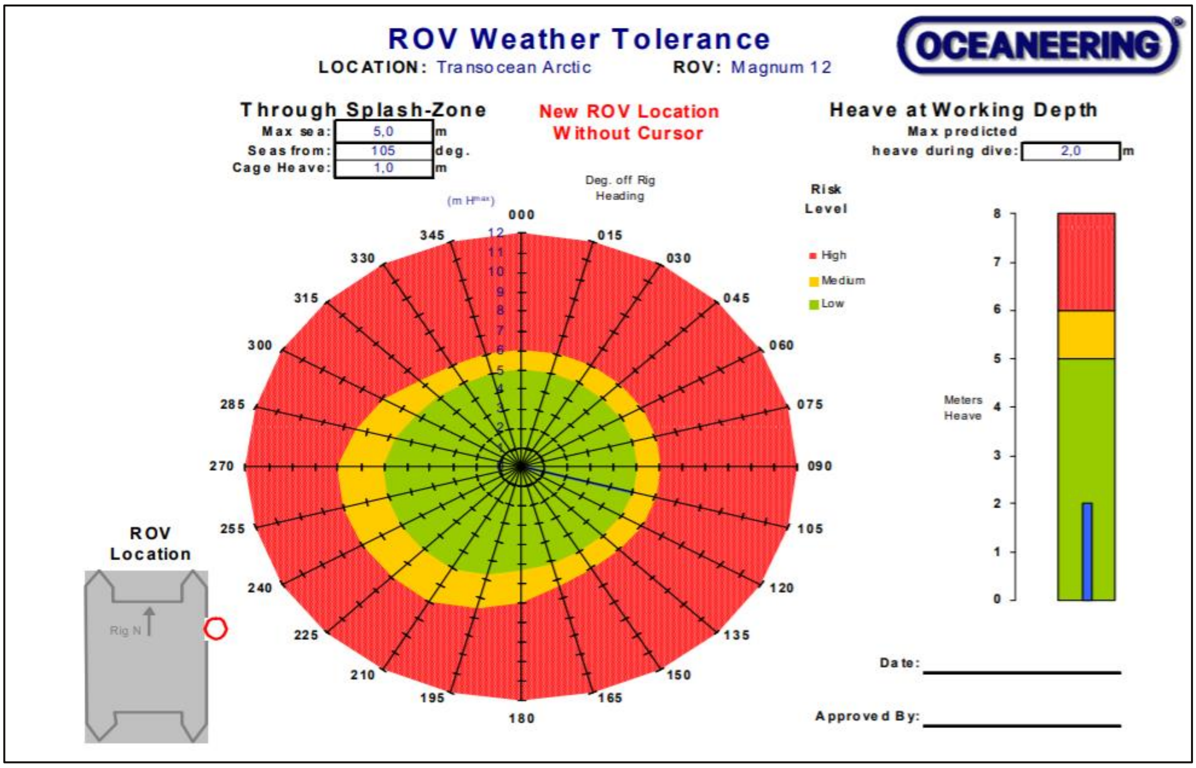

Figure 29. ROV`s weather tolerance diagram without Cursor system [68]

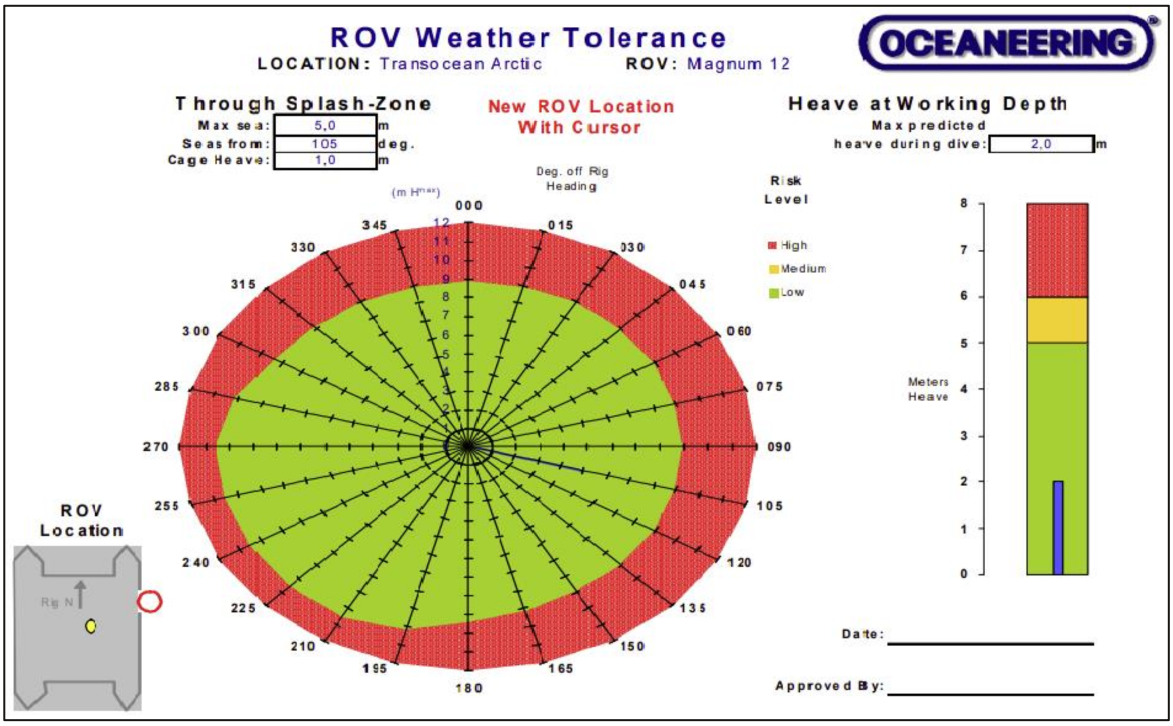

Figure 30. ROV`s weather tolerance diagram with Cursor system [68]

Here, when the cursor system is used the significant wave height limit is increased to 9 meters. Heave value and splash zone limits are the same for both cases. Thus, we can notice that using LARS system with cursor frame will significantly eliminate the risk of waiting on weather situations so important when operating within NCS [68].

In addition to cursor frame, USV should be equipped with heave compensation system to increase weather window and to safely deploy ROV. In journal article prepared by J. Herdzik, we can read that when vessel is in constant motion, large load fluctuations will act on lifted or lowered ROV. In order to reduce those loads and vertical movements, heave compensating systems must be installed. For electric winches, Active Heave Compensation (AHC) will compensate wave movement by operating the winch automatically in the opposite direction and at the constant speed [72]. One of the disadvantages of AHC is its big power demand. However, if USV would be fitted in hybrid power set-up, then such energy requirements can be covered by the vessel itself.

7.3. Communication

Depending on the design, quality and invested money, USV will use different communication networks and satellites. According to AWAA`s Position Paper, most of the high bandwidth satellite systems will allow operator to steer the USV regardless location. However, considering remote character of USV`s operations and their constant supervision, the operator must consider the influence of adverse weather influence on communication network. Disturbances caused by heavy rains and snowing will depend on frequency band, that the satellite network is using. For instance, Ka-bands of more than 20GHz is much more fragile to fading than L-band of 1-2GHz. This indicates that Ka-bands are not recommended frequency band for adverse and harsh weather conditions of NCS. The best option would be to mix these two bands, which would minimize risk of communication loss. Such solution has been used in Inmarsat Global Xpress system with positive outcome. This system allows for switching between the satellites without input from the operator. It is important to consider lower capacity of L-band satellite when considering RCC- USV communication and sensor data transfer [27]. The areas of different communication qualities within NCS demonstrates Figure 31.

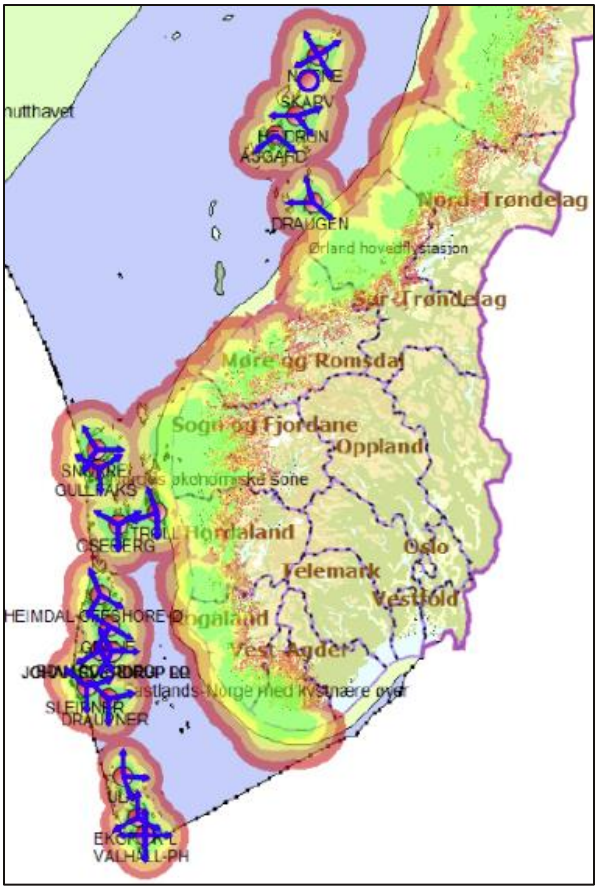

Figure 31. Communication coverage map [73]

It is obvious that IMR operations using USV will not be undertaken during rough conditions. Nevertheless, disturbances of satellite system may happen during slightly deteriorated weather conditions. Thus, before departure operator must ensure that satellite and land-based communication network will work flawlessly [27]. Continuous communication between RCC and USV, as well as with the installation`s OIM/MRP will be of particular importance when ship is operating within safety zone. It is required by GOMO and “Operasjonsmanual for Offshore Service Fartøyer Norsk Sokkel” to report any changes in USV`s position to the installation`s OIM/MRP up to date. Moreover, it is required to establish alternative way of communication between vessel and installation in case of any emergencies [74]. Therefore, within safety zone the high bandwidth and low latency communication will be demanded.

When it comes to data transfer, B.J. Vartdal et al. suggests that the latency should be minimal to provide operator with live information from sensors. It will depend on communication bearer, which is available at ship`s location and technology installed on vessel`s board. In case of USV operating within safety zone, the satellite or 4G communication will be the only options. If USV would operate close to the coast, then it is possible to use terrestrial bearers, such as radio and mobile systems. As the USV is unmanned, the quality of communication link between vessel and RCC is necessary. Therefore, communication equipment redundancies should be considered. Moreover, in order to reduce amount of data transfer; reduction of raw data should be performed. Image parameters such as colour depth, frame rate and field of view should be restricted [21].

To sum up, it is important to consider satellites` fragility to weather condition when planning USV`s voyage. Maintaining SA at a high level is a priority for safety on unmanned operations. Additionally, AWAA`s Position Paper indicates that choice of satellite should be dictated by their transfer capabilities. On the open sea, sensor data should be minimized to only necessary information for safety of navigation so the L-band satellite would be an appropriate choice. However, USV approaching safety zone should transfer detailed sensor data to RCC. In this case operators' sense of surrounding is vital, due to presence of other manned vessels, vicinity to the platform and subsea operations conducted by ROV. Lastly, quality and reliability of communication link at NCS should be taken into consideration, as it can vary depending on the area. Therefore, alternative and numerous communication methods should be possible to use, such as VHF, satellites and 4G to eliminate likelihood of communication loss with the USV [27].

7.4. Situation awareness

7.4.1. Situation awareness and sensors

Situation awareness can be defined as follow: *"The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* [75]. Furthermore, above definition can be divided into three levels of SA: Level 1- perception of the elements in the environment, Level 2- comprehension of the current situation and Level 3- projection of future action [76]. Therefore, if we want to transfer crew members from ships to RCCs then remote-control stations must fulfil each of the above levels to provide operators with full situation awareness. This can be done by equipping RCCs with same type of facilities as vessels have onboard [75].

Moreover, in order to provide operators with sufficient situation awareness, the analysis of human senses, i.e., sight and hearing should be undertaken. Class Guideline DNVGL-CG-0264 suggests, that new developments concerning sensors should be designed to reflect vision and hearing in the same way or better than human onboard. When it comes to sight, sensors should provide operator with picture containing enough details of prevailing conditions. Based on that image, operator should fully understand situation in which vessel is at the moment and thus, conduct safe and efficient operations [20].

Another important sense that must be replaced by the sensors is hearing. Hearing is especially crucial to recognize hazardous situations, such as whistles and foghorn signals made by the other ships. In addition to that, DNVGL guideline indicates that direction of the sound should be also provided through i.e., an array of microphones and fusion of sound signals with other sensor data. Recording of the sounds should be provided with the function of noise elimination, so the operator can focus on relevant sound interpretation [20]. For instance, loud noise can be generated from the propulsion system of deployed ROV, making it hard for operators to listen the sounds above the water surface.

These were two basic senses, that are the minimum to provide operator with some level of SA. However, in order to fully enhance SA of remote operators, other senses should be also considered. Those are temperature, smell, balance and acceleration. They should reflect vessel`s movements, vibrations, high and low temperatures and weather conditions such as strong wind, heavy rain, visibility, strong currents [20].

However, the biggest challenge indicted i.e., in AAWA Position Paper will be to gather all sensor data in one sensor fusion, so the operators can in transparent way obtain high level of situation awareness. Further considerations concerning sensor fusion will be given after description of the basic sensor technologies used on unmanned vessels, as presented below [27] :

1) High Definition (HD) Cameras

Basic sensor installed on USVs is HD cameras. They can differ in sizes and quality of produced picture. In order to use them in NCS harsh weather conditions, they need to meet some technical requirements, i.e., colour recognition for better obstacle detection and durability as they are going to operate away from the shore. In addition to that, cameras can be equipped with thermal Infra-Red (IR) imagers for night vision and stereoscopic configuration for 3D sensing. However, those solutions have also some disadvantages.

