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Western Norway University of Applied Sciences

MASTER'S THESIS

Safety Challenges and Risks due to Alarms in DP Vessels.

Emphasis on Impact of New Energy Solutions. Applicable to Oil and Gas, Offshore Wind and Aquaculture.

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May 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.

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Starting a master's degree after six years of an educational gap has been challenging but nine years of sea going experience made it interesting. The last two years of masters education have been a fantastic journey, where I could learn new about myself and rediscover my strengths and weaknesses. The journey of completing this master's degree has been outstanding as the feeling of exploiting my strengths has given me much satisfaction, and at the same time, fighting to fix my weakness has been painful. Throughout the process, I have only become better than who I was before.

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Abstract

Compared to regular sea-going vessels, DP vessels operate in an area with a high risk of accidents. This research investigates some of the main risks and challenges of DP vessels. Thus, the purpose is to investigate the research question related to safety challenges due to alarms and risks caused by new energy solutions. Furthermore, the research addresses issues facing alarm systems installed in DP vessels, their current technical requirements, and risks of position loss, fire and explosion due to hybrid fuel technology (hydrogen and battery).

This research provides a scientific rationale to find suggestions for improvements in DP vessels by using *HTO Analysis* for safety challenges and issues regarding alarm system. Examples of three accidents from the past and requirements and guidelines from regulatory bodies are qualitatively studied for evaluation and comparison with a survey performed among forty-five DPO and DP instructors. Risk analysis is conducted using bow-tie method for loss of position/heading and alternative fuel source in DP vessels. Risk picture for safety hazards and their consequences are assessed using impact load and collision energy due to rising interest in oil and gas exploration in the Barents Sea, and for the future use of hybrid solutions.

The research in alarm systems showed that alarm fatigue is widespread and unnecessary distractions in the bridge during DP operation are prevalent. The most alarming factors are lack of proper training in alarm error codes and messages, the absence of flexibility in the alarm system's adjustment, and manufacturers lacking interest in feedback from the end-user. The risk of position loss has many challenges, including cyber security and fire and explosions due to alternative fuel sources, requirement of better technology in the difficult weather conditions and lack of proper infrastructure. Challenges for hydrogen and battery-based hybrid solutions have issues in production, transportation, and distribution. Battery technology is yet premature and has issues in cooling system, power storage, and uncontrollable fire and explosions.

From this research, it is apparent that there is a need for improvements in humans, technology, and organizations. Personnel should engage in reporting undesirable events while keeping up with checklists and procedures. Operators and shipping companies must improve working culture towards safety and have a resilience engineering perspective towards accidents and High-Reliability Organization. Manufacturers should come back to the end-user for feedback to improve the alarm system on DP vessels. Two papers are written during this master's thesis preparation and are attached in Appendix G and Appendix H. The papers will be published in proceedings of Marstruct 2021 Conference, Trondheim, and TransNav Journal, respectively.

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List of abbreviations

AIS	Automatic Identification System
ALARP	As Low as Reasonably Practicable
AMP	Alarm Management Philosophy
ASOG	Activity Specific Operating Guidelines
BLEVE	Boiling-Liquid Expanding-Vapor explosion
CAM	Critical Activity Mode
CoG	Center of Gravity
DGPS	Differential Global Positioning System
DP	Dynamic Positioning
DPO	Dynamic Positioning Operator
DNV	Det Norske Veritas
DNVGL	Det Norske Veritas Germanischer Lloyd (Name change DNV 01.03.2021)
ECA	Emission Control Areas
ECDIS	Electronic Chart Display and Information System
EU	European Union
FMEA	Fault Mode Effect Analysis
FPSO	Floating Production storage and offloading
FSVAD	Flag State Verification and Acceptance Document
GDPR	General Data Protection Regulation
GHG	Green House Gases
GNSS	Global Navigation Satellite System. (Generic)
GPS	Global Positioning System
HFO	Heavy Fuel Oil
HRO	High Reliability Organization
HTO	Human, Technology and Organization
IAS	Integrated Alarm System
IEC	International Electrotechnical Commission
IGF Code	International Code of Safety for Ships using Gases or other Lower-flashpoint Fuels
IMCA	International Marine Contractors Association
IMO	International Maritime Organization
ISA	International Society of Automation

IT	Information Technology
ITU	International Telecommunication Union
LFF	Low Flashpoint Fuel
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MOU	Memorandum of Understanding
MPSV	Multipurpose Supply Vessel
NCS	Norwegian Continental Shelf
OCIMF	The Oil Companies International Marine Forum
OSV	Offshore Support Vessel
OSRV	Oil Spill Response Vessel
OVID	Offshore Vessel Inspection Database
PLSV	Pipe Laying Supply Vessel
PRS	Position Referencing System
PSA	Petroleum Safety Authority, Norway.
PSV	Platform Supply Vessel
RO-RO	Roll On- Roll Off
RO-PAX	Roll On/Roll Off Passengers
ROV	Remotely Operated Vessel
RPT	Rapid Phase Transition
SDG	Sustainable Development Goal
SFA	Statfjord A
SMS	Safety Management System
SOLAS	Safety of Life At Sea
TAM	Task Appropriate Mode
TMSA	Tanker Management and Self-Assessment
UKCS	United Kingdom Continental Shelf
UK HSE	United Kingdom Health and Safety Executive Agency
UPS	Uninterruptible Power Supply
VRS	Vertical Reference Sensor
WCF	Worst Case Failure
WCFDI	Worst Case Failure Design Intent

1. Introduction

Humans have been interested in mobility through water and have been building rafts, boats, and ships for an extended period. We can trace maritime archaeology and boat archaeology can be traced to the end of the eighth millennium BC. During these Archaeological periods, wooden boats were being built with the help of planks (McGrail, 2009). Since then, the maritime industry has developed through time due to necessity, curiosity, and accidents, hence learning from those accidents. These changes fulfill the core purpose of invention, which is transportation, and at the same time, increase safety while making crew's tasks convenient to perform onboard with the help of technology.

Improvement in maritime technology has evolved in time, especially after the second world war. Some of these evolutions were a necessity in order to increase safety and to reduce accidents. The aviation industry inspires several of these technological changes, for instance, by using radar, Automatic Identification System (AIS), digital charts, procedures, and checklists. Technological improvements have helped relevant industrial workers to get tasks done with simplicity, increased efficiency, and, most notably, with reduced effort. Eventually, technological advancements have led to comfort in working life by increasing capacity in both quantity and quality and brought profit to the entire maritime industry.

Technology is a necessary evil. Technology in itself doesn't make an industry. It helps to create an industry which benefits more with the help of the technology than without. In a maritime industry whose growth is dependent on technology and its usage, it is reasonable to understand the merits and demerits of its involvement. It is beneficial to exploit it being cognizant that it has many drawbacks, in the world of limited resources and unlimited desires. In some cases, over-dependency on technologies can also cause accidents.

1.1. Historical background:

After discovering oil and gas on the Norwegian Continental Shelf (NCS) in 1969, demand for offshore vessels and technology increased exponentially. For the industry, there was a challenge to increase safety -- by reducing the loss of human life and damages to the environment and property.

Figure 1 The Eureka was the world's first automatically positioned vessel. Picture courtesy of Howard Shatto.

The first vessel (Drillship Eureka) which effectively enabled the Dynamic Positioning (DP) system was in 1961 (Drilling in Gulf of Mexico), where the vessel held its position with the help of thrusters (Bray, 2015). In shipping, the development of DP vessels was established as essential for the offshore industry. Initially, the DP system started with elementary systems. During the 1970s and 1980s, technological improvements and developments began and led to the well-established system that is present today. Some of these changes were, for instance, changes in propulsion, control systems, position reference, operations, and hull design.

In the last twenty years, the maritime industry has been looking forward and backward to plan its future and reduce the shortcomings from the past. As the industry is getting standardized, many deficiencies are not just making working life harder for Dynamic Positioning Operators (DPO) but also increasing the risk of accidents. The introduction of new technology is vital to reduce complexity and increase efficiency, but the involvement must be well analyzed, and existing safeguards have to be checked. If not, the barriers to prevent accidents will fail. It will primarily be challenging for the DPO to keep up with such changes in the industry. DPOs will have a limited number of vessels lacking the most up-to-date technology.

1.2. Concept of the DP vessel

DP is an integrated system that controls the position of a vessel and heading with the help of active thrust. Control of yaw, sway and surge as shown in *Figure 2* is done with the help of controllers, which receive several feedbacks from the sensors present onboard.

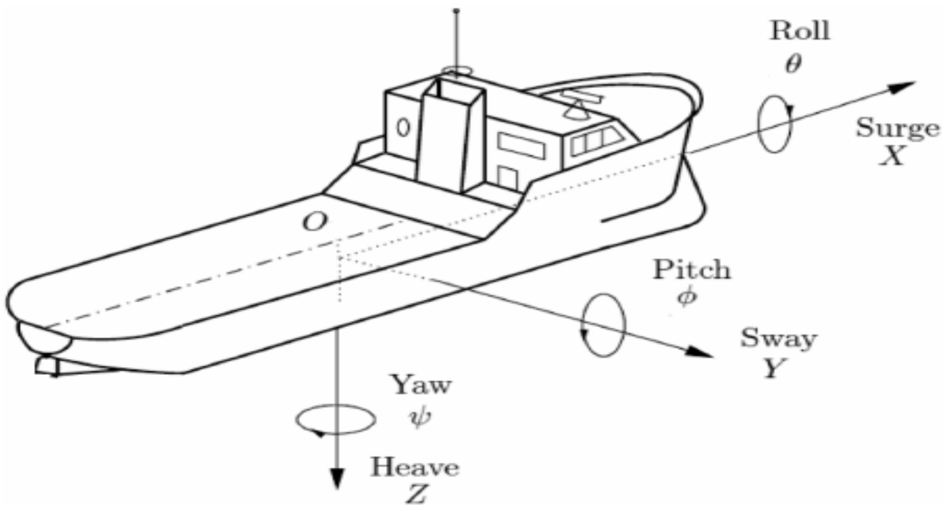

Figure 2 Vessel's movements in six degrees of Freedom (Kookhyun K. et al., 2009).

These feedbacks are crosschecked with the set-point values inserted by DPO. In case of deviation from the set-point values, the vessel will make necessary changes to the thrust to keep the desired position. DP vessels are very popular as a result of their excellent reliability. In addition, it is possible to find various DP vessels with several different types of redundancy and equipment class. Typically, they are divided into three classes of vessels according to Guidelines from International Maritime Organization (IMO) (IMO, 1994).

These redundancies come with a price, where the vessel with low redundancy is cheaper to operate while the vessel with maximum redundancy is the most expensive to operate. However, all these costs minimize the risk of accidents/incidents during a DP operation.

1.3. Guidelines for DP Vessel class

There are several guidelines for the operation of DP vessels that are issued by IMO, Classification Societies, International Marine Contractors Association (IMCA), and in some cases, by the operators. The purpose of such guidelines is to advocate operating requirements, necessary equipment, design criteria, testing, and documentation of integrated systems that are installed in DP vessels. It will eventually reduce the risk of damage to the environment, loss of assets, and, most importantly, personnel involved in the operations.

When a system in a DP vessel is running, it consists of several different parts that work together to keep the position and heading of the vessel. Typically, static components are not considered to fail whenever enough protection from damage is evident. Reference is given to static components such as cables, pipes, manual valves, and others. Active components are referred to as generators, thrusters, switchboards, and remote-controlled valves.

DP systems are classified into three different classes (IMO, 1994) and in *Table 1* a Class requirement (Thigpen, Boyer, & Stewart, 2018) is shown.

Description	**IMO**	**DNV**	**ABS**	**LR**
Manual position control and automatic heading control under specified maximum environmental conditions	-.	DYNPOS-AUTS	DPS-0	DP(CM)
Automatic and manual position and heading control under specified maximum environmental conditions	Class 1	DYNPOS-AUT & DPS1	DPS-1	DP(AM)
Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault excluding loss of a compartment. (two independent computer systems).	Class 2	DYNPOS-AUTR & DPS2	DPS-2	DP(AA)
Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault including loss of a compartment due to fire or flood. (at least two independent computer systems with a separate backup system separated by a60 class division).	Class 3	DYNPOS-AUTRO & DPS3	DPS-3	DP(AAA)

Table 1: Vessel Classification Chart (Thigpen, Boyer, & Stewart, 2018)

- Equipment Class 1 has no redundancy. Loss of position may occur in the event of a single fault.
- Equipment Class 2 has redundancy so that no single fault in an active system will cause the system to fail. Loss of position should not occur from a single fault of an active component or system such as generators, thruster, switchboards, remote controlled valves etc., but may occur after failure of a static component such as cables, pipes, manual valves etc.
- Equipment Class 3 which also has to withstand fire or flood in any one compartment without the system failing. Loss of position should not occur from any single failure

including a completely burnt fire subdivision or flooded watertight compartment. These vessels are the most redundant class of ships available; however, some challenges are present underlying the operational, technical, and innovative side.

1.4. Operation and Redundancy

Redundancy is defined as the ability of a component or system to maintain or restore its function when a single failure has occurred(DNVGL, 2017 c). Such redundancies can be achieved, for example, by having multiple components or alternative means of performing a function. There are several layers of redundancy in a DP vessel. Such redundancies differ in all equipment present in three classes of DP vessels (DNVGL, 2017 c).

- Redundancies in Controllers

The first barrier of redundancy is present in controllers (computers). A Class 1 DP vessel has a single redundant controller, also known as a simplex system. In contrast, a Class 2 DP vessel has two identical controllers and will operate independently of each other while fulfilling the same operations from the same feedback system and sensors, also known as a duplex system. This occurs when one computer is online the other is on standby. In case of failure in the first system, there will be a smooth transfer to the controller on standby. During the transfer of operation, the vessel will be continuously holding its position and heading. For DP vessels on Class 3, they are robust DP class 2 vessels with fire and flood protected systems. In the Class 3 system, all systems run in parallel, where one is online, and the rest are on standby. All signals are compared to results from other systems; if any deviation occurs, the controller with the error is isolated from the entire system. However, in class 3 DP vessels, the third controller must be in a separate compartment remotely from the primary set of functional controllers. (Bray, 2015)

- Redundancy in position and heading reference

For the vessel to be Class 1 DP, there have to be two Position Referencing Systems (PRS). There is a risk of “drive off” or “drive on” in the case of frozen PRS during a DP operation. Along with that, there is a single gyro for heading reference. Nevertheless, for Class 2 and 3 DP vessels, there have to be three different PRS that are independent of each other and three different gyro compasses (Bray, 2015).

- Redundancy in Propulsion

A DPO must always be aware of the situation and ready to take over the situation manually if necessary. The worst-case single-point failure mode relative to propulsion might occur anytime. For a diesel-electric vessel of Class 2 and 3 a typical worst-case failure would be losing a complete section of a switchboard. Hence a typical class 2 and 3 DP vessel has three propellers in bow and three at the stern powered with a split switchboard. (Bray, 2015)

- Redundancy in Power System

For the power system, there has to be a power management system for both class 2 and 3 DP vessels. In addition, it is mandatory to have the primary switchboard bus tiebreaker, one for a class 2 vessel and two for a class 3 vessel. For thrusters, there have to be redundant thrusters for both class 2 and 3 vessels. At the same time, thrusters have to be in a separate compartment. It is compulsory to have 3 sensors (PRS, wind, Vertical Reference Sensor (VRS), Gyro). All the controllers have to be connected to Uninterruptible Power Supply (UPS). (Bray, 2015)

1.5. Scope

Every system comes with some level of risk in various forms. The consequences of such risk have variance in acceptance criteria. "*Risk is a curious and complex concept. In a sense, it is unreal in that it is always concerned with the future, with possibilities, with what has not yet happened*." (Rausand, 2011). Risk can be understood as the possibility of harmful events that might occur at any moment. These events might occur due to human error, technical issues, or natural calamities. In few cases, some risks are protruding, and others are clandestine. To prevent such risks, there are safeguards or barriers. These barriers or safeguards are installed in the system to the level where the system meets the acceptance criteria. In summary, risks are analyzed by looking for the answers to three main questions;

a) What are the hazardous events?
b) What is the likelihood of occurrence of a hazard?
c) What are the consequences of these events?

Compared to regular sea-going vessels, DP vessels have a high risk of getting into accidents, even though it is a very reliable system. It is because most of these vessels operate close to offshore installations. A typical sea-going vessel has restrictions when entering within five hundred meters of radius to an installation. Therefore, there is an added risk of collision of DP vessels to the offshore installation. Statistically, only a few accidents occur during a DP operation compared to accidents in other sea-going vessels. In addition to that, there are significant amounts of electronic equipment with increased complications in DP vessels, which in return also gives higher risk. Humans are at the sharp end, and the chances of making an error are relatively large. Thus, it is of great interest for the maritime industry to check if mitigation or elimination of the risk can occur. Few examples of such risks are; collisions of DP vessels with offshore installations, oil spills, the sinking of the vessels, or total loss of installations or vessels due to explosion.

The primary objective of this thesis is to analyze safety issues in DP vessels regarding alarms during emergencies, risks related to position loss, and the use of hybrid solutions as an alternative fuel source. In the end, suggestions have been put forward to strengthen the approach of the maritime industry and the influencers to ensure safer offshore operations.

The first chapter introduces the history of shipping along with the current state and potential prospects. In the second chapter, the data and research method are described along with an explanation of the research question to determine the research direction. Guidelines and recommendations from regulatory bodies are studied and analyzed in chapter 3 to understand current rules and regulations for the research question. Furthermore, chapter four describes the challenges and hazards with the help of the past three accidents in the North Sea and the Indian Ocean. Additionally, data analysis is performed using survey results among DPOs and DP instructors in the fifth chapter. Forty-five persons participated in the survey for the alarm system on DP vessels, including forty-one DPOs, and 4 DP instructors.

The sixth chapter includes discussions of the research and is divided into four segments. The first part includes the results of data analysis from the survey, and the second part comprises of a risk picture using a bow-tie diagram for Global Positioning System (GPS) position loss. In the third part, the risk picture is drawn with the help of a bow-tie diagram for alternative fuel sources; hydrogen and batteries. Finally, the consequence in the form of impact load is studied for risks of position loss and alternative fuel source combined with alarm management in a DP vessel.

The final chapter addresses the research question with main challenges for the maritime industry towards alternative fuel sources, GPS position loss, and alarm management. It also provides suggestions and recommendations for the offshore industry to improve safety within these three areas. Definition of special terminology used in this thesis are listed in Appendix A: Definitions.

2. Data and Methods

- How can complexity due to the high volume of alarms be reduced for DPOs during DP operations?
- Is the redundancy for loss of GPS signals enough for future operations?
- For DP vessels with alternative fuel source, is there enough redundancy for safe operations?

These three questions address different causes that may lead to a severe accident and are interconnected. Complex alarm systems are difficult to interpret and might confuse operators, which may lead to a collision. Similarly, the consequences of GPS signal loss may also lead to collision, fire, or explosion, especially in vessels planned to be built in the future or have already installed alternative fuel sources. Alternative fuel sources installed on DP vessels might escalate the fire or cause more severe accidents, even in minor collisions.

Above mentioned research questions are the newest or upcoming challenges in the maritime sector. The problems in question exist in the current situation as the working environment is getting demanding. Thus, a realistic conclusion has an excellent possibility to reduce accidents or mishaps that might occur in the future. The first research question investigates confusion, ignorance, high volume of alarm in a DP bridge.

The cause and effect of inefficiency and confusion in a bridge will be evaluated with the help of Human, Technology, and Organizational Analysis. Human, technology, and organizational factors comprise potential in system analysis, design, and improvement. This method reflects on the foundation of understanding, improvement, and development of a properly functioning system. The issues in all three sections regarding the accidents will be covered in a fully functioning system. It is essential to study guidelines, responsibility, procedure, and practice, and such events will be analyzed and compared with standard practice methods in DP vessels. HTO analysis in this research is based on the following methods (Tinmannsvik, Sklet, & Jersin, 2004)

A. Perform structured analysis by use of an event and analysis of survey results.

B. Change analysis by describing how events have deviated from earlier events or standard practice.

C. Barrier analysis by identifying technological and administrative barriers in which have failed or are missing. Following are the Steps for Barrier Analysis

- Identify the hazard and the target.
- Identify each barrier and how the barrier performed
- Identify and consider probable causes of the barrier failure.
- Evaluate the consequences of the failure in this accident

As there is no quantitative data available in such scenarios, a qualitative approach based on literature review and survey is adopted. An investigative approach is taken in order to fulfill the goal of the research. Whereas, in case of redundancy for the loss of GPS signals possibly due to cyber-attack and evaluation of redundancies present for the implementation of new fuel source, a risk analysis is performed using bow tie analysis due to inadequate data available. The HazID method is used to identify hazards. It is a qualitative technique for early identification of hazards that might be present for people involved in the activities, reputation of institutions involved, the environment where the operation takes place, and assets such as time and money used in operation.

This research is a part of an established system in DP alarms, where many guidelines and technical requirements are already present. Nevertheless, the industry is developing in cybersecurity and has initiated research and improvement in technology to implement new fuel types in existing and newly built vessels. Thus, the findings are transferable throughout the industry wherever it is deemed relevant. In addition, further research is possible in case of any questions that remain unanswered through this research. An explorative nature of this research points towards qualitative research. Qualitative research is also known as "Interpretative research," which uses non-numerical and subjective data (Christensen, Johnson, & Turner, 2015). Interpretative research helps the research extract information from the participant's subjective perspective and compare it with existing guidelines. Additional methods such as interviews and questionnaires will triangulate the results that are achieved after exploration. Hence, increasing the validity of the results and improving the understanding of the subject under analysis. Data acquired via interview and questionnaire will be compared with the relevant guidelines to find an error in the system or an alternative solution that could minimize if not eliminate the risks of accidents. Additionally, hazard identification is made to document and systematize the risk assessment process. It will eventually help find the cause, consequence, existing safeguard, probability of occurrence of such hazards, the impact (on people, asset, environment, and reputation), and mitigating measures, which will reduce the probability of a hazard from occurring.

2.1. Literature study

There is rich information that lies in terms of guidelines by various parties involved in DP operation—starting from IMO, classification society, IMCA, operators, charterers, shipping companies. It is a maze to navigate through such information and is not just complex but ample. There are always grey areas when it comes to legal issues. The aim is not to dwell in grey areas, but to gap bridges and move towards the objective. A primary investigation is done during the initial phase of the research process and data collection. Due to the limited experience of the researcher in the DP sector, professional and experienced help is acquired from colleagues and employees of Equinor who have relevant experience and knowledge regarding the subject. A survey decorum was conducted during the data collection phase to gather relevant information during the research process, after survey guidelines were looked into, from three different parties IMO, Det Norske Veritas Germanischer Lloyd (DNVGL), and IMCA for the triangulation process.

Further study is needed in order to understand the results of the survey. Information from the internet, university library, eBooks, and research databases (e.g., ResearchGate) is used to gather information. The researcher's time and experience onboard were also used for the analysis of the survey. Further on, resources provided by the supervisor were used as guidelines and information while developing the research. Various criteria are set up in the research process and followed to increase the reliability of the results.

2.2. Survey

From the survey, relevant and insider information regarding their practices and observation is given by the participants through their experiences in the maritime industry from the DP environment. The survey decorum, once prepared, was reviewed by professionals and supervisors, and is completed with consideration of feedback on participant's thoughts, experience, and knowledge. These surveys have importance as they will benefit the research by increasing its validity by obtaining detailed and critical information from the participants. A copy of the survey, which contains both the questionnaire and interview, is attached in the Appendix C.

The survey is divided into two different parts, where one set of questions are targeted for DPOs and another one for the DP training instructors in simulators. Questions in the survey are both open and closed. Nevertheless, attempt is made to reduce confirmation of any bias presented by the researcher. Due to travel restrictions from COVID-19, a physical meeting was not possible; an appropriate alternative was chosen as per agreement with the participant, which most likely is online.

2.2.1. Data Validity

In qualitative research, it is critical to re-enforce the idea of validity and reliability to achieve the objectives defined in the research question, as the research covers a good part of the maritime industry. However, thought is always given to the sample size. In order to increase the validity of data collected, an effort is made to reach professionals from different parts of the world (Norway, Finland, The Netherlands, Germany, Brazil, The Philippines, and many more). It is assumed that the answers provided by the participant are correct. At the same time, the answers are independent of any bias.

The contribution of companies connected with the thesis were not affecting the results of the research. Thus, keeping the results genuine and neutral. Participants with high operational experience in the DP sector were chosen whenever possible. An experienced supervisor in the field was also present who assisted in removing biases and help correct the results.

Limitations of the survey might be dishonesty or biased from the participant's side and might affect the data's validity. It is also important to emphasize that the purpose of the survey can be hampered by the fabricated answers provided by participants due to fear of slipping unwanted information. In many cases, people might be hesitant to participate in the survey as the survey intends to figure out issues in the system that a ship, shipping company, instrument producers, charterer. Therefore, people connected to such institutions might not be sincere if they take part in the survey.

2.2.2. Bias

The researcher had no past hands-on experience other than maritime education in university regarding DP operations related to new technology and cybersecurity. Dependability and confirmability were achieved by neutral interpretation of the data. Thus, this research has a negligible bias in the form of information, selection, and cofounding while doing the research or preparing the survey question and finally analyzing the results from the survey. Any of the analyses was not influenced by personal prejudice. A focus was be laid on research procedures to produce results by avoiding bias throughout the research process. People with different DP experience (Type of DP vessel) and vessels with different integrated bridge systems are included. In addition, if any of the participants with experience from the same type of vessel are involved, the results can be biased. Therefore, this process confirms that the research can be reproduced with the same research process for similar results.

2.2.3. Ethical Considerations

The surveys were kept anonymous; no recordings were made for any of the interviews or mentioned in the survey decorum. A consent form was provided in order to get written approval for participation in the survey. The appropriate distance was maintained, sanitizers were used, facemasks were used for physical interviews as per authorities' recommendation for preventing contamination of coronavirus. As participants chose to respond through the internet, it was made sure that no track would lead to the participant in any way whatsoever. According to the new European Union's (EU) rule of General Data Protection Regulation (GDPR) for privacy, rules regarding privacy were kept of the highest value throughout the research process.

3. Relevant Guidelines

The primary purpose of the guidelines is to reduce the rate of occurrences of accidents or near-miss situations while operating these machines. Regulatory bodies issue them for industrial standardization for both machines and their operators. For such guidelines to be practical, they must be comprehensive, specific, extensive, bring scientific evidence and effectiveness, and include expert's opinion. In the maritime industry, there are various trading branches; however, for the offshore industry, the guidelines for operators and DP vessels are mainly issued by IMO, classification societies, IMCA, and the operator of chartered vessels. Furthermore, guidelines can be brought in front of the regulatory bodies and be discussed before enforcing them if acknowledged by the majority of the parties involved. This process is valid for the introduction of new guidelines or amendments of old guidelines. These documents are just standards, and their contents are open for discussion.

3.1. IMO

IMO is an international body that issues compulsory guidelines required for vessels that are trading all over the world. MSC/Circ.645 is specially designated for guidelines for the vessels with a dynamic positioning system. These guidelines are put forward by members of government to all concerned institutions' attention and get implemented. A Flag State Verification and Acceptance Document (FSVAD) should be issued for all vessels surveyed and tested according to the guidelines by the institution, duly authorized by the governmental body. With the new concept of triple redundancy (DynPos AUTRO(ER)(CBT) according to media) installed in the North Sea with the installation of *K-Pos DP-21, K-Pos DP-11 BU, K-Pos DP-11/cJoy* (DNVGL, 2020), it is evident that the offshore vessels are getting safer than before. Extremely high redundancy is achieved with minimal loss of the diesel-electric system. However, according to code on alerts indicators (Alarm code) published by IMO on resolution A.1021; there are no specific guidelines for different types of alarms that a complex DP vessel has in its bridge and engine control room. Nevertheless, this document provides general guidelines for alarm presentation both with an indicator (visual) and signal (audio). It is specified that all alarms should be clear and distinctive, unambiguous, and consistent (IMO, 2009).

Cyber Security, MSC. 428(92) ensures that all shipping companies need to have cybersecurity in their management system. Flag states check the implementation of such systems after the first annual audit of 1st January 2021. Currently, cybersecurity is a standard requirement for the maritime industry. International and national regulations are coming into force in addition to IMO. These regulations can vary depending on each nation. However, there are further requirements that relate to cybersecurity and data privacy, such as EU GDPR. These regulations are enforced to reduce the financial risk and keep the demand in the market for the charters. Companies are required to stay updated on their contracts and insurance policy for the requirements and coverage, respectively. A good example is TMSA scheme from OCIMF that reflects on the importance of cybersecurity.

In 2003 UN had an agenda of 17 Sustainable Development Goals (SDG) that needed to be accomplished by all member nations by 2030. These goals have a shared outline for peace and prosperity for the global population and the planet. Tackling climate change is regarded as one of these goals and works to preserve our planet. These goals are traced to other UN bodies since IMO is also a part of the UN family and a global regulator of the shipping industry. IMO responded by adopting the SDG in 2015, and all the member countries are promoting the agenda of "saving the planet" and enforcing the green revolution. IMO has developed a raft of measures designed to control emissions from the shipping industry by reducing emissions by 50 % by 2050 compared to 2008. In 2018, IMO brought a vision of phase-wise reduction of Green House Gases (GHG) emission. The initial strategy was slow steaming, meaning that the vessel was supposed to reduce its cruising speed lower than average but economical to limit GHG. The second strategy was

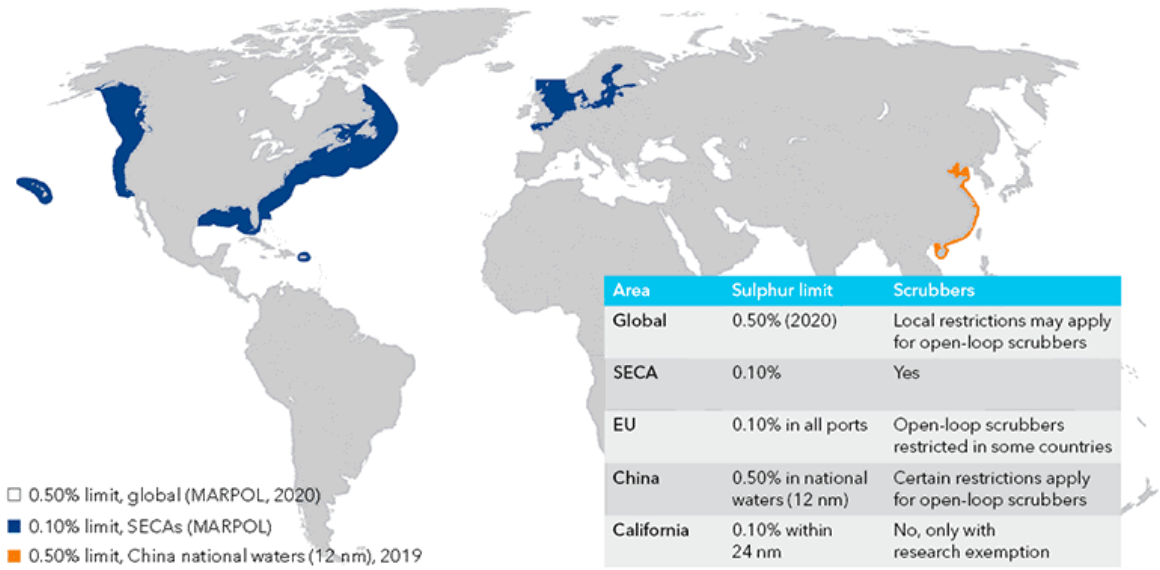

Figure 3: Emission control area (DNVGL, 2019 b)

to use low sulfur fuel in the regulated areas and install scrubbers in the vessels before 2023. The final strategy was to implement regulations for 2030 and improve emissions in newly built vessels (IMO, 2018).

IMO has issued guidelines via International Convention for the Prevention of Pollution from Ships (MARPOL) convention. Several annexes are issued to clarify and increase the precision and effectiveness of the Memorandum of Understanding (MOU) in Emission Control Area (ECA) as shown in *Figure 3*. In the figure it is seen how the ECA are separated in present and plans for future. Annex VI focuses on air pollution caused by ships and measures to take preventive actions. Annex VI of MARPOL sets international requirements on the limitation of Nitrogen Oxides (NOx) emissions and requires ocean-going vessels with more than 130kW of power output to comply with the guidelines. These guidelines are for primary engine emissions and auxiliary power sources. Thus, it is required to use hydrocarbons with low sulfur content, which eventually will protect health and the environment by reducing the rate of ozone depletion. In addition, the protocol from London acknowledges carbon capturing and injection to subsea geological formations and ocean fertilization as a mitigating measure.

3.2. DNVGL

DNVGL (name changed to DNV 01.03.2021) is a major classification society within the shipping industry which plays a critical role in maintaining the standards. DNVGL has issued a requirement for new buildings to certification, classification, verification, and training (DNVGL, 2016 a). These rules put down procedural and technical requirements to obtain a class certificate. In the guidelines, it is mentioned about procedures for certification, documentation, and survey. Additionally, it includes a general arrangement of redundancy and failure modes, system arrangements, and internal communication (DNVGL, 2017 c).

Similarly, guidelines for the control system are well-elaborated details. Sections such as automatic control system, thruster control mode selection, PRS, sensors, display and indication, thrusters, power system, auxiliary systems, and alarm monitoring, and the analysis of its consequences are issued with requirements for managing the risks to make the industry safe and responsible (DNVGL, 2017 c). Guidelines help identify, access and advise risk management by developing best practices within the industry.

In the case of cybersecurity, DNVGL has issued a recommended practice for the oil and gas industry. DNVGL recommends including cybersecurity in the ISM manual since it has become standard practice after 2021 January. According to DNVGL, this recommended practice is a collective effort made by industry pioneers such as ABB, Emersion, Honeywell, Kongsberg Maritime, Lundin Norway, Petroleum Safety Authority (PSA) Norway, AS Norske Shell, Siemens, Woodside Energy, and Statoil (name changed to Equinor 15.05.2018). These recommendations are to prevent IACS in the energy sector (Oil and Gas). It will eventually lift the standards in the overall maritime industry's outlook on cybersecurity. It is recommended to separate the entire system into zones, with basic and primary zones separated from an isolated safety instrumented zone and control zone. These individual zones comprise various parts of their significance. Configuration tools, diagnostic tools, and engineering tools come with different size complexity and criticality. These tools must be permanent for a very critical system, and all other temporarily connected devices should be separated. Wireless communication also can be separated. There can be a dedicated connection for the vessel's operation and crew's entertainment. Finally, it is highly recommended to separate devices that get connected via untrusted networks (DNVGL, 2017 a).

Marine diesel engine today on a seagoing vessel uses very cheap fuel known as Heavy Fuel Oil (HFO). This fuel type has high Sulphur content and promotes emissions of GHG and NOx into the atmosphere. Such emissions are regulated in particular areas, also known as ECA as shown in *Figure 3*.

