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Design of service vessels for operations in exposed aquaculture

Development of a new deck platform with risk-based ship design

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Master's in Marine Technology
Submission date: June 2021
Supervisor: Stein Haugen

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"A ship in harbour is safe, but that is not what ships are built for"

William G.T. Shedd

Preface

This thesis provides the final 30 ECTS of a Master of Science degree in Marine Technology with a specialization in Marine System Design, at the Norwegian University of Science and Technology (NTNU), in Trondheim. The thesis is written during the spring semester and the workload correspond to a full-time semester.

The thesis' contents are the engineering design of the deck arrangement of a aquaculture service vessel used for exposed farming. The goals of this thesis have been to establish a deck design that provides technological systems and equipment, for which reduces the overall risk in the aquaculture industry related to service vessel operations. During the writing of the thesis, I have expanded my theoretical background, learned new concepts and methods, and it has in its whole been a rewarding semester. I believe the thesis has provided me with valuable experience in the risk-based ship design method and the aquaculture industry, with regard to the risk in the industry and aquaculture service vessels.

As last year, the COVID-19 pandemic has affected the working habits if both students and professors. The meetings with my supervisor have been a mix of physical and virtual, depending on the current situation, and I feel we have handled it well. I would like to thank my supervisor, Professor Stein Haugen, for being supportive and give valuable guidance throughout the process of this thesis. Thanks to Ph.D. candidate Inunn Marie Holmen for input in the analysis process. I wish you all the best, Marie, Andreas, Benjamin, Vincent, Ingvild, and Malin.

Dani Andersen

Summary

The aquaculture industry is among the most risk influenced occupations in Norwegian industry, in terms of fatalities. The expansion of the aquaculture industry towards more exposed locations can lead to an increase in this risk, because of uncertainties of how the offshore aquaculture industry will evolve. Operations performed with an aquaculture service vessel has shown to be a major contributor to the overall risk. Enhanced focus to establish a safe and efficient design for an aquaculture service vessel for exposed locations could greatly influence lowering the possible high risk in offshore farming.

This thesis aims to perform a risk-based ship design for the deck platform of an aquaculture service vessel. This is done to find the best combination of operation related systems and equipment, to enable for safe performance of required operations. The combination of systems and equipment and the operations the vessel will be performing is based on the findings of a preliminary hazard analysis. The framework utilizes the vessel design of a Macho 40 as the basis for the vessel platform.

The results provided from the preliminary hazard analysis showed that the majority of all the identified hazardous events were located in the personnel risk category, making it a focus of reduction. Among the operations focused on in this thesis, is anchor handling and mooring operations regarded as the major contributor to the identified hazardous events. Lifting operations showed to be the major contributor to hazardous events ranked as unacceptable.

The final design for the deck platform of the Macho 40, is chosen based on its motivation for reducing the overall risk to personnel. The vessel is equipped with different operation related systems and equipment to perform IMR, supply and transport, support during operations, and emergency response and rescue operations. Technological and organizational risk-reduction measures are implemented to reduce operations risk, with a special focus on lifting operations.

Sammendrag

Havbruksnæringen er blant de mest risikopåvirkende yrkene i norsk industri, når det gjelder omkomne. Utvidelsen av havbruksnæringen mot mer utsatte områder kan lede til en risikoøkning, på grunn av usikkerheten av hvordan offshore havbruk vil utvikle seg. Servicefartøy operasjoner har vist seg å være en stor bidragsyter til den samlede risikoen. Forbedret fokus for å etablere en sikker og effektivt design for et servicefartøy ment å operere offshore, kan ha stor innflytelse i å senke den mulige høye risikoen i offshore-opprett.