First, problem may arise from transportation of big amount of high-resolution data produced by HD cameras. In order to transfer such data, USV would need to use high-bandwidth links, so the operator can receive visual image with tolerated latency. Other flaws of visual cameras are their performance in bad weather conditions, which are common for NCS area. Solution here could be Long Wave Infra-Red (LWIR) cameras, which are active to IR radiation between 8-14μm wavelength range. LWIR are highly effective as almost all objects emit thermal radiation. Therefore, they can be used in total darkness as well as when visibility or illumination is restricted. Examples of LWIR cameras imagining illustrates Figure 32.

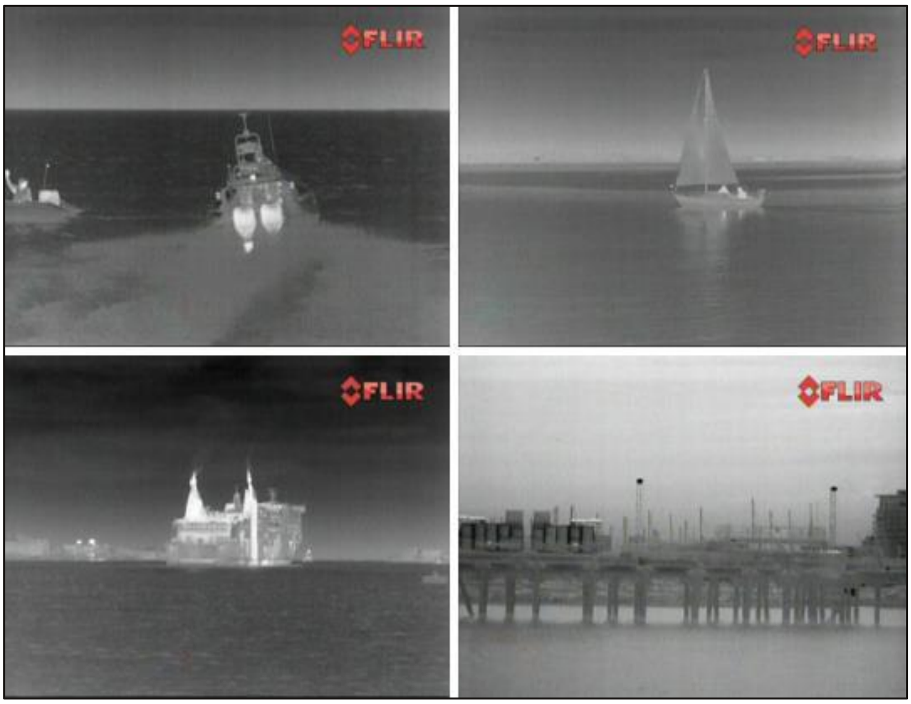

Figure 32. LWIR camera images [77]

Unfortunately, LWIR cameras as well as visual spectrum cameras are fragile to environmental conditions, such as humidity. It makes the IR-bands attenuate differently, causing diverse seeing ranges. Solution here would be other type of cameras, namely Short Wave Infra-Red (SWIR). Originally it is military technology, which is now available for commercial and scientific purposes. SWIR cameras operates between 1-3μm wavelength region, where detected signal reflects radiation. Those cameras have better performance in restricted visibility than visual spectrum cameras, however they cannot operate in total darkness and they are more expensive. On the other hand, SWIR cameras performing better in humid conditions than LWIR cameras.

2) Radar and Light Detection and Ranging (LIDAR)

Due to camera`s fragility to the environmental conditions and issues with transferring big amount of data, additional sensor technologies should be also considered. Radar is a well- known device for object detection and mapping. It uses microwaves X or S- bands. The main issue with radar application to unmanned vessels is their range. Common radars are highly effective when vessel is navigating on the open sea. However, when it comes to harbours or narrow channels conditions, their resolutions may not detect all the small obstacles.

On the contrary, radar has some features that make it very usable when operating within safety zone. Function "Guard Zone" allows for setting a zone around the vessel. The alarm will sound when other vessel, buoy or structure will enter established zone. Another feature is split-screen display, which is helpful for operators to simultaneously monitor all objects around the vessel within the safety zone and those outside.

LIDAR is scanning laser sensor, which is used for distance measurements. They are very accurate, and thus they can produce very precise 3D map of vessel`s surrounding. The biggest disadvantage of LIDAR is its fragility to weather conditions, as its uses IR laser similar to those used by IR cameras. It has also many moving mechanical pieces, that can be damaged by long exposition to harsh weather. An example of LIDAR image illustrates Figure 33.

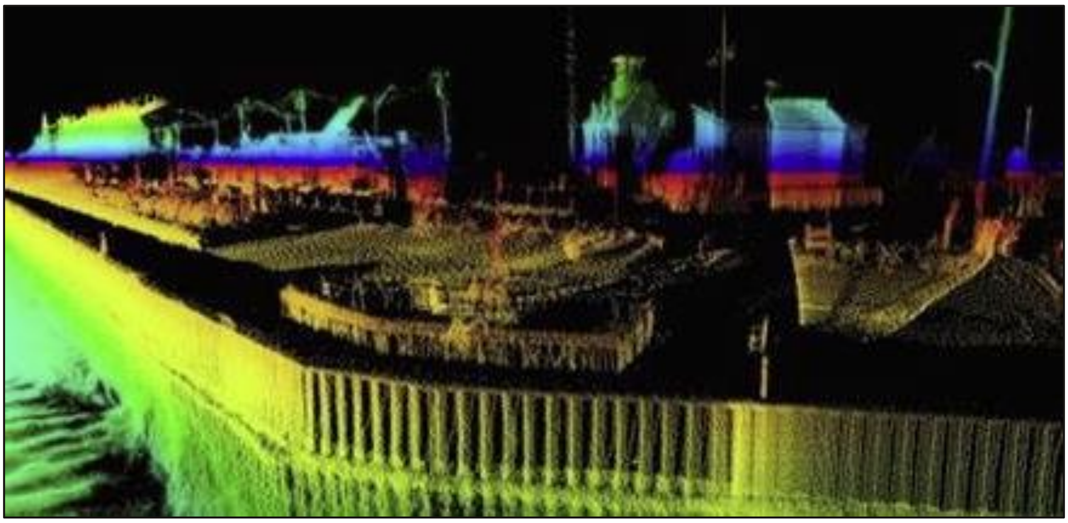

Figure 33. LIDAR image display [78].

Each of the above sensors have some advantages and disadvantages. All of them will be to some extend influenced by the prevailing weather conditions at NCS. However, it seems possible to combine them together in order to eliminate their individual weaknesses and thus, to enhance their overall performance [27]. Figure 34 summarises pros and cons of discussed sensors in relation to situation awareness.

	Visual HD cameras	Thermal IR cameras	Radar	LIDAR	Sound devices
Marine robustness	**	**	**	?	?
Distance measurements	-	-	**	**	- -
Weather resistance	- -	*	**	* ?	- ?
Object identification	**	*	*	*	*
Special accuracy	**	*	- -	**	- -
Field of view	*	-	**	*	**
Data transfer load	- -	-	**	- -	*

Figure 34. Marine sensor`s comparison [27].

Where:

- (**) – particularly good
- (*) – good
- (-) – bad
- (--) – very bad
- (?) – no data

All presented sensors were positively tested as a possible solution for remote SA by AAWA. Visual cameras can enhance object identification detected by the radar and can be used for segmenting objects in the water [27] (see Figure 35).

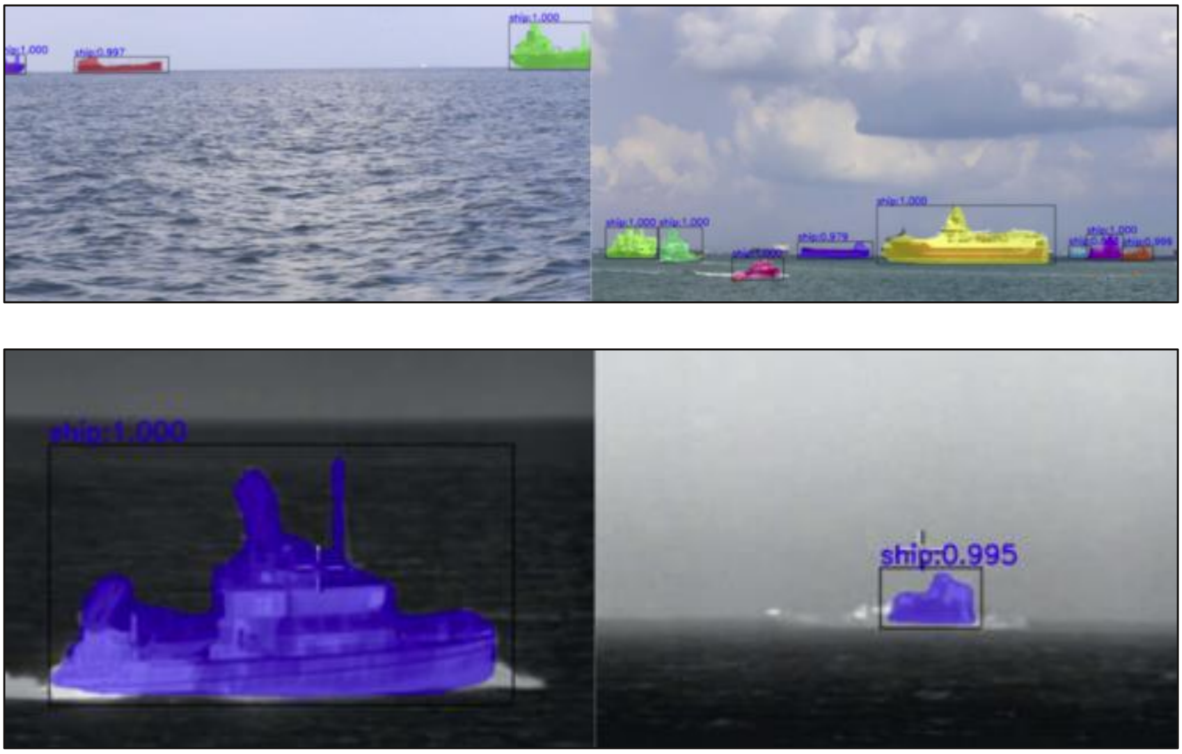

Figure 35. Object detection and object segmenting using visual HD cameras [79].

Moreover, IR thermal cameras can be used for night operations, whereas radars are highly resistant to weather conditions and allow for distance measurements to the target. Combination of cameras and radar would be more beneficial than usage of LIDAR, as they are more cost-effective and at the same time reliable [27]. GPS, ECDIS, Automatic Radar Plotting Aid (ARPA) should be used in addition to sensors to obtain complete situation awareness. Combination of all information collected from the above sensors allows for “data fusion”, which provides remote operators with detailed overview of vessel`s surrounding [27].

Having all of this in mind, it is important to analyse how sensor data can be transferred and displayed for remote operators. According to B.J. Vartdal et al., the emphasis should be placed on latency, type and amount of data that the operator will receive. The more sensors are installed on the vessel the more fusion data must be transferred to the RCC. Moreover, sensor data should only support remote operator and not make him/her more confused.

Therefore, operator should receive only the most concrete information, having still access to more detailed data in case of some uncertainty [21].

Furthermore, B.J. Vartdal et al. indicate that SA level will be influence by regular maintenance activities to keep all the onboard sensors and RCC equipment continuously functioning and reliable. It is important to perform maintenance or inspection of onboard sensors every time before departure to maintain continuous communication link. Moreover, when designing the USV and its detection systems the emphasis should be placed on quality and reliability of the sensors. Moreover, they must be tested in real sea conditions, surveyed and maintained in regular time periods, as their failure can pose a great threat to unmanned operations. In order to enhance their availability, appropriate number of redundancies for those sensors which are vital in critical events [21].

The benefits of numerous and advance sensor system can greatly impact the lookout performance, and thus avoid collision with the platform, vessel or other object. It can also contribute to reduction of fatigue and inattention of operators.

7.4.2. Situation Awareness in DP

K.I. Øvergård et.al have conducted extensive interviews with dynamic positioning operators for article *"Critical incidents during dynamic positioning: operators` situation awareness and decision making in maritime operations"*. All DP operators were involved in incidents with DP system. Those accidents have been categorized in groups together with occurrence number [80]:

- *"Human error- 6 times*
- *PMS error- 6 times*
- *Component failure- 2 times*
- *Environmental factors- 7 times*
- *DP software failure- 1 time*
- *DP reference system failure- 2 times"*

In article prepared by K.I. Øvergård et.al we can read that only in 10 incidents base event was correctly identified by DP operators during situation assessment. In 14 out of 24 events operators identified the base event after incident was over. This means, that he/she did not obtained Level 1 of SA. However, they were still able to avoid collision or other accident. In 19 out of 24 events, operator obtained Level 2 of SA, which indicate that he/she was able to understand importance of some information and thus, identify issues before the incident happened. In rest cases DP operator did not understand that there are some issues until critical incident happened. Level 3- Projection, was obtained only in 5 events out of 24. In the remaining 19 incidents, the DP operator was not expecting the accidents and was surprised by that fact. Furthermore, in 14 events out of these 19, operators knew that something is wrong, however they could not identify cause of the problems [80].