The development of lithium-ion batteries has significantly changed various industries from consumer electronics, oil and gas energy, and transportation, including the maritime industry. Batteries help in optimizing power and thus reduce both fuel consumption and emissions. Other advantages have reduced maintenance, improved ship responsiveness, regularity, operational performance, and safety in critical situations. DNVGL has provided a guide for using batteries in shipping, rules for classifications of ships for propulsion, power generation, and auxiliary systems focusing on the involvement of battery systems in seagoing vessels. In addition, a technical reference for lithium-ion battery explosion risk and fire suppression is also present in the guide. There is a handbook for maritime and offshore battery systems published by DNVGL with more detailed information (DNVGL, 2016 b).

Currently, seagoing vessels trading in the controlled areas use marine diesel with low sulfur content. Using alternative fuel such as Liquid Petroleum Gas (LPG) / Liquid Natural Gas (LNG) is an option but has a severe disadvantage of producing instant power when needed, and such deficiencies could be complemented by the usage of a battery pack (Eliassen, 2019). A battery pack reduces the probability of blackouts due to failure in the primary source of power as it is an additional source of redundancy. As battery technology is developing, there is an electric vessel with the battery as the primary source of power. Ships with battery systems used as an additional source of power and battery systems used for miscellaneous services are developing and need constant updating.

A class notation for vessels classified by DNVGL "*battery (power)*" is introduced. This class notation is compulsory for all vessels where the battery is used as a redundant source of power for main or additional class notations (DNVGL, 2018 a). Installation of lithium-ion battery systems with a capacity less than 20kWh without the class notation will be based on safety assessment. SOLAS or the HSC Code 2000 does not cover the regulations regarding the fire safety of lithium-ion battery installations. The requirements should be put together for the battery pack in general fire safety measures in SOLAS REG.II-2/2000 HSC Code Ch7 (DNVGL, 2018 a). New requirements for ventilation are added in 2018 for vessels with the battery pack. The place of installation of the battery system is designated as a hazardous area. In case of fire in the battery system, an explosion is highly probable due to hazardous gases. Thus, DNVGL has asked shipbuilders to comply with zone two requirements when building the ships.

3.3. IMCA

In the offshore industry, IMCA plays a crucial role in improving quality, health, safety, environmental and technical standards, with the help of publication of notes, codes of practice safety flashes. All member institutions are self-regulatory by adopting the guidelines that are published. However, institutions like IMCA need to maintain the guidelines issued and improvise on the documents published for the industry. When it comes to building offshore vessels, there are guidelines from IMO, classification society, and IMCA, which comes out with standards and guidelines that help to uniformize the industry. Examples of guidelines include the guidelines for the safe operation of DP offshore vessels, guidance/requirements on the use of simulators in training and operations, syllabus for training of personnel in supervisory positions, the design and operation of DP vessels, and many more. These guidelines are not just for traditional sea-going vessels, but also for DP vessels with new hybrid battery technology. Such diversification will contribute to focusing on shortcomings and improving those shortcomings. There are recommendations for DP status in operational guidelines, parts of these guidelines are for the design and operation of dynamically positioned vessels. The recommendations unequivocally reflect on the DP vessel's status according to the alarm, type, location, and required response from the DPO; to acknowledge the alarm and eventually eliminate the risk (IMCA M103, 2019).

Cybersecurity is a major concern in the Information Technology (IT) world. IMCA reflects standards set by International Electrotechnical Commission (IEC) 62443; an international series of standards on industrial communication networks- IT security for networks and systems. It is a standard that reflects on different technical and process-related aspects of cybersecurity that are present in the current industry. A risk-based approach is taken to prevent the industry from cyber-attacks. The entire industry is divided into operators, integrators, and manufacturers. This standard brings guidelines for the operators/integrators of automation solutions and defines each segment's requirements for its duties and responsibilities to make operations safe and reliable. This research will primarily put focus on end-users and institutions that are connected to them. Guidelines release such as IMCA 359 primarily focuses on security measures and emergency response, reflecting the industry's interest and reason for reliance on cybersecurity throughout the industry.

For hybrid vessels, IMCA has brought forward recommendations with the help of "Introduction to hybrid battery systems for DP vessels". In this guideline, IMCA has stated the basic hybrid system and advantages of hybrid systems. It has also analyzed hybrid systems for new build and existing vessels in operation, maintenance, and safety aspects of hybrid systems. IMCA M 250 shows different ways to develop a hybrid system using a battery storage system. Firstly, the battery system is connected to the low voltage switchboard on either side of the redundant group. Secondly, battery storage systems are connected straight to the individual thrusters and finally connected to the medium voltage switchboard on or both redundant groups via a step-up transformer (IMCA M250, 2020). These installations of battery systems require monitoring, control, and its interface with the DP and power management system. The data on efficiency, emission, and other technical aspects are based on the information provided by the vendors (IMCA M250, 2020). According to IMCA, the application and viability of the hybrid system in a modified vessel and a new vessel will be significantly, different even though the concept is similar. Generally, battery installation helps the existing power system enhance power and efficiency by reducing the number of running engines and saving fuel and maintenance costs. It will eventually reduce GHG emissions (IMCA M250, 2020). Thus, IMCA shows that using a battery system is enhanced by the hybrid system instead of using it as the primary source of propulsion or operation of the vessel (IMCA M250, 2020).

4. Hazards and challenges

Many principles for safety came during the start of the 1900s, which became the foundation for our safety culture that we are practicing today. The theories of scientific experimentation, theorizing, and logical reasoning have their roots stretched to the 18th and 19th centuries, which are brought to bear on the safety issues that we face now (Dekker, 2019). These events made a shift of perception that accidents could be scientifically understood. Those perceptions became fundamental in creating new departments such as maintaining safety rules and practices, regulatory bodies, classification societies, investigative institutes, flag states, and port state control.

"*In 1930, Heinrich used the analogy of a row of dominoes to explain how distant causes lead to accidents. Ancestry and the social environment give rise to character flaws in a work such as bad temper, ignorance or carelessness*" (Dekker, 2019).

In modern terms, such character flaws are the main reasons for the unsafe working environment and mechanical hazards, which will eventually cause an accident due to human error. Later such human factors were improved by the use of "*Kaizen*" or popularly known as the lean method. The problem was not put in one person alone but on the entire system. The system had to work to prevent such accidents that might occur by changing its practices, procedures, and disciplines in the workplace. This method will help continue to reduce deficiency in human characters and increase cognitive capacity.

Towards the end of the 20th century, there was a significant increase in technological development. All the industries, including maritime, started to incorporate the technology available to increase safety and efficiency. During this time, technologies started to improve and were more reliable than ever before. As the reliability started to increase, users started to rely heavily on them without cross-examination. In addition to that, lack of maintenance, necessary updates, and misuse of the system resulted in many accidents. Some examples of advanced technology used in the maritime industry are radar, Electronic Chart Display, and Information System (ECDIS), GPS, gyrocompass, autopilot systems, and integrated bridge systems. The prime example is the dynamic positioning system, a combination of entire advanced technology summed up together to perform a single operation. Technology such as ECDIS/GPS has changed from celestial navigation or paper chart navigation. Gyro compass or optical compass had moved on from magnetic compass, from traditional sails to diesel engines. All bridge equipment today is installed as a part of integrated bridge equipment. These equipment increases precision and decrease errors in navigation, operation, and safety.

In an integrated bridge, all alarm systems are unified with information regarding criticalities onboard the vessel and its operation. In the past, there were few redundancies in a DP vessel. However, the use of technology helped to increase the redundancies to a greater level. Once the launch of various classes of DP vessels was introduced, progression of the DP class, the level of redundancy increased with the help of technology. The use of battery power to cut emissions and store excess power generated by vessels will eventually increase reliability. Now the industry is looking forward to the evolution of power sources to hydrogen or gas-powered system. These are just a few examples of technological marvel that is happening in today's world. In the future, the maritime industry is looking forward to sustainable shipping with autonomous capabilities.

Environmental causes trigger either human error or technical error as a cause for an accident. Usually, the environment is a cause for an accident, while technologies and humans are the existing safeguards. However, in few cases when the safeguards cannot foresee the consequences by knowledge or by experience, there is a risk for an accident to occur. When it comes to environmental factors being the cause of accidents, it is good to establish a system where seafarers are trained and have good experience with environmental parameters. In order to do so, the usage of simulations, real-life situation drills might be critical for establishing preparation for future challenges. Improvement in reception and analyzing the weather data could be critical in planning an operation and identifying the risks.

Organizational failures are another cause of accidents. Some examples include improper management, cost cut, ignorance of quality or effectiveness of barriers, and disregard of tightness between control structure and technologies. Unawareness of feedback between different levels (top-bottom or bottom-top) and inability to cope with surprises by not monitoring normal performance variability, buffering capacity, the balance between flexibility and stiffness, and cross-scale interactions will lead to organizational accidents (SINTEF, 2010). There are six ways to see and understand the organizational mechanisms related to accidents and their resilience (SINTEF, 2010).

Thus, mitigation measures such as risk assessment, quality management, internal audit, external audit, survey, port state control are used to provide safeguards. The regulatory body has set an acceptance criterion for the industry to follow these parameters. Generally, accidents occur due to two main reasons; technical and human error, if uncontrollable parameters such as weather conditions are ignored. In the maritime industry, most of the accidents are caused due to human error, which might have several reasons. The reasons can vary from fatigue, inexperience, carelessness, stress, mental health, and many more.

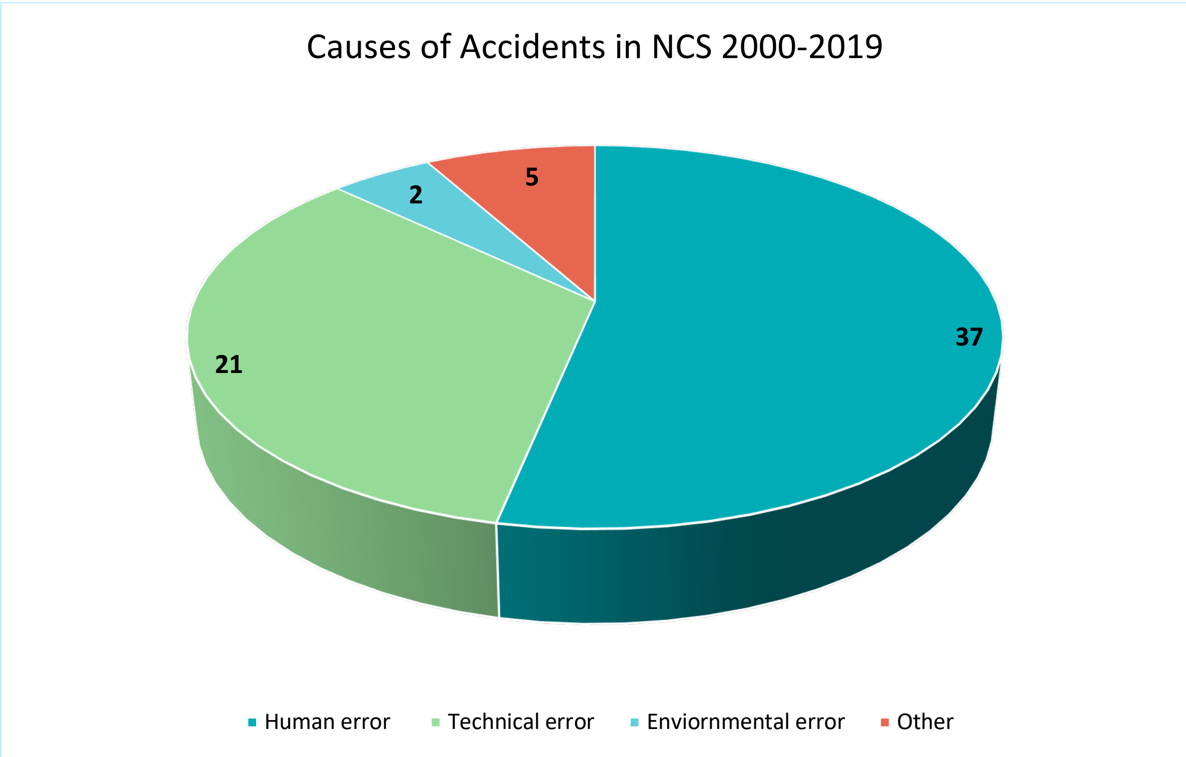

Figure 4 Causes of Accidents in NCS 2000-2019 (PSA, 2020).

In the following case study, the scenarios mentioned above will be explored. Statistical analysis will be given, related to causes of accidents in NCS, after the year 2000. The list of accidents was provided by PSA related to DP vessels operation in (PSA, 2001) the Norwegian Continental Shelf. In the years between 2000 and 2010, there have been 26 accidents, including collisions between vessels and offshore installations. Out of which six were very critical. In UKCS, five accidents with severe damage occurred at the same time. Between the years 2010 and 2019, 13 accidents were reported, out of which two were of high severity (PSA, 2020). An overall view of the list of accidents is shown in *Figure 4*.

As seen above, the majority of the accidents occur either due to human or technical error. Both the equipment made by humans and humans themselves are imperfect. Error is synonymous to humans when it comes to performance. Thus, the industry needs to find out and design systems that reduce human weakness or limitations. It is challenging to eliminate human error as the response to a situation is random and unpredictable. People do unexpected things; thus, disasters are challenging to predict. Similarly, with or without the involvement of humans and their malevolent acts, there are issues in the technical equipment. Generally, they are reliable, but sometimes, they fail. If attention to detail regarding its functioning is not given, a failure can occur at any time. After establishing standards in the industry after the year 2000, it is visible from the pattern shown in the graph (*Figure 5*) on how the technical issues are eliminated. There has been a significant reduction in the number of accidents due to technical issues. However, the accidents regarding human errors are consistent even though it is of descending nature.

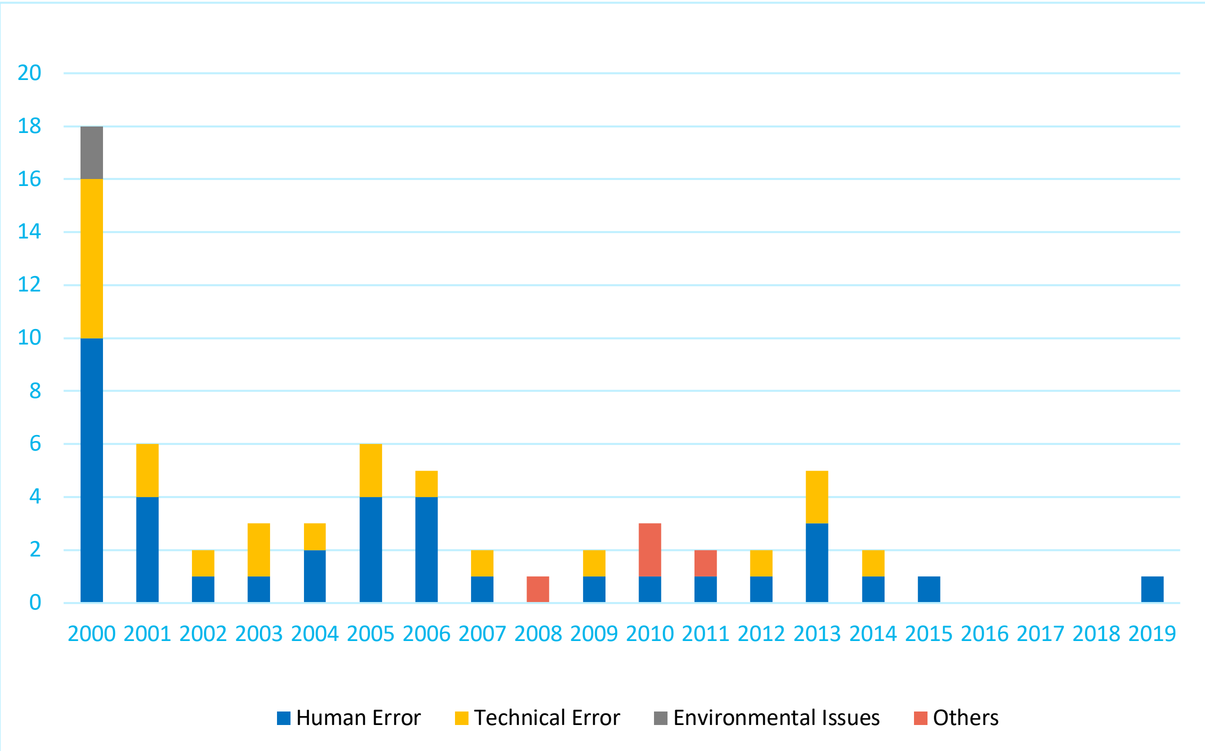

Figure 5 Classification of reported incidents to fixed installations in UKCS (Liverpool John Moores University, 2019)

There is a difference in perception of minor and major classification around the world. Levels for a threshold for minor, moderate, and major classification might vary more or less depending on the part of the world. An example of spilling of 1.6 tons of hydraulic oil in the Barents Sea caused national havoc in Norway's Parliament on 12th April 2005 (Bjørnestad & Olaussen, 2005). While decades of oil spills, leading to severe damage to the environment and lives of people living in the Niger Delta has been played down (Amnesty International, 2018). Considering that, in UKCS, according to its national standard, it is seen that during the late 20th century, there were a lot of minor accidents, including unspecified accidents. There have been primarily minor accidents along with occasional moderate incidents. These signs might reflect improved working practices due to periodic release in safety regulations as seen in *Figure 6* (Liverpool John Moores University, 2019).

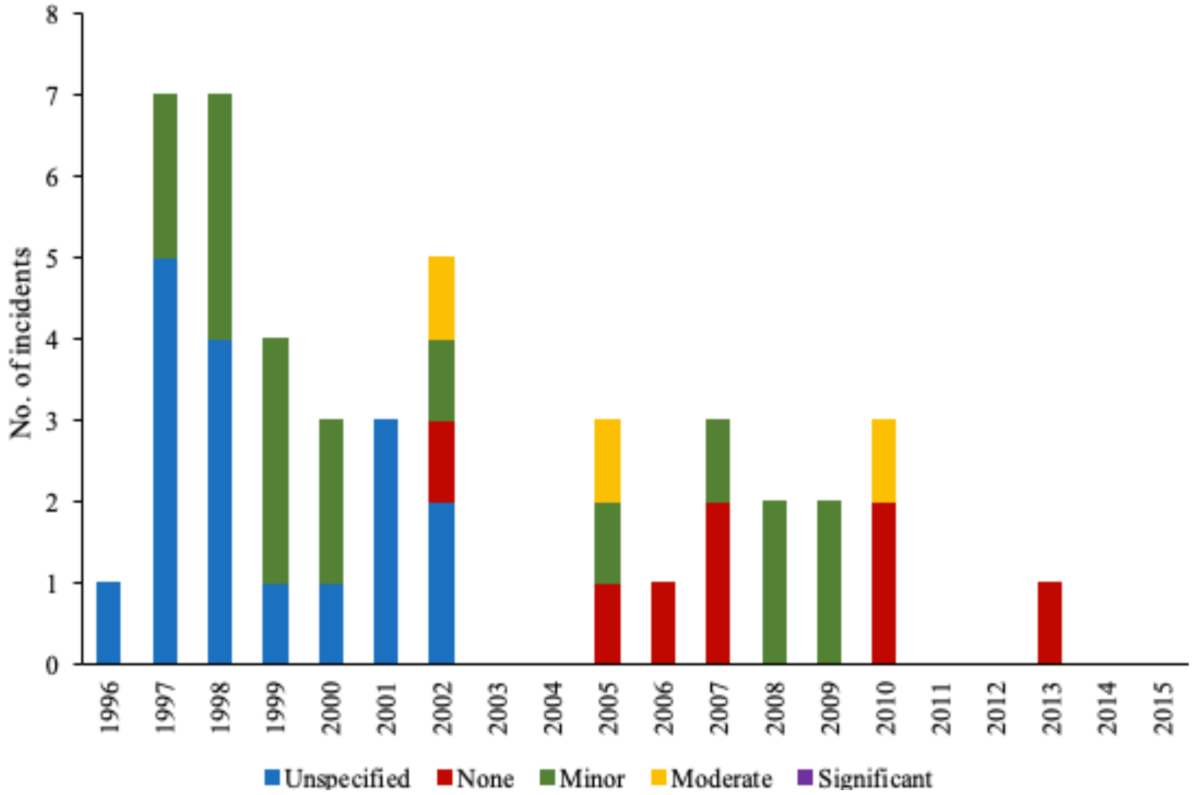

Figure 6 Number of accidents in NCS per year since 2000 (Liverpool John Moores University, 2019)

According to the report from UKCS, most of the vessels involved in the collision were the vessel which had the intention to operate within the proximity of the installations (Liverpool John Moores University, 2019). Generally, there is a tendency to have very few near misses recorded in the official statistics as many of the incidents are ignored as their importance is not well evident or no damage has taken place. In 20 years, both on the Norwegian continental shelf and United Kingdom continental shelf, the frequency of significant accidents has reduced considerably, along with other moderate and minor accidents. An incident frequency of accidents in UKCS is reflected in *Figure 7*, where the mean frequency of occurrence had dropped with an occasional spike in incidents. However, the "Cumulative Mean Mean" is reflecting a negative slope. This reflects on how the industry is progressing in terms of safety standards and working practices in offshore operations.

Despite the reduction in accidents in recent times, accidents occur from time to time, and the culprits of such accidents are mainly human deficiencies. Such revelation in the deficiency in human error and technical issues diverts our attention from the research question. Increasing the complexity of bridge equipment and looking into the capacity of operation of such equipment by a human must be investigated. It is the industry's responsibility to make the equipment user-friendly by using the advanced technology available while increasing the efficiency and handling the complex tasks of the operations.

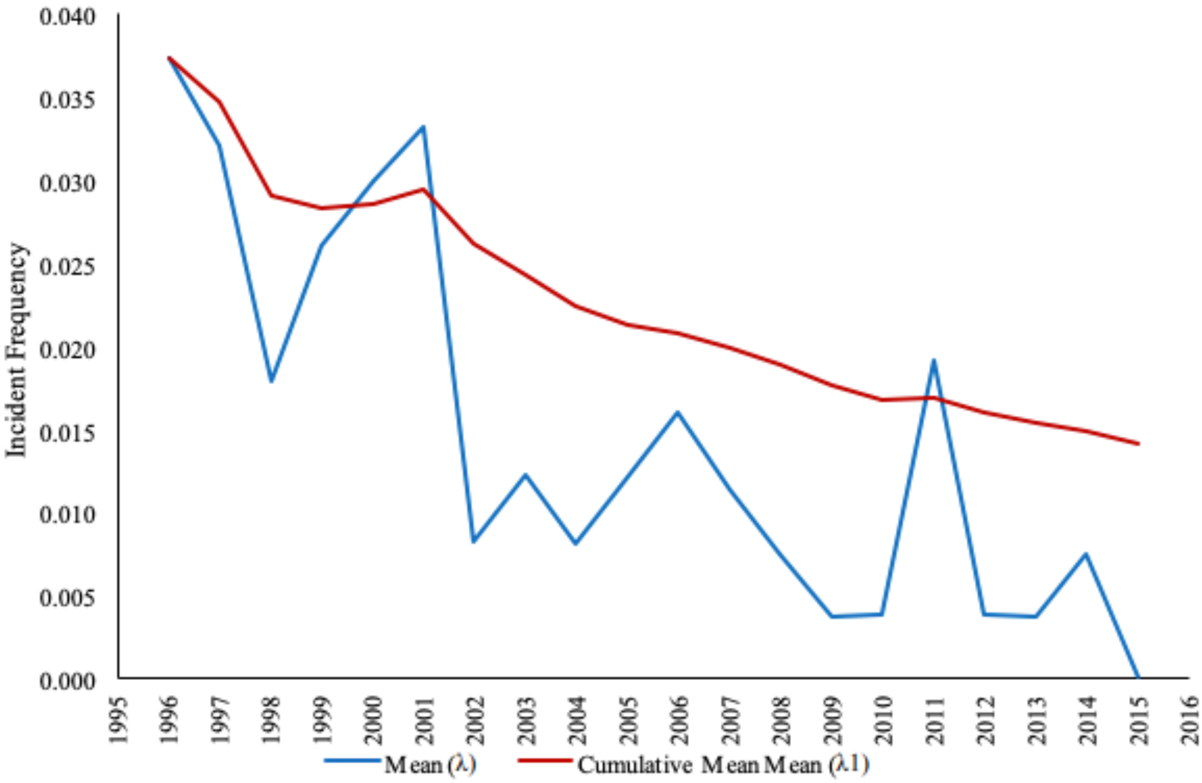

Figure 7 Mean and cumulative frequency of all reported incidents to fixed installations per year. (Liverpool John Moores University, 2019)

In case of an alarm situation in the bridge, both technical and human issues need to be addressed. The worst-case scenario could be a collision to the fixed installation. At the same time, there are a lot of technical issues that need to be tackled when it comes to loss of GPS signal (cybersecurity) and redundancies for the new fuel types that are about to be implemented in mass in the maritime sector. Both the Norwegian and English sectors' statistics reflect on the importance of focusing on the human and technical error to avoid collision or other forms of catastrophe. Regulatory bodies, shipping companies, and instrument developers need to have the farsightedness to improve and develop new technology and equipment.

4.1. Case 1: Review of events

To have situational awareness about DP technology, its growth, development, operators' handling its issue in terms of safety and accidents is vital. Three events with different characteristics from different times are considered. These contemplations will not just include the events in Norwegian waters but from around the globe. Eventually, the purpose is to have a better overview and increase safety and better working practice on vessels. The list of events illustrates what types of accidents might happen and the consequences of it. These accidents are taken as lessons learned to improve technology, working practice, and organizational strategy to reduce or eliminate hazards. Improvements can be achieved by implementing new mitigation measures, transferring risks, and improving the existing safeguards. Further research and evaluation of improvements in technology will be performed with the help of a survey. Challenges presented in this chapter are first narrowed down through a survey or HazID then discussed. Possible solutions are presented in the form of recommendations.

4.1.1. **Event 1**

The most recent accident between a vessel and an installation in the NSC will be addressed in this event. Events are summarized from the accident investigation report produced by Equinor and PSA, Norway. According to the reports issued by both organizations, Platform Supply Vessel (PSV) Sjoborg collided with Statfjord A (SFA) on 7th July 2019. Sjoborg was transferring fresh water, diesel oil and some deck cargo to SFA on the night of the accident. The vessel entered the 500m safety zone with a technical fault, and Sjoborg was operating in load reduction mode.

Consequently, the thrusters' power was reduced by 10 to 15 percent, according to the investigation report provided by Equinor (Equinor ASA, 2019). DPO was operating the vessel with prior knowledge of fault in the DP system. The operator then maneuvered the vessel near the installation on the weather side as the crane on the lee side was not operational. In the early morning of 7th June 2019, about 1 hour after the change of watch between both bridge and in the engine room, there was a sequence of alarms that came up in the IAS screen in the bridge saying, "FAULT IN BOSS SYSTEM PS," "FAULT IN BOSS SYSTEM SB" and several others in regular intervals. These alarms were not perceived as critical by the officer of the watch and in the engine room and were just acknowledged but not responded with an action. The crew was aware that the vessel was operational in these conditions and was not unusual and thus continued with the operation. While maneuvering the vessel alongside the platform for the convenience of loading and discharging of the cargo "BT1 AUTOSTOP", DP alarm: "TUNNEL BOW 1 NOT READY" and "BT3 AUTOSTOP" DP alarm: "AZIMUTH BOW 3 NOT READY" came from thruster system on the Integrated Alarm System (IAS) Alarm panel.

Eventually, the vessel lost its heading and position as the two bow thrusters dropped, drifted and collided with the platform. The DPO on the watch tried to switch to a partly manual position without success. The captain was called to the bridge when the vessel had already damaged the lifeboat station in SFA. Once the master took control, the aft section of Sjoborg hit the drilling shaft in the south of SFA. The vessel was then controlled with the manual DP positioning system. While moving away from the SFA, the fresh water and diesel hose came in tension and hit the deckhand on the face. The vessel took off from the 500m safety zone, and all the responsible parties were informed about the collision

Table 2 Vessel Details PSV Sjoborg

VESSEL PARTICULAR	DETAILS
IMO	9591923
CALLSIGN / YEAR BUILT	OZ2075 / 2012
FLAG	FAROE ISLAND
GROSS TONNAGE	4000
DEADWEIGHT	4543 (SUMMER)
LENGTH	86 METERS
BEAM	19.54 METERS

4.1.2. **Event 2**

Similarly, another accident occurred on the 8th of June 2009 between Big Orange XVIII and Ekofisk 2/4-W in the NCS. This accident has been investigated by Schlumberger, ConocoPhillips, and PSA, Norway. The event is summarized according to the investigation reports issued by the respective parties. In the early morning, Big Orange XVIII was headed for Ekofisk field for well simulation. The vessel was leased by Schlumberger. Since 2004, Wilhelmsen Ship Management AS was responsible for the Safety Management System (SMS), crewing, and technical management of the vessel. Before the change of the watch between watch officers, the second officer called Schlumberger supervisor about the approach to Ekofisk so that he can wake his crew. The captain takes the command at 0400.

Captain gets a call from Ekofisk by Schlumberger to ask about the vessel's operational readiness once they are in place.

Before picking up the telephone, the captain sets up the vessel's navigation system to autopilot. Once returning to the control station, none of his navigational inputs had any positive results. Captain experienced a lack of control of propulsion and azimuth thruster and switched to emergency control without any success. The vessel was heading for Ekofisk installation and passed many structures without contact, including Rigmar, a jacket accommodation platform, by 4-10 meters. Finally, the vessel hit Ekofisk 2/4 W at high speed. The emergency stop button was pressed on the bridge after the stop, and all the breakers were open. Engine room staff reset the breaker and restarted the azimuth thrusters. Complete control was possible from the bridge, and the vessel was towed away from the safety zone. This is one of the most significant collisions between platform and DP vessel on the Norwegian continental shelf. There was significant damage to the offshore installation, and the vessel itself resulted from the collision. However, there was no loss of life or injuries to personnel on the rig and the vessel. Nevertheless, there was significant economic damage caused to both parties because of the accident. Production on Ekofisk was also stopped, and the vessel Big Orange XVIII was heading for drydock for significant repairs.

Table 3 Vessel Details Big Orange XVIII

VESSEL PARTICULAR	DETAILS
IMO	8311314
CALLSIGN / YEAR BUILT	C6LD3 / 1984
FLAG	Nassau, Bahamas
GROSS TONNAGE	3719
DEADWEIGHT	3424 (SUMMER)
LENGTH	76.09 METERS
BEAM	18.01 METERS

4.1.3. **Event 3**

On 27th July 2005, the multipurpose support vessel Samundra Suraksha was in the finishing stage of a diving support mission. The location was about 160 km west coast of Mumbai, India, on the Arabian Sea. Around 1400 local time, there was a medical emergency in the galley of the vessel Samundra Suraksha. The diving operation was suspended temporarily, and a medical evacuation was requested. There was no reply from any of the stations. The vessel required medical assistance. It sailed closer to the Mumbai High North Platform even if there was no reply on the radio. After arriving near the rig, the rig responded with POB issues onboard and the absence of a doctor. The weather conditions were also poor, and the helicopter could not fly in these conditions (25knots wind and 4–5-meter swell).

However, after an agreement with the offshore installation manager, the patient was agreed to be transferred with the crane, on a basket, from the windward side. Crane on lee side was out of operation. During the transfer, the master perceived that the starboard azimuth thrusters pitch was sluggish. As the captain was under time pressure to evacuate, he approached the platform by operating the thrusters in emergency mode.

After the injured person was transferred to the platform, the vessel was on its way to move away from the installation; a big swell hit the vessel and pushed it against the installation. The helideck hit the gas lift risers and resulted in an explosion as the gas started to leak in a place where there was no provision for fire protection. Unfortunately, this led to the loss of life on twenty-two people, where eleven perished at sea and another half were found dead. There were a total of 384 personnel on the rig, and 362 were evacuated successfully. After 36-hours the vessel sank, and the entire platform Mumbai High was lost due to fire. (Daley, 2013)

Table 4 Vessel Details MSV Samundra Suraksha

VESSEL PARTICULAR	DETAILS
IMO	8109383
CALLSIGN / YEAR BUILT	NA. / 1982
FLAG	India
GROSS TONNAGE	5006
DEADWEIGHT	4347(SUMMER)
LENGTH	101.81 METERS
BEAM	19.50 METERS

4.2.Case 2: Hazards in loss of position in DP vessel.

In terms of the future aspect of the DP vessel, there are several reasons for collisions while performing a DP operation. The loss of GPS signal is critical as many of the redundancies rely on the GPS system. There are multiple reasons for a ship to lose position while operating in DP. However, the focus is kept on the loss of position due to GPS signal. The hazards can be categorized into two different statuses; the first being internal, where the risks are from inside the ship, such as individuals working onboard, technical issues on board, and organization responsible for the overall functioning of the vessel, the second, is the risk from outside the physical vessel and the ship's management. As digital technology and advanced automation are upgraded, the industry relies on it and has a big challenge to use optimally use the equipment with the highest safety standards and increased effectiveness. Generally, the DP class 3 vessels are equipped with three redundant systems: the independent GPS system and the third being a separate position reference system. The independent antennas for each GPS system are usually located at a reasonable distance apart and are usually in a monkey island or on the funnel of the exhaust system. These two GPS systems with another PRS (CyScan, RadaScan, SceneScan, HPR, Taut wire) will work together to keep the ship in position and their heading at references. The purpose is to see if the current redundant systems are good enough to prevent hazards that might appear in the future to prevent the operation from reaching its goal.

Internet coverage is increasing with the help of satellite technology and will further extend the reach among the global population. About four billion people have internet, as stated in the statistics of ITU in 2019 (International Telecommunication Union, 2020). It shows the increase in the risk of cyber-attack to-and-from any part of the world. Regulatory bodies, classification societies, and other associated parties need to take the initiative to address the risk of cybersecurity issues.

DNVGL is giving cybersecurity a class notation (DNV, 2021). Acknowledging the importance of cybersecurity in the changing world signifies its importance and prepares the industry for upcoming challenges. Cybersecurity is one of the biggest challenges in the maritime industry as vessels rely upon *Information Technology*. Computers are dealing with the most complicated tasks; with the help of sensors and feedback data provided. They can achieve the goals that are set for the operations. Automation and digitalization increase the complexity in DP vessels together with efficiency. Eventually, increasing the risk present, which might cause the loss of position in DP vessels and collision with an installation, increases significantly. In worst-case scenarios, there is a possibility of overloading the network with excessive traffic, commonly known as *netstorm*. In this regard, the controllers are overloaded with an increased packet flow. Network overloading will make the system kneel by not being able to operate thrusters, monitor shutting down conditions (ESD), or protect switchboards (PMS). These malfunctions prevent signals from reaching the appropriate termini. Under netstorm conditions, successful delivery of data signals is not guaranteed and thus increases the risk of losing control in real-time.