Målet med denne oppgaven er å utføre en risikobasert skipsdesign for dekkplattformen til et servicefartøy for havbruksnæringen. Dette er gjort for å finne den beste kombinasjonen av oppdragsrelaterte systemer og utstyr, for å sikre utførelsen av nødvendige operasjoner. Kombinasjonen av systemer og utstyr og operasjonene skipet kan forvente å utføre, er basert på funnene i en preliminær fare analyse. Rammeverket bruker fartøy design av en Macho 40 som grunnlag for fartøyplattformen.

Resultatene fra analysen viste at flertallet av alle de identifiserte farlige hendelsene er plassert i risikokategorien for personell, noe som gjorde dette til et fokus for reduksjon. Blant operasjonene som er fokusert på i denne oppgaven, er ankerhåndtering og fortøyning betraktet som den største bidragsyteren til de identifiserte farlige hendelsene. Løfteoperasjoner viste seg å være den viktigste bidragsyteren til farlige hendelser rangert som uakseptable.

Den endelige utformingen av dekkplattformen til Macho 40 er valgt ut fra motivasjonen for å redusere den samlede risikoen for personell. Fartøyet er utstyrt med forskjellige oppdragsrelaterte systemer og utstyr for å utføre IMR, forsyning og transport, støtte under operasjoner og beredskaps og redningsoperasjoner. Teknologiske og organisatoriske tiltak for risikoreduksjon er implementert i designet for å redusere risikoer knyttet operasjoner, med spesiell fokus på løfteoperasjoner.

Contents

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Nomenclature

GGE	Greenhouse Gas Emission
PHA	Preliminary Hazard Analysis
NAV	Norwegian Labor and Welfare Administration
GT	Gross Tonnage
LOA	Length Overall
DNV	Det Norske Veritas
SOLAS	Safety Of Life At Sea
GM	Metasentric height
IMR	Inspection, Maintenance and Repair
ROV	Remotely Operated Vehicle
AHTS	Anchor Handling Tug Supply
ERRV	Emergency Response and Rescue Vessel
DP	Dynamic Position
COG	Centre Of Gravity
AOPS	Automatic Overload Protection System
CTS	Constant Tension System
LARS	Launch And Recovery System
TMS	Tether Management System

MOB	Man-Over-Board
FCR	Fast Rescue Craft
RPN	Risk Priority Number
RBSD	Risk-Based Ship Design
QRA	Quantitative Risk Analysis
BBN	Bayesian Belief Network

Chapter 1

Introduction

This study revolves around establishing a design for the deck platform of an aquaculture service vessel expected to perform operations at exposed locations. The study's first chapter will present the background and motivation of performing a risk-based ship design of an operational vessel for exposed aquaculture. The objective of this thesis will be presented, together with the different necessary assumptions and limitations that were experienced through the study. It will also give an overview of how the structure of the thesis is built and a description of each chapter.

1.1 Background

The world population has had a rapid increase over the last centuries, going from 1 billion in 1800 to a stunning 7,8 billion today [1]. With a growth rate of 1,05%, it is expected that the population will exceed 10 billion by the year 2060. This rapid increase will force global food production to keep up with the increase, in order to supply the world population with enough food. The majority of the food produced in the world comes from agriculture, which also stands for around 37% of all the land used in the world [2]. The increase in the world food demand could, therefore, require agriculture to expand its production. Hence, would require more land to be used for agriculture production, which will require an increase in deforestation and drainage of peatlands to make the land ready for agriculture production [3]. The agriculture industry, together with forestry and land use, directly accounts for 18,4% of the total greenhouse gas emission (GGE) in the world. This makes it the leading contributor after energy use in industry (73,2%) [4]. With the constant focus on global warming, it would be beneficial to reduce the

GGE impact of agriculture or focusing on finding a better source for food, that can keep up with the population growth. This will be important to ensure a safe and sustainable future for the next centuries to come.