Furthermore, K.I. Øvergård et.al, indicates that operators have problem to transit their situation awareness from Level1 through Level2 to Level3. Even though most of them have problem to identify what is wrong, they were still able to make correct actions to avoid, i.e., collision. What is also interesting, that in 6 out of 24 incidents, operators had to either break or act accordingly to the procedures to avoid final accident. Those who broke the rules were confident in their actions, as their technical and navigational skills allowed them to find better solutions for those situations. This indicates, how still following of the procedures and good seamanship is important for safety of maritime operations [80].

The article`s findings are important for USV operations within safety zone, where dynamic positioning would be used to keep vessel in position. First, good seamanship skills should be required from the USV`s operators as well as good knowledge of emergency procedures relating to DP system. RCC operators should also be able to perform actions by reducing the level of automation and cooperate with DP system, by understanding its functioning. Advanced technology on USV can also enhance SA of remote operators within Level 1, fitting vessel with self-diagnostic systems. Such system would inform operator about the failures in transparent and fast way, giving the operator extra time to take appropriate countermeasures [80].

8. Sustainability and environmental impact of USVs.

If USVs are going to take over safety zone operations performed so far by offshore conventional vessels, their employment must be economical, ecological friendly and social sustainable. According to Kretschmann et al., economic sustainability stands for vessel which is operating in a cost effective and efficient manner. The environment sustainability indicates that ship is environmentally friendly, where social sustainability stands for work safety environment [81]. If USV is equipped with technology that provides cost effective, reliable and safe operations, then demand for such ships will be greater than for conventional offshore vessels.

8.1. Economic sustainability

Ship revenue will depend on freight rates, productivity and cargo capacity [21]. Freight rate and cargo capacity refers to cargo transporting vessels, such as containers and bulk carriers. In case of USV employed for light IMR operations, the revenue will depend on its productivity. Productive vessel is the one with good operational planning, reduced off-hire and which proceed with optimal speed [82]. Off-hire for USV can be reduced but, in some cases, increased as well. By implementing regular maintenance activities and self-diagnostic/self-monitoring systems the off-hired can be notably reduced. However, periodical or regular maintenance can be only performed when vessel stays in the port thus, increasing the off-hire time. Moreover, based on environment data received from USV onboard sensor, it is possible to optimise vessel`s speed and thus, reduce fuel consumption [82].

Beside revenue, company is burdened with costs associated with vessel, such as Operating Costs, Voyage Costs and Capital Costs. Operating costs are those that keep vessel operational. They are independent from type and duration of voyage. Those are: maintenance and repair costs, crew costs, insurance and administration costs. Voyage costs will vary from voyage to voyage and will depend on fuel prices. Those costs will be also influenced by air resistance and hull resistance of the vessel. Lastly, capital costs will relate to ship purchase, i.e., shipyard payment for ship construction and construction financing [82].

Figure 37 represents only those costs that will significantly differ between Offshore Service Vessel and USV. Detailed explanation of each values is given below the table with numbers corresponding to upper indexes assigned to each value. Costs relating to OSV and USV are given in percentages. This is due to difficulties in precise estimation of costs relating to unmanned vessels, as they are still under development. At the same time, it was impossible to obtain detailed costs data.

Each OSV will generate different expenses, due to various voyage distances, fuel prices and types of operations. Thus, purpose of the following table is to indicate how the unmanned ship concept may affect costs distribution for each cost category. This will guide us towards benefits of USV implementation within offshore industry.

Considered here OSV is manned with 30-100 people, where bridge and engine room are manned 24/7. USV`s remote centre is manned by approximately 12 people who works in shifts. Below are presented some of the OSV and USV main particulars:

Main dimensions	**OSV**	**USV**
Length O.A.	95.0 [m]	19.0 [m]
Breadth mld.	20.0 [m]	5.0 [m]
Draft	8.0 [m]	2.0 [m]
Deadweight max.	4694 [t]	45.0 [t]
Propulsion		
Diesel-electric main engines	Total: 11200 [kW]	Total: 700 [kW]
Fuel type	MDO/MGO	MDO
Speed		
Service Speed	13 [kn]	11 [kn]
Max speed	≈ 16.5 [kn]	14 [kn]

Figure 36. Assumed main particulars for OSV and USV.

Costs	OSV	Remote USV
Operational Costs (OPEX):	18% out of Total Costs	**Reduced**
Crew costs (annual)[1]	≈30-100 people 65-70% of Operational Costs	≈12 people
Stores and consumables[2]	15-30% of Operational Costs	Reduced by 100%
Maintenance and Repair[3]		Reduced by 50%
RCC (power supply, software subscription, technical support, training costs)[4]	N/A	Full Price
Electrical power balance[8]	+ Auxiliary systems for propulsion service + Auxiliary systems for ship operation + Heating/ ventilation air conditioning + Galley and laundry + Deck machinery + Lightening + other auxiliary systems	Heating/ventilation air conditioning - Reduced by 100% Galley and laundry - Reduced by 100% Lightening - Reduced by 50%
Capital Costs (CAPEX):	22% out of Total Costs	**Reduced***
Auto-remote ship technology[5]	N/A	Full Price
Redundancy of technical systems[6]	N/A	Full Price
RCC investment (RCC equipment)[7]	N/A	Full Price
Voyage costs (VOYEX):	≈60% out of Total Costs	**Reduced**
Fuel price[9]	Will vary. (50-70% of Total Costs)!	Reduced
Light Ship Weight[10]	Will vary.	Reduced
Air resistance[11]	Will vary. (ballast and design conditions)	Reduced
Total Costs	**100%**	**Reduced**

Figure 37. Cost comparison between OSV and USV [83]

- **Reduced* -** Even though employment of USV will introduce new capital costs as it is demonstrated in Figure 37, total capital costs will be still smaller than for conventional OSV. Further explanation is given in Chapter 9.3.

1) Crew costs

Reduction of onboard crew will have its advantages, such as reduction of human factor, lower crew costs, etc. Moreover, by reducing or eliminating ship`s onboard crew, new design solutions can be implemented to increase vessel`s sustainability in i.e., fuel consumption. On the other side, it will force company to invest more money in advanced onboard technology to make the vessel able to navigate safely and efficiently from the remote centres.

Crew costs related to manned vessels will represent the biggest percentage of the operational costs, as they contain crew wages, travel, training, recruitment, agency expenses etc [82]. Those costs will increase with ship`s age, as larger crew is required for older vessels. When it comes to USV, crew number can be reduced from around 100-30 people to 12 people due to advanced automation of ship`s system.

In order to conduct remote operation 24/7, 3 shifts per 8 hours are assumed. One shift consists of 4 people which in total gives 12 people. Crew wages for RCC are estimated from the "ITF Uniform TCC Collective Agreement" from 2014 for conventional vessels (see Appendix G). The remote centre operators would receive wages that corresponds to second officer/ chief officer payment, which is around 3.500USD a month [82]. Having operators onshore, the expanses relating to crew`s travel costs etc. can be significantly reduced.

2) Stores and consumables

MUNIN`s quantitative assessment estimates that stores and consumables costs can account for 14-15% of operating costs for manned vessels. Consumables consists of lubricants for machinery, such as oils and food for the crew members. By employing USV, costs relating to stores, such as medical cabin, safety and protective equipment can be significantly reduced [82]. However, when it comes to lubricants it will be still needed if there is rotating machinery onboard. Costs associated with catering for the onboard crew will be reduced but not eliminated, as they will be incurred for employees in remote centres [82].

3) Costs of maintenance and repair

Maintenance and repair costs for OSV increase with its age. Maintenance can be performed as a routine on-board tasks or complex repairs when drydocking.

According to Kretschmann et.al., maintenance and repair costs for USV are estimated based on the composition of the maintenance group and their wages when vessel stays in the port. Maintenance group may consist of chief engineer, electricians, fitters/repairers and other engineers [82]. Based on weather analysis conducted in Chapter 7, we can estimate that maintenance group can be employed for around 150 days out of 365 (from September to March).

Lower maintenance costs in comparison to conventional OSV are caused by technological advantages installed on USVs (self-diagnostic and self-monitoring systems) and stricter condition monitoring/robustness requirements [21]. Moreover, the maintenance costs of life rafts are not anymore applicable for unmanned vessel.

4) RCC

With USV development the demand for RCC is inevitable. Kretschmann et.al. report indicates that creation of such control centre will increase overall operational costs as RCC require power supply, annual software subscriptions, technical support and training costs for employees. Moreover, company must pay for annual rental costs for RCC space [82]. The overview on operating costs of RCC can be found in Figure 38:

	One-time costs [US$]	Operating Life [y]	Annual costs [US$]
SCC Equipment			
Situation Rooms	1,050,000	8	
Software	765,000		
Hardware	117,000	3	
Office Equipment	199,800	13	
Rent for office space			411,033
Operational Costs			
Power supply			22,624
Software subscription and support			153,000
Training costs for employees			287,300
Total	2,131,800		873,957

Figure 38. Operational and capital costs for the RCC [82]

5) Additional auto-remote ship technology

Unmanned vessels in order to operate safely without crew onboard beside traditional onboard devices must be equipped with advanced technology, such as sensors, E-navigation, collision avoidance system. Conventional OSV do not necessarily need those advancements, as look-out, navigation and anti-collision maneuverers are performed by the crew members.

6) Redundancy of technical systems

USV in order to navigate safely and efficiently must be equipped with redundancies for technical systems, such as communication system, propulsion and electrical system. This will contribute to increase of production costs of the vessel. However, it will be still smaller costs than those associated with OSV.

7) RCC investment

MUNIN`s report indicates that investment costs for RCC will contain equipment of situation room(s), software, hardware, office equipment. Moreover, it is estimated that equipment should be replaced between 3- 13 years of constant usage [82]. Overview on investment costs for the RCC can be found in Figure 38 presented as one-time costs.

8) Electrical power balance

According to B.J. Vartdal et.al., energy required for propulsion system for offshore service vessels represents around 50% of the total energy requirements. This means, that rest of the energy requirements goes to axillary power supplies for onboard hotel system and other ship`s functions [21]. By transferring onboard crew from vessels to RCC, the energy requirements can be greatly reduced. In case of USV, auxiliary machinery, generator engines, electrical systems, air conditioning, heating and ventilation for onboard hotel system are not anymore needed [82]. This in turns, will result in lower fuel consumption and pollutions.

9) Fuel price

As fuel price changes daily, it is impossible to precisely estimate future values. Moreover, the fuel price will depend on speed in which vessel is proceeding, its design and size. Vessel`s reduction in speed is often called “slow steaming” as it is proportional to ship`s design speed [83], as it can be seen below:

$$F = F^{*} \times \left(\frac{S}{S^{*}}\right)^{\alpha}$$

Where:

F*- design fuel consumption

S - actual speed

S*- design speed

α- depends on engine type (2-for steam turbines, 3- for diesel engines)

[83]

In case of USV, the fuel consumption will be much lower as unmanned vessels will introduce new lightweight ship`s design. Furthermore, USV is not going to use Heavy Fuel Oil (HFO) as a main fuel due to technical problems for unmanned vessels [83]. Therefore, it can be assumed that USV will use Marine Diesel Oil (MDO), which is unfortunately very costly solution in comparison to HFO. Figure 39 presents possible scenarios for future MGO and IFO prices.

Figure 39. Perditions on fuel prices [83]

As fuel costs can often vary between 50-70% of total costs, any reductions in energy requirements will have significant impact on company`s economy [82]. Therefore, by reducing number of crewmembers and optimizing USV`s design, it is possible to generate more savings than in case of OSV.

10) Lighter ship design

Lighter ship design increases fuel efficiency. It can be achieved due to partial elimination of vessel`s superstructure and deckhouse. In addition to that, weight relating to life rafts with launching system, freshwater tanks, auxiliary systems, wastewater treatment systems can be subtracted in favor of lighter ship weight [82]. However, the effect of eliminating living spaces for crew will depend on ship`s type and operations. Thus, for large vessels with small on-board crew, this effect will be smaller than for smaller vessel with larger crew [21].

11) Air resistance

For manned vessels air resistance will vary from vessel to vessel, depends on its design, ballast conditions and speed through the water. Ships with high hull will have larger resistance than those with lower hull. Around 4-8% of Total Ship Resistance accounts for Air Resistance [84]. Formula for frontal air resistance is given below [82]:

$$R_A = \frac{\rho}{2} * C_d * {V_{app}}^2 * A_F$$

Where:

R_A- air resistance caused by vessel proceeding through calm air.

ρ- air density [kg/m^3]

C_d- wind resistance coefficient [-]

V_{app} – apparent wind speed (ship speed+ true wind speed) [kn]

A_F – frontal reference surface (ship`s cross section area above the waterline) [m^2]

No need of deckhouse and onboard hotel system leaves big space for new vessel design, which will contribute to reduced air resistance and thus, fuel consumption (see Figure 40).

12) Other

Another important expense relating to unmanned vessels is cost of transferring data from vessel to remote centre and back. Those expanses, which are considered as a voyage costs, will depend on the amount of data to be transferred and costs of communication medium [21].

According to Kretschmann et.al., smaller vessels with no superstructure would need less steel for hull than i.e., 95 meters traditional OSV. Therefore, shipyard expenses to build USV would be much smaller than for OSV. On the other side, advanced technology and automated machinery will costs much more than those used on conventional service vessels [82].

Furthermore, vessel`s automated functions would contribute to less energy requirements, as ship`s manoeuvres are performed in more precise and optimised way. Quantitative assessment by MUNIN suggests that, if USV is going to have two rudders and two propellers, then its manoeuvrability and stability in keeping the course will increase [82].