4.3. Case 3: Redundancy in DP vessels for new types of fuel.

The Paris Climate Agreement (United Nations, 2015) focuses on a long-term goal of stabilizing GHG concentration in the atmosphere to a level that would prevent anthropogenic interference to the global climate. The global strategy is to:

a) Limit average global temperature increase to below 2 degrees centigrade.
b) Increase adaptive capacity to the adverse effect of climate change by developing low GHG projects
c) Ensure financial stability of the projects to achieve climate-resilient development and reduction of GHG.

According to the long-term vision, GHG will be at the peak by 2020 and is expected to be reduced to zero before the end of the century. In order to control the temperature increase within 1.5 degrees centigrade to safeguard future living conditions, the emission of GHG must be zero before 2050. To achieve this goal maritime industry is making an effort by not waiting for environmental changes to be implemented for newly built vessels but by making current vessels diesel electric. The current emission budget for 1.5-degree Celsius will be finished within few years (Hausfather, 2018). Shipping companies are coming forward with Zero-emission operations on the offshore market. Some industry segments are leaning on hydrogen as the ultimate solution, whereas others towards electrification. The expansion of offshore wind, solar, redundant lithium-ion batteries make the segment equally promising. Nevertheless, there are concerns in using both fuel types, which brings new challenges.

Hydrogen as Fuel

Hydrogen is colorless, odorless, tasteless, and nontoxic gas that could be used for combustion. Hydrogen has been in use in spacecraft rocket engines, even though its use has safety concerns. Those safety concerns must be addressed as there have been disastrous accidents. Some of its safety concerns are similar to those encountered with LNG. Nevertheless, its properties are entirely different from methane or LNG.

Hydrogen oxidizes by producing harmless substances. As hydrogen has a higher energy density per unit weight than methane and LNG, it is more prevalent within rocket technology as the dangers and phenomena are well understood and recognized. However, it is not so common in the maritime industry to use hydrogen in smaller vessels.

Along with that, hydrogen has a high diffusion rate under average temperature as it is the element with low atomic mass. It is lighter and tends to rise upwards.

The biggest challenges for ships must be acknowledged, by ship designers, to utilize hydrogen as a primary fuel source.

Some of the challenges of hydrogen that are seen in today's context are mentioned below.

- *Storage*

Hydrogen in its natural state is in gaseous form. Its boiling point is -253°C. Thus, it needs to be cooled and compressed in order to increase the volume of fuel carried. This property causes hydrogen to boil quickly, having a slim frame for ignition. Hydrogen is the smallest element in the periodic table, and its physical property enables it to escape through porous surfaces. Thus, the container containing hydrogen must be thick and solid to keep hydrogen at the correct temperature and pressure. The flames of hydrogen are visible under daylight but have no shoots compared to other fuel sources. Hydrogen can ignite once mixed with air or explode at both lower and higher concentrations of the gas in the atmosphere, making it one of the easily ignitable gasses present. Static electricity can also ignite it.

- *Transportation*

Lack of efficient transportation medium or facility to end-user is another challenge for hydrogen. Chilled hydrogen is transported in liquid form at less than -253°C. There is a significant risk of cold burn if it comes in contact with living tissue. Such transport systems contain bulky and thick walls and are usually not a cost-effective way to transport fuel. Low temperature causes any container material to become brittle when used to transport or store hydrogen for a long time. An alternative source of transportation is in the form of Ammonia (NH_3). Much research is ongoing regarding this subject; solid porous materials and carbon nanotubes are in the early stage of development (Minnesota Department of Public Safety). Another issue is the lack of refueling infrastructure, which is a challenge for hydrogen-based ships. These refueling stations are just as crucial as the hydrogen-based ships to function efficiently. Currently, there are few options available for refueling around Europe.

- *Leak Detection*

As hydrogen molecules are tiny, technologies to detect the leak concentration of hydrogen below the lower flammability level are still costly or are not readily available (Minnesota Department of Public Safety). It is not possible to give hydrogen gas a distinct form of smell. It is challenging to combine odorants that are similar to LPG or LNG. The sulfur content of current odorants is damaging to fuel cells. However, several studies are conducted into finding the possibility of removing these odorants before the fuel enters the fuel cell (Minnesota Department of Public Safety). Even with today's advanced technology, it is challenging to detect odorants; even though, they are cheaper than hydrogen detectors.

A new piece of technology has developed to detect hydrogen on the principle of thermal conductivity by comparing a test gas (Hydrogen) with a reference gas (air). The principle is that different gases conduct heat at different rates. This system performs optimally when differences in thermal conductivity between the target gas and reference gas (air) are significant, for example, in hydrogen or methane (Minnesota Department of Public Safety). This equipment is available in both portable and fixed installation forms.

Battery as Fuel

Primarily, batteries are introduced in DP vessels to save surplus power in the switchboard due to variation in load. Later such power could be used when demanded by exempting the usage of a diesel motor. It will eventually help increase efficiency, reduce emissions and decrease operational costs. DP vessel benefits from battery technology by reducing the termination of DP operations due to the occurrence of DP incidents (DNVGL, 2019 a). Battery technology has become extra redundancy for DP vessels to prevent accidents, even though there have been very few DP-related accidents in the past five years in vessels in NCS. Thus, proper development of battery systems is essential for the offshore industry.

This benefit comes with few disadvantages; the chemical reaction hazards and the risk of thermal runaways and are considered the biggest challenges for the battery industry. The scale on which the reaction happens has a significant likelihood of runaway. Internal fire due to thermal runway while charging the battery is one of the major challenges for the shipping industry. It questions the reliability of these systems (Eliassen, 2019). Internal fires might be due to failure in the battery system or short circuit or thermal runaways. Battery packs store high direct current and voltage. The head produced increases the volume of toxic exhaust gases, increases pressure, and impairs the capacity to ventilate such gases (Health and Safety Executive, 2014). The battery system might escalate any external fire if it reaches the battery storage compartment. It might occur because of multiple thermal runaways with the release of flammable gases. It is commonly known that battery fires burn for an extended period by releasing toxic and flammable gases, thus reflecting on safety challenges onboard the vessel.

Similarly, there are risks related to hydrocarbon gas released from subsea wells reaching lower explosive limits, leading to an explosion if these gases reach close to the battery packs. Challenges in design requirements to isolate hydrocarbon gases before reaching the battery compartment. If done correctly, it will eventually reduce the ignition of gases. Other health-related risks include injuries to personnel due to electric shock, as the ship is built with a good conductor of electricity (Iron). Water Ingress in the battery storage compartment is another challenge in case of flooding. Such flooding might be caused by malfunction of the fire extinguishing system or breach of watertight doors. The battery compartment must be well above sea level to reduce the risk of flooding. Finally, lithium-ion batteries' lives are relatively low, and the uses of such batteries put responsibilities to the parties involved to come up with a proper solution for waste management or recycling method to prevent environmental damages.

5. Results of literature study and analysis of data collection

DP operations have been in offshore business for more than half a century. The industry has learned a lot about safety, risks associated with DP operations, and its mitigation. The frequency of accident trends is going down. However, it is difficult to fine-tune the DP system to remove the risks while on operation altogether. Investigation report on Collision of Sjoborg with Statfjord A on 7th June 2019; showed issues on human behavior towards alarm, organizational issues, and technological drawbacks (Equinor ASA, 2019). Especially during emergencies when numerous alarms arrive quickly, the DP operators are challenged to process the criticality and spotlight critical alarms to avoid calamities. More challenges are apparent, mainly due to oil and gas exploration in the Barents Sea and the implementation of hybrid vessels using Hydrogen and battery technology as an alternative fuel.

5.1. Literature study

During the literature study, it was found that there are limited resources available for the research question. The majority of this research is connected to DP vessels and its risks that are present in operations. There are few technical requirements available to support this research and many of which have restricted access. This situation limits the amount of information that is open and accessible. Literature that is used for the research is open and of non-classified nature. For alarm systems and their classification, primary information is derived from YA-711 guidelines provided by PSA (PSA, 2001).

5.1.1. Alert system

Codes, standards, and practices are implemented in DP vessels to ensure that no single failure leads to loss of position or heading, or both. Alert systems are a combination of different warning systems, functioning singularly or in a combination of several alarms, Fault Mode Effect Analysis (FMEA), Activity Specific Operating Guidelines (ASOG), vetting, audit, inspection, and others. Its primary function is to warn the operator or the system that something is out of order and requires attention. Such alerts can be divided into several different categories according to severity and complexity. In alarms, alerts are represented in various forms, such as visual and audio, where some alerts are in text forms such as reports from vetting and FMEA.

Many traditional alarm systems are based on a "*one sensor-one alarm*" framework (O'Hara, 1998). There are several requirements for an alarm to be operational. Functional requirements for alarms are divided into the following categories as shown by "*Principles for alarm system design*" (PSA, 2001).

- General requirements
- Alarm Generations
- Alarm Structuring
- Alarm Prioritization
- Alarm presentation
- Alarm Handling

A table for the classification of alarm systems is presented in Appendix B, along with the requirements for each category. A schematic of how integrated automated system is connected on a bridge is shown in *Figure 8*.

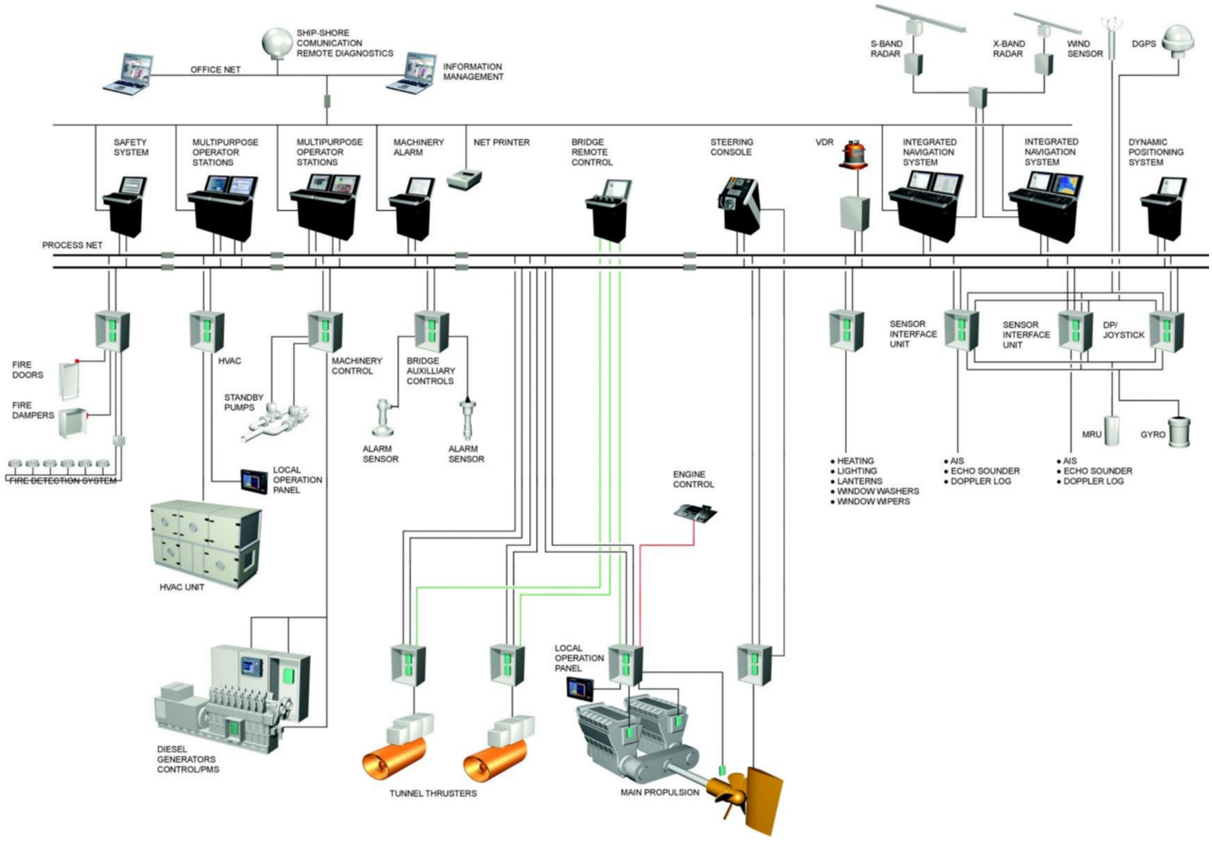

Figure 8: Integrated automation system provided by Kongsberg (Standal, 2013)

Application of alarm in DP vessels is a basic form as it edifies operators' performance during DP operation.

5.1.1.1.Alarm management philosophy

Alarm management philosophy (AMP) is part of the alarm management life cycle. AMP aims to yield an alarm system with effective design, proper implementation, and efficient operation. An alarm management life cycle can be seen in *Figure 9* where APM is practiced. The alarm management system is ideal for a DP vessel as it shows abnormalities or disturbance to the operator from numerous components engaged, especially during DP operation. In order to avoid the inability to diagnose and control such abnormal situations, an effective alarm system is necessary to reduce damage to assets, environment, reputation, and most importantly, human lives. The advanced alarm management system has several advantages where it improves operators' effectiveness, which reduces downtime, increases safety, reduces losses, and identifies issues in alarm, including its performance and operators' workload (Mehta & Reddy, 2015).

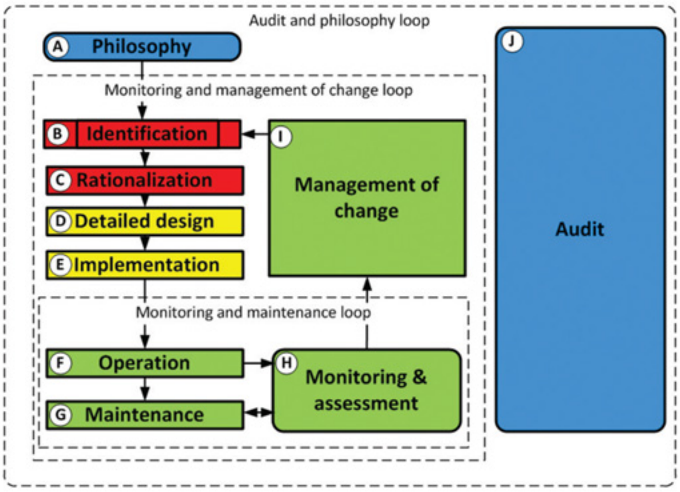

Figure 9 Alarm Management Lifecycle from International society of Automation (ISA) Standard (Fitzpatrik, 2016)

Alarms are a primary alert system for preventing deviant situations during any operation, and operators must use alarm systems to find critical errors or disturbances in DP vessels with high efficiency. Nowadays, many of the alarms are found in an automated form and manual versions. First, an alarm has its primary function as a warning system for operators to indicate an abnormality in the system. Second, it is a log where the sequence of events could be analyzed later to find the problem or prevent deviation from an occurrence.

Generally, alarms can be categorized into different classes according to its accountability presented by PSA (PSA, 2001),

- *A basic alarm* is a fault detection system due to a deviation detected by one sensor or one process.

- *Aggregated alarms* are an assembly of basic alarms that together perform as a sub-system or system.
- *Model-based alarms* are alarms generated based on remote simulations by mathematical modeling of the process.
- *Key alarms* are a selection of essential alarms available for operators during overload for precision handling of the situation. All safety alarms are part of key alarms, but some other alarms could be a part of the key alarm.

There are different methods for processing and handling the alarms. According to (PSA, 2001) installing an alarm system should help operators perform tasks safely and efficiently.

The following flowchart (*Figure 10*) shows the relationship between alarm systems, their processing, and handling concepts.

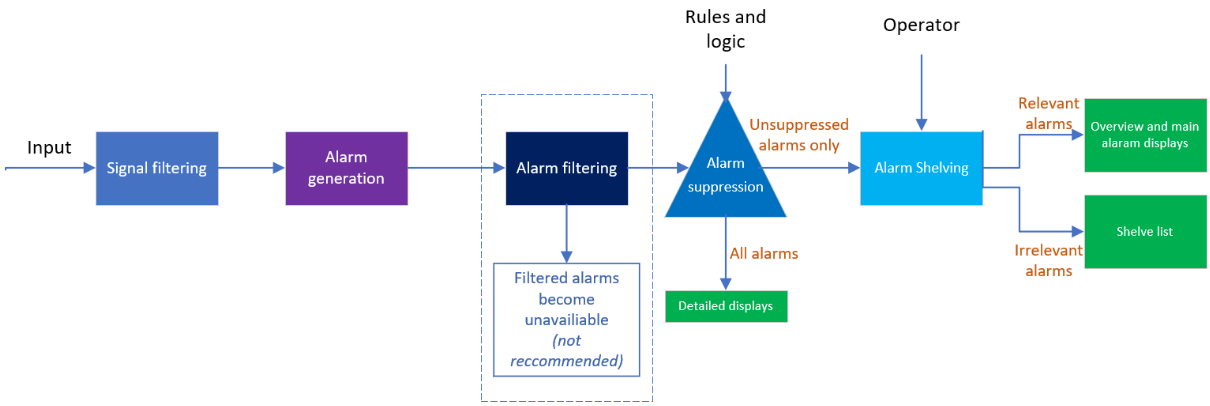

Figure 10 Flowchart for alarm system Processing and handling. (PSA, 2001)

As shown in *Figure 10*, *signal filtering* is used to process the input of raw signals entering the alarm system, and there is always a possibility to have an error signal, noise, and other unimportant data. Signal filtering is a primary barrier that protects the alarm system from getting triggered for the wrong reasons. A filtered signal should be validated as a signal *validation process* to avoid a failure or drifting signals that could trigger the alarm system (Hoffmann, Fantoni, de Oliveira, & Bye, 2000). In a worst-case scenario, it could hide important information or distract operators from a non-critical anomaly. When the signal is validated, an alarm is generated, and an option of *alarm filtering* might prevent the alarm from reaching the operator. However, if these functions were disabled or unavailable, an alarm would be triggered. The alarm filtering option might not let operators find alarms in any part of the system, which is not recommended by a regulatory body (PSA, 2001). At times there is a possibility for an operator to be overloaded by irrelevant alarms. *Alarm suppression* function aids in filtering the alarm for displaying or heard by the operator from the main alarm list.

Nevertheless, the alarms are accessible in the system at a more comprehensive level. *Alarm shelving* is a feature that allows the user to remove any alarm or a category of an alarm from the main list and shifting it to a shelve list (Schneider-Electric, 2005). *Alarm block or inhabit* is an action where the input signal is disabled to avoid a complete shutdown of the system while still presenting the alarm to the operator (Standard Norway I-002, 2001). Some of the definitions used regarding alarm systems in this literature are listed in Appendix A.

Categorization of individual functional requirements is mentioned in YA 711 is tabulated in Appendix B. There are 43 functional requirements according to YA 711 standard published by PSA (Veland, Kaarstad, Seim, & Fødestrømmen, 2001). Functional requirements are categorized into different subsections such as "*general requirements, alarm generation, alarm structuring, alarm prioritization, alarm presentation and alarm handling*" (Veland, Kaarstad, Seim, & Fødestrømmen, 2001). These requirements are sorted out according to the researcher's observation on categories of *Human, Technology, and Organization*.

5.1.1.2.Failure Mode and Effects Analysis (FMEA)

IMO MSC 1580 defines FMEA as '*A systematic analysis of systems and subsystems to a level of detail that identifies all potential failure modes down to the appropriate subsystem level and their consequences*' (IMO, 2017). For a vessel with Class 2 and 3, IMO 1580 requires monitoring hidden failure or *worst-case failure design intent*. FMEA is a reliability tool that functions as a pre-warning system for a design or functioning system. FMEA acknowledges vulnerabilities of the DP system that could spread throughout the redundant system. The aim of FMEA in a DP vessel (redundant system) in a specified unit is to show extensive, objective evidence of the required redundancy and fault tolerance (OCIMF, 2020). FMEA is one of the barriers that aids in identifying deficiencies and reduces the probability of occurrence of risk or the impact of the hazard that tends to occur. It gives parties involved in offshore operations confidence and enhanced comfort that the vessel is fit for purpose and that the operations will be performed with minimum risk and increased safety.

Typical DP classes 2 and 3 are required to have class-approved DP FMEA and DP FMEA proving trials. These trials are supposed to occur either in regular intervals according to class requirements or immediately after each modification or addition in a DP system, which might affect the redundancy of the DP system. Most of the time, FMEA is used as an acceptance criterion by the classification society and other parties involved in offshore operations for a vessel with Class 2 and Class 3; usually, it is done on a case-by-case basis. FMEA describes the effects of failures for any system components when the whole system is in use. At the same time, FMEA is a document that helps DPOs to find the procedure to find the solution for the situation for unknown failure. Thus, in *Table 5* parties are usually interested in DP FMEA are listed,

Table 5 Users and institutions which are interested in FMEA and their needs.

Institution / User	Purpose
Classification Societies	FMEA is needed for acceptance criteria
Owners	FMEA is required to satisfy the charters need and be confident
Charters	for confidence about the vessel, if it is fit for purpose
Operators	procedures can be developed to mitigate any failure modes
Maintenance Staff	any critical area that can give rise to a severe problem during failure can be targeted by planned maintenance during downtime.
Offshore Vessel Inspection Database (OVID) / Accident Investigators	FMEA shows procedures during an emergency thus, FMEA is an essential document for examiners.

Investigations have revealed that *common points* between redundant equipment groups are frequent and contributory factors for loss of position. These factors are confirmed by the United Kingdom Health and Safety Exclusive Agency (UK HSE)/ Det Norske Veritas (DNV) *Review of methods for demonstrating redundancy in dynamic positioning systems for the offshore industry* (2004). In the study mentioned above, it was suggested that vessel operators and managers were not always implementing the guidance available and, in many cases, were not aware of it (OCIMF, 2020). Along with that, it was seen that there were flaws in the FMEA technique. There are plenty of guidelines on producing comprehensive FMEA, but it is apparent that the guidance is not being implemented uniformly across the industry.

There are few common weaknesses in FMEA, where lack of understanding of DP design and its configuration is explained by (OCIMF, 2020).

- Common points

In a redundant DP system, a common point is used as a point of reference. In some cases, common points are required to achieve referencing objectives. Inadequate identification and assessment of common points might occur as common points might be out of FMEA's scope or were not identified in the DP system. Even if the common point was identified, the range of failure modes considered might not be adequate or comprehensive. In order to avoid confusion, misuse of common points should be avoided. By the principles of autonomy, independence and segregation should eliminate misuse of common points (OCIMF, 2020). Designs using these principles are convenient to verify and validate compared to different substructure integrated designs with multiple hardware and software adjuncts. Test on demand and design to testing is efficient functions for such a process.

- Closed bus ties and cross-connections

FMEA should show all the configurations and modes that the vessel is capable of performing. According to the industry guidelines, the requirements for demonstrating the effectiveness of close bus ties and open bus vary greatly. These requirements depend on various regulatory bodies, including classification societies. Requirements for validation of tests continuously change as there are new developments of technology and, at times, to deal with new risks (Dynamic Positioning Committee, 2015). According to IMO MSC 1580 the bus tie breaker should always be left open as it prevents the transfer of failure to other redundant sections of the ship. In addition, for the IMO class 3 vessel, there needs to be flood and fire protection so that failure in one system should never be transferred to other systems. Thus, charterers require that the DP vessel should be operated in an open bus configuration to compass redundancy.

- Hybrid power

Hybrid power (Hydrogen + Battery) comes with many advantages, such as compliance to SDG, reduction of greenhouse gases, peak shaving, meeting requirement for spinning reserve with stored energy, improved dynamic response with an instant supply of energy, and improved resilience of the DP System (OCIMF, 2020).

A new technology that the industry is implementing or experimenting with should be clearly stated and well understood by parties involved. Essential elements of the redundant system should be verified for hybrid systems. Performance, protection, and detection of the risk and redundancy should be well established as there are many permutations and common points of failure in hybrid power systems.

According to (OCIMF, 2020) verification and validation of hybrid systems are done by using the following criteria,

- Performance

In the FMEA trial, it should be documented that both power delivery, energy storage capacity, and spinning reserve should be well defined compared to diesel generators. If hydrogen is used as an energy carrier, it should be demonstrated that prime mover performance meets the design intent. Any divergence from performance compared to traditional fuel systems should be identified along with post-failure criteria.

- Protection

As hydrogen is unstable, a safety standard is necessary to be established. The development of hydrogen-based systems is well ahead of codes, standards, guidelines, and recommendations; the protection of redundant systems and seaworthiness of the vessels has to be ensured. A spinning reserve is a form of protection — lack of spinning reserve is another potential hidden failure as hybrid power provides spinning reserve effectively (OCIMF, 2020).

- Detection

Detection of degradation of performance is vital and needs to be tested thoroughly both continuously and periodically. Detection of hydrogen leakage is challenging, especially when it has very ambiguous flame characteristics and undetectable physical properties. Section 3.2.7 of IMO MSC.1/Circ. 1580 defines the measurements included in the DP control system consequence analysis (OCIMF, 2020).

Below (*Figures 11 and 12*) it is shown how the redundancy table for DP class 2 and 3 vessel visualizes along with schematics of DP operation groups

Subsystem	Independent/ Common	Ref	Port		Starboard	
Gyros	Independent		Gyro A		Gyro B & C	
Anemometers	Independent		Wind A & B		Wind C	
DGPS	Independent		DGPS A		DGPS A	
MRU	Independent		MRU A		MRU B & C	
Networks	Independent		NET A		NET B	
Power supplies	Independent		PSU A (input)		PSU B (input)	
Controllers	Common	1	PSU A	PSU B	PSU A	PSU B
			Con A		Con B	
Serial hubs	Common	2	PSU A	PSU B	PSU A	PSU B
			Ser A		Ser B	
Network hubs	Common	3	PSU A	PSU B	PSU A	PSU B
			Hub A		Hub B	
I/O interface	Common	4	PSU A	PSU B	PSU A	PSU B
			I/O A		I/O B	
Laser Position Reference System (PRS)	Common	5			Laser PRS	
Controller	Common	6	Online controller			
Redundancy network	Common	7	RED Nen (A to B) & (B to A)			
I/O	Common	8	Internal I/O bus A			
	Common	9	Internal I/O bus B			
	Common	10	Network			
Thruster control mode	Common	11	Mode selector			

Figure 11 DP Control System (Redundancy Verification Table) (OCIMF, 2020)

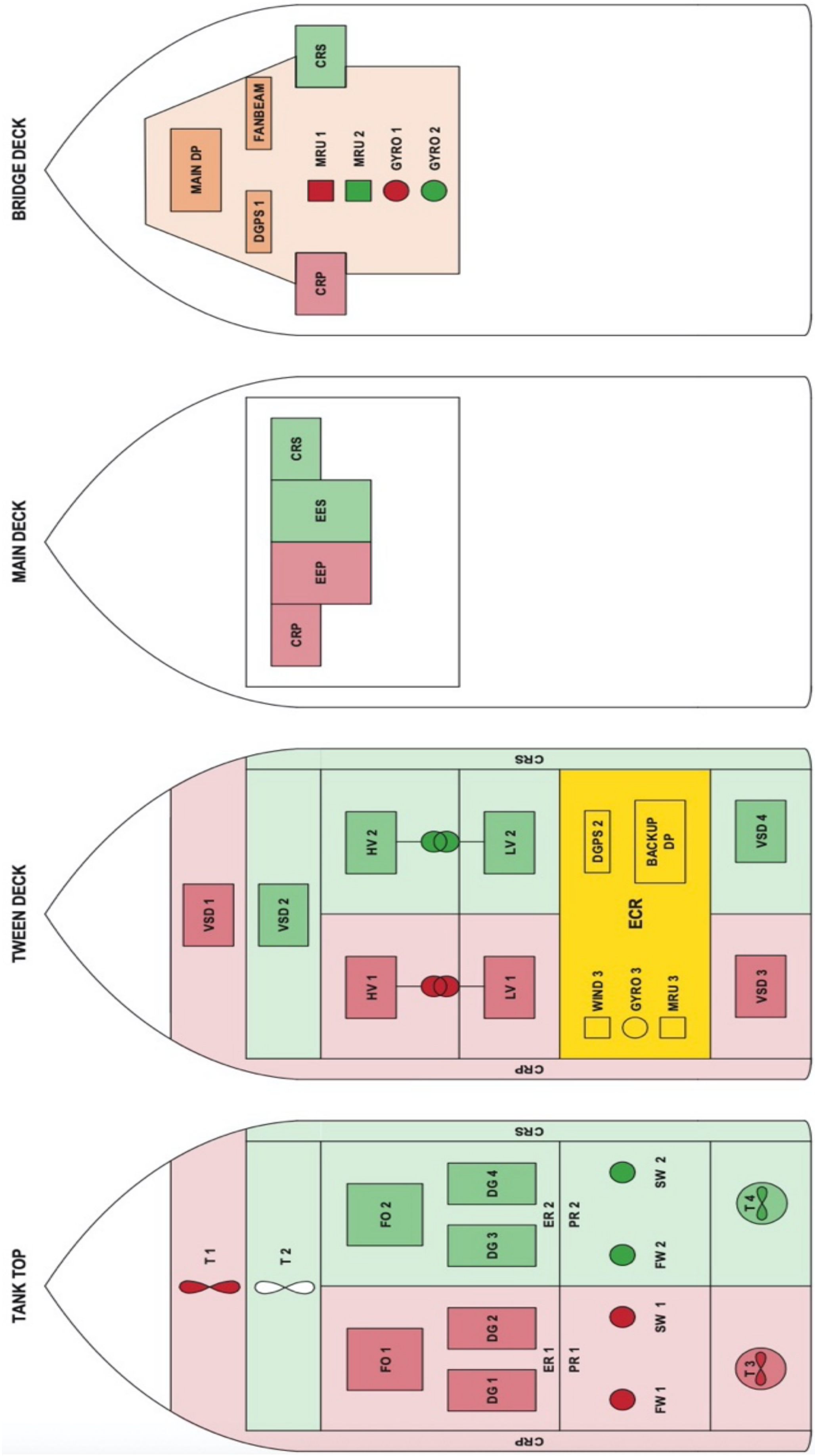

Figure 12 Schematic diagram for DP redundancy

Similarly, separation of analysis of power and propulsion along with DP control can be seen in the following tables (*Tables 6 and 7*).

Table 6 Separation Analysis for Power and Propulsion (OCIMF, 2020)

Separation – POWER and PROPULSION					
	Port DP equipment group			Stbd DP equipment group	
Deck	Compartment	Components	Colocation	Components	Compartment
Tank top	T1 – LOWER	T1, Motor and HPU	NDU A2 cables to FS in STBD GROUP NDU B2 cables to FS in PORT GROUP	T2, Motor and HPU	T2 – LOWER
	ER1	FO1 DG1 DG2		FO2 DG3 DG4	ER2
	PR 1	FW1 SW1		FW2 SW2	PR 2
	T3 – LOWER	T3 and Motor		T4 and Motor	T4 – LOWER
Tween deck	T1 – UPPER	VSD1		VSD2	T2 – UPPER
	HV – PORT	HV1 HV XFMR1		HV2 HV XFMR2	HV – STBD
	LV – PORT	LV1 LVXFMR 1		LV2 LVXFMR 2	LV – STBD
	T3 – UPPER	VSD3		VSD4	T4 – UPPER
Main deck	EEP	UPS1		UPS2	EES

Table 7 Separation analysis for DP control (OCIMF, 2020)

Separation: DP control			
DP control system	Deck	Compartment	Components
Main DP control	Tween deck	ECR	NDU B1 MRU 1 and 2 WIND 1 and 2 GYRO 1 and 2 DPC 2
Colocation	Main deck Tween deck	Port cable route	Cable for fire backup switch Cable for sensor isolation box Backup DP system to NDUA1 Net A
		Stbd cable route	Main DP system to NDUB1
Backup DP control	Main deck	Forward bridge	NDU A1 MRU 3 WIND 3 GYRO 3 UPS 3 DPC 1

5.1.1.3.Activity Specific Operational Guidelines (ASOG)

ASOG is a decision matrix where operational guidelines are defined for the safe operation of the DP vessels by providing an overview of methods used to plan and execute offshore vessels or routine offshore activities (IMCA M220, 2021). ASOG procedures are based on FMEA. IMO has presented guidelines in MSC. 1/Circ. 1580 to "*recommend the design criteria, equipment, operating provisions, testing and documentation for DP system to reduce the risk to the Personnel, vessels or structures, and environment while performing operations under DP operations*" (IMO, 2017).

ASOG should continuously be developed and implemented by a DP vessel for all offshore activities (location specific). Thorough knowledge of the DP system, DP FMEA, operational manual, vessel's operational location, and risk assessment are used to prepare ASOG, CAM, and Task Appropriate Mode (TAM). According to IMCA recommendations, all operational activities should address the vessel's systems, including all equipment and its configuration associated with the task or activity that is about to undertake. Similarly, activity planning should address limits in equipment capacity and operation depending on the location. The limiting parameters should trigger a change in the lighting system used in ASOG. At the same time, ASOG should define the responsibility and duty of the personnel in a clear and user-friendly manner to act during the change of status in ASOG lights (IMCA M220, 2021). These procedures should be clear to key vessel personnel responsible for acting during change of status in ASOG traffic lights.

In addition to ASOG, the Critical Activity Mode (CAM) defines the forbearing design for a DP vessel. All external forces, including environmental factors must be considered, and implemented in all critical activities performed by the vessel. Worst Case Failure Design Intent (WCFDI) is ensured for class 2 and 3 DP vessels and will not exceed the threshold limit to ensure safety. Similarly, it is possible to keep a vessel operating under a condition where the consequences of exceeding the vessel's Worst-Case Failure (WCF) are acceptable. Such operational modes are based on risk assessment and are known as TAM. ASOG, CAM, and TAM should be comprehended by all parties involved in the DP operation. DPOs need to acknowledge the operational and technical limits used to prepare the ASOG and contribute during its development.

The ASOG is prepared for the performance necessary for all operations, environmental challenges, and equipment for a DP vessel. A central component in the ASOG is proven knowledge of *Blackout recovery time.* As ASOG requires different conditions and locations for the vessel to perform its operation, the following things must be considered while preparing according to IMCA M220 (IMCA M220, 2021).