The global aquaculture industry has shown to make an important contribution to food security by increasing food availability and accessibility [5]. Compared to agriculture, has the aquaculture industry shown to only account for 0,49% of the global GGE in 2017. In agriculture industry is this similar to the GGE from sheep production, making aquaculture an excellent starting point for ensuring sustainable food production. Considering that the planet consists of about 71% water, makes the aquaculture industry a good area for increase [6]. Aquaculture farming has become one of the largest industries in Norway, as well as being one of the top exporters of farmed fish globally [7]. The reason for aquaculture's success in Norway is because of world leading technology solutions and management strategies, as well as a high amount of sheltered locations in the Norwegian fjords. The sheltered environment in the fjords makes sea-based farming less challenging since the environmental loads experienced are mostly not too high. The sheltered fjords are, however, limited, meaning that there is a decrease in available space for the expansion of sea-based farming. There is a strong Norwegian industrial interest in moving aquaculture industries to more exposed locations, which stretches over a far bigger area than the fjords of Norway [8].

Exposed aquaculture farming will open up the possibility of an increase in the production of farmed fish, as well as leading to a noticeable technological improvement. Exposed farming will, additionally, minimize the environmental footprint in the fjords, improve fish welfare and avoid space constraints, and provide greater opportunities for responsible, environment-friendly fish farming [9]. Even though moving fish farming offshore will lead to several benefits, it will also present unique challenges to operations, structures, and equipment due to severe irregular waves, wind and current conditions. The aquaculture industry can today be recognized as the second most risk influenced occupation in Norway in terms of fatalities, ranking second after fisheries [10]. The goal of moving fish farming to exposed locations will amplify many of the operational challenges present at sheltered locations, as well as introducing new challenges. It should, therefore, be of focus to reduce known risks in the industry, to enhance safety and production at offshore locations.

The majority of fatalities experienced in the aquaculture industry occurred at an aquaculture service vessel, mostly during operations. Focus to reduce the risks related to an aquaculture service vessel could, therefore, be a great start to reduce the overall risk experienced in the industry. There are already two pilot projects for offshore farming, Ocean Farm 1 and Havfarm 1, that are used to analyze the technical and biological sides of operating an offshore farm [11] [12]. These projects will help in understanding offshore farming and ensure safe production. Service vessels for offshore farming, on the other hand, have had little focus in the project of moving production to exposed locations. Service vessels have had a major role in the fish production at sheltered locations, as it is often used daily for different purposes, such as lifting operations, support in different operations and maintenance and repair of farm components, to mention some. It is still much uncertainty of both the design and the service vessel's role for production at exposed locations. It could, therefore, be beneficial to focus on understanding the need and purpose for these types of vessels, as well as their design and operation related systems and equipment.

1.2 Case objective

To reduce the possible increase in the overall risk for exposed aquaculture production, will it be important to understand the risks and find good solutions to reduce the risks. As mentioned, is there little research performed on aquaculture service vessels for exposed aquaculture, leading to much uncertainty regarding its role in offshore farming. Since operations performed with a service vessel has shown to be a major contributor to the over risk in the industry, will it be beneficial to get a better understanding of the design and role of an aquaculture service vessel for exposed locations. This thesis will, therefore, perform a study of the risks in the aquaculture industry, and what role and design a service vessel for exposed location can be expected to have; operations, operation related systems and equipment and its goals and requirements. The objective of this thesis will be to use this study to perform a risk-based ship design, to establish a deck platform with the required operation related systems and equipment for an aquaculture service vessel for exposed locations. This is done to find a deck design that makes it possible to perform required operations, with as low risk as possible to personnel, material assets, environment and fish health. The thesis will only focus on risk related to operations performed with a service vessel and will not consider the risk to other operations that are not performed with a service vessel.

1.3 Assumptions and limitations

The lack of data and research on the different risks of performing operations with an aquaculture service vessel in the industry has shown to be one of the main limitations in this thesis. This made it difficult to use other risk analysis methods than the preliminary hazard analysis (PHA) method since many of these rely on the probability that an accident would occur. The PHA has shown to be a great tool to use in the early stages of a design process to identify hazardous events and establish risk-reduction measures, but as it relies solely on expert judgment can make it a limitation.