8.2. Environmental sustainability

Maritime transport greatly contributes to air and water pollution. It is estimated that around 2.5% of global greenhouse gases are emitted by vessels. The 87% of emissions from maritime transport accounts for international shipping using mega-vessels. 8% accounts for domestic shipping and 5% fishing (see Figure 42) [85]. Moreover, it is predicted that numbers can significantly increase by 50-250% until 2050, if appropriate actions are not undertaken [86]. Fortunately, there have been some reactions from the industry which results in Sulphur Cap 2020. It aims at forcing companies to change fuel type to one with sulphur content of 0.5% and less [87].

	Third IMO GHG Study (million tonnes)						ICCT (million tonnes)		
	2007	2008	2009	2010	2011	2012	2013	2014	2015
Global CO_2 Emissions*	31,959	32,133	31,822	33,661	34,726	34,968	35,672	36,084	36,062
International Shipping	881	916	858	773	853	805	801	813	812
Domestic Shipping	133	139	75	83	110	87	73	78	78
Fishing	86	80	44	58	58	51	36	39	42
Total Shipping % of global	1,100 3.5%	1,135 3.5%	977 3.1%	914 2.7%	1,021 2.9%	942 2.6%	910 2.5%	930 2.6%	932 2.6%

Figure 40. Global CO2 emission [85]

When we look at the offshore service vessels, the biggest issue for environment sustainability is their operational profile (see Figure 43). They are used for subsea operations, anchor handling, standby etc. When they are operating within installation`s safety zone, they are obliged to use Dynamic Positioning system. DP system is keeping at all the time power resources in case of increased sea state and heavy winds that require peak powers to retain vessel in fixed position. All this together will result in ship having many combustion engines often running simultaneously in any sea conditions [88].

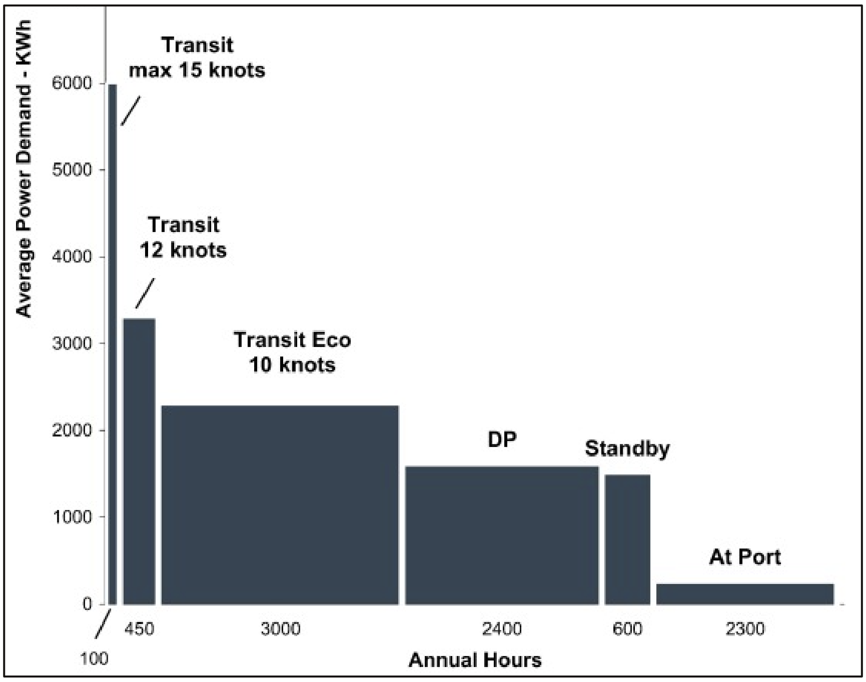

Figure 41. Annual operational profile for Offshore Support Vessels and average power demand [88]

According to article written by H.E. Lindstad et.al., most of the time OSV will spend on transit at Eco speed from and to operational location. Each of the given speed will depend on level of supply importance, reduction of fuel consumption etc. Around 35% of the time, vessel will spend operating in DP mode within installation`s safety zone. This number can change, as for instance anchor handlers will spend less time in DP mode than subsea and inspection vessels. On the contrary, standby vessels will spend less time on transit and in the port than traditional supply vessels [88].

One of the most known solution to reduce emissions produced by the OSV is retrofitting them to use alternative power supply. Vessel can become i.e., hybrid when electric batteries are added to traditional power arrangement. This solution has following advantages [88]:

- *"It allows combustion engines to operate at more constant and thus, optimized load.*
- *It eliminates combustion engine performance on low loads, which means lower fuel consumption and emission.*
- *Required by the DP system peak power can be easily provided by the electric batteries, even in case of failure of one of the engines".*

Furthermore, H.E. Lindstad et.al., indicate that hybrid power supply can reduce number of combustion engines significantly and thus, produced emissions. Considering CO_2 emission, 6-8% of diffusion can be reduced using hybrid power setup. When including rest of the emissions, the hybrid solution gives around 20% of reduction [88].

Problems with hybrid power set up arise when it is a subject to economic analysis. H.E. Lindstad et.al., explain that current fuel prices of Marine Gas Oil (MGO), which is around 513.00 USD/MT does not fill with the optimism about retrofitting OSV with batteries. The payback time of such investment is then 12.5 years or longer, which can exceed duration of the batteries. Traditional power set up for OSV operating in North Sea is an expense of around 7 million USD. This includes four main engines and generators. By adding batteries, the total costs will raise to 8.25 million USD. Therefore, if owner is not forced by the regulations or he/she has no pro-ecology motives, the OSVs will be not retrofitted with hybrid batteries [88].

H.E. Lindstad et.al. suggest that payback time can be shortened up to 2.5-5 years if batteries are combined with two engines instead of four. This solution will only make a sense for new build vessels. In this case vessel can be built with only two engines and larger batteries, which will cost around 7.5 million USD. Thus, there are no additional costs relating to removing two engines and doubling the capacity of one of the remaining one. Moreover, difference in capital costs between standard power set up and a hybrid is around 500.000 USD [88]. Here, the possibility for USV employment within offshore industry arises.

Hybrid power set up usually require much space for batteries storage. However, by eliminating living quarters from the vessel it is possible to create an additional space for the batteries. Moreover, electric batteries are appropriate choice for the remote or autonomous vessels due to their robustness and low maintenance requirements [88].

9. Discussion

In following chapter, we will discuss obtained through literature review and quantitative analysis results, in order to answer thesis` research questions:

1. What are the features of USVs that make them safer in comparison to manned vessels?
2. How offshore installation and USV can work together to guarantee safer maritime operations within safety zone?
3. What are the economic and environmental benefits of USV employment in offshore industry?

9.1. Research Question 1

First feature that can possibly make USV safer in comparison to conventional vessel is large number of redundancies for critical onboard systems [20]. The idea of equipping USV with such systems is dictated by its unmanned nature which makes ad hoc repairs impossible. In case of conventional vessels, equipment or system is usually maintained only when faults occur. Late discovery of failures can contribute to further damages and this in turns, longer repair time reducing ship`s availability. If failure is profoundly serious, it may even result in vessel`s drydocking for several weeks.

According to thesis, USV will be characterised by higher technical resilience. This means that in case of an equipment or system failure, USV will provide more barriers, such as redundancies of critical systems [20]. In order to perform operations within safety zone, communication with installation should be constant and uninterrupted [9]. What`s more, constant communication between vessel and RCC is vital to comply with STCW Convention, where it is stated that vessel must be constantly “attended” [26]. Therefore, various communication methods such as satellites, 4G and VHF should be considered to obtain constant link between vessel and RCC [21]. Besides that, USV`s technical systems would provide prognostic maintenance, thanks to self- contained and self-diagnostic capabilities of onboard system [20]. USV`s large number of redundancies may guarantee better overview on vessel`s condition and thus, fewer maintenances.

Autonomy level of the vessel is another feature that makes USV a safer alternative. In following thesis, the USV has autonomy level AL3-AL4, which means that the ship is constantly operated from RCC. Decision support system can be switched on/off, and operators stays active in-loop [7]. According to DNVGL-CG-0264, such system configuration allows vessel to develop some solutions on its own, i.e., alternative passage plan. Then, once checked by the operator, it may or may not be approved. In this thesis, we called it “independent supervision” which keeps operator actively involved in the vessel`s operations. This in turns, eliminate feeling of fatigue and raise operator`s vigilance [20].

Moreover, autonomy levels AL3-AL4 would be appropriate for subsea inspections and light interventions within installation`s safety zone. Ø.J. Rødseth states that as AL3-AL4 levels belongs to constrained autonomy, it required detailed definition of vessel`s MRCs and development of fallback procedures. As a result, remotely operated vessel will be a subject to stricter and thus, safer operational rules and regulations. On the other hand, it will depend on operator`s vigilance to notice that vessel is outside ODD, and it needs to enter one of the MRCs. It may happen that the operator decided to enter MRC too late, resulting in Last Resort condition. Then USV can`t proceed with the voyage or operations and must wait for the help from the outside. This will obviously generate additional costs related to off hire, as assigned tasks cannot be completed in time [49].

Another USV`s feature is Remote Control Centre. In following thesis, it is considered that vessel is operated by operators in the RCC onshore. Thus, the biggest benefit is safer working environment for crew members, as they are not directly exposed to sea hazards. Furthermore, lack of human presence onboard minimizes probability of accidents caused by human factor, such as fire onboard, collision, grounding etc. Such accidents mainly occur due to crew`s non-compliance to safety rules, poor look-out, fatigue, distraction etc [51].

On the other hand, ship`s automation will contribute to creation of new hazards, that may emerge from nature of remote operations, namely situation awareness. In order to obtain complete and reliable situation awareness, operators must obtain sensors data in most organised and simply manner [27]. Therefore, RCC`s displays should be divided into tabs showing the most necessary information for operators, such as battery status (in case of hybrid power set up), weather forecast, radar view, camera view, conning, charts etc. (see Appendix B) [89]. Such data layout reduces distraction and allow operators to multi-task without feeling overwhelmed [55]. On conventional vessels situation looks slightly different. OOW must focus on one activity at the time, as various navigational aids are in different places on the bridge.

USV and ROV operators should be actively engaged in designing and testing of RCC, as they will be the future users of those centres [56]. Moreover, it is vital to remember that reduction of human factor does not exempt engineers to ignore or forget about them when designing RCC. As USV is remotely operated with level of autonomy AL3-AL4, human will stay active in loop [7]. It means that operator can still make a mistake by misappraisal of the situation, tiredness or other factors influencing his/her performance. Therefore, further investigations should concern for instance, influence of system automation on operator's performance [56].

When it comes to sensor technology, it must be designed to replace human`s ears and eyes in the best possible way. This means, that they should provide complete and detailed information on vessel`s surrounding as if the operator was onboard [20]. Besides that, USV that is going to operate at NCS should be equipped with sea state sensors, presenting constant data on significant wave heights, wind and currents. This would help operators to make better decisions regarding operations.

In addition to that, AAWA Position Paper states that operators in remote centre can perform better look-out than OOW, thanks to advance sensor technology. Night look-out on traditional vessel is limited to observation of ship`s lights and to interpretation of radar indications. When it comes to USV, beside radar, vessel can be fitted with LWIR cameras that allows for object recognition in total darkness. What`s more, USV can be equipped with LIDAR scanning laser, that creates detailed 3D map of vessel`s surrounding in poor visibility conditions. Therefore, by using object detection systems such as onboard sensors, operator does not have to rely constantly on his perceptive abilities as much as OOW does. Hence, it is right to say that thanks to advance technology look-out in remote centres is performed in accordance with COLREG regulations, fulfilling conditions of "proper" and "by all available means" [26].

On the other hand, presented in thesis sensors are sensitive to harsh weather conditions that are common for NCS. According to AAWA Position Paper, HD cameras have the lowest resistance to weather conditions. Their performance is restricted by heavy rains, deteriorated visibility and objects` illumination. However, they have excellent object detection and marine robustness capabilities. LIDAR is an appropriate choice if accurate distance measurements and special accuracy are desired [27].

On the other hand, AAWA Position Paper points out that there have not been yet many studies investigating LIDAR`s marine robustness and weather resistance. What`s more, it is an expensive solution that significantly overload data transfer. Radar has proven its weather resistance and marine robustness over the years. Moreover, it works well in measuring distances and does not overload data transfer. It has no object identification functions or special accuracy, but in combination with HD and IR cameras it can become the best solution for USV`s condition detection. Nevertheless, the HD and IR cameras should have their redundancies in case of technical failures [27].

Having appropriate sensors onboard is not enough for safety operations within safety zone. According to DNVGL-CG-0264 sensor fusion should be presented to remote operators in organised and uncomplicated way. It should not make the operator confused, overwhelmed or tired over time. On the contrary, sensor fusion should contain only this type of information, which are significant to obtain situation awareness. For instance, more detailed data should be provided in navigation within safety zone, harbours and narrow straights, whereas during the passage on the open sea sensor information can be significantly reduced. Nevertheless, system should keep detailed sensor data in case of operator's uncertainty [20].

Another feature, that makes USVs safe are their design. As it was presented in the thesis, USV design will depend on types of operations and their location. However, one thing all of them will have in common, is that they will have no need of crew onboard accommodation. L. Kretschmann et.al. indicates that vessel`s superstructure and living quarters can be removed from the design project. This in turn comes down to building smaller vessels with reduced air resistance. Such design will have two vital advantages, namely fewer fuel consumption and lower load impact [82]. Fuel consumption will be discussed in Chapter 9.3. When it comes to load impact, USV lightweight construction will generate lower impact than in case of conventional OSV. Therefore, in case of collision with offshore platform, USV will make smaller damages to rig structure [9].