- Technical suitability
- CAM and TAM identification
- Understanding the vessel's capacity for handling of Worst-Case Failure.
- Environmental conditions
- Consequences of loss of position or heading

A typical ASOG lighting system consists of four traffic lighting systems. These lighting conditions explain the operational conditions and the risks that are attached to them. In addition to that, it guides the operator to take appropriate actions according to ASOG or FMEA. The tabular format of column definition for CAM, TAM, (example shown in *Figures 14*) and ASOG (example shown in *Figures 13*)could be explained as follows

- Green DP status (Normal)
  A green light reflects on normal operating conditions where the operation could move forward within the agreed safety limits. In this case, conditions such as operational, environmental, and equipment are performing as usual as possible.
- Blue DP status (Advisory)
  A blue light indicates that the operation could continue simultaneously as no immediate risks of losing position or heading are present, but a risk evaluation process is undergoing. It shows that the limits for operational, environmental, or equipment performance have been reached. It also indicates an event or a failure that did not comprise single fault tolerance of the DP system. The outcome of the advisory status is that either the vessel uses mitigating measures to reduce the risk and change the light to green (standard) or cease operation in a case where the mitigating measures could not decrease the risk of losing position or heading.
- Yellow DP status (Degraded)
  A yellow light indicates a warning where a high risk of vessel losing position or heading or another possible failure might occur. Under such conditions, despite losing some redundant systems, the vessel might be holding position and heading, but the operator should stop the operation and initiate the contingency procedures.
- Red DP Status (Emergency)
  A red light indicates an emergency. It signifies immediate termination, as the vessel

might be losing position and discontinuation of all DP-related operations.

Activity Specific Operating Guidelines – Outline				
	Green	Blue	Yellow	Red
Definition	Normal operations – operational, environmental and equipment performance criteria are all categorised as normal.	Advisory status – operational, environmental or equipment performance limits are being approached. An event or failure has occurred that does not compromise single-fault tolerance of the DP system.	Degraded status – approaching operational, environmental or equipment performance limits have been reached. A condition exists which may require a suspension of operations.	Emergency status – operational, environmental or equipment performance limits have been exceeded. A condition exists which requires an immediate termination of operations.
Response	For DP operations to commence and continue the conditions in the **green** column must be met.	Operations can continue whilst risks are being assessed. Conduct dynamic risk assessment to determine whether to continue, change position or cease operations.	Preparations should be made to suspend operations in a controlled manner. Contingency procedures should be initiated with a view to reducing the time to terminate. The operation should not be resumed before the vessel has regained redundancy or before all risks have been fully assessed to determine whether it is acceptable to resume operations with compromised redundancy.	Abandon operations. Take immediate action, to ensure the safety of people, the vessel, the environment and the operation. The vessel should be moved to a safe position. No DP operation is to be recommenced until a full investigation has been implemented with the failure resolved and full normal capacity verified by testing.

Figure 13 Outline table for ASOG (IMCA M220, 2021)

A CAM and TAM table usually has two columns of blue and green in color. However, a TAM column differs for normal conditions compared to CAM.

	Green	Blue
Definition	Normal operations – all systems and equipment fully operational, DP verification processes completed, and DP set up confirmed.	Advisory status – where any of the green conditions are not met.
Response	For DP operations to commence and continue the conditions in the green column must be met.	Conduct dynamic risk assessment to determine whether to continue, change position or cease operations.

Figure 14 Outline table for CAM and TAM (IMCA M220, 2021)

5.1.2. Position Loss

The purpose of enforcing requirements for preventing loss of position is to manage the risk associated with the loss of position during a DP operation. Management of such risks is first done with the help of FMEA, ASOG, and with the help of risk management tools available for DPOs, vessel operators, charterers. Eventually, safe completion of a DP operation is ensured. In order to achieve the safe operation, a redundancy concept is created where a worst-case failure design intent is acknowledged by valid documentation of DP FMEA trials. A risk analysis is performed for a single failure that can be the basis of complete loss of position of the vessel during DP operations. This trial documentation contains the analysis of risk, consequences, impact, probability of occurrence, existing barriers, and mitigation measures. Actions in terms of measures are well explained for failures for all personnel responsible for preventing the loss of position.

According to DP Vessel's design philosophy guidelines provided by DNVGL, there are several desirable elements in the DP redundancy concept (DNVGL, 2015 a).

- Independence

  The central machinery is supposed to be as independent as possible. Measures are supposed to be taken to decrease failures to less than one generator or one thruster to an absolute minimum.

- Segregation

  Systems used for redundancy are connected with a common point and should be as minimum as possible. The probability of propagating failure from one redundant system to another increases with the increase in the number of common connection points. Physical separation is encouraged in order to decrease the effects of internal and external causes which might overthrow the concept of redundancy.

- Autonomy

  Decentralization of control and automation function should be installed as the central machinery can make itself ready for DP operations independently of any centralized control system. Reliability of redundancy increases as the removal of human interference decreases due to automation in the DP system.

- Fault tolerance

  For a defined single failure criterion, DP class 2 and 3 vessels should have no loss of position. A comprehensive DP FMEA will aid in the assessment of fault tolerance of a DP system.

- Fault resistance

  All DP-associated equipment should perform to produce high reliability and defiance to external and internal factors, which aids in reducing reliability. Where appropriate, DP equipment should perform in harsh environmental conditions along with extreme technical loads. Attention is required to the susceptibility of the DP equipment due to interference and the effect of transient phenomena.

- Fault ride-through capability

  The DP equipment should continue to perform its tasks without malfunction when exposed to stimuli, reducing the reliability. There are possibilities of fault propagation paths due to intentional and unintentional cross-connections or other common points in secular DP systems. Effects of voltage fluctuation due to short-circuit are a prevalent issue in a power system.

- Differentiation

  Control systems should use measurements from different instruments and methods to reduce common-mode failures. There have to be multiple barriers in order to protect the vessel from losing the position and heading. Multiple devices and technologies should be combined to increase redundancy and reduce the risk. The combination of Differential Global Positioning System (DGPS), HPRs, and Tout Wire is widespread in today's DP industry.

IMO Marine Safety Committee Circular 645 'Guidelines for vessels with dynamic positioning systems' provides the international standard for DP systems. Following such guidelines, Classification Societies have defined three different classes of DP equipment, which provide different levels of station-keeping reliability associated with consequences during the loss of position. The three different equipment classes are defined in the previous segment where the effect of and the nature of the failure are made a high priority.

5.1.3 Alternative Fuel Sources

The development of alternative fuel sources is at its peak as the maritime sector is stepping up to keep the carbon reduction within its promised limits before the end of 2030. The development of new technology and new forms of energy carriers is way ahead compared to codes, standards, and regulations (Valvorita, 2018). IMO resolutions have made several amendments made to Safety of Life At Sea (SOLAS) through MSC. 392(95) in four different categories regarding ship's construction, operation, manning or crews' competence and management. Since 1st January 2017, these amendments are enforced with International Code of Safety for Ships using Gases or other lower flashpoint fuels (IGF Code) to minimize the risk to ships, their crews, and the environment.

- Construction of ships

On 'Part G' of SOLAS chapter II-1 it is stated that the new IGF Code shall apply for vessels with Low Flashpoint Fuel (LFF) built after 1st January 2017 or delivered after 1st January 2021. In new paragraphs 29 and 30, vessels using gases or other fuels with lower flash points are prioritized. "*Where low-flash fuel means gaseous or liquid fuel having a flashpoint lower than permitted under regulation II-2/4.2.1.1*" (IMO, 2015). In 'Part F,' a methodology for alternative design arrangements for equipment, including storage and distribution systems for low-flashpoint fuel, is discussed (IMO, 2015). A provision is made to make an alternative design or an arrangement of the requirements to reach acceptable criteria to reach the adequate safety level. Nevertheless, those alternative designs or deviations regarding other chapters need approval after evaluating designs and arrangements according to regulations (IMO, 2015). At the same time, the engineering analysis should be thorough with evaluation and requirements and submitted to administration.

- Fire protection on ships

In part B, chapter II-2 of SOLAS, a new amendment is in force for the protection against fire and explosion due to low-flash fuels for reducing the probability of ignition. In 'Part C,' provisions are made to suppress the fire in case of unfortunate scenarios. A special provision is made for cargo vessels, passenger ships, and tankers. There is a requirement for prevention from damages due to under and over-pressurization. The condition for using LFF is that the fuel cannot be stored in spaces close to machinery space, and a regulatory body should approve the storage space. Requirements on Part G SOLAS chapter II-1 are applicable with new subparagraph 5 is valid. Thus, an isolation segment should be created in order to reduce the damage. SOLAS regulation II 2/20 standardizes the requirements for an effective ventilation system. No relaxations are offered to the rules for ventilation systems that are discussed in SOLAS regulation II-2/20.3.2.2. In passenger ships, it must have two different ventilation systems for power and other ventilation systems. For cargo ships, the ventilation should typically run according to need. However, there should be a particular focus on taking away the exhaust gas in the case of RO-RO and RO-Pax vessels before loading and discharging operations, with the help of several portable gas detection instruments carried by personnel. Ventilation ducts allocated for RORO or RO-Pax operations shall be capable of being effectively sealed for each cargo space. Similarly, the ventilation system should prevent air stratification and the formation of air pockets (IMO, 2015).

- Qualification and certificates for seafarers

The amendments to STCW are made via MSC.396(95) and MSC.397(95) due to the implementation of the IGF Code starting from 1st January 2017. Changes are made to the Certificate of Proficiency (CoP) requirements, both advanced and basic training for the vessels, equipped according to the IGF Code requirements LFF (Norwegian Maritime Authourity, 2016). According to the Norwegian Maritime Authority, the amendment of section 19, sixth paragraph for regulations for the qualification requirements for seafarers, is done. In section 69, seafarers' requirements for training and qualification with specifically assigned duties onboard a vessel with LFF are specified. Certificate of proficiency is required for the personnel working onboard no later than 1st July 2018 (Norwegian Maritime Authourity, 2016).

A newly added section of the fifth paragraph in 69 and 69a has requirements for training and qualifications for personnel working onboard vessels with LFF with direct responsibility for the upkeep and use of LFF. There are more than 50 vessels that are operating with LFF under the Norwegian flag, including passenger ships and cargo vessels (Norwegian Maritime Authourity, 2016). It is required that seafarers working onboard shall have "A training" as basic training. Deck Officers are required to have "B training," and captains are required to have "C training" as part of advanced training (Norwegian Maritime Authourity, 2016).

- Safety Management System for ships

Safety Management System ensures safe operation of ships and protects the environment in compliance with relevant international and flag state legislation. SMS ensures the procedures to prepare and the methods to respond in case of emergencies and procedures for internal audits and management review. Regulations of SMS apply to the vessels in compliance with the requirements of the ISM Code. These regulations on SMS apply to all vessels inter alia to passenger ships. However, permanently moored offshore installations like Floating Production Storage and Offloading (FPSO) are exempted from certification and audit requirements in SMS (Norwegian Maritime Authourity, 2016). Section 17, in NMA's requirements for fixed installations in NCS under Norwegian shelf regulations, set out a requirement for SMS linked to health, safety, and environment, including few supplementary regulations for petroleum activities. Special provisions exist for polar regions (IMO, 2016) Discussion of polar codes are out of the scope of this thesis.

5.2 Data Analysis

Qualitative data analysis was done for this research. Data was collected from DPOs from various parts of the world, including DP Simulator instructors. First, the analysis aimed to identify current issues in an alarm system in DP vessels, then the data analysis from two different groups is evaluated individually, and the results are classified according to the table presented in Appendix A. Second, the resulting data was evaluated with the help of HTO analysis. Besides, a risk analysis using the bow-tie method was used to identify challenges present due to hybrid fuel technology and risks of position loss during oil and gas exploration in the arctic region. A general risk assessment was done using HazID to identify hazards and threats that might affect people, the environment, assets, and reputation.

5.2.1 General

Methods preferred for quantitative analysis were questionnaire and interview. Questionnaires were sent through the internet, and interviews were done via telephone. A total of forty-five participants took part in the survey as distribution is shown in *Table 8*. During the analysis, it was expected to find common trends or patterns from the survey responses. Those patterns and responses were considered to come with suggestions to improve alarm systems in the future of DP vessels. A comparison of primary research findings with literature review, guidelines, and HTO analysis would help achieve the research's aim and objectives. Initially, data was evaluated and compared to the guidelines (YA 711) as categorized in Appendix A: Classification of Alarm requirements, which would help find shortcomings in a human, organizational or technological segment of the DP alarm system.

Table 8 Survey methods and target group involved

Target Group	Questionnaire	Interview
DPO	40	1
Simulator Instructors	3	1
Total participants	45	

Participants with experience from PSV, Pipe Laying, Anchor Handling Tug Supply Vessel (AHTS), Oil Recovery, Construction Support, Survey, Multipurpose Supply vessel (MPSV), Offshore Support Vessel (OSV), Icebreakers, Drilling Rigs, Pipe Laying Support vessel (PLSV), Oil Spill Recovery Vessel (OSRV), Shuttle Tankers, Mobile offshore drilling unit, Emergency Response Rescue Vessel, Remotely Operated Vessel (ROV), Seismic, Crane, Jack-up and Cruise vessels took part. Simulator instructors from Norway, Finland, Germany, and the Netherlands took part in the survey.

5.2.2 Human, Technology and Organization (HTO) Analysis

HTO analysis is preferred to analyze the survey responses due to its simplicity in projection and understanding of the issues in three vital categories of a system. It is unpretentious to segregate any functioning structure to human, technology, and organizational division. Thus, implementing change or mitigation measures would be straightforward and effective for impact on the safety, performance, and efficiency of DP Operations.

First, humans as subsystems and technology and organization reflect on humans' importance as the core value of the entire system's performance through human activity (Berglund;Karltun;Karltun;& Eklund, 2017). Second, humans' contributions and limitations because of abilities and flaws show the performance of the total system and the importance of effective organization and advanced technology. Finally, the concept of HTO illustrates analysis and proper understanding of the system, which is not possible without proper evaluation of each section of a system.

In HTO analysis, research is done using the term *Humans,* pointing towards the operator operating the DP system, while the *organization* is the supplier of the equipment or the shipping company, or an operator/charterer. Finally, *technology* is aimed to use for the sensors, equipment, or instruments, both digital and analog, that aid in the safe and successful completion of DP operation.

5.2.2.1 Analysis for data collected from DPOs

The analysis of the responses from the first target group (DP Operators) is presented. A total of 13 questions were given with a mix of both open and close end questions as shown in Appendix B. Questions are put forward to get information regarding the fulfillment of requirements (PSA, 2001) of criteria mentioned in Appendix A as per participants' experience and knowledge.

- General Requirements (requirements from 1 to 12):
  An alarm system is a tool for operators to handle critical and atypical situations with precision and effectiveness.

From a *Human perspective,* according to guidelines published in the requirements (PSA, 2001), in order for a DPO to perform his tasks, the alarm systems should help the DPOs to reduce human errors and reduce the disadvantages caused by human limitations. Operators should also receive instructions and training to use the alarm system installed onboard DP vessels. Similarly, while working with the alarm systems, the information should be cognitively processable. The instrument's response time should be lower than two seconds, while safety and critical functions should be identified and documented.

The survey reflects the importance of several factors, "contributors", which reduce the attention and cognitive ability to handle alarm systems properly as shown in Figure 15. One question from the survey was the effect of a client's presence on the bridge while working on a DP operation. This event increases the stress and anxiety level of the DPO and increases the risk of accidents during a DP operation.

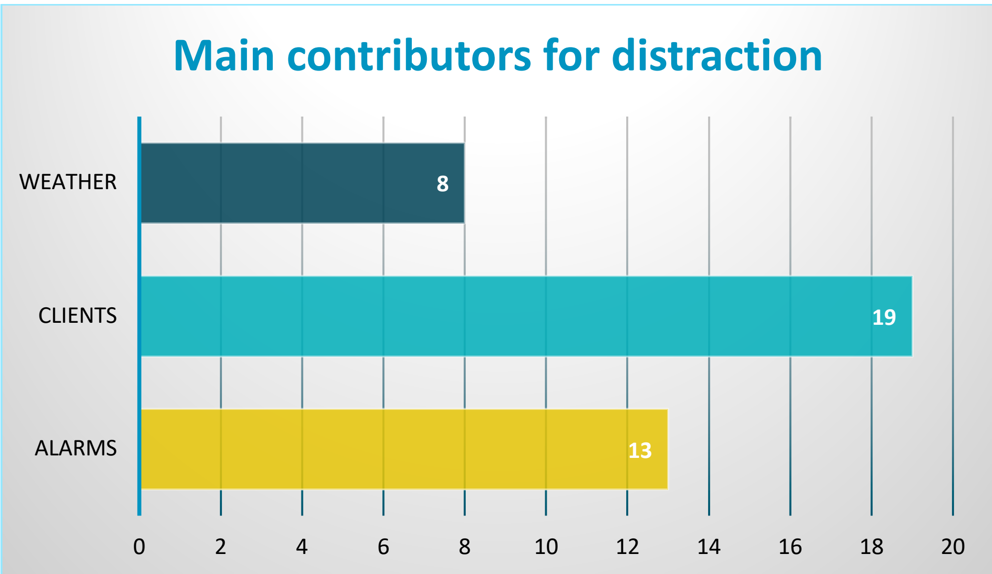

Figure 15 Main contributors for distraction in the bridge during operation.

From a *technological perspective*, an alarm system should be built context-sensitive, where alarms necessary for the operations are only presented. It should be possible for all other alarms to be suppressed on the user's preference. Simultaneously, alarms should be fault-tolerant and should provide status regarding blocking and overriding with a dedicated list of these alarms in the main panel. The technological solution should identify critical functions and present alarms regarding alarms' status and failure in the dedicated display. Participants agreed that the alarms that were present were reliable and were technologically sound. However, the fact that the general requirements for extreme weather conditions were not well covered. It is up to the operator's digression to decide if it is safe enough to continue with the DP objective with available equipment and the measurements received from sensors available. Suggestions like the adaptation of the traffic light model of alarms are brought forward, similar to the lighting model of ASOG but in an automatic form with no human involvement.

From an *organizational perspective*, several things should be done according to the requirements from YA 711. All operators should get training in the usage of alarm systems for realistic situations. The Nautical Institute is responsible for standardizing, managing, and validating the required training for DPO working in DP vessels. It is an organizational responsibility to clarify the crew's responsibilities via ISM, SMS, FMEA, or ASOG to increase the safety and safe execution of DP operation. At the same time, the development of a self-correcting alarm system while maintaining its knowledge and intelligence is critical. It is necessary to have the supervisory body access the alarm system's changes and accompanying documentation when required. All the failures and safety-critical functions should be identified and documented for future improvement and preparation of the next mishap. It is the organization's responsibility to ensure that the administrative glitch should not hinder a DPO's performance.

- Alarm Generation (requirements from 13 to 19):

The technological part plays a more prominent role in generation alarm where it should be ensured that there are no unnecessary alarms triggered in the system. Nevertheless, alarm systems should provide a solution that could alert the operator even with the simplest of the operation's disruptions. When basic alarms are suppressed, the manufacturer should ensure that the operators should be guided towards the problem rather than the symptoms. In the survey, it is found that it was not allowed to change the alarm suppression system in many cases, and if allowed, the alarm suppression systems were used for the wrong reasons. An example during the interview was that the alarms were toned down, especially when the clients were on board. In addition, there are several alarms for one variation or deviation from the preinstalled limit, and this one deviation affects several functions or positioning parameters. Alarms are triggered for all the connected systems/ associated with the deviated parameter, which causes alarm fatigue to the DPOs. The alarm system's flexibility should be allowed to adapt the alarm system and the operator's personal preference to conduct the DP operations effectively. Effective use of signal filtration and validation should be used to prevent fluctuation and increase signal reliability. Manufacturers should provide appropriate solutions to prevent false alarms because of error signals.

Manufacturers, shipping companies, operators, and charters should define and check the limits of alarm generations used for the operations and have safety implications; detailed descriptions should be presented in SMS for the responsible crew.

- Alarm Structuring (requirements from 20 to 23):

As in alarm generation, the primary responsibility lies in the technological sector to provide improved alarm structuring. Provision for grouping, sorting and selecting various alarms and features should be provided as per operators' needs. A simple overview of alarms that are suppressed, shelved, or inhibited should be displayed. The alarm suppression system should be understood by the operator and its presentation method in the overview display. Simultaneously, the operator must understand the different alarm features such as suppression of alarm and alarm filtration. PSA does not recommend the latter, according to YR 711.

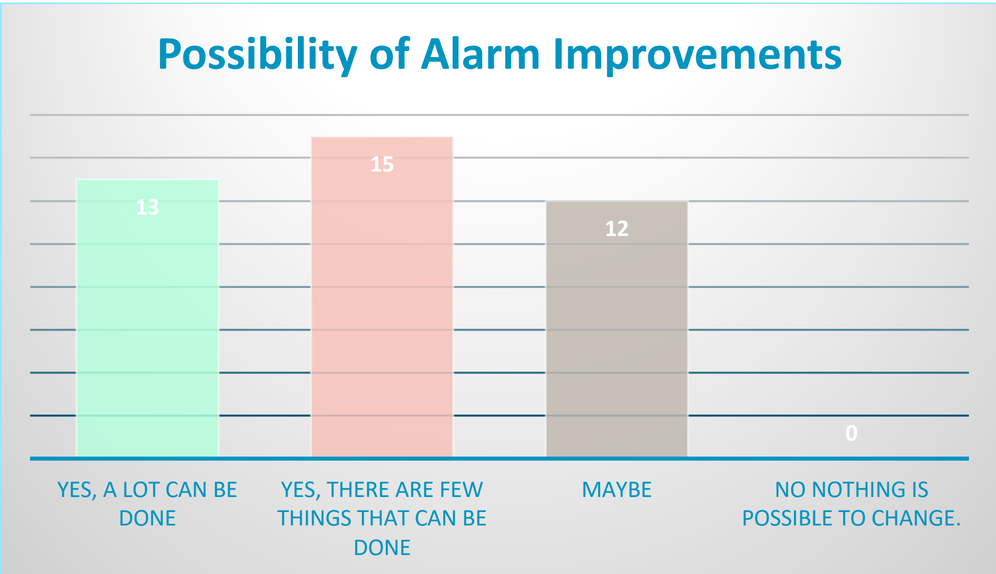

Figure 16 Areas where alarm performance could be improved.

According to the survey results shown in Figure 16, the DPO suggested a preferable technology for the end-user where alarms are manufactured according to human-centered design. These improvements will not just improve the end-user experience but will aid in reducing accidents.

- Alarm Prioritization (requirements from 24 to 28):

From a human perspective, an operator should prioritize the urgent alarms first; thus, the operator should use this feature to be efficient and effective during abnormal situations. However, it is not recommended to prioritize more than four alarms at a time. Priority alarms list should aid operators to draw their attention towards urgent alarms while a tremendous number of alarms occur during emergencies.

From both technological perspective and human perspective, manufacturers should make sure that alarm priorities should help operators focus on the conditions that, if not corrected, will have a severe impact on operations. Nevertheless, manufacturers should develop solutions that aid in processing the conditions with enough time to prioritize and handle the urgent issues. These features help an operator focus on a small fraction of manageable high-priority alarms when there are numerous alarms during abnormal incidents. It is mentioned in requirement 27 of YA 711 that the frequency of alarm of various priorities should decrease by a factor of 5 with an increase in priority. For example, about 80% of alarms should be of low priority, while 15% can be of medium priority and only 5% can be of high priority.

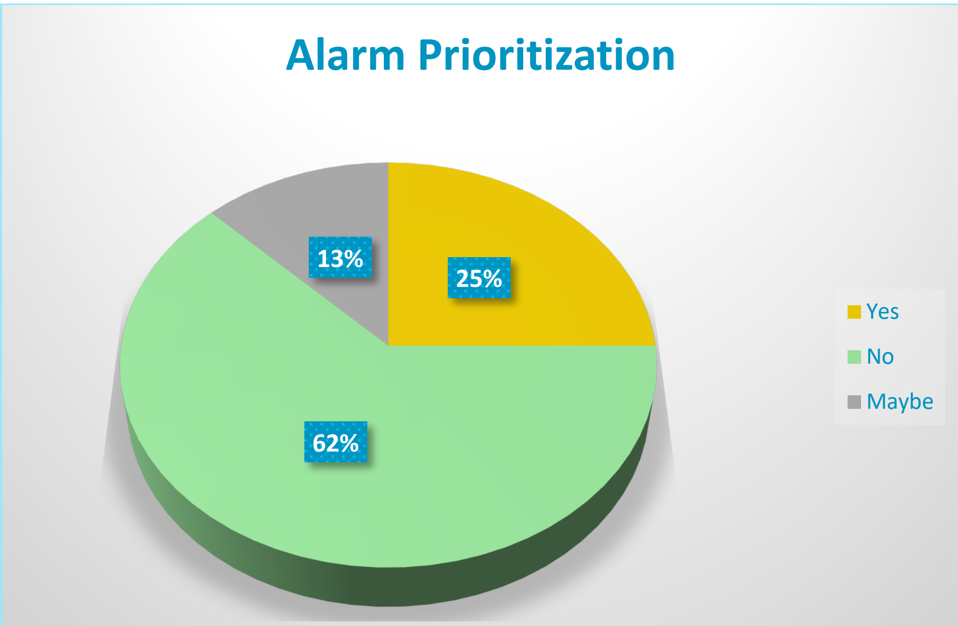

Figure 17 Possibility of improvement in Alarm Systems

From an organizational perspective, shipping companies should develop a strict policy to implement alarm routines and procedures. Standing orders from captains in the vessel should be clear and well-rehearsed in advance. These routines are constructive as it makes operators familiar and comfortable with the prioritization procedures that the system designers have developed.

Survey result in Figure 17 shows, about 62% of the survey participants reflected the impracticality or lack of flexibility to prioritize alarms dedicated to critical operations. In contrast, 25% were sure that it was possible to prioritize alarms. Prioritization is critical as it eliminates human limitations by reducing the observation parameters to critical alarms only.

- Alarm Presentation (requirements from 29 to 39):

Design, implementation, and installation of equipment for use onboard a vessel is a manufacturer's responsibility. Thus, a technological perspective covers the alarm presentation section. As explained in the requirements, a central display is required to present all the alarms collectively. Besides, the primary display should support monitoring and attracting the operator's attention towards the actual status of the ship and operation. An integrated alarm system installed in a ship must have standard color codes, symbols, and alarm categorization methods, which helps the operator be precise and effective. A 'dark screen' concept should be implemented because there should be no alarms on the main display when there are no genuine abnormalities in the ship or operation, which increases the operator's effectiveness. Segregation of alarms in different categories improves alarm overloading of an operator as the alarm list will be flooding during emergencies. Essential alarms should help operators to distinguish the difference between non-essential alarms. All the alarms that appear in the alarm list should be recorded with features such as sorting, grouping, and searching for incident analysis for the future.

Audible alarms should be used but not so that it overwhelms the operator during alarm flooding in emergencies. Visual alarms should be used together with audible alarms to get attention from the operator, while the alarm notification blinking should be limited. Both forms of alarms should be informative and easy to understand. Messages should be standard and consistent; abbreviations and terminology should be agreed upon in advance. All alarm messages should be accessible from all workplaces; to ensure that responsible personnel have good information regarding the actual condition and can give the corrective command as soon as possible. Figure 18 shows the response for the necessity for alarm flexibility by DPOs.

When it came to reducing audio and flashing lights in alarm, the majority of the participants said it was possible to reduce the overwhelming intensity of alarms both for visual alarms and audio alarms. Thus, alarm designs without a human-centric approach do not facilitate effective operator intervention.

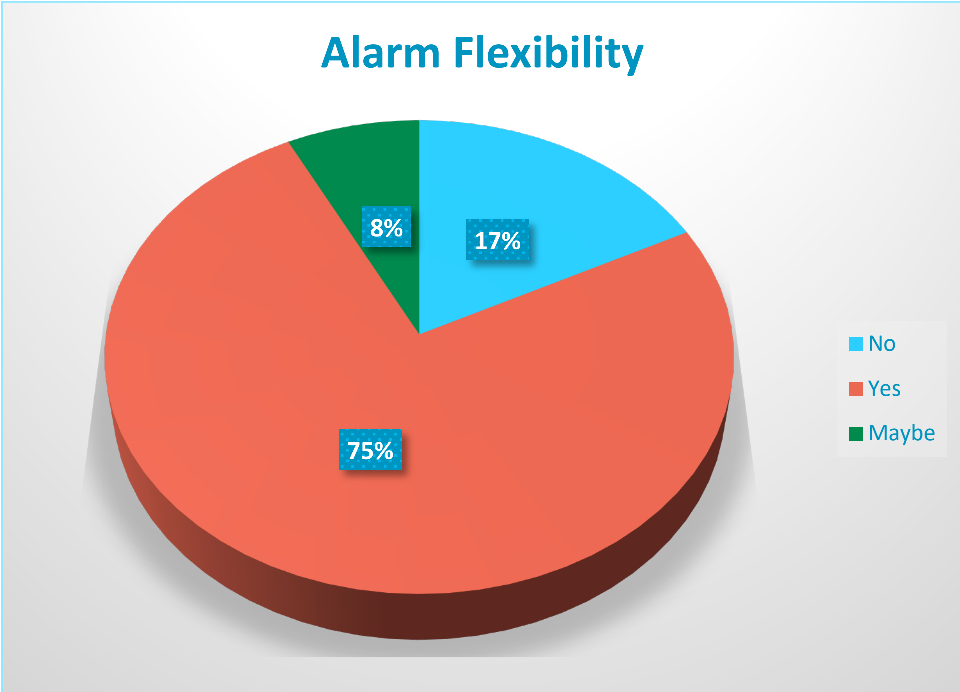

Figure 18 Necessity of alarm flexibility according to DPO survey.

- Alarm Handling (requirements from 40 to 43):

In alarm handling, all three parts of HTO have their roles. In terms of organizational perspective, necessary provisions should be made for the operator to respond to alarms as quickly as possible. Shipping companies should request instruments that are not just cheap but easy to handle while purchasing the vessel or bridge equipment. Proper training should be arranged for the responsible personnel. Generally, contracts are binding for modifications or improvements only when there is a proven safety issue onboard. In such cases, modifications with safety issues are free of charge. However, extra service cost is imposed when the shipping companies send request for improvements to instruments that has unproven safety issues. All modifications or updates should be encouraged to be free of charge, whenever there is something that makes system more reliable and effective.

From a human perspective, operators should acknowledge all alarms that are triggered. Acknowledge, meaning the purpose of the alarm is first to be read, and then understood, and finally accepted. Alarm philosophy should describe whether an alarm should be accepted once the operator has read it or after they have dealt with it.

From a technological perspective, a provision for alarm shelving should be provided so that the operator can remove standing or nuisance alarms. Shelving must be kept as a 'last resort' for handling irrelevant nuisance alarms that have not been successfully filtered or suppressed. A list of shelved alarms should always be available to the operator. Manufacturers ought to provide the solution that supports operators to make a quick and precise decision. Finally, procedures for individual persons responsible for monitoring and controlling operations, including emergencies, have to be readily available and familiarized.

Escalation of DP incidents has to be prevented by operator intervention. In several cases, sometimes DPO alone cannot act independently to prevent an incident. Thus, it is vital that the onboard crew function as a team. Sometimes misunderstanding between bridge and engine crew might be the cause of escalation of DP incident. Nearly half of the survey participants said, "it depends on the person in the engine room," or questions are perceived negatively as shown in Figure 19. A culture of promoting safety culture, reporting of near-miss situation is fundamental for future development of new technologies and maintaining a safe working environment in current aspect.

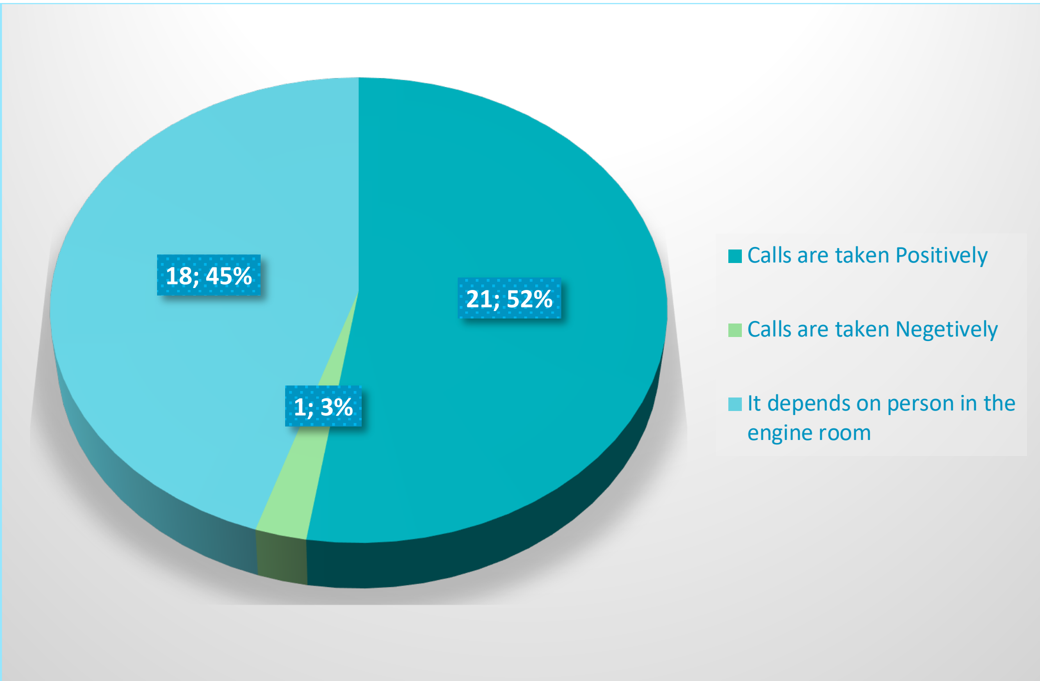

Figure 19 Crew Behavior for alarm handling.

In *Table 9*, a highlight of the survey with DPO is listed. Both strengths and weaknesses of alarm systems in categories of Human, Technology, and Organization are visualized. Some of the answers from the participants were not clear, as it might be due to a lack of experience or interest in answering the questionnaire. It was the main drawback of the questionnaire; participants could choose not to answer the listed question, either because of lack of knowledge, motivation, or understanding of the questions.