9.2. Research Question 2

Second research question relates to cooperation between RCC and Installation team. Basing on thesis outcomes, we can conclude that the partnership will largely depend on training and experience of RCC operators, OIM and MRP. Therefore, if USV is going to perform operations within 500m safety zone, operators should have previous experience in working with installation on conventional vessels. That would make operators already familiar with GOMO regulations, communication and common for safety zone hazards. Therefore, it would be much easier for OIM and MRP to cooperate with an experienced operator than with personnel who has no working experience within the area of installation.

According to thesis, OIM and MRP should also undergo additional training in working with unmanned vessels. They should be familiar with general architecture and components of USV as well as to be able to communicate with RCC team in an effective and organized manner. Furthermore, installation management should designate person with adequate education and skills for weather forecast analysis or employ additional meteorological personnel [17].

Beside working experience, it would be necessary to train operators in USV automation. Only then, operator can be aware of system`s limitations and possible failures. It would also help the operator to faster assess the situation and undertake correct counter measurements. In addition to that, experienced and qualified operators are vital for USV compliance with international regulations, such as SOLAS. In following convention, it is clearly stated that in order to provide safe navigation, vessel should have a competent Master. This means, that if USV want to comply with SOLAS, operators should have an adequate to master education degree and experience [26].

Another aspect of cooperation between installation and RCC will relate to exchange of weather information collected on the platform. It is particularly important as IMR operations, such as subsea inspections are weather restricted. In addition to that, detailed weather assessment is necessary to complete pre-entry checklist to get permission to enter the safety zone [90]. Despite USV having onboard sea state sensors, it may turn out to be not enough for accurate estimation of prevailing conditions at sea. Sensors may also show wrong values due to failure as well as operators may have limited confidence in their measurements.

Furthermore, PAFA Engineers indicates that some weather measurements can differ from those obtained by the vessel and platform. For instance, wind values close to sea surface will vary from those measured at the platform. This is due to fact, that installation`s weather station is usually located at the top of the structure. In order to solve that problem, company that owns the installation should invest in wave rider buoys, current meters and other devices which would measure sea state conditions close to the surface [17]. That would make the measurements more reliable without creating misunderstandings between installation and RCC. After that, operator and OIM should exchange views on risk and dangers that USV may encounter during the operations. Moreover, any sudden changes in weather conditions should be reported by MRP to RCC immediately [13].

Next aspect of discussed cooperation is installation`s support in some of the USV functions, such as condition detection and action planning. When it comes to condition detection, USV may have problems to identify objects due to deteriorated weather conditions or operators doubts. Thus, installation can provide that information to RCC as it has more accurate information on nearby vessels. In addition to that, installation can help vessel in action planning, i.e., establishment of possible escape routes in case of an emergency [9]. It should be done before USV enters safety zone and after throughout analysis of all possible solutions. What`s more, in case of emergencies OIM should act as an on-scene coordinator to assists operators in evacuating USV in a way that does not endanger other vessels and the installation itself [12].

Lastly, along with the replacement of manned vessels with USVs, organizational part of operations can be simplified. So far, IMR operation have been based on the Operational Multiteam System [11]. In following system, vessel`s crew is working under different affiliations, such as vessel owner, subsea contractor and operator. As it was indicated in this thesis, Operational Multiteam System can lead to problems with distribution of the responsibilities and communication between the teams and leaders [11]. By introducing USVs, numbers of teams will be reduced, as most of the tasks will be performed remotely by automation systems. Supervisors of the operations can be replaced by various displays located in RCC and directed by the remote operators [89]. This may allow for much easier cooperation between vessel and installation, as there are fewer people to supervise.

9.3. Research Question 3

In offshore industry, vessel is seen as a sustainable when it has long period of availability over the year. In other words, its operational limits are high enough to be able to perform in demanding weather conditions. Before USV can be employed to conduct operations within installation`s safety zone, it is necessary to determine probability of weather window large enough to complete the operations.

In following thesis, it was analysed probability of favourable weather windows for different significant wave heights in individual months. Thanks to that, it was possible to see what operational limits must be achieved so the ship is able to operate in desired periods of the year. We assumed, that ship`s operations will last in first case 24 hours and in second case

48 hours, including the contingency period. 24 hours is a common duration time for IMR operations. Platform “Åsgard” at the North Sea was chosen as a location of ship`s operations.

According to conducted analysis, the longer operations, the lower probability of weather window large enough to complete them. Such dependence can be observed on Figure 30 and Figure 32., where green colour (representing probability of ≤ 70%) is much more common on Figure 30 than on Figure 32. Such discrepancies result from uncertainty and inaccuracy in weather forecasting. This in turns is dictated by the fact that NCS is an area of adverse weather conditions. Therefore, alpha factor for 48 hours operations will be much lower than for 24 hours, as it is hard to predict how weather is going to change. Therefore, to increase USV availability, conducted operations should be planned so that they last as short as possible.

If USV want to achieve operational limits large enough for operations in higher sea states and thus, increase its availability, then it is necessary to equip it with harsh weather LARS system. Such system will be characterised by i.e., cursor frame that would stabilise ROV during deployment and anti-heave system [62]. It is important to remember that LARS must be adapted to the needs of an unmanned vessel. This means, that it must be highly automatized, robust and failure resistant [69]. As it was suggested in the thesis, the most appropriate would be moonpool deployed system.

L.O. Nordmark indicates that moonpool should be located as close to vessel`s roll and pitch axis which would minimize angular motions when ROV is lifted. ROV hangar would be located inside the vessel, which would prevent the asset against environment conditions. What`s more, ROV would be lowered and recovered from the water using guide rails with cursor, which decrease pendulum and stabilize ROV. As it was presented on Figure 36 and Figure 37, usage of cursor system can significantly raise ROV weather tolerance allowing for safer deployment in higher sea states [68]. In addition to that, USV should be equipped with active heave compensation system. Such system would be an appropriate solution for electric winches, which are easier to operate by automatic systems [72]. All this would increase USV availability and thus, make the vessel more sustainable solution for light interventions for spring and summer season.

Another aspect of USV sustainability it is profit and loss analysis. According to L. Kretschmann et.al., investing in USV will initially involve high capital costs. This is due to new costs associated with construction of the RCC and its equipment. Furthermore, due to unmanned nature of USV, it will need to be equipped with large number of redundancies and advanced auto-remote technology. This will generate quite high “one-time costs”. However, over the years those costs may decrease as USV will gain more trust in maritime industry. This in turn, will increase demand for USV onboard technology as well as price competitiveness among manufacturing companies. Consequently, in some years costs associated with auto-remote technology and RCC equipment will decrease, making the USV even more desirable [82].

When it comes to operational costs, we can notice big reduction in costs associated with crew, stores, consumables and electrical power balance. Crew costs are much lower due to advanced automation of ship`s system, that can be operated by i.e., two operators onshore. Moreover, as operators are in RCC, costs of travel and victualing are reduced to minimum [82]. Stores for medicines, safety equipment and food are not needed on the vessel anymore [82]. However, costs for consumables will be still incurred for RCC employees, but not to that extent.

When vessel`s crew is transferred onshore, then electricity used for heating, air conditioning, laundry, galley is reduced by 100% [82]. On the other hand, those costs will be incurred by RCC, namely its power supply, software subscription, technical support and operators` training [82]. Lastly, cost of maintenance and repair can be expected to decrease by 50% [82]. This is due to diagnostic capabilities of the onboard systems, that would detect failure in time not allowing for further damages [21]. Remote onboard systems are also subject to stricter condition monitoring regulations, as they are burdened with higher risk.

Last costs that are associated with economic sustainability are voyage costs. Voyage costs will depend mainly on fuel prices [82]. According to this thesis, those costs can be significantly reduced thanks to innovative USV design. No need of vessel`s superstructure will have advantageous influence on ship`s air resistance. In addition to that, lack of superstructure will lower costs incurred in shipyards, as less hull is needed to build the vessel. This in turn, will result in lightweight construction and again reduced fuel consumption [82].

Fuel consumption is closely related to exhaust emission. Moreover, stricter environment regulations already came into force, forcing owners to retrofit their vessels with more ecologic power set ups. H.E. Lindstad in her journal article suggests that when retrofitting vessels for offshore operations, the focus should be placed on their operational profiles and their power demand. Most of the offshore vessels will demand power for operations in DP mode or for transferring goods for installation. Therefore, it was suggested that the best solution for USV would be the hybrid power set up. This is due to few reasons. First of all, electric batteries can provide power peaks required by DP system. Secondly, in hybrid power set up, combustion engines can operate at constant and low loads. This in turns, optimizes engines performance and reduced fuel consumption [88].

10. Conclusion

The aim of the following master thesis was to investigate whether USVs are safer and more sustainable alternative for operations within installation`s safety zone. In order to find an answer, it was necessary to examine concept of unmanned vessels in terms of design, technology, legislation, economy and marine environment.

The results indicate that USV can be treated as a safer and cost-effective substitute for offshore operations within installation`s safety zone. USV development is on the right track to replace conventional vessels in light offshore operations, i.e., subsea inspections, simple maintenance and repairs. However, it is still impossible to employ USV to perform more complicated tasks, such as subsea constructions, complex repairs and replacement of underwater components. USV must be first hired for easier tasks in order to test its functioning under demanding weather conditions of NCS. Only when USV has lived up to its expectations, it will be possible to begin improving the vessel for more demanding operations.

As illustrated earlier in the thesis, there are several studies that have investigated unmanned vessels and their possible applications within maritime industry. They all concluded that there is a potential to use autonomous or remotely operated vessels to enhance safety at sea, reduce emissions and cut down the costs associated with maritime operations. Human factor is minimized, onboard sensors allow for better look-out and advanced technical systems provide better monitoring of vessel`s condition.

When it comes to economic sustainability, USV employment has capabilities to reduce overall costs associated with operations within installation`s safety zone. Moreover, it will also contribute to more environmentally friendly operations at sea as USV will run on alternative fuels.

In summary, the following thesis supports existing knowledge about unmanned vessel concept and contributes to clearer understanding of benefits of USV employment within installation`s safety zone. To better understand the implications of following thesis results, future studies could address influence of ship`s automation on operator`s situation awareness as well as risk assessment of new hazards emerged from ship`s automation.

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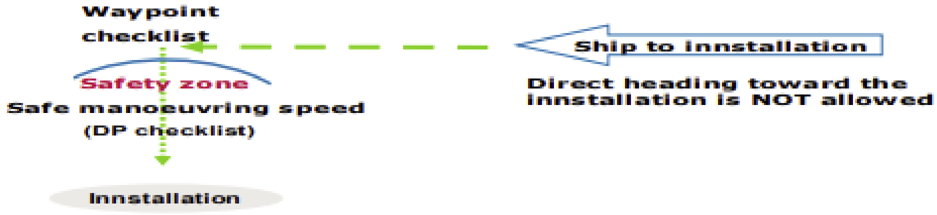
APPENDIX A: Pre-entry checklist for vessel who seeks to enter safety zone [90].

A-4 Checklist for entering the Safety zone



Installation:__________

Waypoints must be set so that the closest point of approach (CPA) to the installation is outside the installation's safety zone

Checklist ref: NWEA / OLF 061B with adjustments in item. 15 og 16

		Checked
1	Sea state and weather conditions acceptable for safe operation	
2	Limitations due to sea state/weather conditions	
3	Safe approach heading toward the installation assessed	
4	Bridge and engine room manned in accordance with the requirements	
5	Communication established	
6	NO hot work/smoking on deck within 500 metres	
7	Autopilot off (Manual steering)	
8	Manoeuvring system tested	
9	Emergency manoeuvring system tested	
10	Working side confirmed by the installation	
11	Loading operations (cargo, bulk cargo, liquid cargo) confirmed by the installation.	
12	The installation must confirm that they are ready for the operation and for the arrival of a vessel (incl. shutting any drains)	
13	Manoeuvring mode for the operation has been chosen? (In DP mode the DP checklist must be used in addition)	
14	Other ongoing and/or scheduled activities within the 500-metre zone?	
15	Entering the safety zone with safe manoeuvring speed.	
16	DP test at the installation	

Date__________________ Signature___________________

Figure 42. Pre-entry checklist for safety zone entrance

APPENDIX B: Examples of USV`s performance displays in RCC [89]**.**

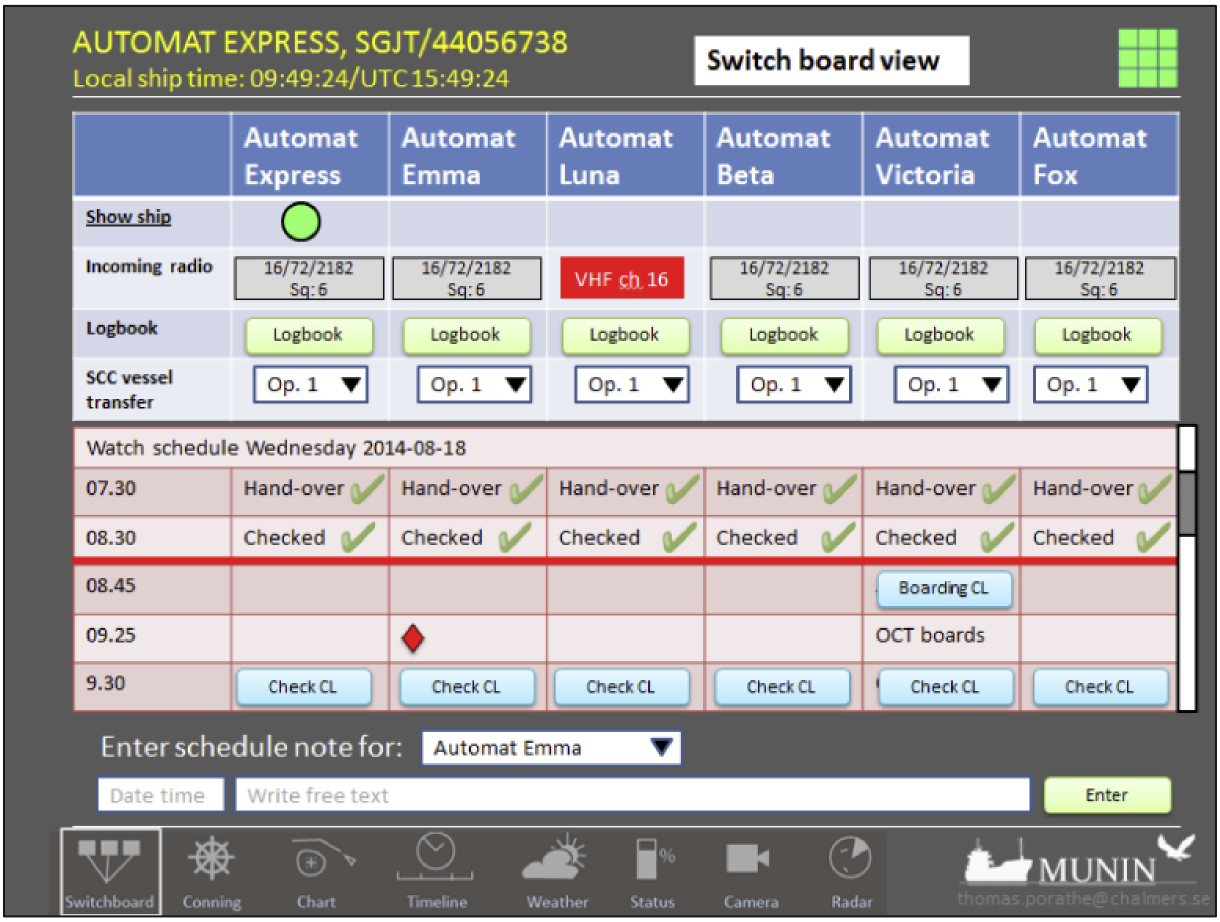


Figure 43. Switchboard view

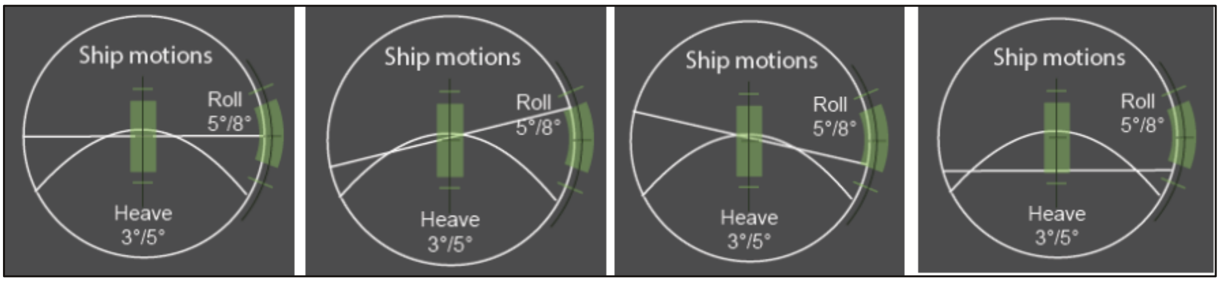


Figure 44. Ship motions indicators

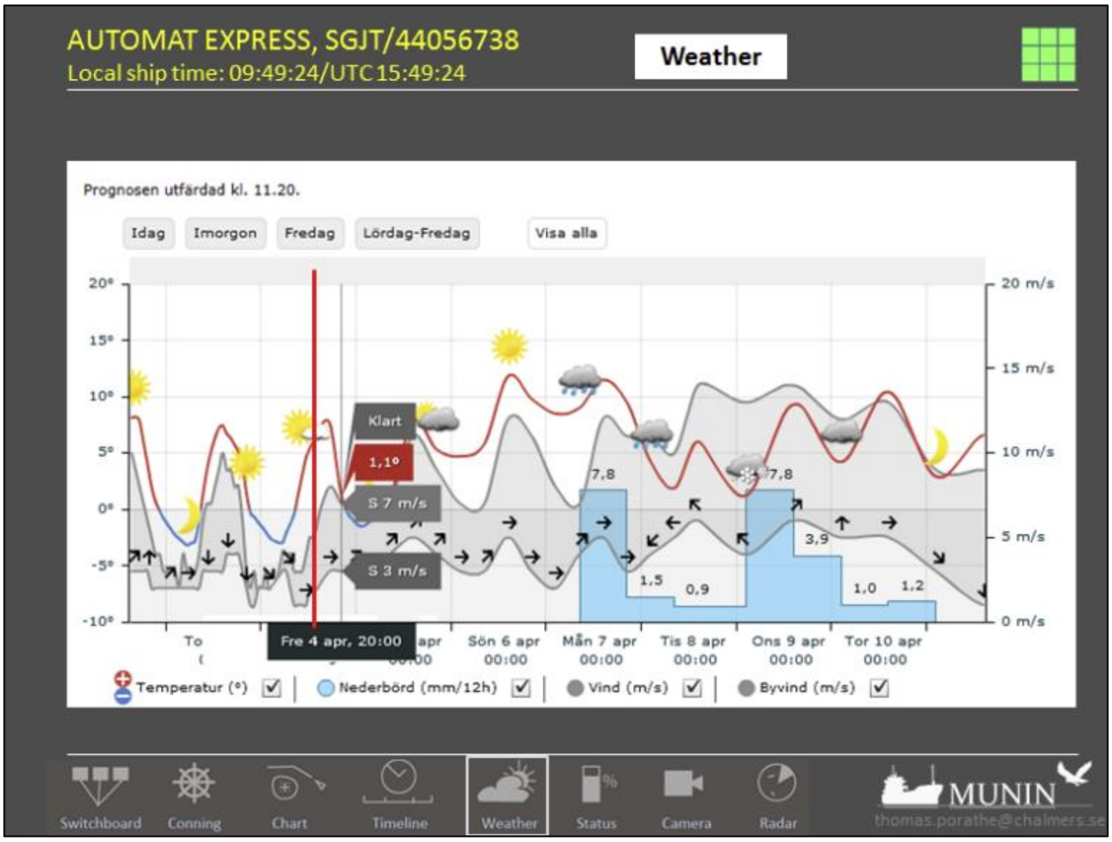


Figure 45. Weather forecast display

Figure 46. Conning display

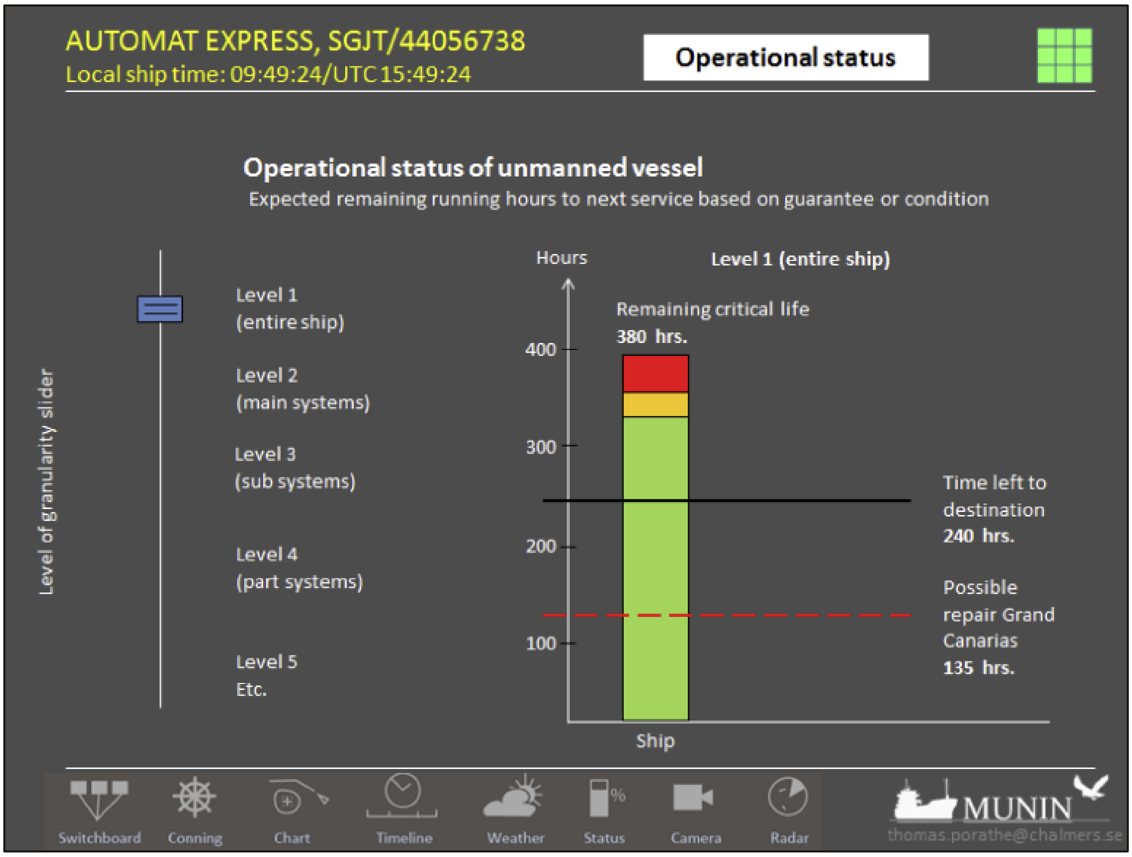


Figure 47. Vessel`s operational status display

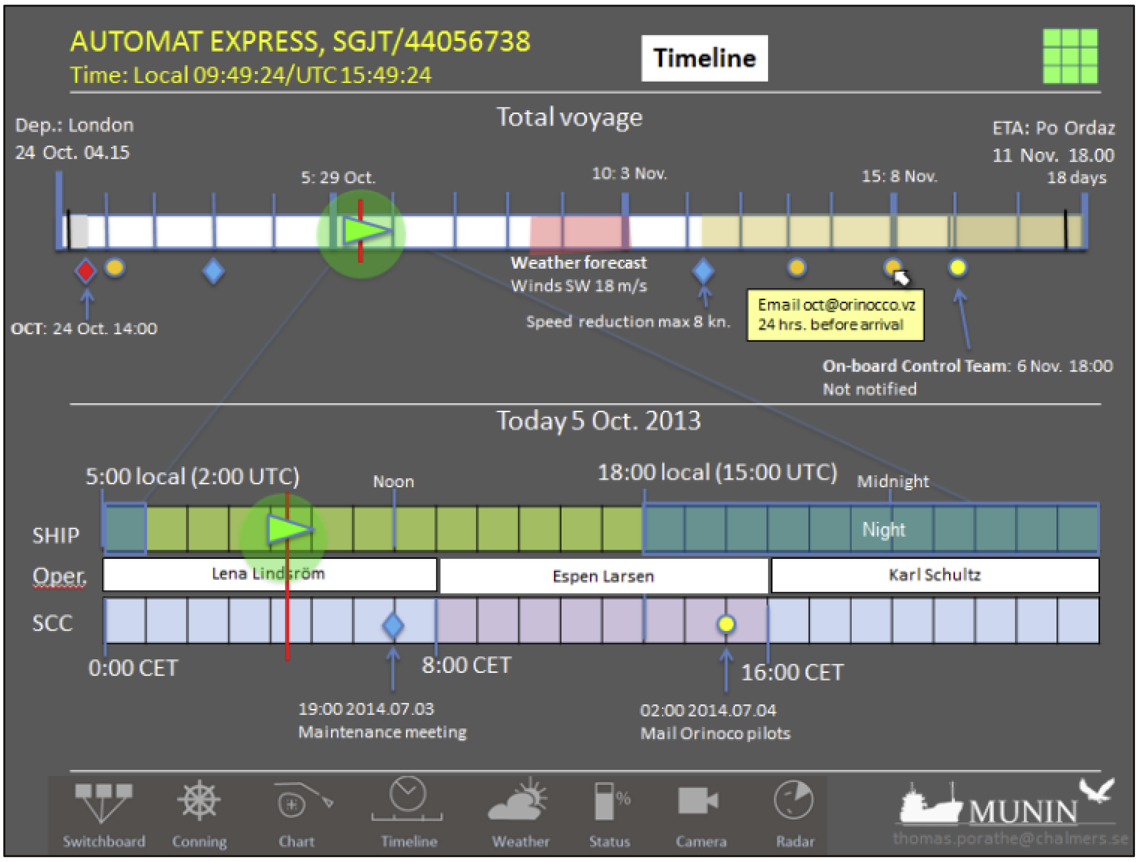


Figure 48. Vessel`s timeline

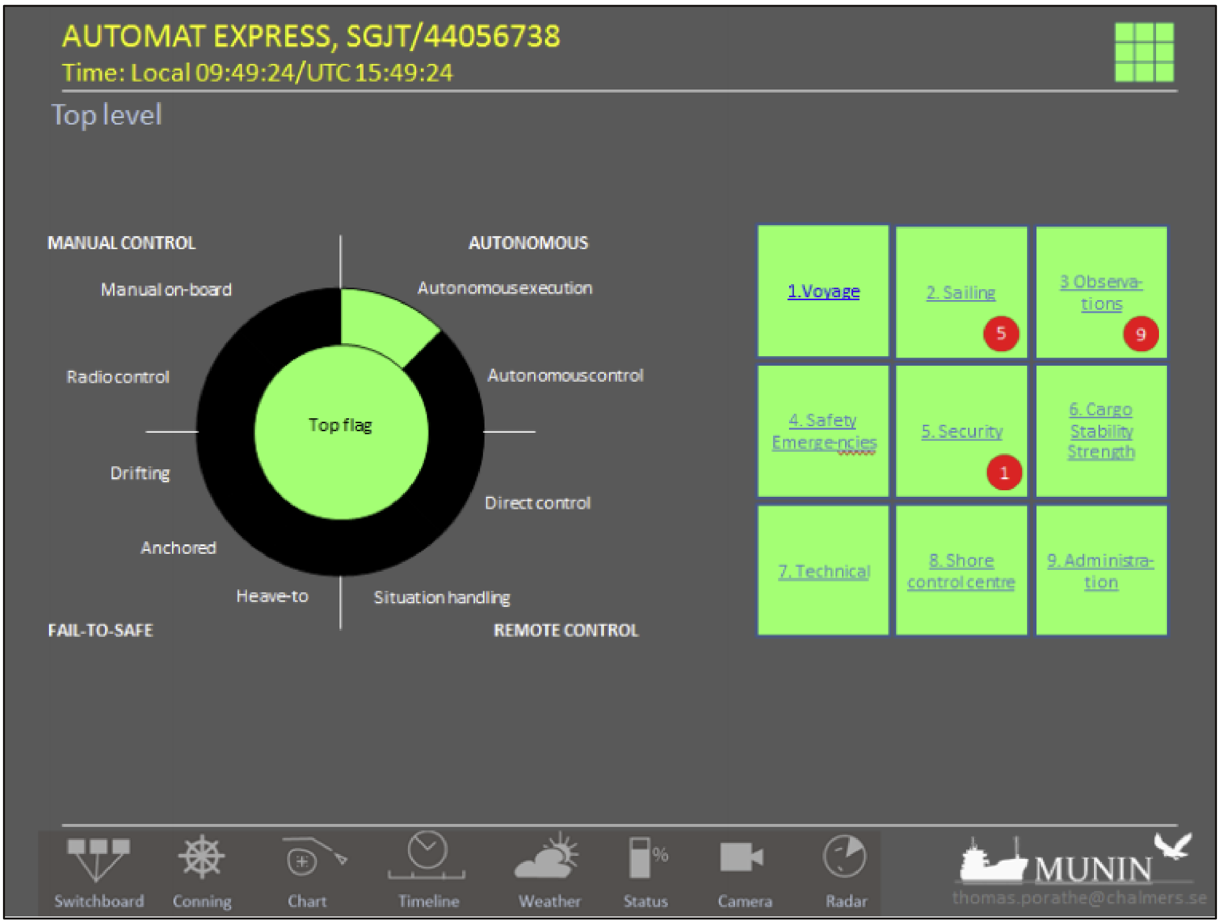


Figure 49. Switchboard display

APPENDIX C: List of potential Minimum Risk Conditions [20].

APPENDIX A LIST OF POTENTIAL MINIMUM RISK CONDITIONS

Appendix A

The minimum risk conditions (MRCs) for an autonomous or remotely operated ship depend on many aspects, for example the ship's functionality, the manning, it's location and the current weather.

Below is a list of possible MRCs that may be applicable. However, the MRCs that should be included in the operation of a specific ship needs to be decided based on thorough case-by-case analysis. This list below is not exhaustive, it is only intended to give examples and serve as inspiration when defining MRCs for a specific ship (see the description of the MRC concept in Sec.2 [5]).

Potential MRCs:

1) Stay moored at quay: may be applicable for many events and failures that takes place while the ship is still alongside the quay.
2) Move away from the quay and other vessels: especially relevant if the ship has caught fire or if there is a fire in close vicinity of the ship.
3) Limp home: only relevant if the ship still has some propulsion, steering, and navigational functionality left. Limping' may be defined as a limited speed, rudimentary anti-collision functionality and turning on the "not under command" signal lights. 'home' should be a pre-defined place.
4) Move as slowly as possible: if the ship does not have position-keeping capabilities, but still has some outlook, propulsion and steering, it may move slowly without posing a danger to others, the environment, or itself. This may give the operator(s) and systems time to rectify the situation.
5) Navigate to next waypoint and stop there: may typically be applied if the event leading to the MRC is failure of a secondary function or system.
6) Call for assistance (tug): in addition to calling for assistance, the ship normally need to provide some means for other ships (typically tugs) to fasten tow, e.g. by extending towing lines.
7) Drop (emergency) anchor: may be used if the water-depth is within a suitable range. If used as a 'last resort MRC', the anchoring system will typically need an independent power supply.
8) : maybe one of the more extreme MRCs, and requires that suitable beaching zones have been identified up front. This MRC may typically be used when energy reserves are about to become depleted.
9) Keep position: may typically be used if the data-link to the remote-control centre is lost, but requires considerations regarding the current waters and the position of the ship, e.g. when navigating narrow straits. This MRC comes in two variants:
    1) If moving, stop and keep position.
    2) If stationary, stay at current position.
10) Abort current operation (e.g. hoisting, loading, fuelling, charging): the operation in question should be aborted. It should be defined if the operation should just 'freeze' where it is, or if it should continue/ reverse to some pre-defined state.

APPENDIX D: Hazard analysis for safety zone operations [51]**.**

Accidents	Hazards	Hazard description	Causes	Mitigation
Fire onboard	1. Ignition of electrical equipment or wiring	Modern USVs are equipped with large number of electrical devices and wiring, as a potential source of ignition. Such hazard may not only result in loss of the asset (ROV and vessel itself). It can also cause pollution of the marine environment and injuries/loss of human life (people working on installation/other vessels in vicinity of burning USV)	Overheating Corrosion of the wiring Incorrect choice of cables and electronic equipment on the board Loose connections between the wirings Overload Short circuits	1. Accurate and detailed plan of the USV`S electrical installations and wiring 2. Effective cooling/heating of electrical installations 3. High-quality fire detection and extinguish systems in close proximity to electrical appliances and electrical boxes. 4. Preventive maintenance

Capsizing/sinking	1. Flooding	Excessive amount of water on USV`s deck and between compartments may affect ship`s stability. This in turns, may lead to rapid sinkage.	Damage to vessel`s hull Firefighting actions with large amount of water Heavy raining	1. Double hull USV`s structure. 2. Firefighting system, which uses very little water or no water (foam). 3. Effective drainage system and bilge pumps installed on board. 4. Monitoring system for pipes, tanks and cofferdams and their status display in control centres. 5. Bulkheads design with watertight compartments
Capsizing/sinking	2. Shifting of the weights	Shifting of the weights contributes to the formation of free surfaces. This is very dangerous phenomenon that can lead to USV`s capsizing and sinkage.	Loose or free cargo onboard, such as ROV and other heavy equipment Firefighting water can contribute to free surfaces development.	6. Better sea fasting 7. Implementation of anti-heeling system on USV. 8. Continuous monitoring of ship`s cargo, i.e., temporary (ROV) and permanent cargo (ship`s equipment and systems).

Capsizing/sinking	3. Overloading of the vessel	Overloaded vessel has lower stability, than vessel loaded in a fair manner. Overloading of the USV can deteriorate its manoeuvrability and thus, can lead to sinkage or capsizing.	Too much cargo Too much of extra equipment, i.e., heavy working ROV(s)	9. Each time additional cargo is added, stability of the USV should be recalculated. 10. Ship stability monitoring system that would calculate draft, GM, trim, etc. and not permit for voyage with exceeded stability values.