Table 9 List of highlights of findings from survey for DPOs

Features	Human	Technology	Organization
Strengths	Pre warning alarms are helpful to keep DPOs one step ahead.	With several DP screens in the bridge, it is impossible to keep an eye on all screens all the time. Audio alarms are helpful but could be more versatile.	FMEA and ASOG should be given more priority; these are one of the passive barriers.
	Pre-alarms helps the operator to figure out the situation before it gets complex	Minor failure and more undersized issues are easy to handle compared to more significant problems such as blackout and loss of thrusters	The alarm log helps in the investigation and analysis of near-miss incidents.
	Due to human limitations, alarms are helpful to figure out critical situations in advance.	Pre warning alarms help operators, as they know both the critical limits and input prewarning conditions.	
	Alarm in general increases situational awareness	Kongsberg and Rolls Royce have systems to reduce alarm fatigue.	
	Watch overlap between DPOs during DP operations.	Color coding of alarms are helpful	
		The help menu is helpful in understanding alarms.	
		Traffic light modeling of alarm is convenient. Similar to ASOG lightings.	
		The most common alarms received are loss of position or heading.	
Weaknesses	Redundant alarms are not solutions but at times cause of a problem. Specially with an improper handover of watch or carelessness during checklist filling up.		
	It is mentioned that redundant alarms sometimes distract or hinder DPO from working efficiently. As the DPO acknowledges all alarms repeatedly, the workload increases		Manufacturers need to come back to the DPOs for feedback for

	significantly during an emergency, limits situational awareness, and reduces the decision-making capacity, a phenomenon known as alarm fatigue.		improvements in their system.
	Frequent unnecessary alarms increase the risk of overlooking critical alarms.	Alarms reflect on the current situation, not the consequence of the cause for alarm. Awareness of consequence and its impact is critical, especially when the problem is evolving during the initial stage.	
	If several alarms are not acknowledgeable, it forces DPO to exit DP mode.	Multiple redundant alarms are distracting	Multiple alarms should be filtered, with the help of additional layer of filtering algorithm. Also, first alarm can be normal for same cause but the second alarm could be alarm without buzzer.
	Reduction in commutation with the bridge team due to alarm noise; a 'one-button mute all' feature would be practical. All alarms needs to be acknowledged before addressing the real issue.	It is often challenging to understand alarm codes and their abbreviation, which leads to ignoring or misunderstanding the alarm.	Makers should put effort on combining alarm due to one cause instead of triggering every possible alarm station because of the vulnerability / unreliability. As same fault can affect several functions/positioning systems.
		Many alarms during DP operations are irrelevant, such as AIS, ECDIS, Radar, and others.	Remove abbreviations from error message and make user friendly.
		Decentralized alarm locations are challenging during operations as OOW/ DPO must go to each alarm station to acknowledge it.	Group alarm system for one fault
		Several alarms have similar audio tones. It is challenging to prioritize critical alarms during hectic situations.	Intervals in some alarms should be longer.

			Shipping company should improve ISM and SMS for alarm handling.
			Operator should prepare checklist together with shipping company according to the project requirements.
			Makers should give proper service after 12-18 months of vessel commissioning.

5.2.2.2 Analysis of data collected from simulator instructors

Four instructors took part in this survey. Participants have more than ten years of experience as DP operator in average and have been an instructor for several years. Participants have been instructors in various platforms such as Kongsberg, Rolls-Royce, Navigation, and Ice navigation. First three survey was done via questionnaire, and the final poll was conducted via interview.

- Participant 1:

During the survey, a participant mentioned that alarms for thrusters, engines, rejection of PRS, position deviation, and several other alarms are practiced. It is said that there is a dedicated segment for handling alarms during simulator training. All simulator training for alarm and its handlings are in accordance with The Nautical Institute's guidelines. However, the participant was not sure about cooperation with the simulator's manufacturer to improve the simulation courses. About one hour of simulation training is provided for the alarm simulations. The final test is approved with a written test online and a test in the simulator.

The main issue with alarm systems is that there are numerous alarms from different vendors. These variations are difficult to communicate in detail with the trainee DPO. However, a brief introduction is provided to the trainee.

- Participant 2:

Participant has experience from the Kongsberg DP layout and alarm system. Contributor mentioned that simulation of alarms about thruster, engine, reference system, position drop out, several other sensor failures, and consequence analysis is done in simulator training. Some parts have simulation training dedicated to alarm simulations and handling of alarms. However, the participants reflected that there was no cooperation among vendors for improving the simulators and their features. A total of ten hours of the simulator is dedicated to alarm systems in the simulator. It was described that ASOG was followed throughout the simulation training process. Simulator training participants get their course approved with both simulator training and theoretical evaluation.

While the participant mentioned that, there was no additional improvement required in the Kongsberg simulator. In their experience, there is no significant fault that is present in the existing DP alarm system.

- Participant 3:

Survey participants had used full-scale DP simulators from Kongsberg, Rolls Royce, Navis, and others. According to the participant, all the contents regarding position keeping, DP class, and maker's manual were covered in the simulator training. There were dedicated alarms present in the simulator training, and training participants always took part in those sessions. However, exercise outside the recommendation of The Nautical Institute is also practiced. Simulator training was conducted according to the regulations and requirements of The Nautical Institute and the recommendation of IMCA. Finally, competence is tested with a theoretical test in combination with a simulation exam. Nevertheless, it was mentioned that there was no cooperation between the simulator center and the manufacturer to improve the equipment and the procedure for simulator training.

According to the participant, a review from DPO is also necessary, combined with the operational requirements and classification society. As it is the DOP who use the DP system daily, it is vital to make them a part of the team so that suggestions could be heard.

- Participant 4:

Final data were collected via interview. Survey participant has been involved in DP simulators from multiple manufacturers. In the simulator, the training segments are related to keeping position and controlling the thrusters' engine according to sensor feedback. Simulator training is focused on making course participants aware that 99% of the accidents are because of boredom and the remaining 1% because of panicking. Course participants are made aware that the DP operation is teamwork where there are two operators present during the DP operation. It is not just the alarms that are active as an alert, but the teammate acts both as alarm and redundancy in case of emergencies. A procedure and job description are reviewed during the introductory phase as the new course participant was familiarized with the routine and responsibilities.

The survey partaker emphasized that a good routine, checklist, and procedures are vital to minimize the risks of accidents. Additionally, *reporting the undesirable event* should be present in the paper and practice and as a foundation from the shipping company to the end-user. List of strengths and weaknesses observed in survey are are listed in Table 10.

Table 10 Highlights of strengths and weakness in alarm systems according to DP instructors.

Features	**Human**	**Technology**	**Organization**
Strengths	Alarm system keeps DPO alert and goal oriented.	Alarms are not always at fault.	Bridge is always maned with two crew. Where one can focus on operation and the other can take care of alarms
	If situation is analyzed with lean philosophy, it is not always human that is a problem.	Modern sensors and technology improve situational awareness and decision-making capacity.	Familiarization always takes place for new crew or for new operation.
			FMEA, ASOG, Risk assessment tools are used to avoid accidents.
Weakness	Lack of awareness among DPO and panic causes accidents	Too many alarms from multiple vendors	Lack of proper routines or procedures and checklists
			Improvement in safety culture and promotion of reporting of undesirable events.
			Improvement or introduction in dedicated simulation training in alarm handling skills

6. Discussion

The purpose of the discussion is to find suggestions that could aid the maritime industry in developing the alarm system, improve shortcomings, and make the DP vessels safer.

The results from data analysis after evaluating the answers from the forty-five participants and discussions are done in this chapter. Shortcomings and strengths in the alarm sector for the DP vessels are also cataloged. The possibility of position loss due to fire and explosion in a DP vessel with hybrid solution (hydrogen and battery) is evaluated with the help of risk analysis using the bow-tie diagram. Discussion about impact load and collision energy is prepared to reflect the risks of using alternative fuel sources.

6.1. Alarm System

A process of listing problems, acknowledging what can be improved, and at last recommending improvements in each category (human, technology, organization) for DP alarm systems are the objectives of this analysis.

6.1.1. Problems

Problems that were seen in the alarm system during the survey can be listed in three categories as follows:

- Human

  The main highlights of the survey result are graphically shown in *Figures 15, 16, 17,18,19.* Three main human factors are into play which is limiting human performance in DP vessels.

  First, in a redundant system such as a DP system, *alarm fatigue* is the primary concern for DPOs. The new integrated bridge monitoring and control system gives crew on watch an efficient tool for supervision. However, in case of failure or malfunction, all alarms are brought to the operator's disposal. It might be late for the operator to counteract in some cases, especially when there are numerous alarms installed on DP vessels (Dęsoł, 2018). The survey agrees with the article by Dęsoł, that the alarms in a DP bridge are more liability than assets, especially during emergencies and alarm flooding.

Second, the presence of clients in the bridge during the DP operation may be distracting cause for DPOs to focus on DP Operation as it is shown in Figure 15. This situation might be caused by fear of facing a 'tough boss,' which may be due to the client's abuse of power or authority (Daniel, 2009).

One other research conducted in medicine shows that the impact of distractions or case-irrelevant conversations on stress, workload, and teamwork, was astonishingly severe (Wheelock et al., 2015). They resulted in poor team performance, increased stress, and added more room for error. The research, therefore, suggests that it is better to avoid small talks and irrelevant conversations to avoid unnecessary errors during operations, when it is necessary to be highly alert on the workplace (during the need of increased concentration). A chain of causes in between hazards and accidents is shown in Figure 20 with reference to Human Factor Analysis Classification System (HFACS).

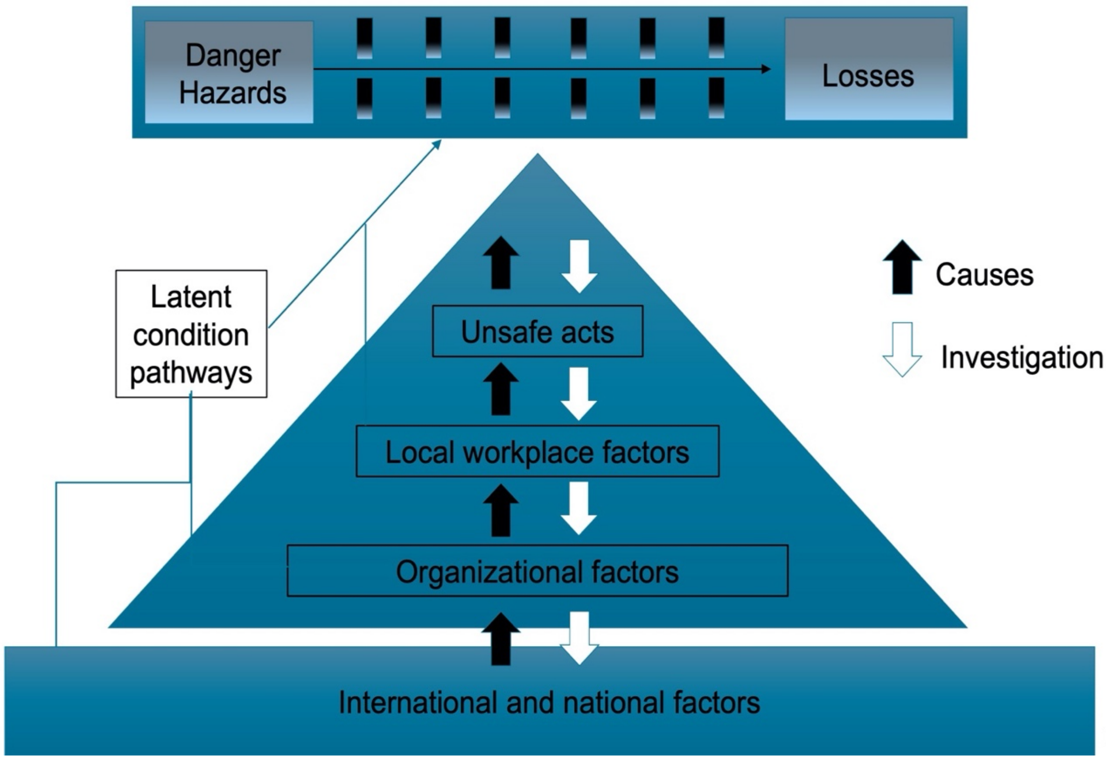

Figure 20 Human Factors Analysis and Classification System (Batalden, 2019).

Third, a team in the bridge and engine does not seem to be in harmony. An individual's preexisting knowledge and cognitive characteristics influence their distributed situational awareness (Salmon, Stanton, Walker, Jenkins, & Rafferty, 2010). There is a communication gap or personality difference between the two teams in the bridge and engine control room. If these two teams are not synchronized in situational awareness, it is challenging to create a safe working environment and make proper decisions. A study made by the University of Central

Florida explains that five major parameters are essential in teamwork, with three additional factors listed below (Salas, Sims, & Burke, 2005):

a) Leadership
b) Mutual performance monitoring,
c) Backup behavior,
d) Adaptability and
e) Team Orientation.

Supplemented by

f) Shared mental modes
g) Closed-loop communication
h) Mutual trust

Results from the survey in *Figure 19* show bridge crew's reaction when it came to teamwork. Those results were not wholly positive and required significant effort to amend the current working culture onboard many offshore vessels. The decision-making capacity was severely reduced during emergencies with increasing workload, and the demand for attention became more critical, limiting operators from acquiring and interpreting information (Endsley, 2014).

Highlights from the survey with DP instructors pointed out that the lack of experience or confidence in handling the equipment might cause panic and anxiety for new DP operators. The redundant system reduces human attention due to expectation bias and confirmation bias. An example of Big Orange XVIII, from studies of events in chapter 4.1.2 (*Event 2),* shows that the captain, despite all knowledge, skills, and training and above all experience, forgot to disengage the autopilot function. Additionally, the junior officer chose not to participate effectively in the troubleshooting process. These events show the vulnerability of humans. A flow diagram of the effect of human factor analysis (causes and investigation) and latent condition path is shown in Figure 20.

- Technology

Technology is an opportunity that enables increasing functionality, which in turn increases complexity. As technology develops, blind faith is often put in the inherent good of technology (computers). Such blind faith is based upon a technology's characteristics: speed, accuracy, diligence, versatility, reliability, and memory. Once used for a long time, these features will be the root cause for drift, expectation bias, and eventually confirmation bias.

From the survey, it is seen that there is a severe lack in the flexibility of alarm systems, where DPOs cannot change the form of audio or visual alarms. More than 75% of the participants revealed a lack of flexibility in present alarm systems. Similarly, there are no possibilities of prioritizing critical alarms to increase efficiency while focusing on the objective during a DP alarm.

'Technophobia' a psychological impact where technology simplifies life by providing functions in each device while complicating life by making the device harder to learn and use (Norman, 1990 a). In an automated system, the operator performs appropriately under normal conditions. However, the problem is in the inappropriate design of the system, especially when there is inadequate feedback and interaction with the human controlling the overall task (Norman, 1990 b). When automated systems are flooded with error signals during hectic situations, it is not convenient for a human with limited capacity to process all the relevant information and take exact steps to avoid calamities.

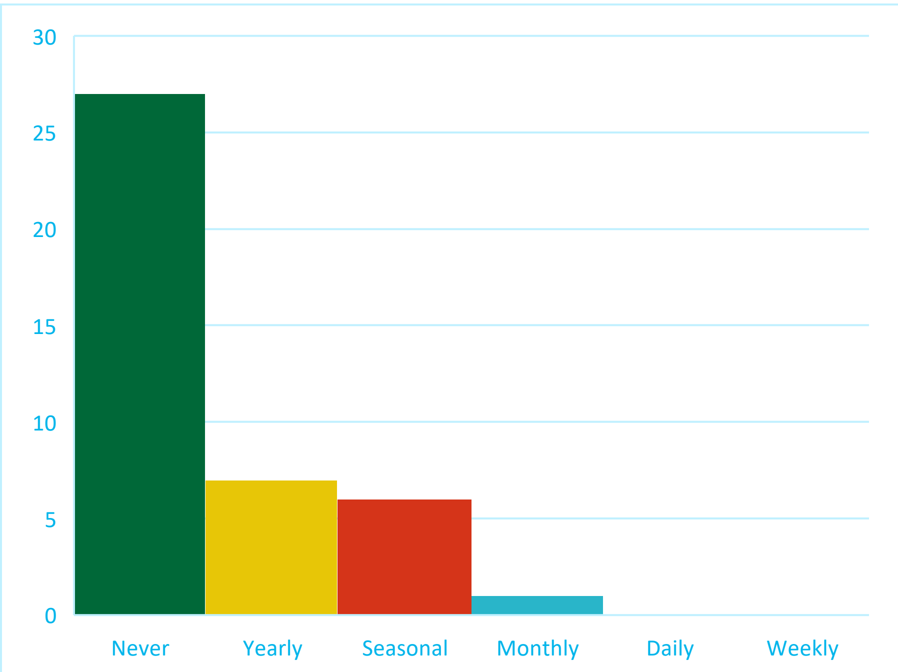

Figure 21 Feedback session held by makers with end users.

In the survey, there is no feedback loop present between the manufacturer and the end-user. It can be seen in the *Figure 21* that about 75% of the manufacturers don't go back to the end user for feedback. Blind faith in the inherent good of computers and beta testers hired by the manufactures is of high risk as producing a new alarm system might be misleading the results by confirming the designers' bias. Human-centered design is required to increase efficiency and reduce the risk of making unfortunate mistakes by an operator. An example of Sjoborg in chapter 4.1.1 Event 1 showed that the DPO could not decipher the regularly occurring error code "FAULT IN B.O.S.S SYSTEM PS" and "FAULT IN B.O.S.S SYSTEM SB". These alarms were not taken seriously and later turned out to be the turning point in the collision between Statfjord A and Sjoborg.

- Organization

Survey results shed light on both strengths and weaknesses from an organizational point of view. The industry is yet to figure out solutions for complex problems; how can an operator of a DP vessel avoid disaster and regain control of the vessel despite having numerous complex alarms during emergencies? The problem should be seen from a different angle to find solutions.

An example of Mumbai High mentioned in the example in chapter 4.1.3 Event 3, shows that the mistrust in technology by the captain and overconfidence in his skills and capabilities lead to a total loss. It can be pointed that the organization lacks characteristics of High Reliability Organization (HRO). The crew were not able to beat the odds of having an accident that they were not prepared for, regardless of purpose of the organization (Roberts & Bea, 2001). Captain was not comfortable with complexity and did not realize the risks present in switching to manual controls. He judged the standard functioning system as faulty and switched over to manual control. The hallmark of a high-reliability organization is not error-free but resilient towards such errors and failures. Together with that culture of ignoring the near-miss situations is critical as it reinforces the belief of the operation being successful and ignores the risk of the near-miss situation.

Scott Snook defines practical drift (*Figure 22*) as the slow uncoupling of practice from the procedure (Snook, 2000). Practical drift is another phenomenon where actual performance deviates from 'ideal' or designed performance. Practical drift continues to be dominant in the system until an incidence or an accident occurs. A global function of having a functioning alarm system is that its maintenance and improvement are ignored until an accident occurs. In case of the accident of Sjoborg, the alarms were ignored by the crew on previous occasions. An accident on the 7th of June 2019 resembles some of these scenarios where DPOs acknowledged a deviation from the main objective.

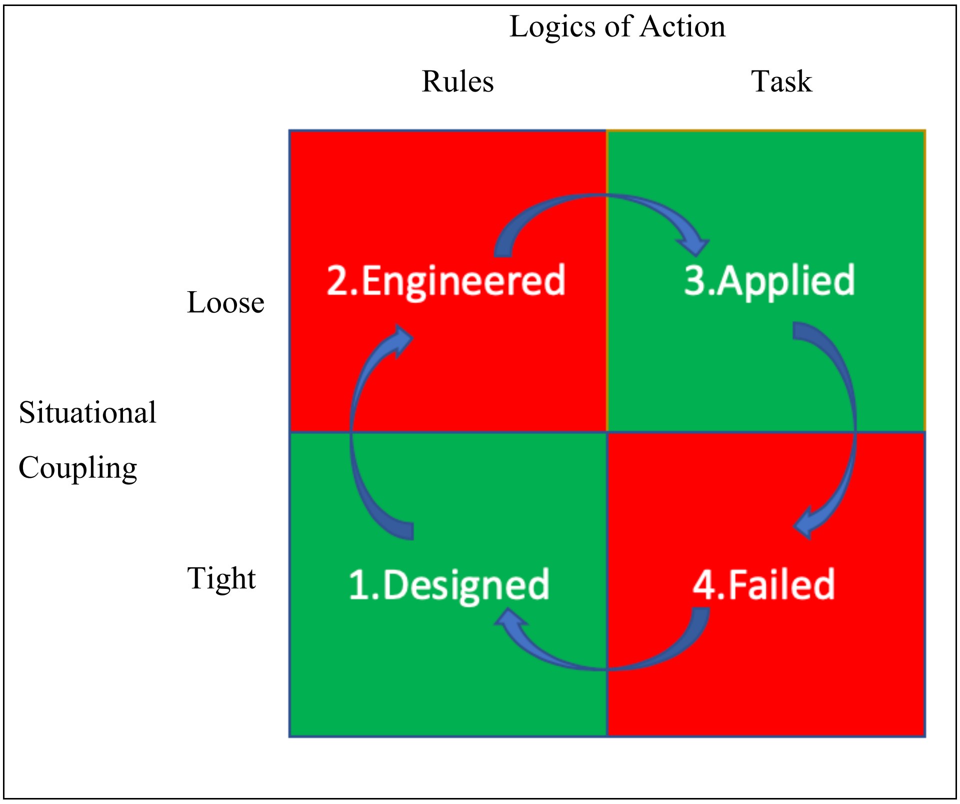

Figure 22 Theoretical matrix of practical drift (Snook, 2000)

Organizations are transforming into team-based structures, especially with the division of departments according to their field of expertise. In the maritime sector, it is discovered that bridge and engine room personnel are divided into collaboration and communication teams (Katarina, Holder, Praetorious, Baldauf, & Schröder-Hinrichs, 2015). The inherent decision-making required and the importance of having shared understanding for joint critical tasks have shown their importance through the study. The results from survey also revealed the problems faced by personnel on-board concerning interdepartmental communication and gave initial ideas about developing potential solutions (Katarina et al., 2015).

A decision-making perspective is another approach to investigate the problem where operators make choices when faced with conflicting objectives such as time, effort, money, and others (SINTEF, 2010). Captain of the Big Orange XVII made an unnecessary move while being close to the Ekofisk platform. The captain was distracted and was not showing proper seamanship. Eventually, when returning, no procedures were available to find if the vessel was engaged in autopilot.

FMEA, ASOG are the tools that aid in the precise decision-making process. Operators are made aware and trained while developing FMEA, ASOG, and detailed operational procedures for specific operations so that the level of distributed situational awareness is high among the entire crew in both the engine room and the bridge.

6.1.2. Suggestions

Life is a learning process, and there is no such thing as incompatibility when it comes to development, progress, and learning. An example can be taken from University Hospital Wales, Cardiff which modelled its newborn delivery theaters (neonatal unit) on "Formula 1™" pit stops, mapping out work areas on the floor and stripping trolleys down to just the most essential tools (McClean, 2016) in order to improve the cooperation and efficiency of the team. Suggestions presented in this section are not absolute; nonetheless, it is a guide for the maritime industry to focus on areas of improvement as reflected by survey results.

6.1.2.1.Alarm systems

Benefits of improved and superior alarm system improve operator effectiveness while reducing downtime and increase safety. It will be easy to maintain the alarm system if proper maintenance and training are used (Marquez, 2007). Logs from alarm and proper maintenance procedure identify alarm system problems and performance and operator's workload.

- Human

A typical response of tightening procedures in practical drift illustrates the reality of complex human behavior. The drift will inevitably take place in an operation in time. It is vital to understand why humans prefer to take shortcuts and divert from following a procedure. Increasing safety awareness by involving the team in dialogue and discussion might be more effective than imposing rules and sanctions.

The development of human-centered design in terms of alarm codes and error messages for disturbance is necessary. According to the frequency of use, the first step towards human-centered interfaces for marine navigation systems (Vu, Lützhöft, & Emad, 2019), information overload, particularly overlay and alert management functions, are vital issues in existing systems. Findings from the research of Vu et al., shows that the factors affecting the use of bridge equipment can be grouped into the following categories.

- Individual factors – experience-based decisions and professional habits
- Administrative factors – safety policies, procedures, and checklists
- Characteristics of the sailing area – sea room to maneuver, navigation hazards, and depth.
- Traffic condition – traffic density, traffic complexity, and risk of collision
- Weather and sea conditions – all hydro-meteorological conditions of the area
- Ship management factors – voyage length, manager's instruction, and specific operations
- Geographical locations – ocean waters, near-coastal areas, anchorages, and port approaches.

Personnel onshore and offshore working in the maritime industry should be familiar with these factors and start eliminating the limitations with the help of appropriate procedures and routines. Training should be provided regularly, and the cognitive capacity of the end-users needs to be regularly tested to be aware of the routines and the system in which they are operating. Flooding of alarms and missing actual events could be reduced due to poor configuration or mismanagement; operators must be prepared for these situations through drills, simulations, refresher training, checklists, and procedures.

- Technology

Automated traffic light (like ASOG lights) colors depend on the gravity of the situation relative to the operation in the alarms system and might be helpful compared to the monotonous use of universal red light.

Manufacturers need to add another layer of filter with flexibility for the DPO to prioritize the alarms or the essential instruments for the specific operations. Groupings are necessary not just within the software but also in the hardware. Such grouping will reduce the time spent acknowledging the alarms in several different locations in the bridge while saving time from those movements that could resolve the issue for the disturbance in the alarm system.

Single audible alarm for single failure; some alarms are too loud while others have similar alarm tones. Alarms from radar, ECDIS, AIS should be made distinct in audio so that it does not interfere in the working of DPO during DP operations. The proper segregation of other alarm systems from the DP alarm while in the DP Operation (Harbor/transit/DP) will help the DPOs focus. Integration of other general alarms should be organized while segregating different alarms for their purpose.

Development of software with improved help-function for better understanding of error codes and messages is necessary for DP operators. Alarm text should be displayed in all DP screens present on the bridge and not just the screen in command. This will bring a proper overview for both operators in the bridge.

- Organization

The development of a human-centered alarm system would be optimal and, in the long term, benefit the company, its reputation, and the personnel's health and safety. At the same time, the focus should be on the end-user with simple easy to understand alarm codes and messages.

Building up a resilient organization should be the ambition for organizations in the future. Resilience is achieved when an institution can keep a high safety level, reduce incidence and accidents and come back from downfall. Promotion of reporting an undesirable event should be promoted as a safety culture as these are the early signs for near-approaching catastrophe. A culture of learning by mistake should be deep-rooted in the company, onshore and offshore. The lean concept should be encouraged and developed to make safety culture and resources more efficient while always focusing on the system and not on the end-user.

Manufacturers need to consult to bring suggestions from experienced end-users. Such suggestions could be helpful as it relays the firsthand user feedback. Feedback could develop troubleshooting programs, update deployed systems, bring improvement in new systems, and investigate accidents.

6.2.Risks of Position loss

Position or heading loss is one of the most redundant parts of a DP vessel. A bow-tie diagram is prepared after identifying risks related to GPS signal loss, its consequences, existing safeguard, and mitigating measures. This particular method is chosen due to limited data available for GPS signal loss, especially concerning the probability and consequences of previous events.

The Bow-tie diagram in *Figure 23* is prepared with the risk of position loss in the center, shown in red. Hazards are categorized in internal and external factors shown in blue and green color, respectively. Risks categorized in internal factors are typically caused within the boundary of the ship, while external factors are caused outside the ship's boundaries. On the left-hand side of the diagram, causes of GPS signal loss are presented, whereas consequences are similarly listed on the right-hand side. The yellow vertical pillars represent barriers to prevent the risks. Existing safeguards in DP vessels are presented in the second and third columns from the left. The reason for segregating existing safeguards into two columns is because some risks have multiple safeguards, whereas other risks have only one. A similar method is used for splitting the mitigation measures on the right-hand side. The second column from the right is used as a primary mitigation measure, whereas the third column from the right is used for risk requiring multiple mitigating measures. For a specific mitigating measure or existing safeguard, the risk analysis (Appendix E) will provide a basis for arriving at a measure that can reduce the risk; such measures could be either probability reducing or consequence reducing, depending on whether they apply to the right or the left side of the bow-tie diagram (Aven, 2008).

Correspondence to Appendix E and *Figure 23* will show the complete risk picture of GPS signal loss based on HazID performed with the HazID group. HazID is conducted with a group of 7 people. The group contained two members with DP vessel experience, the other two with expertise in risk analysis and oil and gas experience, one with maritime experience, one with maritime education and experience, and the last with a management background. A list of possible hazards with existing safeguards and mitigation measures was listed in the initial phase. Later risks are categorized according to factors that might occur internally or externally.

6.2.1. Problems

There are several causes for possible loss of position and heading. A list of causes found during HazID meeting and consequences, existing safeguard, and mitigating measures are shown in Appendix E. The following are the leading causes for possible position loss in a DP vessel.

Internally, the position loss might occur due to a lack of maintenance of the instruments related to keeping the position. Possibility of improper update of the software or bugs in the update might lead to system failure and result in position loss. Irregular controller system reboot and overloading network bus (netstorm) might also cause failure in the system. Improper alarm handling and black-out are some of the typical causes that still occur on DP vessels.

On the other hand, the following external factors might play a role in losing position and heading in DP vessels. It is found that there might be an error in the signal received while using CyScan together with a highly reflective object in the fixed installation. Cyber-attack or malicious acts might lead to loss of position. Arctic exploration limits the availability of the number of satellites for position location, along with dilution of precision (HDOP), which might cause loss of position during the DP operation. In addition, error signals received from the satellite might cause the signal to jump occasionally.

6.2.2. Suggestions

Suggestions for making the DP system protected against further risk can be implemented using the measures presented in Appendix E and Figure 23. The mitigating measures for these risks are independent redundancies (inertial reference system); fire and explosion resilient structures, advanced signal processing system, and remote assistance for debugging.

These risks are critical, especially when plans for developing fields are done with FPSO + Production vessel and some subsea solution in the Barents Sea. All these systems are heavily reliant on IT and various forms of communication to and from the field, posing a risk of cyber-attack in these systems. Crew should be trained, and a regular course should be conducted to keep personnel updated about the challenges and knowledge required to tackle malware and phishing attacks. Effective cyber laws, together with cyber-attack resilient systems, need to be in place. Due to polar weather conditions, it is not easily accessible for humans to check physically the equipment in case of issues. Therefore, the operators must investigate the risks present and implement safeguards to prevent risks from occurring.

The use of inertial navigation should be prioritized together with today's positional navigation system and its redundancies. An inertial navigation system is an independent unit that does not require any communication medium to either satellites or any physical structure nearby to refer to its position. Enough barriers should be established so that high-risk operations can be executed safely. An improvement on the maintenance plan must be prepared using either a conditional based or predictive method for maintaining the vessel (Marquez, 2007).

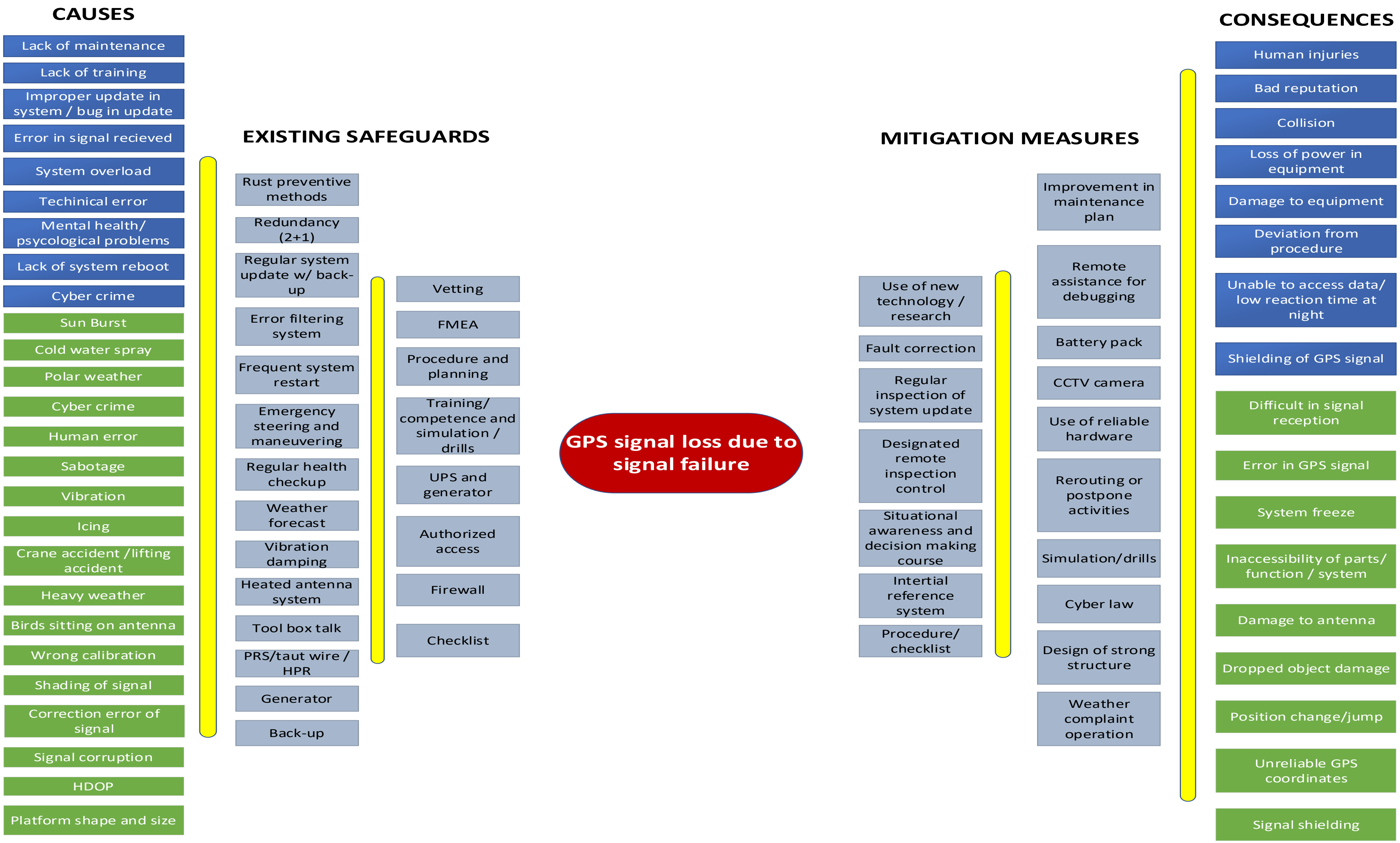

Figure 23 Bow-Tie diagram for risk analysis of position loss.