Capsizing/sinking	4. Extreme weather conditions	Weather conditions at NCS are quite adverse and often very rough. Therefore, for small vessels like USVs, extreme waves can cause it to capsize.	Adverse weather conditions Inaccurate weather forecasts Local weather conditions, i.e., at specific installation) may vary from the area around. No operational limits established. Inappropriate operational limits Incorrect weather observation	10. Proper establishment of operational limits for USV, considering type of operations and their location. 11. Continuous weather monitoring and its status display in remote centres. 12. Equipping vessel with environment sensors.

Collision with the fixed object	1. Object detection sensor failure	Failure of detection system may lead to unreliable information about the USV`s surrounding. This in turn, makes USV not compliant with COLREG and other safety rules and regulations.	Equipment failure Loss of power Icing Overheating Interference Wrong maintenance Wrong location of the sensors Objects that are impossible to detect (often caused by heavy raining)	1. Equipping vessel with redundant sensor systems. 2. Installation of Uninterrupted Power Source (UPS) onboard. 3. Preventive maintenance 4. Effective cooling/heating system of onboard sensors. 5. Regular system diagnosis.
Collision with the fixed object	2. DP System failure	DP System failure may lead to Loss of Position (LOP), Drift off and drive off situations.	Propulsion failures Position Reference System failures DP system computer failures Power System failures	6. Redundant DP system computers, Position Reference System, propulsion and Power System.

Collision with the fixed object	3. Artificial Intelligence (AI) software failure	AI software failure can contribute to issues with COLREG compliance as USV cannot perform safety navigation. This in turn, may lead to collision with installation or other vessels within safety zone.	Error in algorithms coding Error in algorithms specification AI`s failure to recognize the current situation. Learning data faults Computer failure Software updates Overheating Loss of power	7. Equipping vessel with redundant ship`s software. 8. Suitable software design. 9. Regular software testing.
Collision with the fixed object	4. Technical fault and mechanical failure	Technical and mechanical failures can lead to loss of control over propulsion and steering system. This can lead to collision with installation and other vessels within safety zone.	Improper technical design Technical defects made at manufacturing stage. Wrong maintenance	10. Equipping vessel with mechanical and technical redundant systems. 11. Continuous monitoring of USV`s technical systems and their status display in control centres.

Collision with the fixed object	5. Heavy weather/sea condition	Weather conditions at NCS are quite adverse and rough. Therefore, it may affect vessel`s steering and manoeuvring capabilities. This in turn, can greatly contribute to collision with installation or other vessels within safety zone.	Adverse weather conditions Inaccurate weather forecasts Local weather conditions, i.e., at specific installation) may vary from the area around. No operational limits established. Inappropriate operational limits Incorrect weather observation	12. Proper establishment of operational limits for USV, taking into account type of operations and their location. 13. Continuous weather monitoring and its status display in remote centres. 14. Equipping vessel with environment sensors.
Collision with the fixed object	6. Strong currents	Within safety zone vessel is obliged to manoeuvre with slow speed. When strong currents occur within safety zone it can greatly affect vessel`s steering abilities and cause collision with installation or moving objects.	Operators are not familiar with local currents. No current monitoring and its influence on ship`s behaviour	15. Education of operators about the local currents 16. Continuous monitoring of local currents and their impact on ship`s steering and manoeuvring capabilities. 17. Position of the vessel on the safe side of the installation.

Collision with the fixed object	7. Position reference equipment failure	Damage to the ship`s positioning system comes down to non-compliance to the rules and regulations concerning safety of the navigation, i.e., COLREG. This may result in collision with the installation or other vessels within safety zone.	Intentional and unintentional satellite system jamming Loss of power Spoofing of satellite positioning system Dirt on positioning reference sensors Negative impact of heavy rain on the performance of the positioning system Equipment failure Poor maintenance	18. Equipping USV with redundant positioning system and sensors 19. Equipping USV with positioning reference system with jamming detection 20. Usage of both local and satellite position reference systems

Collision with a moving object	1. Object detection sensor failure	Failure of detection system may lead to unreliable information about the USV`s surrounding. This in turn, makes USV not compliant with COLREG and other safety rules and regulations.	Equipment failure Loss of power Icing Overheating Interference Wrong maintenance Wrong location of the sensors Objects that are impossible to detect (often caused by heavy raining)	1. Equipping vessel with redundant sensor systems 2. Installation of Uninterrupted Power Source (UPS) onboard 3. Preventive maintenance 4. Effective cooling/heating system of onboard sensors 5. Regular system diagnosis

Collision with a moving object	2. Technical faults (mechanical faults)	Technical and mechanical failures can lead to loss of control over propulsion and steering system. This can lead to collision with installation and other vessels within safety zone.	Improper technical design Technical defects made at manufacturing stage. Wrong maintenance	6. Equipping vessel with mechanical and technical redundant systems 7. Continuous monitoring of USV`s technical systems and status display in control centres.