6.3. Risks in usage of Alternative fuel source as Hydrogen and Batteries.

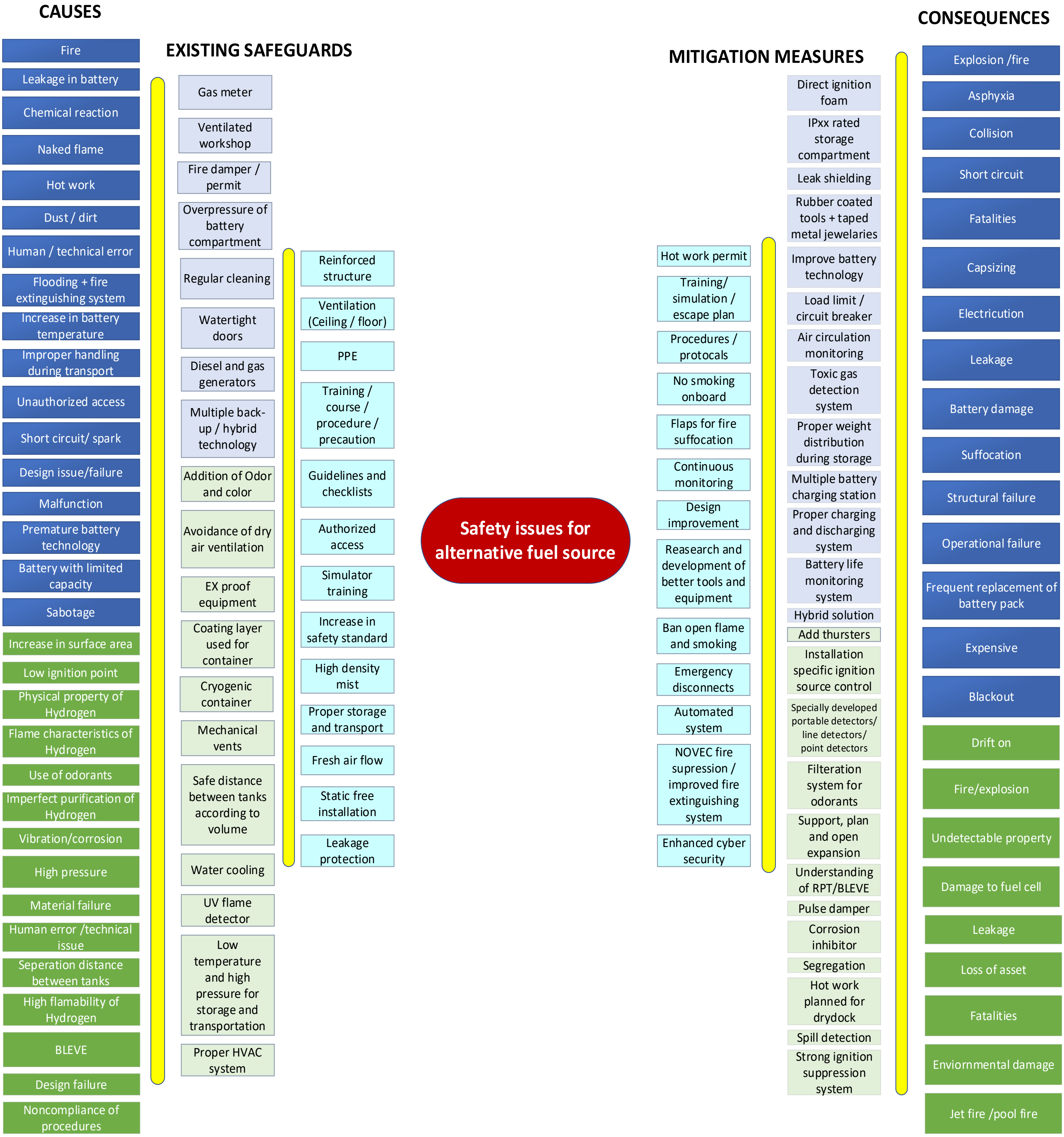

Figure 24 Bow-Tie diagram for risk analysis for use of alternative fuel

The concept of hydrogen and battery as hybrid technology is getting popular and has increased its demand worldwide.

A similar method used in GPS position loss is used to prepare a bow-tie diagram using risk analysis for an alternative fuel source. A Bow-tie method is preferred due to the lack of data for the probability of occurrence of risks and experts with adequate experience to categorize the risk parameters. A HazID team of five was involved in risk identification, where two of the members had experience from battery technology onboard vessels, one person had professional experience with hydrogen-based technology and the last two members with maritime experience. A Bow-tie diagram is prepared with the risk of safety issues for alternative fuel sources, shown in the center with red color. Hazards for battery and hydrogen factors are shown in blue and green color, respectively. The principle for segregation of cause, barrier, existing safeguard, mitigating measures, and consequences resemble the explanation given in chapter 6.2.

Correspondence to Figure 24 and Appendix F will show the complete risk picture of safety issues for alternative fuel sources according to HazID performed with the HazID group.

6.3.1. Problems

Hybrid solutions are valuable and are used to cut emissions, reserve spinning, peak savings, and enhance the dynamic performance of the vessel. Hydrogen with battery technology is redefined solution instead of conventional fuels to meet the zero-emission goal.

The primary risks of using hydrogen as energy carriers are its unknown flame characteristics, low ignition point, boiling-liquid expansive vapor explosion (BLEVE), Rapid Phase Transition (RPT), problems in transportation and storage, undetectable physical properties, and difficulties in extinguishing hydrogen-based fires. Hydrogen has a high vaporization rate compared to LNG; on a typical day, 0.2% of LNG escapes from the ship's system; in the case of hydrogen, the escape rate is 5% vaporization per day (Wuersig, 2018).

Literature review for hydrogen-based fuel technology suggests a more significant advancement in development of hydrogen-based technology, while there is latency in the development of rules and standards. This latency might lead to an accident that might have a major impact on life, property, environment, and reputation.

Similarly, the main risks identified for battery technology are thermal runaway, flame and explosion characteristics, short battery life, and issues with storage capacity.

6.3.2. Suggestions

Finally, suggestions for making the vessels with hybrid fuel solutions safer for everyday use can be implemented using the measures in the HazID table and the bow-tie diagram presented in Appendix F and Figure 24, respectively. After studying the hybrid fuel system (LNG/Hydrogen + battery), it is found that battery or hydrogen alone cannot fulfill the requirements and demand required in the offshore industry. Currently, there are diesel-electric vessels that are utilizing the battery pack. In the case of the new fuel, the main engines and generators will be replaced with the one that runs with gas or hydrogen. Hydrogen is preferable because it has no carbon footprint and is found in abundance in nature in the combined molecular form of water.

In vessels using hydrogen as a fuel carrier, the following mitigating measures are essential to make hydrogen-based hybrid solutions secure and reliable for the future;

- Ignition source control as hydrogen is very flammable by eliminating the source of static electricity.
- Research and development of better tools and equipment; production, handling, and distribution of hydrogen must mature together with technology.
- Improve understanding of fire and explosion due to hydrogen while utilizing the strengths and eliminating the hydrogen-based system's limitations.
- The development and use of portable, line, and point detectors for leak and fire detection are necessary.
- Design improvement of the vessel, as hydrogen is lighter than air and will rise in case of leakage. Improvement in design is necessary to accommodate the newer challenges and technology to utilize the potential in hydrogen fully.

In the case of battery technology, the issues discussed above could be mitigated by

- A proper battery pack design and its cooling system are essential to avoid thermal runaways and irregular fire and explosion characteristics. The development of battery-life monitoring systems and improved charging and discharging cycles must be the primary focus of the industry to make the battery system reliable and efficient.
- Increment in battery storage capacity and battery life will increase usability and possibility.

- EX proofing of equipment used in battery-powered vessels reduces the chance of explosion or ignition by controlling the ignition source control.
- Several fast-charging stations are required as the demand for power for battery-based vessels is increasing.

6.4. Impact Load

In case of position loss or heading or due to fire and explosion, it is critical to evaluate the consequences of impact load and collision energy between a vessel and offshore installation. Impact load is an amount of force delivered during contact and is applied gradually, maintained over time. In such scenarios, the structure takes the force and absorbs it by distributing it throughout the periphery of the point of contact. Such absorption can be visualized in the form of energy transfer, resulting in fracture, failure, structural deformation, dents, heat, vibration, and sound in both ship and platform.

One of the main concerns during a DP operation is the ship's collision with offshore installations. Generally, DP vessels work near offshore platforms and wind farms during their construction and maintenance phases. The risk of collision increases with the increase in the frequency of activities around these structures. This is especially true when newly built offshore vessels are built with a more robust ice-strengthened belt due to an increase in oil and gas activities in the arctic region. Along with that, few more projects are about to start in the polar region. There are concerns regarding the ship's collision and structures in several sectors outside shipping and oil and gas. Research can be found for the transport segment where collision between a ship and a fixed bridge pillar is of interest (Olsen, 2016). A generic collision load between offshore vessels and installation is based on 5000 tons of the vessel size. In general, PSV with a maximum of 8000 tons is used for offshore operation in close proximity to offshore installation. However, in the case of a significantly larger or smaller size vessel, the weight, weather, and other parameters are always taken into account (DNVGL, 2015 b).

For the vessels working offshore in a colder climate, Finnish-Swedish Ice rules are followed as per the structural requirement by DNVGL to help the design of vessels operating in first-year ice conditions (TrafiCom, 2019). Ships classified with ice-class have a region determined as upper ice water line and lower ice waterline, which outlines the ice-strengthening region. This ice belt region is divided into bow region, midbody region, and stern region. The minimum material grade for ships with ice strengthening starts from *Grade B/AH (30mm-35mm)* to *Grade*

D/DH (50mm to 150mm) (DNVGL, 2017 b). These vessels are designed to sail in the open sea with a maximum ice thickness of 1 meter (DNVGL, 2018 b).

As the size of supply vessel increases and the design of those vessels are improved for sailing in the polar region for ice navigation, the collision energy during impact increases along with the damages in the installation. Improved bow design and reinforced ice belt are essential factors to be considered to avoid severe accidents or, in the worst-case scenario, a total loss. It is essential to evaluate how the risk due to these improvements have in existing installations. Calculated maximum impact energy for minimum damage is 11, and 14 Mega Joules for head-on and sideways impact, respectively (Moan, Amdhal, & Ersdal, 2017).

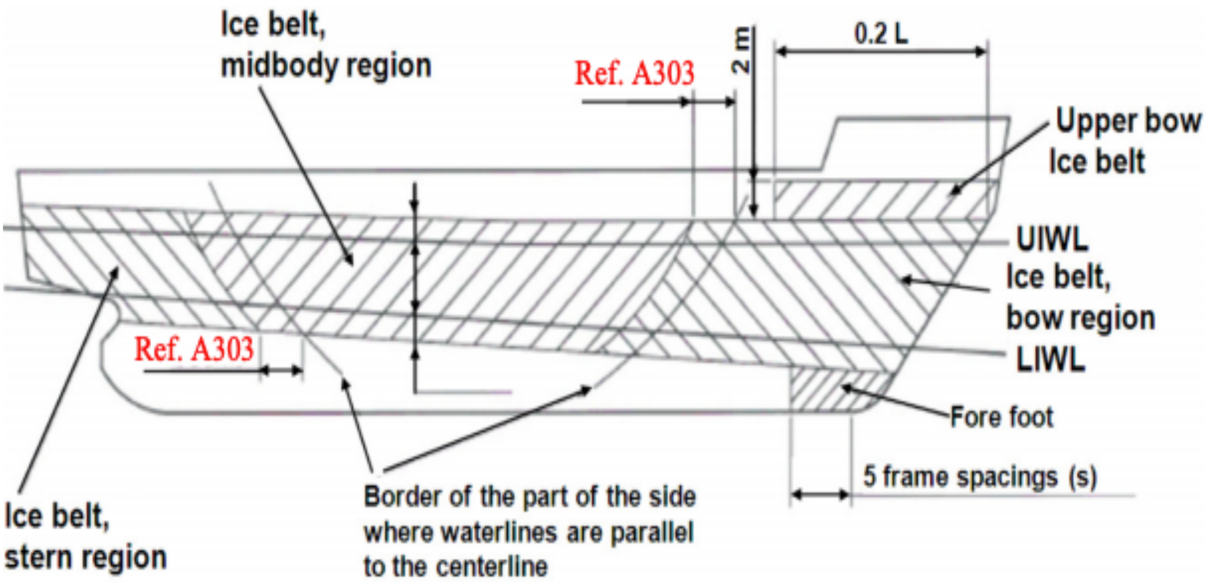

Figure 25 Ice belt design of a vessel. (TrafiCom, 2019)

Steel quality requirement for legs of offshore installations shall be of *Design Class 2* (*low joint complexity*) for the upper part and *Design Class 4* (low joint complexity) for the base (Standard Norway N-004, 2021). In the case of the steel quality level, the highest grade I is used; for the actual calculation of impact absorption load use of NORSOK N001, NORSOK N003, NORSOK N004, DNV GL OS A101, DNVGL OS C101, DNVGL OS C103, and DNVGL OS C104 is advised. For the actual calculation of the load absorption limit, operators should calculate platform-specific calculations considering permanent loads, variable functional load, environmental load, deformation load, accidental load, fatigue load, and combination loads along with aging factors. As a reference, the vessels with displacement of 2000-5000 tons, the impact energy can be up to 60MJ, with a velocity of 6 m/s (Travanca & Hao, 2015).

Analysis of Impact load:

Kinetic energy is converted to elastic energy when two bodies collide. There is a significant effect due to dynamic loading. Methods for collision energy between ships and offshore platforms were developed by Zhang (Zhang, 1999). All the assumptions are unchanged; methods are replicated to visualize how collision is one of the critical concerns in the design of ship and offshore installation for safe operation.

In this case, kinetic energy is given by

$$Kinetic\ Energy = \frac{1}{2} mav^2$$

Here,
m= Vessel Mass
v= Vessel Velocity
a = added mass factor

A collision system may be symbolized in the form of two bodies that are acting against one another. Where, F_b is collision force between ship and platform and F_p is force transmitted during collision on the top side of the platform. The following equations resemble the stiffness force for platform topside and base, respectively.

$$F_b = k_{11}d_b + k_{12}d_p$$

$$F_p = k_{21}d_b + k_{22}d_p$$

Here, $k_{11}, k_{12}, k_{21}, k_{22} \ldots \ldots . . k_s$ are stiffness coefficients.

Thus, an interaction between two bodies can be restructured as follows.

$$F_b \begin{cases} k_s(d_a - d_b)\ for\ v_a - v_b \geq 0 \\ 0 \qquad\qquad\quad for\ v_a - v_b < 0 \end{cases}$$

Here, $d_a$is displacement at point of collision for the ship, where the displacement of the platform can be considered small for minimal movement. Thus, the force can be written as F_p when velocities $v_a$is equal to $v_b$at the end of collision.

$$F_p = \frac{k_{21}}{k_{11}} F_b$$

Impact impulse of the collision can be written as

$$I_b = \frac{M}{D_{ab}}\ v(0) - v$$

Where,

$$D_{ab} = \frac{1}{1+m_{ax}} \sin^2 \alpha - \frac{1}{1+m_{ay}} \cos^2 \alpha + \frac{1}{1+j_a} . \frac{[y_c \sin \alpha - (x_c - x_a) \cos \alpha]^2}{R_a^2}$$

Here

M= Mass of the ship

$R_a$is ship's mass inertia around center of gravity (CoG).

m_{ax}= added mass for surge motion (assumed 0.05)

m_{ay}= added mass for sway motion (assumed 0.5)

j_a= added mass coefficient of moment for the rotation around CoG (assumed 0.25).

Now, Impact impulse on the comprehensive platform mass can be written as,

$$I_p = -M_p v_p = \frac{k_{12}}{k_{11}} I_b$$

When the structures have collided the velocity of the platform and the vessel are equal at the point of collision and can be written as

$$v_a = -\frac{k_{12}}{k_{11}} v_p$$

The energy produced that is absorbed by the collision of ship and deformation of the platform can be expressed as

$$E_{Crash} = E_0 - (E_s + E_p)$$

Here,

E_0= Initial kinetic energy of the ship

E_s= Final kinetic energy of the vessel at the end of collision

E_p= Kinetic energy of the platform at the end of collision.

Now,

Energy dissipated by the ship and platform can be expressed as,

$$E_{Crash} = \frac{k_{11}}{k_{11} + k_s} (E_0 - E_s - E_p)$$

Hence,

Energy used to change the property of the platform can be expressed as,

$$E_P = \frac{k_s}{k_{11} + k_s} (E_0 - E_s - E_p)$$

This shows that *Collision Energy* is calculated using the velocity of the vessel and stiffness coefficient. Thus, the risk of damage to the aging installations increases with the newly built hull strengthened ice-class vessels. According to Offshore Standards A-101 the minimum energy that a structure should be able to absorb is 14 MJ and 11 MJ for sideways and heads on collisions, respectively (DNVGL, 2015 b). Use of vessels inside the safety zone should be done with location-based risk analysis. Risk analysis should be based on the area vessel will operate, the vessel's displacement, information regarding the ice-strengthened belt around the vessel's body, including the bulbous bow and stern (Ice class 1A Super). Below list (*Table 11*) of few accidents in previous years in NCS is given as an example to reflect on how much impact energy one collision encompasses (Kvitrud, 2011).

Table 11 List of significant accidents in between years 2000-2010 on NCS.

Year	Collision Energy	Vessel	Installation
2004	About 39MJ	Far Symphony	West Venture
2005	About 23MJ	Ocean Carrier	Ekofisk
2006	About 61MJ	Navion Hispania	Njord B
2007	About 2MJ	Bourbon Surf	Grane
2009	About 70MJ	Big Orange	Ekofisk
2010	Low (Multiple)	Far Grimshader	Songa Dee

7. Conclusion

The main objective of this thesis was to analyze the safety challenges and the risks on DP vessels by addressing three central areas that are considered significant in the maritime industry: causes of alarms during emergencies, risks related to position loss, and risk of using hybrid solutions such as hydrogen combined with battery.

HTO analysis has been used to find contributions and deficiencies from human, technology, and organization in a working system. General requirements for alarm, alarm generation, alarm structuring, alarm prioritization, alarm presentation, and alarm handling were studied using HTO analysis. Cause and effect for accidents were studied to suggest improvements and ensure safer operations for the maritime industry. Some of the biggest challenges when an alarm sounds are maintaining position or heading and avoiding fire and explosions while attending to the course of the alarm.

If the alarms are not handled properly, there is a high possibility of accidents. Therefore, handling such alarms are crucial. However, there are issues with the current alarm system on DP vessels — unnecessary and irrelevant alarm generations according to the operation, which causes “alarm fatigue”, lack of prioritization and flexibility in alarm handling, and decentralized alarm location on the bridge. In conclusion, to improve the alarm system present today the following are suggested,

- Manufacturer of alarm systems should return to the end-user for feedback to improve the system
- Unnecessary and irrelevant alarms should be segregated according to the status of vessels
- Automatize traffic light color coding of alarm messages
- Make understandable alarm codes and error messages (minimum abbreviations)
- Operator must focus on operation while attending the alarms

The suggestions above for improving the alarm system are relevant for agencies or agents in human, technology, and organization.

Hybrid power solutions are valuable and are used to cut emissions, reserve spinning, peak savings, and enhance the dynamic performance of the vessel. In order to meet the zero-emission goal, hydrogen with battery technology is a possible solution instead of conventional fuels. The main risks of using hydrogen as energy carriers are its unknown flame characteristics, low ignition point, problems in transportation and storage, undetectable physical properties, and difficulties in extinguishing hydrogen-based fires. In vessels using hydrogen as a fuel carrier, the following mitigating measures are essential to make hydrogen-based hybrid solutions secure and reliable for the future,

- Ignition source control
- Research and development of better tools and equipment
- Improvement in the understanding of explosion
- Development and use of portable, line and point detectors,
- Design improvement of the vessel.

Literature review for hydrogen-based fuel technology suggest that there is a greater advancement in development of hydrogen-based technology, while there is latency in development of rules and standards.

Similarly, the main risks identified for battery technology are thermal runaway, explosion characteristics, state of health of battery, and issues with storage capacity. These can be mitigated by proper battery pack design, increment of battery storage capacity and life, EX proofing of equipment used in battery-powered vessels, several charging stations, proper charging and discharging cycles, and battery life monitoring systems.

This research also extends to risk identification for position loss on DP vessels. It is essential to maintain the position of the vessel to avoid collisions with offshore installations which may lead to loss of life, fire and explosion. The leading causes for position loss could be blackouts, netstorm, errors in reception of GPS signal, and cyber-attacks. The mitigating measure for these risks are use of extra independent redundancy (inertial reference system), cyber-law, fire and explosion resilient structures, advanced signal processing system, and remote debugging setup.

Recent study and development in battery technology suggests that a new battery system is under research (graphene) which has longer life and increased battery storage capacity. The conclusions here apply to all types of marine operations including Oil and gas, Offshore Wind farm attendance and the aquaculture industry.

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Appendix A: Definitions.

The following definitions are used in this research and are derived from the commonly used industry literatures. Sources of these definitions are main maritime publications from regulatory bodies, classification societies and scientific literatures.

Alarm prioritization is defined as a organization of alarms by the importance of each alarm for operators tasks.

Activity-Specific Operating Guidelines (ASOG) describes guidelines performance limits on three different aspects, i.e. on operational, environmental and equipment aspects for the location and specific activity.

Annual DP trial can be defined as a sequence of tests to confirm the integrity of DP system, performed annually *during a specific time, as described by IMCA M190 publication.*

Bus-tie breaker is an instrument to connect or disconnect switchboard sections ("open bus-tie(s)" means disconnected).

Cognitive processing occurs when new information appears to an individual who already has a basis of the knowledge acquired before. The efficiency of handling the new information is based on the form of knowledge and how it can be accessed (i.e., by simple recognition or demanding recall).

Cognitive response is a type of response where internal processing of information is more vital rather than any performance of physical actions.

Common cause failures are failures that are apparent on redundant DP equipment groups induced by external effects (including automatic intervention, such as ESD or auto stops)

Common mode failure is defined as a subset of common cause failure where redundant equipment also fails in a similar manner.

Common points describes the elements that effect redundant group and can overcome the redundancy concept, where mission-specific equipment presented also are involved.

Comprehensive analysis refers to

- Coverage of all areas of design and proposed functionalities
- Clear conclusions from analysis performed
- The foundation of conclusions is evidently expressed and independently confirmed.
- The objectives of tests required to confirm and validate activities are supported with analysis and conclusions.
- Comprehensive range of failure modes such as benign, aggressive and hidden failure modes are also considered by testing and analysis.

Configuration is defined as the vessel's configuration documented in FEMA. Some examples of configurations include

- Fuel, control power supplies and cooling water valves.
  Several DP configurations installed on vessels ensures flexibility. The vessels' configuration ought to be examined and verified to be fault-tolerant regarding the specified equipment class.

Conventional fuels in marine applications, conventional fuels are typically Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO), Marine Diesel and in some context LNG.

Consequence analysis continuously verifies that the vessel will remain in position even if the worst-case failure occurs.

Design to test systems are confirmations completed by testing the system performance to its operational limit that can be completed without the risk of damaging the equipment.

A digital survey is a tool that verifies complete or specific parts that are managed and then incorporated. The tool includes methods to collect data that may be used as proof of verification by another party.

Dynamic Positioning control station (DP control station) is a work center chosen for DP operations. Indicators, displays, alarm panels, internal communication systems, and control planes are present in this work center. DP control and independent joystick control are also included as well as required position reference systems' Human Machine Interface (HMI), manual thruster levers, mode change systems, thruster emergency stops, internal communications.

Dynamic positioning design philosophy is defined as a philosophy of achieving redundancy goals with the intended performance of the system to commence its operation inside the verified post-failure capability and WCFDI.

Dynamic Positioning operation (DP operation) is an operation where the DP system automatically controls at least two degrees of freedom in the horizontal plane as a minimum of two degrees of freedom.

Dynamic Positioning Verification Acceptance Document (DPVAD) is a document issued by the Administration or its Recognized Organization to a DP vessel conforming with guidelines.

Dynamically positioned vessel (DP vessel) is a unit or a vessel that automatically holds its position and/or heading (fixed location, relative location, or predetermined track) by using thruster power.

Dynamic Positioning control system (DP control system) defines all control elements and systems such as hardware and software vital to position the vessel dynamically. The DP control system contains the following components:

1. Computer system/joystick system
2. Sensor system
3. Control stations and display system (also called operator panels)
4. Position reference system
5. Associated cabling and cable routing
6. Networks

Dynamic Positioning System (DP system) is defined as the full installation required for dynamically positioning a vessel consisting of sub-systems such as power system, thrusters, and DP control system.

Emission Controlled Area is an area or specified area under regulation 13 and 14 of MARPOL Annex VI. Ships are required to use fuel oil on board with sulfur content less than 0.1%.

External Interfaces and influences are interfaces between the DP system and external systems. Some examples include ESD, fire and gas or voltage (such as pipelay, moorings, cable laying, drilling equipment, or depth sensors), whose failures may affect the DP system and cause the WCFDI to be exceeded. Analyzing failure modes is essential. Some examples include failures of external systems, sensors, and interfaces. External influences are electromagnetic interference, acoustic noise in the water column, and dust or smoke in the ventilation system.

The external boundary of a ship refers to the parameters outside the ship's physical location and to systems that are not physically present on board the ship.

Failure is defined as an event in a component or system that causes one or both of the following:
1. Loss of function of the component or system and/or
2. Degradation of functionality to such an extent that the safety of the vessel, personnel, or protection of the environment is significantly affected.

Failure Modes and Effect Analysis (FMEA) is a systematic analysis to discover if the redundant groups of devices in a DP system are independent and fall into a safe state. In this case, independence means no common cause of failure, and fail-safe* means that loss of position and/or heading cannot occur.
*This is the case when the vessel is operating within its capability after a failure DP.

FMEA proving trials describes the test program to verify the FMEA.

Hidden failure describes a fault that is not immediately apparent to operations or maintenance personnel and may result in equipment being unable to perform a function as required, such as protective functions in power plants and switchboards, standby equipment, emergency power supply, or lack of capacity or performance.

High Reliability Organization is an organization that has succeeded in avoiding disasters in an environment where risks and complexity are prominent factors where it is considered normal to expect accidents.

Hybrid power systems combine different technologies to produce power.

Independent is not dependent on a common cause of failure. Generally, sufficiently demonstrated redundancy (concerning the assigned class of equipment) is considered independent. Other organizations may have different definitions of independence.

Independent witness is a suitably qualified and experienced person who is removed from the day-to-day control of operational of the ship.

Independently confirmable record of the test submitted for review contains sufficient knowledge for the verifier to independently determine if the stated test result is correct, that the test was administered correctly, and that the test objective was met.

The internal boundary of the ship is the physical space present on board that can be changed by the ship's crew along with the variables that are available.

Lean Concept is a mindset or a culture in an organization; that brings change in the way of thinking towards effectiveness and is incorporated in daily working routine.

Loss of position and/or heading means that the vessel's position and/or heading is outside the limits set for the performance of the current DP activity.

Overview displays are constructed to help the operator get an overview of the process. They may consist of; main alarm lists, tiles or annunciator alarm displays, and large screen displays with important information.

Perception is the recording of sensory inputs. Alarms must be clearly visible, easily understood, and contain the important elements, such as what is wrong, where is it, how serious is it-these are the elements that are essential for further cognitive processing.

Position keeping refers to maintaining the desired position and/or course or trajectory within the normal deflections of the control system and the defined environmental conditions (e.g. wind, waves, current, etc.).

Power management system is a system that confirms stability of electrical supply under all operating conditions.

Power System is used when all components and systems require power to the DP system. The power system includes the following but is not limited to these points:

- Prime movers with important auxiliary systems containing piping, fuel, cooling, prelubrication and lubrication, hydraulics, preheating, and pneumatics
- Generators
- Switchgear
- Distribution systems (wiring and cable routing)
- Power supplies, which includes undistrubtable power supplies
- An Energy management system

Peak Shaving delivers peak power from an alternative power source. Some examples are a battery or capacitor energy storage system which are used to provide power peaks to permit diesel generators to function at a reasonably steady load.

Periodic (five-yearly DP trials) are periodic tests completed in intervals that do not exceed five years and ensures full compliance with the applicable parts of the Guidelines in accordance with MSC 645 and 1580 of the IMO.

Proving trials, A series of tests conducted at DP vessels to verify the conclusions of the DP System FMEA.

Redundancy is the ability of a component or system to sustain or reestablish its function when a single failure has arisen. Redundancy can be attained, for example by the installation of multiple elements or systems or other means to executing a function.

Redundancy Design Intent (RDI) is present when the thrusters available to develop surge, sway and yaw, both in the intact state and after a single worst-case failure. Usually presented in tabular format.

Redundancy Verification Table (RVT) represents interpretation of components such as mechanical, electrical and control of each functional group in tabular form with colors to demonstrate redundant groups. Subsequently, makes it easier to identify common anilities.

Redundant equipment group is able to of maintain the position and course of the ship (under limiting conditions). It is also independent of other equipment groups either alone or in defined affiliation.

Reliability is the probability that an element can complete a essential function under given circumstances for a time period.

Remote testing is an inspection made by the crew or other owners without the presence (or remote observation) of a surveyor.

Resilience Engineering Perspective is the capability of a system to resist failure and continue to operate after failing. This includes the strength to recover from a failure without damage.

Selective lists displays a few selected available alarm information, based on selection and sorting conditions identified by operators.

Separation design intent is physically separated redundant equipment groups, which is represented by the complete system design for a particular configuration (DP equipment class 3).

Spinning reserve is defined as the reserve generating capacity in an electrical power system that can be available immediately without the need to connect additional generators. It can be provided by operating more generators than are required to supply the load, or by alternative power sources, such as battery energy storage systems.

Thruster system refers to all components and systems necessary to provide thrust and direction to the system DP. The thruster system includes:

1. Thrusters with propulsion units and necessary auxiliary systems including piping, cooling, hydraulic and lubrication systems.
2. Primary propeller and rudder under the control of the DP system.
3. Thruster control system
4. Manual thruster controls
5. Associated wiring and cable routing.

Time to safely terminate (operations) refers to the sum of time necessary in an emergency to safely terminate operations of the DP vessel.

Verification and validation processes are activities taken to confirm that acceptance criteria are met. Validation in this context is by testing and involves the efficiency of compensating requirements.

Vessel Technical Operator (VTO) is an owner or any other organization, such as a vessel manager or bareboat charterer, that is in charge for the operation of the vessel and has responsibilities as defined by the International Safety Management Code (ISM Code) or other legislative framework.

Worst-Case Failure Design Intent (WCFDI) is the specified minimum DP system that has capability to be maintained after failure. The worst-case failure design intent is used as the base for the design. This commonly refers to the number of thursters and generators that can fail together.

Worst-Case Failure (WCF) is identified as a single failure in the DP system that results in a maximum adverse effect on the DP capability, as determined by the FMEA or other regulatory framework.

Appendix B: Classification of Alarm Requirements (PSA, 2001).

Human	Technology	Organization
General Requirements		
1) The alarm system shall be explicitly designed to take account of human factors and limitations	**2)** The alarm system should be context sensitive.	**3)** Operators shall receive instruction and systematic training in all realistic operational usage of the alarm system.
3) Operators shall receive instruction and systematic training in all realistic operational usage of the alarm system	**4)** The alarm system design shall be based on an alarm philosophy.	**5)** The alarm system shall be properly documented, and clear roles and responsibilities shall be established for maintaining and improving the system.
6) It should be easy for process experts to build into and maintain knowledge and intelligence in the alarm system over time	**9)** The alarm system shall be fault tolerant.	**6)** It should be easy for process experts to build into and maintain knowledge and intelligence in the alarm system over time
8) There should be an administrative system for handling access control and documentation of changes made to the alarm system	**12)** Status information related to safety system functions, such as blocking/inhibit and override, shall be easily available on dedicated lists and in process displays	**8)** There should be an administrative system for handling access control and documentation of changes made to the alarm system
10) System response time shall not exceed 2 seconds		**10)** System response time shall not exceed 2 seconds
11) Safety critical functions should be identified and documented. Status information and failure alarms from these functions should be clearly presented and continuously visible on dedicated displays.		**11)** Safety critical functions should be identified and documented. Status information and failure alarms from these functions should be clearly presented and continuously visible on dedicated displays.
Alarm Generation		
-N/A-	**14)** The alarm system shall be able to generate basic alarms	**13)** Every alarm shall require an operator response.

	15) The alarm system should include generation of aggregated alarms or/and model-based alarms	**16)** All alarm limit settings should be systematically determined and documented during plant design, commissioning, and operation.
	16) All alarm limit settings should be systematically determined and documented during plant design, commissioning, and operation.	
	17) Operators could be permitted to change some alarm limits.	
	18) Signal filtering should be used.	
	19) Signal validation should be used.	
	Alarm Structuring	
-N/A-	**20)** It should be possible to select, group and sort alarms.	**-N/A-**
	21) Alarm suppression functions shall be included in the system.	
	22) The system should use alarm suppression, not alarm filtering.	
	23) The alarm suppression in the system should be familiar to the operators, and it should be documented in an easily understandable way.	
	Alarm Prioritization	
24) Alarms shall be prioritized	**26)** Alarms should be prioritized according to the time available for successful corrective action to be performed	**24)** Alarms shall be prioritized

25) Alarms should be prioritized according to the severity of consequences that could be prevented by taking corrective action	**27)** There should be an effective priority distribution of process alarms occurring during normal operation and in process disturbances	**25)** Alarms should be prioritized according to the severity of consequences that could be prevented by taking corrective action
26) Alarms should be prioritized according to the time available for successful corrective action to be performed		**28)** Every site should have written rules on how priorities should be assigned
27) There should be an effective priority distribution of process alarms occurring during normal operation and in process disturbances		
28) Every site should have written rules on how priorities should be assigned		
	Alarm Presentation	
	29) A main alarm display shall be provided	
	30) Key alarms shall be shown in overview displays that are permanently on view, with spatially dedicated alarms	
	31) An historical log of alarms and events should be available to the operator	
	32) Alarms should be integrated in process displays	
	33) Selective list displays should be provided	
	34) The priority of alarms should be coded using colors and possibly other means	
	35) Audible alarm annunciation should be used when new alarms arrive	
	36) Special visual annunciation should be used for new alarms	

	37) Alarm information should be informative and easy to understand	
	38) Alarm information should be easily readable	
	39) Necessary alarm information shall be available from all relevant workplaces	
Alarm Handling		
40) Every alarm that is triggered should require acceptance	**41)** It should be possible to shelve individual alarms	**42)** Navigation in alarm displays should be quick and easy
41) It should be possible to shelve individual alarms	**42)** Navigation in alarm displays should be quick and easy	
	43) Procedures that specify individual responsibilities for monitoring and controlling large process disturbances and emergency situations shall be available and known by the operators	

Appendix C: Questionnaire.

A copy of the questionnaire sent to the participants is included in this appendix.

Introduction

I am Sandeep Nepal, and I am student of Joint Master's Degree in Maritime Operations, Norway/Germany. I was born in Nepal and have had my education in seafaring in Finland. I did 5 years of studies to acquire my captain's license and went to sea for working and have worked as Chief Officer in Finnish fleet. In my career I have worked in tugboats, fishing vessels, passenger ferries, general cargo, tankers, Roll On Roll Off (RO-RO), Roll on/off and Passengers (RO-Pax), hospital ship along with development and launching of Rolls Royce launching of Falco autonomous vessel between Nauvo and Pargas in Finland.

Due to curiosity and desire to work onshore, I wanted to expand my career by studying master's degree here in Norway. During this education, I have achieved higher and broader level of understanding in terms of operations and activities in field of maritime and offshore industry.

My current masters this is about reducing the risk of accidents by addressing the startling issue of Alarm systems in DP vessels. This research is supervised by Ove Tobias Gudmedstad.

How can complexity due to high volume of alarms could be reduced for DPOs during DP operations?

This research question is derived after discussion about general research problem with Equinor. As it is very specific topic within a complex area of ship navigation. There are limited resources that are available. Thus, it is very important to collect data from a target group in form of questionnaire or interview. This survey reenforces the validity of the research result by providing in-depth knowledge extracted from knowledge and experience of the participants. There will be no possible traceback of the answers to the participants, no recording is done. The survey is within the restriction of LOV-2018-06-15 38 personopplysingsloven commonly known as GDPR.

It is here by that you understand the condition that the survey is taken, and it is for the purpose of the research purpose only and will not be used in any other way mentioned other than mentioned in this document.

Questions for Instructors

1. What types of simulators are used, and which brands do they cover?

2. What are the types of alarms that are covered in the simulator?

3. Do the simulators have parts dedicated for Alarm simulation and situational handling according to Alarms?

4. Is it the guidelines by Nautical Institute used in the development and the practice in the simulator?

5. How is the practice of segregation of simulation done in order to increase efficiency and prioritize accident avoidance?

6. Is there any cooperation among vendors in order to improve the coverage of simulation courses?

7. How many hours of simulation time is dedicated to alarm systems? In the case of dedicated alarm, simulation is practiced. What is the procedure, and which requirements are followed?

8. How is the alarm system covering the different layouts and alarm system for different brands, such as alarm systems for Kongsberg, Rolls Royce, Navis, Veripos, and others?

9. How is the simulation course approved? Is it just the amount of time spent in the simulator that is evaluated, or is there a test for the inquiry about the competence of the DPO?

10. Any suggestions for the alarm system in the bridge?

Questions for DPOs

1. How does the overview of the alarms in current DP vessels look?

2. Speaking about flexibility, is it easy to change alarm audio and lights according to preference?

3. Is there a possibility to prioritize some alarms that are especially critical for operations?

4. There are several alarms for the same fault. How is it to work with such alarms? Moreover, what could be your suggestion in order to avoid extra work for the same purpose?

5. What is the most distracting thing in DP operation? Alarms? Clients? Weathers?

6. How are the standing orders in the bridge for DP operations? Is there something you wanted to change for safety?

7. How is the watch overlapped? In case you are tired or unfocused, is there a possibility to change the watch?

8. In case of alarms, how does the call in the engine room received during hectic situations?

9. Who updates the Software? Are all DPOs aware of the changes in the DP system? What is the handover procedure for the person who comes next?

10. Do you think it is possible to increase priority by reducing the number of critical alarms in the bridge?

11. Do equipment providers come for suggestions for improvement in their new DP system that is recently installed? If yes, how often do they do that?

12. Any suggestions for the alarm system in the bridge?

Appendix D: Risk Assessment

For the research performed in case 1 and case 2 HazID sheets are prepared. The hazards in cyber security (loss of GPS signal) are identified as well as the redundancies that are present for the implementation of alternative sources of fuel in current DP vessel. Consequences for the health and safety of people, damage to the asset or environment and finally the priceless reputation of the company are made priority. Risks are divided into 4 different colors green, yellow, orange and red with increasing risk value. A Bow tie diagram is produced by the use of Microsoft Visio.

Following risk acceptance matrix is used for the risk analysis and the matrix reflects on impact, consequence and probability or likelihood of occurrence of the event. This risk matrix is prepared according to the requirements of our case and by evaluation of various examples available on risk analysis methods.

Severity/Impact	Consequences				Likelihood or increasing probability				
	People	Assets	Environment	Reputation	P1	P2	P3	P4	P5
					< 1%	1-5%	5-15%	15-30%	> 30%
I1	No Injuries	No Damage	No Effect	No impact					
I2	Slight injuries or health	Slight Damage	Slight Effect	Slight impact					
I3	Minor injuries or health	Minor Damage	Minor Effect	Minor impact					
I4	Major Injuries (recoverable)	Moderate Damage	Moderate Effect	Moderate impact					
I5	Cause of permanent disability	Major Damage	Major Effect	Major impact					
I6	Loss of life	Massive Damage	Massive Effect	Massive impact					

Explanation of the Risk Matrix, the probability of occurrence and impact are presented according to past personal experiences and assumptions of the HazID group and researcher. The color for risk rating is given with respect to hazard and consequences prior to implementation of mitigation measures. The biggest impact would be loss of human life followed by damage to the environment and reputation of the company which cannot be tagged with any monetary value. However, in case of any hazards that has not occurred in past it is left with grey color with a suggestion for recommended work in the future.

Risk rating	Steps that need to be taken.
Low Risk	Acceptable situation. Proceed as per As Low as Reasonably Practicable (ALARP) approach.
Medium risk	Operation can proceed given implementation of risk reducing action(s). ALARP measures shall be considered.
High risk	Risk reducing actions must be present and controlled. However, operations can continue given satisfactory risk controls in place as the lowest probability for extreme consequences.
Extreme risk	Unacceptable situation. Risk reducing action to be implemented to reduce the risk and new risk assessment to be done to verify a satisfactory situation following the implementation of the controls. In worst case scenario to avoid risk, the possibility of cancellation of operation is open.

Appendix E: HazID For GPS Signal loss due to signal failure

Offshore oil and gas activities and wind turbines are increasing. Generally, there is lack of infrastructure. With the increase and high risk of cybersecurity, what might be the hazards for the DP vessels operating in Barents Sea? (Group of 7 people participated in HazID, See chapter--for more)

<table>
<tr><th colspan="12">HazID for Loss of GPS signal due to signal failure</th></tr>
<tr><th rowspan="3">Code</th><th rowspan="3" colspan="3">Hazard</th><th rowspan="3">Causes</th><th rowspan="3">Consequences</th><th rowspan="3">Existing safeguards</th><th>Probability</th><th>Impact</th><th rowspan="3">Mitigating measures</th><th colspan="2">After execution of mitigating measures</th></tr>
<tr><th rowspan="2">P 1- P 5</th><th rowspan="2">I 1 – I6</th><th>Probability</th><th>Impact</th></tr>
<tr><th>P 1 – P 5</th><th>I 1-I 6</th></tr>
<tr><td></td><td colspan="11">HazID due to Internal Factors</td></tr>
<tr><td rowspan="3"></td><td rowspan="5">Internal Factors</td><td rowspan="3">Malfunction of Equipment</td><td>Rusty Antenna</td><td rowspan="3">Lack of Maintenance/ lack of training</td><td rowspan="3">Collision, Human injuries, Damage in Asset</td><td rowspan="3">Rust preventive methods, FMEA, Vetting, Redundancy (2GPS+1PRS)</td><td>P 1</td><td rowspan="3">I 4</td><td rowspan="3">-Maintenance Plan
-Introduction of new technology if available
-Research in new and effective technology
- Procedure</td><td>P 1</td><td rowspan="3">I 2</td></tr>
<tr><td>Poor wiring Connection</td><td>P 1</td><td>P 1</td></tr>
<tr><td>Improper handling of Equipment</td><td>P 2</td><td>P 2</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">System Bug/ Issues</td><td>Software update</td><td>Improper updating / Bug in the update</td><td rowspan="2">Loss of GPS signal which might lead to collision.</td><td rowspan="2">-Regular system update with -Backup.</td><td rowspan="2">P 2</td><td rowspan="2">I 4</td><td rowspan="2">-Regular inspection of updated system and restart of controllers</td><td>P 2</td><td>I 2</td></tr>
<tr><td>Rollover</td><td>Error in signal received</td><td>P 1</td><td>I 4</td></tr>
</table>

			Net-storm	System overload		-Checklist / procedure Training / competence Error Filtering tools (Parity Bit check) Restarting system often			-Remote Assistance for debugging.	P 2	I 4
			Misuse of equipment	Human Error						P 1	I 2
		Blackout		Inadequate maintenance/ Technical Error	Loss of power in equipment	Emergency steering, Emergency Generator, Use of UPS, Blackout Drills	P 1	I 5	-Backup Battery pack -Fault Correction	P 1	I 3
		Sabotage/ Misuse by DPO		Mental Health Issue/ psychological problem	Damaging of equipment /software and diversion from procedures	-Authorized Access -Mental health inspection -Firewall	P 2	I 4	Designated remote inspection and control, CCTV camera	P 2	I 2
		Screen block or system freeze		Lack of system reboot/ Cyber Crime	Unable to access data / Low reaction time during night	System Restart/ Firewall	P 3	I 3	Usage of reliable hardware	P 3	I 2

		Structural obstruction because of smokestacks from funnel		Human Error	Shielding of GPS signal	-Planning -Checklist	P3	I2	Simulation, Drills	P 2	I 2
	HazID due to External Factors										
	External Factors	Weather	Solar activities	Sunburst	Error in GPS signal, difficulty in signal reception	weather forecast,	P 1	I 4	Rerouting or postponing the activities.	P 1	I 3
			Icing	Cold water spray							
			Heavy weather	Polar weather conditions							
		IT Issues	Malware	Cybercrime/ lack of training	System freeze, inaccessible system or parts or function of a system	Firewall, Restricted Access, Limited Access, Trainings and Simulation	P 3	I 4	Cyber Law, Drill, Situational awareness and decision-making courses	P 2	I 4
			Phishing	Cyber-crime/lack of awareness							
			Physical breach using Pen drive	Mistake from a crew or intentional act							
			External Jamming of Signal	Intentional sabotage/ cyber crime							
			External Overload of system	Cyber Crime							
		Physical Structural damage		Vibration	Damage in antenna,	Vibration damping,	P 3	I 4		P 2	I 4
				Icing							I 3

			Crane accident from Rig	Shielding of GPS signal, Drop object Damage	heating system for icing prevention, Tool talk with crane driver			Design of strong structure, weather compliant operations Procedure checklist		I 2
			Heavy weather (Motion)							I 4
		Signal Loss	Birds	Collision or position jump or error in signal or unreliable GPS coordinates	Birds repellent spikes, PRS, taut wire, HPR	P 2	I 5	Inertial reference system, Advanced signal processing.	P 1	I 5
			Wrong calibration of GPS Gyro Shading of signal Correction error of signal Corruption of signal because of high Horizontal Dilution of Precision (HDOP) Low satellite angle in North specially in polar region.							I 3

			Less signal in Big or Horseshoe Shaped layout of platforms							

Appendix F: HazID for alternative fuel sources

What might be the hazards for the current fleet of DP vessels if the new fuel source is installed with the redundancy measures present for Class 3 DP vessel without any upgrading?

HazID for possible alternative sources										
Code	**Hazard**		**Causes**	**Consequences**	**Existing safeguards**	**Probability**	**Impact**	**Mitigating measures**	**After execution of mitigating measures**	
									Probability	**Impact**
						P 1 – P 5	**I 1–I 6**		**P 1- P 5**	**I 1-I 6**
HazID for Battery Based Systems										
	Toxic gas		-Fire -Leakage in Battery -Chemical Reaction	-Explosion -Asphyxia	-Ventilation (Ceiling + Floor) -PPE -Gas Meter	P 2	I 5	-Training -Procedure -Protocols	P 2	I 2
	Fire	Ignition of Gases	-Naked flame -Hot Work	-Explosion - Fire - Asphyxia	-Training -Courses -Procedure -Workshop -Over pressure of compartment	P 1	I 5	-Hot work Permit - Direct Ignition of Foam -No Smoking onboard	P 1	I 2

								-Use of flaps to suffocate the fire		
		Dirty Battery Storage	-Dust -Dirt	-Short Circuit, Fire -Fatalities/Injuries to Human	-Regular Cleaning	P 2	I 4	IPxx rated storage compartment	P 1	I 4
		Metal Tools in battery compartment	Human Error	-Short circuit -Fatalities/Injuries to Human	-Procedure -Guidelines	P 3	I 3	-NOVEC Fire Suppression -Use rubber coated tool	P 3	I 2
		Water Ingress	Flooding + Fire extinguishing System	-Capsizing -Fatalities/Injuries to Human -Electrocution	-Watertight Doors -Guidelines -Double Hull	P 1	I 6	IPxx Compartment	P 1	I 4
		Thermal Runaway	Increase in Battery Temperature	Fire, Asphyxia, Explosion	-High Fog Mist	P 3	I 4	Better battery technology	P 2	I 4
	Jewelries like Ring / wrist watches		Human Error	Electric Shock	-Rules -Prohibition	P 2	I 4	Use tape to cover or remove it	P 2	I 3
	Battery Coolant		Improper handling during transportation	Leakage	-Procedure for stowage and transport	P 2	I 4	Leak shielding system	P 1	I 3

	Sabotaging / mishandling	Unauthorized Access	Fire / Asphyxia	-Regulated Access	P 1	I 5	-Regulated Access -Continuous Monitoring	P 1	I 5
	Portable Electronic device	Short Circuit/ Spark	Explosion	-Prohibition	P 1	I 5	EX Proofing	P 1	I 5
	Charging and Discharging rate	-Overheating Design Issue (Overvoltage/ Undervoltage)	-Battery Damage -Fire	-Procedure -Checklist	P 4	I 4	-Load limit -Circuit breaker	P 2	I 2
	Improper Ventilation	Design Failure / Malfunction	Suffocation / Fire	-Fresh Circulation of Air	P 3	I 5	-Monitoring Circulation of Air in Battery compartment -Gas detection system	P 2	I 2
	Big Battery	Battery compartment Design Fault	Structural Failure	Reinforced Structure	P 4	I 4	-Proper weight distribution during storage. -Lighter battery usage	P 1	I 2
	Limited Power Source	Battery Pack with limited capacity	Failure in Operation	-Planning -Diesel/Gas Generator -Multiple Backup	P 3	I 5	-Multiple battery charging stations	P 2	I 3

	Short Battery Life	Premature technology	-Frequent replacement of battery pack -Expensive	-Multiple Backup -Alternative source	P 3	I 4	-Proper charging and discharging cycle -Battery life monitoring system	P 2	I 3
	Cyber attack	Sabotage	-Collision -Blackout	-Firewall -Training to personnel	P 3	I 4	Enhanced Cyber Security	P 2	I 4
	Collision / Grounding	Human Error/ Technical Issue	-Fire -Failure Under emergency	-Training -Rules -Regulation	P 1	I 6	-Simulation Training -Escape Plan	P 1	I 4
HazID for Hydrogen Based System									
	Size of the vessel	Increased surface area	Drift on	-Simulator Training -Weather forecast	P 4	I 2	-Additional thrusters - Hybrid solution (Battery)	P 4	I 1
	Static electricity	Low Ignition point	Fire / Explosion	-Static free installation, clothes -Avoidance of dry air ventilation EX-Proof equipment	P 3	I 3	-Installation specific design -Ignition source control	P 2	I 2

	Odorless/ Tasteless/ Colorless	Physical Properties of Hydrogen Flame Characteristics of H_2	Undetectable leading to leakage, fire or explosion	Addition of Odor and color	P 5	I 4	Specially developed portable detectors/line detectors /point detector	P 3	I 4
	Contamination	Use of odorants on hydrogen, Inefficient purification	Unable to purify H_2, Damage to Fuel cell	-Procedure -Testing/ monitoring of H_2	P 2	I 4	Filtration system for odorants	P 1	I 4
	Material Failure (Hydrogen induced cracking)	Properties of H_2	Leakage, explosion, fire, Loss of asset	Coating layer used for protection of H_2 container, Cryogenic Container	P 2	I 5	Fire extinguishing system for Hydrogen	P 2	I 3

	Fire and Explosion	H_2 has low ignition point	Fatalities and injuries Environmental damages Loss of Assets	Increasing Safety Standards Training about handling H_2	P 4	I 5	-Research and Development of better tools and equipment regarding H_2 system - Better understanding of explosion due to H_2 (flame characteristics, RPT, BLEVE) - Ignition source control	P 2	I 4
	Leakage	Vibration, Corrosion, High Pressure, Material failure	Explosion, Jet Fire, Pool Fire	Mechanical ventilation, Leakage protection, Cryogenic storage.	P 5	I 4	-Monitor Pressure in tanks piping system -Corrosion inhibitors -Pulse Damper	P 2	I 4
	Bunkering of Hydrogen	Human Error Technical Issues	Explosion, Fire, Fatalities, Environmental damage	Precaution, Training Procedure Checklist EX Proof equipment	P 4	I 4	-Emergency disconnection -Ignition source control -Automated system -Spill detection	P 3	I 2

	Layout of storage tanks	Inadequate Separation Distance between tanks	Fire/ Explosion	-Safe distance according to volume -Guidelines	P 1	I 4	Fire and explosion simulation -Proper design	P 1	I 3
	Fire extinguishing system	Highly flammable H_2 with unknown	Uncontrolled fire or explosion	Water for cooling, High density fog, UV Flame detectors	P 3	I 4	Strong ignition suppression system, Gas diversion piping systems	P 2	I 3
	Expansion of H_2	Boiling Liquid Evaporation vaporization expansion (BLEVE)	Explosion	Low temperature, High pressure	P 5	I 4	Support plan and open expansion	P 5	I 3
	Improper Ventilation	Design Failure	Fire	Proper HVAC calculation Fire Dampers	P 2	I 4	Segregation	P 1	I 2
	No Smoking / Naked Lights/ Hot work	Human error Noncompliance to procedure	Explosion	Procedure Permit Training	P 1	I 5	Ban in matches, lighters and hot work only in drydock	P 1	I 2

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Design loads for marine facilities.

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ABSTRACT: For design of marine facilities, a design basis is needed. This design basis will include selection of safety level and codes to be used during the design process. The design basis will include all aspects necessary to design safe facilities, including methods for load calculations. In this paper the design basis for offshore structures and marine vessels is discussed. Particular emphasis is put on robust facilities which will not collapse under loads slightly higher than the design load. Furthermore, the new types of fuel introduced in the marine industry for vessels give rise to concern as these fuels are highly flammable with high explosion pressure. Mitigating measures to reduce the consequences of large loads represent important considerations.

1. INTRODUCTION

For the design of marine facilities, it is important that a design basis for load and load effects be agreed. Norsok Standard N003 (Standard Norway, 2017) was updated in 2017 with respect to loads and load effects from waves, ice and ship impacts etc. The wave crest for design of structures was slightly increased, while the energy to account for an accidental ship impact was substantially increased. The loads from drifting ice and sea spray icing were highlighted due to increased activities in the Barents Sea.

Actions from fires and explosions are also of great concern. The oil and gas industry has developed models to identify fire- and explosion loads following release of gas, and specialized computer models (for example, FLACS, FLame ACceleration Simulator, see Gexcon, 1992) are based on substantial testing. Fire protection to resist temperatures in fires, as well as relevant explosion panels have been developed.

However, with the new types of fuel introduced for maritime vessels, there is an urgent need to develop design basis for the challenges arising from use of these new types of fuel. These challenges include:

- fires and explosions from use of large power-banks like lithium batteries
- cooling effects, fires and explosions in case of escape of LNG from storage tanks
- explosions and fires in case of leakage of hydrogen used for fuel
- fires in transformer stations where electricity is transformed from DC to AC and vice versa.

Fire protection and explosion walls are normally in the oil and gas industry introduced to withstand the loads from explosions and fires caused by burning of traditional fuel or from leakages of methane gas. The challenge to define a design basis for the new types of fuel is urgent, as vessels are being rebuilt or new vessels are built to use the new fuel systems.

Storage of batteries, LNG and hydrogen onboard vessels potentially represents the accidental release of large quantities of energy. Considerations related to load and load effects from accidents alone are, however, not sufficient. Although it might be possible to prepare a design to resist the load, the *probability* of a release and the *consequences* of a subsequent accident shall always be reduced.

Furthermore, the *consequences* of an extreme load/ load effect (collision, fire or explosion) shall be reduced by a *robust design* so that a load larger than the design value, does not cause the escalation of the damage of the facilities into a progressive collapse (for example the sinking of a vessel). Also, the protection of personnel/ crew must be carefully considered when using the new types of fuel to avoid that fires/ explosions escalate into the quarters onboard the vessel. Therefore, new design standards are required, possibly separating the quarters on vessels with new fuel machinery, using separation walls or moving the quarters away from storage tanks, like done in the oil and gas industry.

2.THE DESIGN BASIS

For the design of any facilities, a design basis must be agreed on. The design basis shall cover the following aspects:

- the intended use of the facilities, for example:
  - a vessel for transport of highly explosive materials needs to be designed to resist a defined explosion load
  - a vessel for transport of large deck load must be designed with a strong deck
  - a vessel transporting toxic fluids must be designed with double sides to avoid leakages to the water in case of hull damage
  - most vessels are designed with double bottom to avoid sinking after a grounding
- the selection of safety level for the design is to be made, as the safety level depends on the importance of the facilities for the society and the owners:
  - a cruise ship has to be designed to a high importance class as the vessel is carrying a large number of passengers and crew
  - a vessel transporting nontoxic gravel will not carry large crew and will not pollute in case of damage to the hull
  - a wind turbine structure could be designed for a higher probability of damage as the consequences of damage are lesser than for manned structures
  - an offshore oil and gas production platform must be designed to ensure that an environmental disaster is avoided
- the planned design life of the facilities
  - to ensure sufficient fatigue resistance over the planned operational life of the facilities, often set to 30 years, however, longer for specialized facilities
- the standards selected for the design of the facilities
  - normally the applicable international standards, the IMO or ISO standards, supplemented with design codes as those of Det Norske Veritas, Lloyds or the American Bureau of Shipping (ABS)
  - possibly with the addition of national requirements, like the Norsok Standards (Standards Norway) for offshore structures, or company specific requirements
- the requirements for the construction stage
  - a vessel must for example be checked for the launching operation
  - a module for an oil and gas platform must be designed for the forces during lifting
  - wind turbine facilities must be designed for lifting at the offshore location
- any other requirements set by the legislators or the owner
  - for example, a requirement to local contents during fabrication
  - use of same set of operational procedures as other assets operated by the company

It is noted that new types of fuels challenge the adequacy of existing design basis for marine facilities and there is a need to remind the authorities and owners that any design must be safe with regards to personnel (including the crew) and the environment. The design basis must, therefore, include loading from fires and explosions as some of these fuels can cause highly energetic explosions and are highly flammable.

In addition to the design basis, a risk analysis of the facility during its intended lifetime should be carried out to ensure that the facility is sufficiently ***robust*** to withstand possible unexpected/ abnormal situations without collapse or without causing irreparable damage to the environment:

- The requirement to robustness can be achieved through implementation of redundant members:
  - in a steel truss structure, an x-bracing is redundant while a single strut represents a non-redundant design
  - in a vessel, a certain number, n, of watertight compartments represent n-compartment damage stability. It must be noted that real robustness has to be ensured, "watertight" compartments with openings for piping are not watertight and pipes within pipes is a possible way to ensure the required robustness.
- The requirement to robustness can also be achieved though implementing of operational measures, as for example limiting the size of vessels supporting the operations of the facilities.

3. SELECTION OF OPERATIONAL LOADS

The operational loads are split between:

- The "dead load"/ "permanent load", which is the weight of the facilities themselves. The effects of any additional structural strengthening must be analyzed to check the structural capacity. This type of loading is considered a static load.
  - A library is typically designed for very high floor loads.
  - Note the large and concentrated weights of battery storage packs onboard vessels.
  - When changing to new and more modern machinery, the weight and also the dynamic effects must be considered.

This also applies to vessels during upgrading.

- The “live load”, which is the variable load due to operations of the facilities. This load is determined by the operating company in accordance with the planned use of the facilities. This load will, for example, include the weight of people onboard the vessel and could be considerable for ferries.
  - It is recognized that resonances could occur due to movements of people. In Israel, the floor of a building collapsed when the guests at a wedding started the dance (Guardian, 2001). The structure was close to collapse prior to the disaster and the dynamic motion initiated the collapse.
  - The cargo represents variable loading. The structural strength must be checked in case heavy items are transported.
  - The loading from fluids in storage tanks varies considerably during operations.
  - Walls between storage tanks must be designed for the differential pressure between the tanks which may have different levels of filling.

Mitigating measures to avoid failures are recommended as follows:

- The designer shall consider the use of the facilities and add dynamic effects whenever such effects could occur
- The design brief, including the design basis, drawings and codes applied for the analysis must be part of the key documents of the facilities. This also applies to all marine facilities.
- The operational documents shall clearly state any limitations for the use of the facilities

4. DESIGN BASIS FOR THE LOADING FROM THE PHYSICAL ENVIRONMENT

The estimated loading from the physical environment is used to calculate the load in the Ultimate Limit State (ULS), the Fatigue Limit State (FLS) and the Abnormal Loading Limit State (ALS). The load is determined through statistical analysis of data collected over several years, 30 years of data is recommended for statistical analysis (ISO, 2016).

4.1. Waves

The latest version of the Norsok Standard N003 (2017) gives clear recommendations regarding use of wave theories for load calculations. Higher order wave theories (taking the nonlinear surface boundary conditions into account) are recommended to obtain best possible values of the wave crest heights and the water wave kinematics in the surface zone and It should be noticed that the maximum load acting on facilities is found for a specific combination of wave height and period so the design wave condition be determined by searching the design contour in the wave height/ wave period space (Norsok Standard N003, 2017).

Hindcast data are considered to be reliable metocean data when a hindcast model is calibrated to known datasets (measurements of waves when the wind conditions are known). Statistical extreme value models are tested to check if they fit to the data and extrapolations are made to the level of exceedance probability decided according to the selected safety level. For offshore oil and gas platforms, this safety level is selected as an annual probability of exceedance level of 10^{-2}. A safety factor (load factor) of 1.3 is applied to the load calculated. For structures of less importance, a load factor of 1.15 can be used.

Furthermore, for wind turbine foundations, an annual probability of exceedance level of 2×10^{-2} can be applied according to DNV-GL-ST-0437 (2016), as the standard refers to design “events with a recurrence period of 50-years”.

4.2. Currents

When relevant, the loading from currents shall be added to the wave effects. Realistic, site specific combinations of waves and currents shall be identified. Notice that currents can cause vortex induced vibrations of structures placed in the sea.

4.3. Winds

For vessels, the loading from wind is important to address vessel heel. A vessel will normally take a course against the direction of the wind and waves to avoid large roll motion of the vessel. It must be noted that vortex induced vibrations of slender structural members may occur. Furthermore, together with winds, strong atmospheric icing may occur.

4.4. Ice; drifting ice and sea spray icing

The design basis shall give values for design ice conditions.

- Note that drifting ice represents impact loading and that only 10% of an iceberg is seen above the water level. This means that the ice will be substantially larger under the surface and that an “ice-foot” could be present under the water surface. The impact between a vessel and an “ice foot” could represent a substantial loading (Gudmestad and Alme, 2016, Lu et al., 2018, Amdahl, 2019). Vessels for transfer in the Arctic are designed to withstand impacting ice in accordance with ice-class requirements. Notice that the speed of the vessel must be adjusted in case of drifting ice.

- Sea Spray icing will lift the center of gravity on vessels and loss of initial stability could result. The design basis shall include considerations related to safe voyages when sea spray icing occurs. The period of roll of the vessel increases when the stability parameter, the value of the metacentric height, GM, reduces towards non-acceptable values. An increase of the roll period, could, therefore be interpreted as a warning sign as the safe sailing condition is being reduced.

Mitigating measures to account for loading from the physical environment are discussed below under the heading "Abnormal environmental loading".

5. ABNORMAL ENVIRONMENTAL LOADING

As the environmental data in certain cases will exceed the value representing an annual probability of exceedance level of 10^{-2} (Ultimate Limit State analysis), the facilities have to be checked that collapse under events having lesser probability of exceedance does not occur. The ISO 19900 suite of standards requires that facilities be checked for a load resulting from environmental data having an annual probability of exceedance of 10^{-4}. The load factor is set to 1.0 in this check. Furthermore, it is required that collapse shall not occur should the environmental load with annual probability of exceedance of 10^{-2} occur following the abnormal environmental situation. A load factor 1.0 is used for this check (Abnormal Loading Limit State/ Limit State of Progressive Collapse).

5.1. Waves and currents

It is well known that extreme waves (rouge waves) often occur at sea, however, the probability that such waves occur at a specific site is low. On the other hand, breaking waves occur at known sites.

- Rouge waves (freak waves) occur due to nonlinear interaction between large waves (Osborne, 2019). These waves are extremely dangerous to ships and have caused damage to numerous vessels (Faukner and Buckley, 1995). An abnormal wave was reported to hit the Draugen oil and gas platform located offshore Norway in March 1995 (Gudmestad, 2020). The load caused vibrations ("ringing") of the platform. The loading was within the abnormal design loading for the platform.
- Waves approaching shoals and sloping shoreline, will break causing an impact type load on structures placed at the location of breaking. As wind turbines often are placed at such locations, wind turbine foundations have to be checked for breaking wave loading (Jose, 2017). The loading from breaking waves may be difficult to predict, references are often made to Wienke and Oumeraci (2005).
- Interaction between waves and opposing currents increases the steepness of the waves and is known to cause extreme ship damages, including sinking. The Agulhas current offshore South Africa is an example of a dangerous area, where shipping is avoided.
- Rouge waves can be modeled in a wave tank by focusing wave energy at a location in the tank. Lian (2020) has, furthermore, studied the generation of abnormal waves being generated from normal irregular wave trains, and the associated slamming loads. Local loads can be extreme, however, global loads on facilities are limited.

Mitigating measures to cope with the consequences of abnormal waves and currents should be put in place:

- Fixed offshore structures should be designed with sufficient air gap between still water level and the underside of the deck to avoid that waves are hitting the deck, causing large forces on the structures
- Wind turbines located on shoals must be designed to resist breaking waves (Chella, 2016) occurring with a certain probability of exceedance, decided by the authorities/ owners.
- The meteorologists should attempt to predict situations when rouge waves could occur, and ships must be directed away from such locations.
- In case of large currents, vortex induce vibrations are of concern for slender structures, like pipelines and cables. Also, larger structural elements, like Spar buoys can be exposed. Such structural elements must be equipped with vortex suppressing devices, for example a helix mounted along the exterior of the element.

5.2 Impact loading from floating ice and sea spray icing

- Large ice floes are drifting in the ocean. These floes could be composed of multiyear ice having high compressive strength transferring high impact load to the vessel in case of a collision. Of larger concern is the collision with a large iceberg, a smaller iceberg, a bergy-bit or a piece of an iceberg, termed a growler.

- Under certain combinations of wind, waves and temperatures, the sea spray icing on vessels cold be extreme, (Johansen et al., 2020). This situation could occur quite far south in the North Sea (for example along the west coast of Denmark where 14 fishermen were lost in 1979 due to capsizing of fishing vessels, (Fiskeritidende, 14th Jan 2016). The action of meteorologists to issue warnings is requested. The Norwegian Meteorological Institute is regularly issuing warnings in case of probability of large sea spray icing.

Mitigating measures to cope with the consequences of abnormal ice events should be put in place:

- Impacts from large ice floes are of concern in case vessels without sufficient ice strengthening are in the region. The Northern Sea Route administration (NSR) has, for example strict requirements to vessels allowed to traverse the route.
- Impacts from large icebergs are of grave concern. Vessels are always separated into compartments to avoid sinking; however, captains will avoid sailing in iceberg alleys and look out carefully for “bergy-bits”.
- For floating structures located permanently in regions where iceberg could occur, the vessels should be capable of moving from locations in case iceberg management is not successful. The oil and gas industry is reluctant to implementing the required disconnection capabilities in production vessels located in areas with low probability of occurrence of icebergs. The re-connection time is of concern for the economy of the field production. The potential for large release of pollution in case of collision between iceberg and vessel should, however always be considered.
- To control the situation under a sea spray icing event, the accumulated ice must be removed. A clear warning is when the roll period increases, as the roll period is inversely proportional to the square root of the GM of the vessel. This situation calls for immediate action to remove the ice. A heavy snowfall with subsequent freezing of wet snow has the same effect as sea spray icing. Of particular concern is the situation in Polar Low situations which are followed by heavy snow showers. Meteorologists must warn vessels from these Polar Low situations. A complication is the fact that the track of a Polar Low pressure is difficult to forecast.

6. ACCIDENTAL LOADING

6.1 Impact load from ship collisions

Supply vessels' sizes increase and some of those vessels' design is improved for sailing in the Polar region for ice navigation. Improvement in bow design and reinforced ice belts are factors to be considered in order to avoid severe accidents or, in the worst-case scenario, a total loss in case of impact/ collision with another vessel or a fixed facility like an offshore platform or a wind turbine support structure. It is essential to evaluate the risk these improvements in supply ship design poses in case of collisions with existing installations.

Based on a frequency of impacts by attendant vessels of the order of 10^{-3} per installation year, the calculated maximum impact energy for minimum damage was by DNV in the 1980s estimated to be 11 and 14 MJ (Mega Joules) for head-on and sideways impact, respectively (Moan, Amdahl and Ersdal, 2019). As a reference, however, for vessels with displacement between 2000-5000 tons, the impact energy can be up to 60MJ, with a velocity of 6 m/s (Travanca & Hao, 2015). Table 1 gives a list of few accidents occurring in previous years on the Norwegian Continental Shelf (NCS), as an example to reflect on how much impact energy does one collision encompasses (Kvitrud, 2011).

Table 1 Impact energy from collisions with offshore platforms (Kvitrud, 2011).

Year	**Collision Energy**	**Vessel**	**Installation**
2004	About 39MJ	Far Symphony	West Venture
2005	About 23MJ	Ocean Carrier	Ekofisk
2006	About 61MJ	Navion Hispania	Njord B
2007	About 2MJ	Bourbon Surf	Grane
2009	About 70MJ	Big Orange	Ekofisk
2010	Low (Multiple)	Far Grimshader	Songa Dee

The Norsk Standard N003 (2017) gives recommendations for the energy to be considered in a ship impact event: Visiting supply and intervention vessels: 50 MJ, Shuttle tanker collisions 100MJ. The document also provides a discussion related to energy sharing between the visiting vessel and the facilities where the modern supply vessels designed with ice-breaking capabilities are of main concern.

Mitigating measures to limit the design basis to lesser impact energy values are as follows:

- Operational measures may be put in place to limit the vessel size admitted within the safety zone of the facilities. In case the vessel size and velocity is limited, see Figure 1.

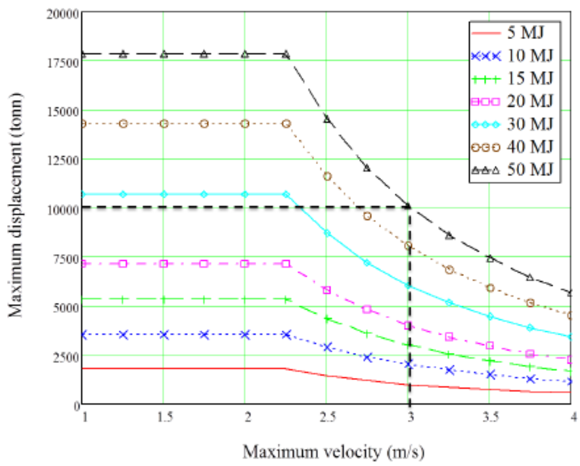

Figure 1. Operational restrictions in the safety zone – acceptable combination of vessel size and velocity is found beneath the respective curve for the documented impact energy capacity (MJ). Based on head on collision and sideways collision in drift condition (Moan et al., 2016, Norsok Standard N003, 2017).