Collision with a moving object	3. Artificial Intelligence (AI) software failure	AI software failure can contribute to issues with COLREG compliance as USV cannot perform safety navigation. This in turn, may lead to collision with installation or other vessels within safety zone.	Error in algorithms coding Error in algorithms specification Al`s failure to recognize the current situation. Learning data faults Computer failure Software updates Overheating Loss of power	8. Equipping vessel with redundant ship`s software 9. Suitable software design 10. Regular software testing

APPENDIX E: Hourly duration of sea states at Åsgard Platform, where Hs are below specific values [50]**.**

	2m				3m			
Month	Mean (h)	Stdev.(h)	Max (h)	# events	Mean (h)	Stdev.(h)	Max (h)	# events
1	42	44	247	3.4	73	84	425	5.1
2	45	44	323	3.9	80	96	610	4.7
3	54	59	430	4.2	99	124	976	5.1
4	69	60	321	4.9	156	221	1.841	4.7
5	104	106	642	5.3	288	301	1.536	3.5
6	112	122	1.034	5.0	376	414	1.790	2.9
7	136	142	745	4.7	451	451	1.852	2.4
8	131	127	823	4.4	327	274	1.224	2.5
9	71	71	441	4.9	126	138	867	4.9
10	52	55	341	4.2	75	93	771	5.9
11	38	38	255	4.0	63	68	400	6.0
12	38	36	243	3.2	58	65	443	5.6
Year	75	92	1.034	49.5	126	207	1.852	47.0

	4m				5m			
Month	Mean (h)	Stdev.(h)	Max (h)	# events	Mean (h)	Stdev.(h)	Max (h)	# events
1	112	137	759	5.2	178	400	4.984	4.8
2	143	216	2.104	4.2	229	453	4.487	4.0
3	183	282	2.089	4.7	392	717	4.795	3.8
4	414	656	3.852	3.5	996	1.230	4.559	2.2
5	768	909	3.746	2.3	1.614	1.303	3.839	1.6
6	1.028	886	3.137	1.7	1.770	1.036	3.147	1.3
7	981	701	2.579	1.5	1.653	626	2.757	1.1
8	603	430	1.835	1.7	963	516	2.013	1.3
9	252	258	1.595	3.3	403	371	1.784	2.4
10	134	184	1.488	5.3	237	267	1.491	4.0
11	111	130	761	5.4	200	219	1.086	4.0
12	80	93	555	6.7	142	190	1.361	5.5
Year	200	389	3.852	36.5	317	633	4.984	25.4

	6m				7m			
Month	Mean (h)	Stdev.(h)	Max (h)	# events	Mean (h)	Stdev.(h)	Max (h)	# events
1	307	683	5.757	4.0	566	1.144	6.698	2.9
2	549	1.073	5.616	2.9	960	1.614	6.326	2.2
3	882	1.534	5.601	3.0	1.994	2.405	7.759	2.1
4	2.263	1.860	5.246	1.6	3.567	2.029	7.480	1.2
5	2.822	1.298	4.713	1.1	3.299	1.714	6.760	1.2
6	2.531	930	3.969	1.1	3.204	1.093	6.016	1.0
7	2.066	634	3.249	1.0	2.707	825	5.296	1.0
8	1.353	556	2.505	1.1	1.963	825	4.552	1.0
9	653	490	1.804	1.8	1.166	789	3.808	1.3
10	435	376	1.494	2.5	747	623	3.088	1.8
11	328	349	2.175	3.0	566	525	2.344	2.1
12	275	339	1.865	3.8	439	515	2.283	2.7
Year	544	1.030	5.757	15.5	961	1.594	7.759	9.0

APPENDIX F: Results of the environment analysis.

- **Case 1: T_{POP} = 12h, T_R = 24h (including contingencies)**

Operational Limiting Criteria OP_{WF}							
Average [h]	**2.02**	**2.23**	**2.45**	**2.66**	**2.88**	**3.10**	**3.32**
January	42.6	49.1	56.0	62.5	69.3	76.9	85.5
February	45.7	53.1	60.8	68.1	75.8	86.3	100.2
March	54.9	64.4	74.3	83.7	93.6	107.4	125.9
April	70.7	89.0	108.2	126.4	145.6	181.8	238.6
May	107.7	146.3	186.8	225.4	265.9	336.0	441.6
June	117.3	172.7	230.8	286.2	344.3	441.2	584.6
July	142.3	208.5	277.8	343.9	413.2	504.0	620.6
August	134.9	176.1	219.2	260.4	303.5	354.6	415.3
September	72.1	83.7	95.8	107.3	119.4	138.6	166.3
October	52.2	57.3	62.4	67.2	72.2	80.9	93.9
November	38.5	43.8	49.3	54.5	60.0	67.8	78.4
December	38.4	42.6	47.0	51.2	55.6	60.2	65.0

Figure 50. Average duration of weather window for each month.

Source: Own study

T_R=24h	Operational Limiting Criteria OP_{WF}						
Probability	**2.02**	**2.23**	**2.45**	**2.66**	**2.88**	**3.10**	**3.32**
January	0.569	0.614	0.651	0.681	0.707	0.732	0.755
February	0.591	0.636	0.674	0.703	0.729	0.757	0.787
March	0.646	0.689	0.724	0.751	0.774	0.800	0.826
April	0.712	0.764	0.801	0.827	0.848	0.876	0.904
May	0.800	0.849	0.879	0.899	0.914	0.931	0.947
June	0.815	0.870	0.901	0.920	0.933	0.947	0.960
July	0.845	0.891	0.917	0.933	0.944	0.953	0.962
August	0.837	0.873	0.896	0.912	0.924	0.935	0.944
September	0.717	0.751	0.778	0.800	0.818	0.841	0.866
October	0.633	0.658	0.681	0.700	0.717	0.743	0.774
November	0.536	0.578	0.614	0.644	0.670	0.702	0.736
December	0.535	0.569	0.600	0.626	0.649	0.671	0.691

Figure 51. Probabilities of weather window large enough for 24 hours operations.

Source: Own study

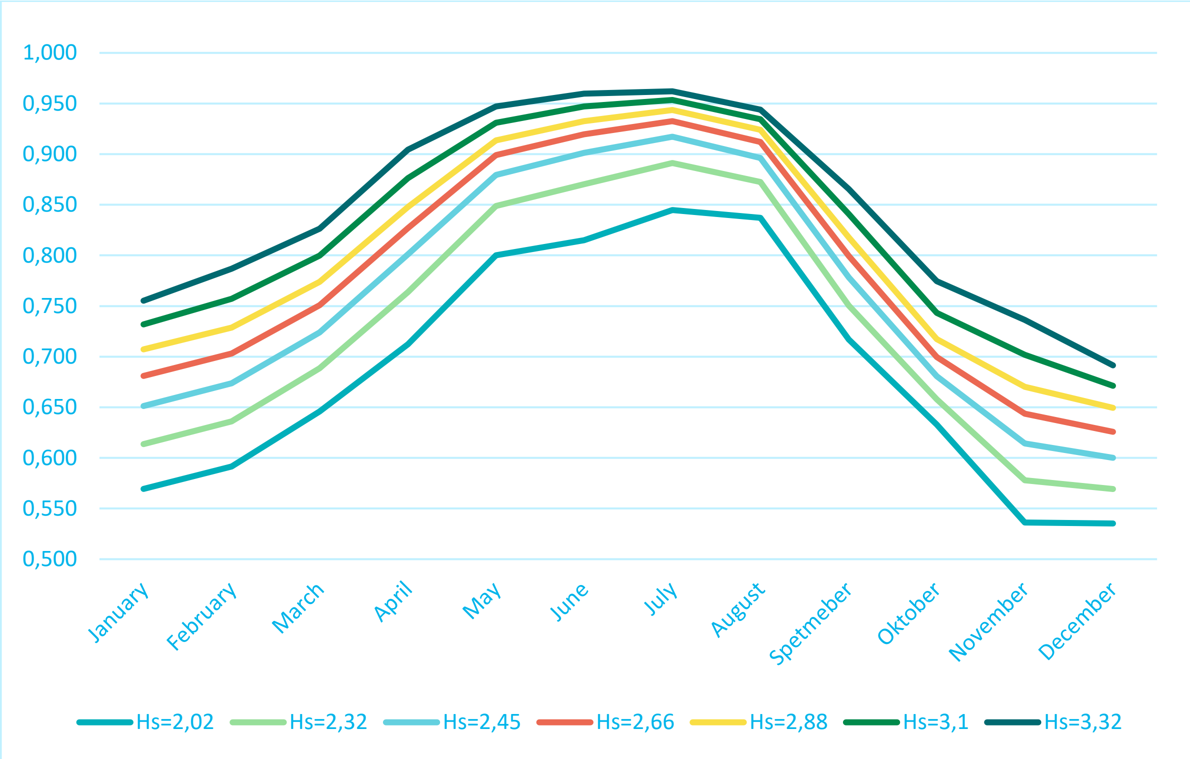


Figure 52. Probabilities of 24 h weather window operations for different operational limits.

Source: Own study.

- **Case 2: T_{POP} = 24h, T_R = 48h (including contingencies)**

T_R=48h	Operational Limiting Criteria OP_{WF}					
Average [h]	**2.15**	**2.36**	**2.56**	**2.77**	**2.99**	**3.20**
January	46.7	53.2	59.4	65.9	72.7	80.8
February	50.3	57.6	64.6	72.0	79.7	92.6
March	60.8	70.2	79.2	88.7	98.6	115.8
April	82.1	100.3	117.7	136.0	155.1	207.6
May	131.6	170.2	207.0	245.7	286.2	384.0
June	151.6	207.0	259.8	315.3	373.4	506.4
July	183.3	249.4	312.4	378.6	447.9	557.0
August	160.4	201.6	240.8	281.9	325.0	382.2
September	79.3	90.8	101.8	113.4	125.5	151.2
October	55.5	60.3	64.9	69.7	74.8	86.8
November	41.8	47.0	52.0	57.3	62.8	72.6
December	41.0	45.2	49.2	53.4	57.8	62.4

Figure 53. Average duration for weather window for each month.

Source: Own study.

T_R=48h	Operational Limiting Criteria OP_{WF}					
Probability	**2.15**	**2.36**	**2.56**	**2.77**	**2.99**	**3.20**
January	0.357	0.405	0.445	0.483	0.517	0.552
February	0.385	0.435	0.476	0.513	0.547	0.595
March	0.454	0.505	0.545	0.582	0.614	0.661
April	0.557	0.620	0.665	0.703	0.734	0.794
May	0.694	0.754	0.793	0.823	0.846	0.882
June	0.729	0.793	0.831	0.859	0.879	0.910
July	0.770	0.825	0.858	0.881	0.898	0.917
August	0.741	0.788	0.819	0.843	0.863	0.882
September	0.546	0.589	0.624	0.655	0.682	0.728
October	0.421	0.451	0.477	0.502	0.526	0.575
November	0.317	0.360	0.397	0.432	0.465	0.516
December	0.310	0.346	0.377	0.407	0.436	0.463

Figure 54. Probabilities for weather window large enough for 48 hours operations.

Source: Own study.

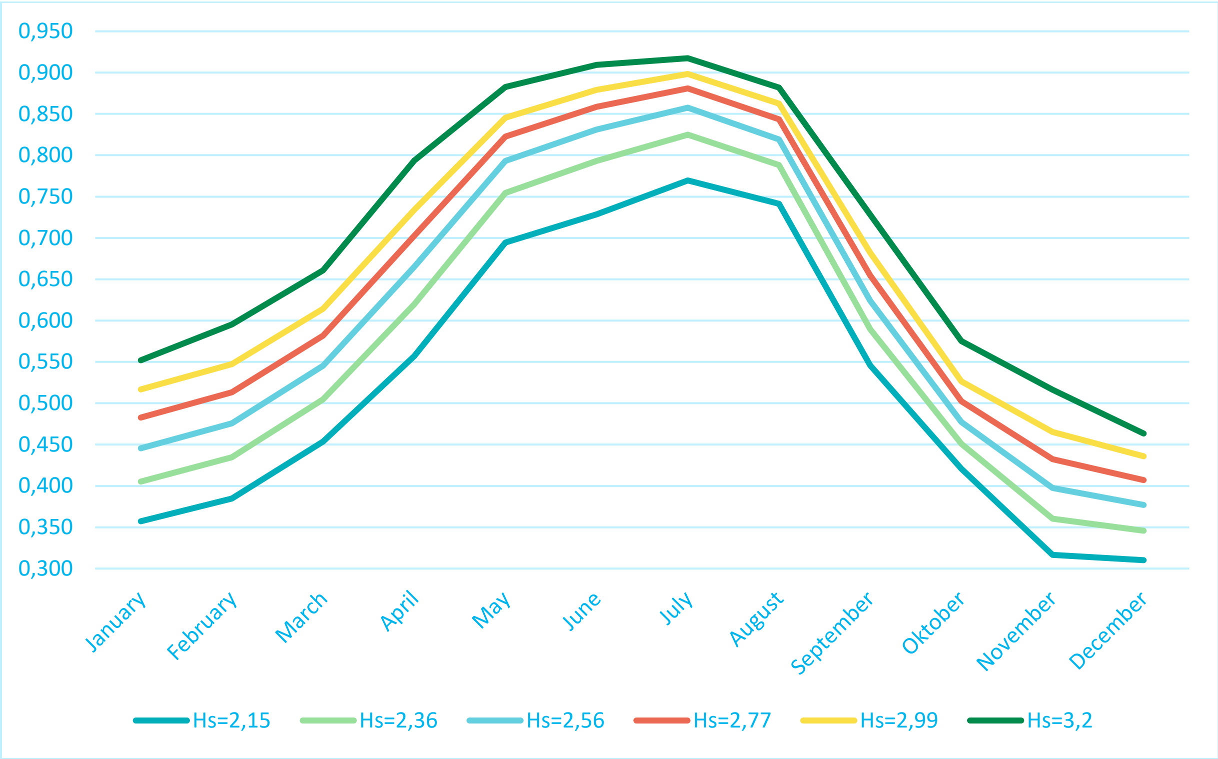


Figure 55. Probabilities of 48 hours weather window for different operational limits.

Source: Own study

APPENDIX G: ITF Uniform "TCC" Collective Agreement 2014 for manned vessels [82]

Pay group	Number	Total salary per month
Master	1	5,786
Chief Off.	1	3,780
2nd Off.	1	3,053
3rd Off.	1	2,946
Boatswain	1	2,001
Able Seamen	3	1,806
Ord. Seamen	1	1,375
Ch. Eng.	1	5,270
1st Eng.	1	3,780
2nd Eng.	1	3,053
3rd Eng.	1	2,946
Electrician	1	2,642
Fitter/Repairer	2	2,001
Fireman/motorman	2	1,806
Chief Steward	1	3,053
Chief Cook	1	2,001
Total	20	47,299