- As most vessels are weaker sideways compared to bow or stern, another mitigating measure is to ensure that the orientation of the vessel is always away from pointing towards the facilities. The shuttle tankers operating at the circular Goliat Floating Production Storage and Offloading (FPSO) platform in the Barents Sea, are always operated in compliance with this requirement to avoid any puncturing of the FPSO.
- In case the Dynamic Positioning (DP) system for a vessel can be documented to be reliable with redundant back-up being mobilized immediately in case of failure of the main system, the probability of a collision will be much reduced.
- Finally, with a market characterized by an abundance of available vessels, there should be no reason to involve vessels designed for ice navigation in non-arctic areas like the North Sea, thereby reducing the consequences of a collision.

6.2 Loading from fires and explosions

Loads caused by fires and explosions are becoming more of concern with the implementation of new fuel systems onboard vessels. This applies to hybrid fueled vessels and vessels only fueled by use of batteries, liquefied natural gas and hydrogen. Firewalls must resist a defined temperature acting over a certain time and explosion panels must resist the explosion load. For a summary of the situation, the following applies:

- Lithium batteries:
  - Thermal run-away can occur in case the energy in batteries is released and the temperature can quickly reach to 600ºC followed potentially by explosion and fire. The electrolyte, one of the main components in a Li-ion cell, consists of organic carbonates. Venting and thermal runaway release organic carbonates and when mixed with air, these gases can result in fires and explosions. Note that wood would catch fire at about 300ºC and that the melting point of Aluminum is 660ºC. In case the oxygen is closed off during a fire, the battery will continue to generate heat and could re-ignite when access to oxygen is again available. During a fire, toxic gases are also released, including hydrofluoric acid.
  - Regarding explosion loads, gas concentrations between 2.5 and 17% could cause explosion with pressures up to 760kPa and an explosion rate of 41MPa/s. (Henriksen et al., 2019).
  - For reference see also DNV-GL, (2015).
- Liquefied natural gas is methane cooled down to -162ºC. During a leakage the following occurs:
  - The LNG is transferred to methane gas and a LNG leakage would therefore cause cooling of the environment to temperatures that cause materials to become brittle
  - Methane gas could lead to explosion when the volume percentage reaches 5% - 15%. The explosion pressure could be 670Pa with an explosion rate of 27MPa/s. (Henriksen et al., 2019).
  - Following an explosion, a fire would be initiated, methane burns at 1950ºC.
  - An alternative to use of LNG would be to use the fluid methanol (CH_3OH).

Methanol has the highest hydrogen to carbon ratio of any liquid fuel. However, methanol is very toxic and when used as fuel, there is also CO_2 emission from the engine.

- Hydrogen is in liquid state at temperature of -253ºC
  - Liquid hydrogen will evaporate, causing the environment to become extremely cold
  - An explosion could take place when the hydrogen volume in the air is 10% to 50%. The explosion pressure could be 653kPa with an explosion rate of 102MPa/s. (Henriksen et al., 2019). An extreme impact will occur in case of an explosion.
  - Following an explosion, it should be noted that hydrogen in air has flame temperature of 2111ºC. The transport of Hydrogen for vessel fuel is regarded as extremely hazardous.
  - The alternative is to use ammonia (NH_3). Ammonia does not need to be stored in high pressure tanks or in refrigerated condition. It could represent a breakthrough with respect to reduce greenhouse gas emission from marine vessels (Gallucci, 2021). According to Brown (2019), Maritime fuel mix could be 25% ammonia by 2050. Unlike ammonium-nitrate (NH_4NO_3; a very explosive product used for fertilizer), ammonium can safely be stored anywhere and be transported onboard vessels.
- Offshore wind farms are dependent on transforming the alternating current (AC) generated to direct current (DC). This is necessary to limit the electric loss in the cable during transfer to shore. The transformer stations are vulnerable as overheating could lead to gas formation and explosions. Care must be taken to ensure the integrity of such stations. It is not recommended that personnel stay overnight on these stations, regular visits for maintenance should be sufficient.

The highly flammable gases introduces as new types of "renewable fuel" are explosive and burn at high temperatures. This is of concern for the safety of vessels. An example illustrates this:

- "On December 30, 1975 the oil/ore carrier M/S "Berge Istra" sank in the Molucca Sea. Two of the crew were rescued. They reported a rapid series of three massive explosions followed by immediate sinking of the ship. In October 1979, the sister ship M/S "Berge Vanga" disappeared in the Atlantic Ocean. Practically nothing is known about that incident. No-one was rescued. The rapid sinking of "Berge Istra" indicates that a gas explosion in the double bottom of the ship ripped the ship structure open and water flooded the double deck and the engine room" (Gexcon, 1992).

  This incident shows that the damaging poten tial of flammable gas cloud in a confined room (like the double bottom of a ship) can generate damaging pressure. Note that such volumes onboard vessels today are filled with inert non-flammable gas.

Possible mitigating measures in case the new types of fuel are introduced in new or retrofitted ships:

- Batteries must be stored in a safe way to ensure there is an over-pressure in the room, so the oxygen is used quickly in case of fire. Formal procedures must be in place to handle the fire so an explosion is avoided (DNV-GL, 2015).
- Liquefied Natural Gas must be stored away from the living quarter of a ship to avoid that any leakages of methane gets to the quarter. The alternative use of methanol has drawbacks due to the toxicity of methanol and the CO_2 emission.
- Explosion panels and fire walls must be in place to secure the integrity of the vessel. International standards for design of facilities and operations of these must be fully in place to ensure acceptable safety. In no way shall an explosion threaten the integrity of a vessel.
- Hydrogen onboard vessels must be handled with extreme care, (DNV-GL, 2018 and 2019, IGF, 2017). Continued research to ensure safety of a vessel using H_2 as fuel is required. The alternative storage of the fuel in form of ammonium (NH_4) is, however, recommended.

7. CONCLUDING REMARKS

In this paper a review of design basis for offshore vessels, oil and gas platforms and offshore wind turbine foundations is given. Reference is made to international IMO and ISO standards as well as to the Norsok Standard N003.

The main contribution in this paper is the discussion and summary regarding measures to mitigate the consequences of large loads and load effects.

Furthermore, concern is raised regarding the safety of vessels incorporating the new types of fuel the maritime industry is considering: Batteries, LNG and Hydrogen. International rules for personnel safety and design basis for structural elements are called for, and measures to mitigate possible explosions and fires must be developed.

A fire and an explosion could well be a rare event; however, it must be documented that the consequences of such an event do not lead to fatalities, large environmental pollution or loss of the vessel, which are unacceptable consequences.

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Appendix H: Alarm handling onboard vessels operating in DP mode.

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ABSTRACT

This paper explores concerns regarding the design, implementation, and management of alarms in DP vessels that, while in operation, need an incredibly high level of accuracy along with high reliability and safe operations. The Human, Technological, and Organizational factors (HTO) method is primarily used as analysis tool to find weaknesses in alarm handling during DP operations. The research focuses on results collected from Dynamic Positioning Operators (DPO) and instructors. Findings from the survey are presented and compared to the results from past accidents and technical requirements from Petroleum Safety Agency Norway via YA 711. Three accidents from past are reffered to picturize the findings from the survey results. Furthermore, the conclusion is given with recommendations reflecting the findings from the survey. The main findings are an urgency to establish a centralized marine accident investigation system which enforces learning and recommendation to make operations safer. In addition, the survey also suggests that prohibition of clients or limiting their access to the bridge is necessary. Manufacturers could focus on research and development of alarm prioritization, on structuring and presentation, and profiting by taking feedback from end-users to make DP operations safer.

Keywords: *DP Alarms, DP Accidents, HTO analysis, technical requirements on alarm system, alarm handling, improvement on alarm systems on DP vessels.*

1. INTRODUCTION

Compared to regular sea-going vessels, DP vessels have a high risk of getting into accidents due to their proximity of operations with the installations, even with a very reliable system. This reliability is achieved using a significant amount of electronic equipment due to increased complications in DP vessels. Humans are at the sharp end, and the chances of making errors are relatively large. Therefore, the maritime industry must reduce these risks to make the industry safer and more efficient.

This paper will review three accidents related to DP operations. Furthermore, a survey among experienced DP operators and instructors will be addressed. Issues regarding human performance, technological challenges, and organizational handling will be discussed and compared with the technical requirements published by Petroleum Safety Authority of Norway (YA-711) [8] as the codes on Alerts and Indicators 2009 by IMO only gives basic provides general design guidance [6].

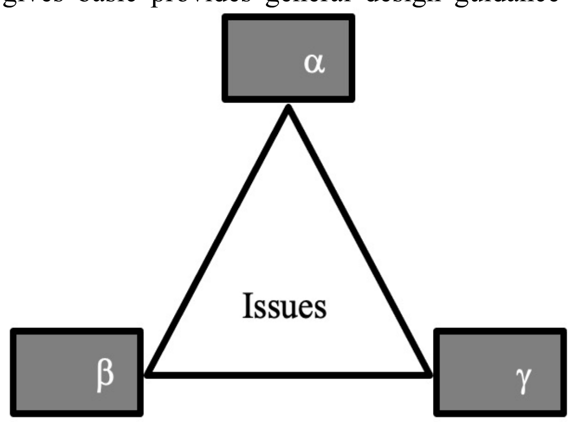

Figure 1 Triangulation of parameters.

A triangulated model is used to reflect on the issues in bridge operations and the alarm handling process. The three parameters for the triangulated model are survey results (α), technical requirements (γ), and past (three) accidents (β) as shown in Figure 1.

The cause and effect of inefficiency and confusion on a bridge will be evaluated with the help of Human, Technology, and Organizational Analysis [10]. HTO factors comprise potential in system analysis, design, and improvement. This method reflects on the foundation of understanding, improvement, and development of a properly functioning system [13].

Finally, the results will be presented by discussing findings from the survey. HTO analysis will reveal the weaknesses of the current alarm system based on survey results. The revelation of practical issues occurs because the survey questionnaire focuses on practical issues during alarm handling while the vessel is in a DP mode. Hence, the accidents that have occurred on DP vessels under the operation in a DP mode will be used to validate the survey results.

2. METHOD

A qualitative approach based on literature review and survey is adopted as there are little quantitative data available. An investigative approach is taken in order to fulfill the purpose of the research [2].

HTO analysis is preferred to analyze the survey responses due to its simplicity in projection and understanding of the issues in three vital system categories. It is unpretentious to segregate any functioning structure to be implemented in the human, technology, and organizational division. Thus, implementing changes or mitigation measures would be straightforward and effective for impact on the safety, performance, and efficiency of DP Operations [13].

In HTO analysis, research is done using the term *humans*, pointing towards the operator operating the DP system, while the *organization* is the supplier of the equipment and the shipping company or an operator/charterer. Finally, the term *technology* is aimed to be used for the sensors, equipment, or instruments, both digital and analog, that aid in the safe and successful completion of DP operations.

An analysis is done by comparing existing guidelines (YA 711, [8]) for alarm systems with survey results. YA 711 has classified alarm design requirements into the following categories [8].

- General requirements
- Alarm generation
- Alarm structuring
- Alarm prioritization
- Alarm presentation
- Alarm handling

A list of 43 requirements in YA711 [8] for the six different categories mentioned above is divided into either human, technology, or organizational references, as shown in the appendix.

3. SCENARIOS

The main concern about alarm systems today is that offshore vessels are ineffective in resolving issues regarding alarm systems with advanced technological tools. It is essential to examine the fundamental issues hindering offshore vessels' resilience towards accidents caused by alarm systems.

Three past accidents are studied; the first is the collision of PSV Sjoborg with Statfjord A (2019) published by Equinor [4], the second the collision between Big Orange XVIII and Ekofisk 2/4-W (2009) investigated by [1], and the last the collision of Samundra Suraksha with Mumbai High North platform (2005) analysed by [3]. These scenarios will be used for the validity of survey results.

A collision occurred between Statfjord A and PSV Sjoborg on 7th June 2019 while loading and discharging from the platform that was under a maintenance stop. Sjoborg was operating in load reduction mode with a preexisting technical issue, i.e. 10-15% reduction in thruster power. During operation, power to two of three bow thrusters was lost. The vessel drifted against the installation, resulting in severe material damages to the lifeboat station and monkey island but with no human or environmental fatalities [4].

It is seen from the accident investigation report by PSA that underlying causes resulted in insufficient thruster power [9]. This could be related to the failure of, or incorrectly installed components, or disruption from defective components, which led to network failure in the blackout safety system ("network storm"). Furthermore, loss of network frequency measurement on the main switchboard, activation of the load-reduction mode with restriction of all thrusters to 10-15 percent of maximum output, nonconformity between DP commands and automatic shutdown of thrusters 1 and 3 [4] occurred before the collision. Due to the overwhelming amount of error messages and alarms, Dynamic Positioning Operators (DPOs) could not take proper action to avoid a collision even with experienced DP operators.

On 8th June 2009 the well simulation vessel Big Orange XVIII (5000 tonnes) ran into Ekofisk 2/4W. The ship lost control after entering the 500-meter safety zone surrounding the Ekofisk complex [1]. The vessel with a speed of 9.7kn collided heads-on with approximately 71MJ collision energy with Ekofisk 2/4 X and 2/4 C [7]. Detailed analysis and calculation of impact loads is drawn in research performed by Shengming Zang in "*The Mechanics of Ship Collisions"* [15] . Due to severe damage to the jacket installation, ConocoPhillips decided to shut down the installation and permanently plug the wells. New ice class vessels that are built with new standards will complicate the situation. Design of these vessels can be seen in Guidelines for Finnish Swedish Ice class by TRAFICOM [14].

It is seen from the accident investigation report by ConocoPhillips (2009) that lack of cooperation between the bridge team and lack of situational awareness, together with shortcomings in the decision-making capacity of the bridge team, was the primary cause of the accident. However, the root cause of the accident was a distraction by an irrelevant bridge routine call to the captain within the 500 meters safety zone [1].

The third accident is Samundra Suraksha, a multipurpose vessel that collided with the Mumbai High North platform on 27th July 2005 to ensure the medical evacuation of ship personnel. The vessel collided with the riser leading to a leak of hydrocarbons, which eventually led to an explosion and total loss of both installation and ship (later on, 1st August). On the day of the accident, the vessel had no preexisting issue in its instruments or its navigational system and was seaworthy. However, the vessel experienced challenging weather conditions (35kn wind, 5m swell and 3kn current) [3].

The collision risk management principles were insufficiently implemented in the third accident for in-field vessels' risk management as mentioned in the guidance on enforcement [5]. In the case of Samundra Suraksha, no procedures were established to manage risks of collision, which governs the overall approach to identify hazards, assess risk, and establish an appropriate procedure for the detection, control, and mitigation. This is reflected by the the captain's misjudgment (observed that starboard azimuth thruster pitch was sluggish) while switching the vessel to manual maneuvering in tough weather conditions. These actions reflect on a poor organizational safety culture, where operating policies were not followed into operations by the DPO. The pre-entry checklist and procedures following the operation within the 500m safety zone were ignored.

4. RESULTS OF DATA COLLECTION

The safety culture has been shifting in time with the evolving concept of quality management (change management), the approache termed Kaizen (continuous improvements), emphasis on resilience organizations, and many other philosophies. However, the possibility of accidents occurrence depends on several minor details deep-rooted in the organizational structure. In order to understand issues regarding the alarm system present onboard offshore vessels, the study of relevant guidelines and technical requirements was done. At the same time, the results from the survey were evaluated under the umbrella of the YA 711 technical requirement published by Petroleum Safety Authority Norway (2001). While doing so, weaknesses in the current system are anticipated to be outlined.

A questionnaire for the target group was prepared to figure out the issues as per the technical requirements in YA 711, in six different categories. Each category has individual requirements for either human perspective, technological perspective, organizational perspective, or any combination of these three, as showen in Appendix.

Survey results were collected from two target groups, one being DP operators and the other being DP instructors. End-user input is expected from DPOs regarding training methods and information regarding the preperation of seafarers for DP operation.

Table 1 List of Participants in Target Group

Target Group	Questionnaire	Interview
DPO	40	1
Simulator Instructors	3	1
Total Participants	45	

HTO analysis is used for the categorization of answers and comparing them with relevant guidelines. Results from the survey are found to be as follows:

In *general requirements* of alarm development and function, the primary purpose of an alarm system is to act as a tool for operators to handle critical and atypical solutions with precision and effectiveness [8].

On the other hand, the survey reflects the importance of several factors, such as contributors, that reduce the attention and cognitive ability to handle alarm systems properly. One of the questions from the survey was the effect of a client's presence on the bridge while working on a DP operation. This event can be seen as distraction for DPO and hence, raises the risk of accidents during a DP operation. Nearly half of the participants agreed to this as shown in Figure 2.

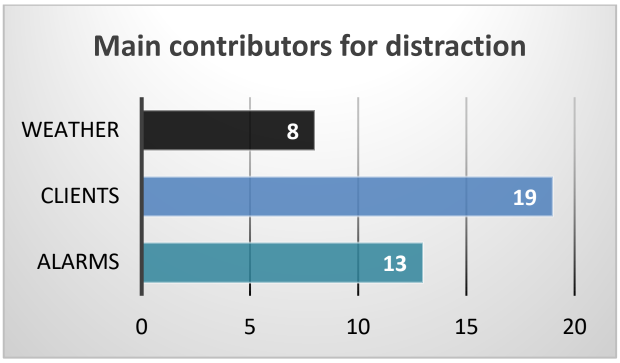

Figure 2 Main contributors for distraction in the bridge during operation.

The criticality of distraction on the bridge can also be seen from the collision between Big Orange XVIII and Ekofisk 2/4. The captain lost his focus while fulfilling responsibilities that had no connection with the vessel maneuvering. The captain enabled autopilot before taking a phone call. After his return, he could not figure out why the vessel was not responding to his input [1]. This fact supports that unwanted events affect the cognitive ability of DPO, especially when there is a need for full concentration in operation.

For *alarm generation*, there were a high number of technical requirements compared to human or organizational requirements [8]. The survey found that it was not allowed to change the alarm suppression system in many cases, and if allowed, the alarm suppression systems were used for the wrong reasons. An example during an interview was that the alarms were toned down, especially when the clients were onboard. In addition, it was revealed that there were several alarms for one variation or deviation from the preinstalled limit, and this one deviation affected several functions or positioning parameters. Alarms were triggered for all the connected systems / systems associated with the deviated parameter, which caused "*alarm fatigue"* to the DPOs.

The alarm generated and displayed on the bridge of Big Orange XVIII was not effective, as the captain could not notice the vessel was on autopilot that he initiated earlier. Thus, the captain did everything else but disengaging the autopilot before the collision.

In *alarm structuring*, the primary responsibility according to YA 711 lies in the technological sector to provide improved alarm structuring [8]. Provision for grouping, sorting and selecting various alarms and features should be provided per operators' needs. A simple overview of alarms that are suppressed, shelved, or inhibited should also be displayed. The alarm suppression system and its presentation method should be understood by the operator in the overview display. Simultaneously, the operator must understand the different alarm features, such as suppression of alarms and alarm filtration. PSA does not recommend the latter, according to YA 711.

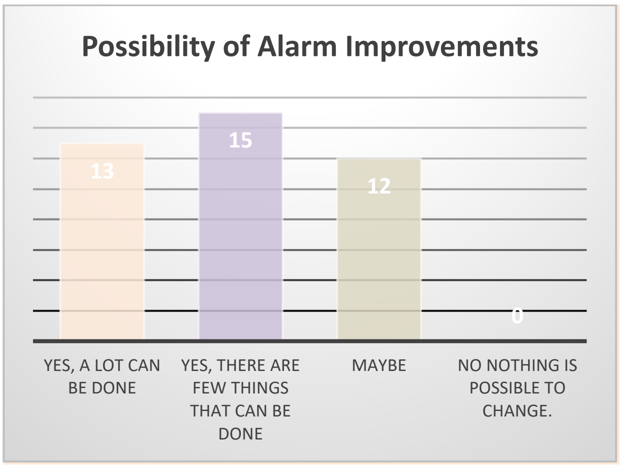

Figure 3 Areas where alarm performance could be improved.

According to the survey results shown in Figure 3, the DPOs suggested a necessity for improved technology for the end-user where alarms are manufactured according to human-centered design. These improvements will not just improve the end-users' experience but will aid in reducing accidents.

In the collision between Sjoborg and Statfjord A, after the loss of 2 bow thrusters, the DPO onboard Sjoborg faced the challenge of keeping the vessel away from installation while sorting out the relevant alarms to avoid a collision. The DPOs were struggling because of overwhelming and numerous alarms in a short time [4]. This fact supports the finding from the survey where significant efforts are required to stage a structured alarm system that could increase the DP operator's effectiveness and reduce the limitation.

For *alarm prioritization*, all three parts of HTO play a role. Firstly, operators should prioritize the urgent alarms; thus, the operators should use this feature to be efficient and effective during abnormal situations. Given that manufacturers would provide a system that aids alarm prioritization, improving operators' focus will severely impact operations.

From an organizational perspective, shipping companies should develop a strict policy to implement alarm routines and procedures. Standing orders from captains on the vessel should be clear and well-rehearsed in advance. These routines are constructive as it makes operators familiar and comfortable with the prioritization procedures that the system designers have developed.

Figure 4 shows that about 62% of the survey participants reflected the impracticality or lack of flexibility to prioritize alarms dedicated to critical operations. In contrast, 25% were sure that it was possible to prioritize alarms. Prioritization is critical as it eliminates human limitations by reducing the observation parameters to critical alarms only.

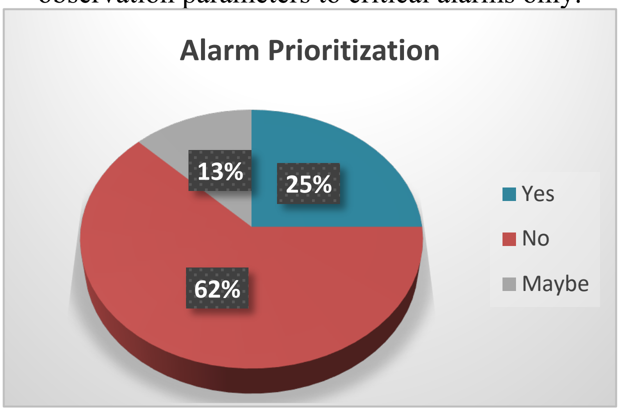

Figure 4 Possibility of improvement in Alarm Systems.

In case of the collision between Mumbai High North and Samundra Suraksha, the captain doubted the instrument message as "acting sluggish" in his opinion and switched to manual control once the medical evacuation was completed [3]. This might be because of a practical drift [12] in the organization or lack of procedures or in-field vessel risk management system. This incident reflects on the importance of alarms and their effects on the result of an operation. Ultimately, the DPO's underestimation of the value of a working system led to the catastrophe.

For *alarm presentation*, it is asked from the manufacturers that the design of an integrated alarm system installed on a ship must have standard color codes, symbols, and alarm categorization methods, which help the operator be precise and effective. A 'dark screen' concept should be implemented because there should be no alarms on the main display when there are no genuine abnormalities on the ship or operation.

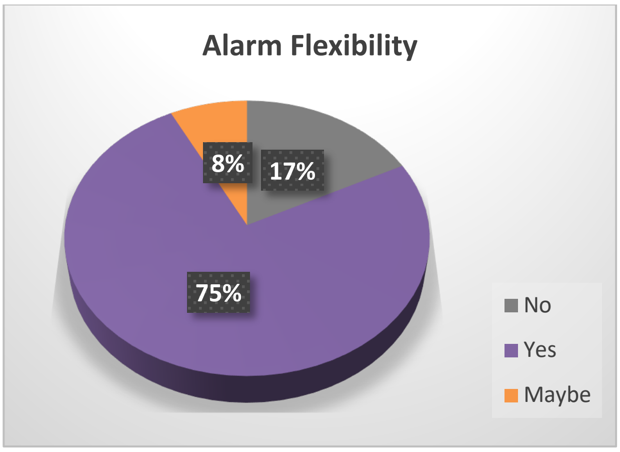

Figure 5 Alarm flexibility necessity according to DPO survey.

A necessity for flexibility is seen in Figure 5, when it came to reducing audio and flashing lights due to alarms. The majority of the participants said it was possible to reduce the overwhelming intensity of alarms both for visual alarms and audio alarms. Thus, alarm designs without a human-centric approach do not facilitate effective operator intervention.

Alarm logs from DP vessels are usually long and deterrent as they use many abbreviations and is like a maze to navigate through. Sjoborg, before colliding with Statfjord A, received numerous alarms, which never pointed to one specific problem but pointed at all the deviations caused by one problem. Hence, it was hard for the DPO to pinpoint issues and find a proper solution. Thus, the alarm presentation is critical as it helps to save valuable time to avoid accidents.

In the case of *alarm handling*, all three parts of HTO have significant roles. From a human perspective, operators should acknowledge all alarms that are triggered. Acknowledge, meaning the purpose of the alarm is first to be read, and then understood, and finally accepted. The alarm philosophy should describe whether an alarm should be accepted once the operator has read it or after they have completed an action.

From a technological perspective, a provision for alarm shelving should be provided so that the operator can remove standing or nuisance alarms. Shelving must be kept as a 'last resort' for handling irrelevant nuisance alarms that have not been successfully filtered or suppressed. A list of shelved alarms should always be available to the operator. Manufacturers ought to provide the solution that supports operators to make a quick and precise decision. Finally, procedures for the individual person responsible for monitoring and controlling operations, including emergencies, have to be readily available and familiarized.

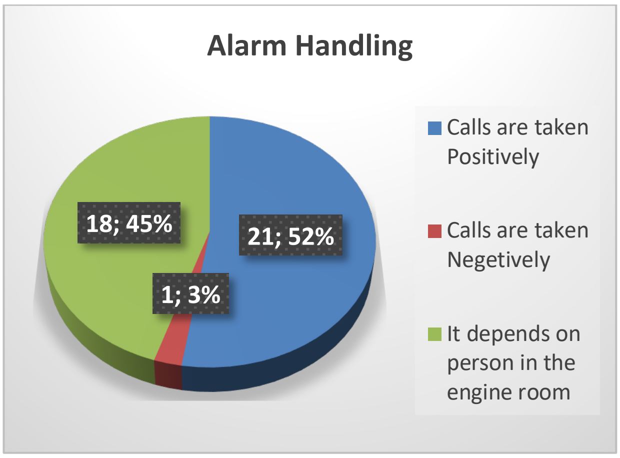

Figure 6 Crew Behavior for alarm handling.

Escalation of DP incidents has to be prevented by operator intervention. In several cases, the DPO alone cannot act independently to prevent an incident. Thus, it is vital that the onboard crew functions as a team. As seen in Figure 6, there is a demand for better cooperation between the bridge and the engine crew. At times, misunderstandings between bridge and engine crew might be the cause of the escalation of a DP incident. Nearly half of the survey participants said, "it depends on the person in the engine room," or calls from the bridge are perceived negatively. A culture of promoting safety culture, and reporting of near-miss situations is fundamental for future development of new technologies and maintaining a safe working environment.

The alarm system should increase efficiency by eliminating limitations of an operator; while doing so, alarm fatigue should also be acknowledged. Alarms received on the night of 7th June 2019 on Sjoborg were generated for the first time. The crew did not take the alarm seriously and were heading towards severe danger. This may be due to practical drift as nothing serious happened in the past or due to lack of operational procedures for alarm handling. Sjoborg was a DP class 2 vessel and had redundancies, which gave crew confirmation bias that everything would be alright. This was improper handling of alarms. A possibility to mute alarms irrelevant to the DP operation should be provided, and if not, there will be distractions leading to increased risk of incidents. There are lack of routines to come back for feedback from end users; this practice can be seen from the survey in Figure 7.

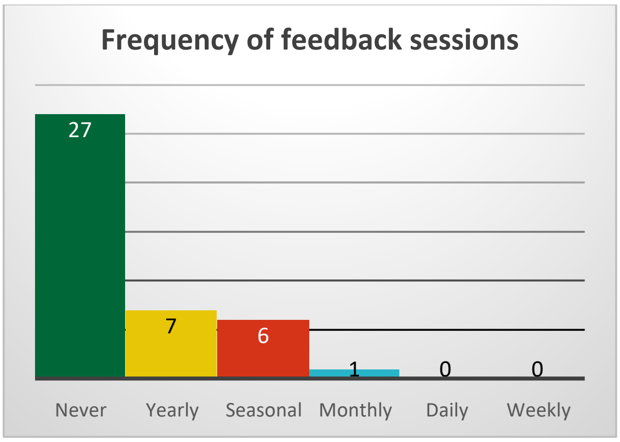

Figure 7 Feedback sessions held by makers with end-users

5. CONCLUSIONS AND SUGGESTIONS

The survey results and previous accidents show that several improvements can be made in the offshore industry, especially on DP vessels. Implications are broad and significant while the industry is expanding in the field of offshore wind and aquaculture together with oil and gas. The following conclusions may be drawn after the research:

Instead of making an individual shipping company or a maritime cluster resilient, IMO should take the initiative to centralize the accident investigation process or take part in accident investigations to enforce the learnings and recommendations to the ships under the IMO umbrella. This will eventually lead to strengthening the structures for improvement and to come back strongly after any setbacks. In addition, companies should work to figure out how to avoid practical drift so that there is relatedly tight situational coupling between the designed methods back to the engineered or applied logic action.

Also, instrument designers and producers should have a routine to get regular feedback from the end-users and utilize the technology to record the performance of their equipment onboard vessels. As a result, those data and information could be used to further research and develop alarm systems and upgrade the existing systems installed. In addition, manufacturers should focus on making the alarm systems user-friendly. All abbreviations should be understandable; if not all, the translation of error codes should be provided in the help menu and training manual.

Similarly, the presence of clients on the bridge has a negative influence, which is one of the major causes for poor performance of DP operators. In most cases, clients are provided with separate observatory and detailed operational information regarding offshore operations. Unnecessary visits and involvement in the DP operation should be criticized, prohibited, and in any case established before starting the operation.

Suggestions like the adaptation of the traffic light model of alarms are brought forward, similar to the lighting model of the Activity Specific Operating Guidelines (ASOG) but in an automatic form with no human involvement.

Manufacturers, shipping companies, operators, and charters should define and check the limits of alarm generations used for the operations and emphasis on those alarms that have safety implications; detailed descriptions should be presented by Fault Mode Effect Analysis (FMEA)/ ASOG for the responsible crew.

Proper training and familiarization of new crew members towards instruments and alarm panels should be prioritized. Extra courses regarding alarm systems and error messages should be part of the recruitement process as it helps the new crew integrate with the bridge and engine crew and educately familiarize them with the operational instruments.

The future recommendation for this research is to extend the survey to more DP operators and instructors worldwide to validate current findings or discover new findings.

The offshore industry is transitioning towards new fuel solutions in order to keep up with sustainable development goals. For future research on issues with alarm systems, it is recommended to perform a detailed study about the challenges created by implementing new hybrid fuel sources as hydrogen and batteries in DP vessels. As technology advances, there will be an increase in the number of alarms on a bridge. Thus, measures to avoid alarm fatigue must be explored to limit human errors and increase the efficiency of DP operators.

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APPENDIX: CLASSIFICATION OF ALARM REQUIREMENTS (PSA, 2001)

Human	Technology	Organization
	General Requirements	
1) The alarm system shall be explicitly designed to take account of human factors and limitations	**2)** The alarm system should be context sensitive.	**3)** Operators shall receive instruction and systematic training in all realistic operational usage of the alarm system.
3) Operators shall receive instruction and systematic training in all realistic operational usage of the alarm system	**4)** The alarm system design shall be based on an alarm philosophy.	**5)** The alarm system shall be properly documented, and clear roles and responsibilities shall be established for maintaining and improving the system.
6) It should be easy for process experts to build into and maintain knowledge and intelligence in the alarm system over time	**9)** The alarm system shall be fault tolerant.	**6)** It should be easy for process experts to build into and maintain knowledge and intelligence in the alarm system over time
8) There should be an administrative system for handling access control and documentation of changes made to the alarm system	**12)** Status information related to safety system functions, such as blocking/inhibit and override, shall be easily available on dedicated lists and in process displays	**8)** There should be an administrative system for handling access control and documentation of changes made to the alarm system
10) System response time shall not exceed 2 seconds		**10)** System response time shall not exceed 2 seconds
11) Safety critical functions should be identified and documented. Status information and failure alarms from these functions should be clearly presented and continuously visible on dedicated displays.		**11)** Safety critical functions should be identified and documented. Status information and failure alarms from these functions should be clearly presented and continuously visible on dedicated displays.
	Alarm Generation	
-N/A-	**14)** The alarm system shall be able to generate basic alarms	**13)** Every alarm shall require an operator response.
	15) The alarm system should include generation of aggregated alarms or/and model-based alarms	**16)** All alarm limit settings should be systematically determined and documented during plant design, commissioning, and operation.
	16) All alarm limit settings should be systematically determined and documented during plant design, commissioning, and operation.	
	17) Operators could be permitted to change some alarm limits.	
	18) Signal filtering should be used.	
	19) Signal validation should be used.	
	Alarm Structuring	
-N/A-	**20)** It should be possible to select, group and sort alarms.	**-N/A-**
	21) Alarm suppression functions shall be included in the system.	
	22) The system should use alarm suppression, not alarm filtering.	
	23) The alarm suppression in the system should be familiar to the operators, and it should be documented in an easily understandable way.	
	Alarm Prioritization	
24) Alarms shall be prioritized	**26)** Alarms should be prioritized according to the time available for successful corrective action to be performed	**24)** Alarms shall be prioritized
25) Alarms should be prioritized according to the severity of consequences that could be prevented by taking corrective action	**27)** There should be an effective priority distribution of process alarms occurring during normal operation and in process disturbances	**25)** Alarms should be prioritized according to the severity of consequences that could be prevented by taking corrective action

26) Alarms should be prioritized according to the time available for successful corrective action to be performed		**28)** Every site should have written rules on how priorities should be assigned
27) There should be an effective priority distribution of process alarms occurring during normal operation and in process disturbances		
28) Every site should have written rules on how priorities should be assigned		
Alarm Presentation		
-N/A-	**29)** A main alarm display shall be provided	**-N/A-**
	30) Key alarms shall be shown in overview displays that are permanently on view, with spatially dedicated alarms	
	31) An historical log of alarms and events should be available to the operator	
	32) Alarms should be integrated in process displays	
	33) Selective list displays should be provided	
	34) The priority of alarms should be coded using colors and possibly other means	
	35) Audible alarm annunciation should be used when new alarms arrive	
	36) Special visual annunciation should be used for new alarms	
	37) Alarm information should be informative and easy to understand	
	38) Alarm information should be easily readable	
	39) Necessary alarm information shall be available from all relevant workplaces	
Alarm Handling		
40) Every alarm that is triggered should require acceptance	**41)** It should be possible to shelve individual alarms	**42)** Navigation in alarm displays should be quick and easy
41) It should be possible to shelve individual alarms	**42)** Navigation in alarm displays should be quick and easy	
	43) Procedures that specify individual responsibilities for monitoring and controlling large process disturbances and emergency situations shall be available and known by the operators	