It has been assumed that the thesis will only focus on four of the five dimensions of risk; risk to personnel, risk to material assets, risk to the environment and risk to fish welfare. Risk to food safety will not be of focus, since this thesis only focuses on the risk that can be experienced during operations with an aquaculture service vessel.

Since the objective of the thesis is to find the best deck design to reduce the overall risk, it has been assumed to use the vessel design of a Macho 40. This is seen as the best suited design for the purpose of this study.

1.4 Structure of the thesis

The thesis is divided into six chapters, where the buildup is based on the IMRAD (Introduction, Methodology, Results, and Discussion)-structure. Chapters 2 and 3 present the different theories and methods that are required to perform the risk-based ship design process. Chapter 4 and 5 presents and discusses the different results and design concept provided through the risk analysis. Chapter 6 will conclude the findings in the study and establish further work of the thesis. The thesis also includes appendix A-C, which provides an overview of the different characteristics of the Macho 40 vessel and the PHA.

- **Chapter 2** provides an introduction to aquaculture service vessel, where an overview of the different risks related to service vessel operations, central rules and regulations for the design process, different groups of service vessels and characteristics, will be presented. The chapter will also present proposed operations and operation related systems and equipment that the vessel can be expected to perform offshore, and establish goals and requirements for the design of an aquaculture service vessel for exposed locations.

- **Chapter 3** presents the methodology used in this thesis, where an overview of different risk definitions used in the analysis and a description of the risk-based ship design process is provided.
- **Chapter 4** presents the results acquired from the PHA, as well as presenting the different design concepts for the deck platform of the Macho 40 vessel.
- **Chapter 5** presents the discussion of the result and the design concepts found through this study. The chapter will also provide a discussion of which deck platform design that would be best suited for offshore production on the Macho 40, as well as an illustration showing how the implementation of the concept can change the risk picture.
- **Chapter 6** presents concluding remarks and recommendations for further work.
- **Appendix A** provides an overview of the different vessel characteristics of the Macho 40.
- **Appendix B** presents the PHA of the different proposed operations that the service vessel could be performing at an exposed location.
- **Appendix C** presents a detailed risk matrix of the findings in the PHA.

Chapter 2

Introduction to aquaculture service vessel

In the same way that agriculture has tractors for everyday use, the aquaculture industry has service vessels. The service vessel can be used to perform a wide variety of operations. Examples of mentioned operations could be day-to-day operations such as maintenance, inspection and transportation. This chapter will present central rules and regulations for the design of service vessels, along with an introduction of service vessels for exposed locations and an overview of possible operations and technology that could become important for offshore production. It will also give a short overview of the risk related to the aquaculture industry today.

2.1 Risk in today's aquaculture industry

The aquaculture industry has become a driving force for the development of new technology, concepts and management strategies that meet the requirement of sustainable production [13]. The industry is characterized by operations that are susceptible to changing weather, wind and currents, which has shown to affect the availability, safety and integrity of fish farms. This has made the industry become a place where personnel, environment and fish welfare have become subjects of different risks and challenges.

2.1.1 Risk to personnel

The unpredictable work methods used today, along with a working environment that is highly influenced by unpredictable and uncontrollable forces of nature, exposes the operators to many hazards during the workday [10]. The aquaculture industry still requires much manual labor which, additionally, increases the risk that operators experience injuries or fatality. To be able to reduce the risk that operators experience in the aquaculture industry, it is important to understand and perform studies on how accidents happen. This is especially important if the industry should have a future farming at exposed locations.

Figure 2.1, shows data on occupational safety in the period 2001-2012 collected from the *Norwegian Labor and Welfare Administration* (NAV) [14]. The data covers 721 occupational injuries, where 609 injuries originate from sea-based production and the remaining 152 from land-based production. The figure shows that the number of injuries has had a rapid decrease over the years, which can indicate an increase in focus on occupational safety. It shows, however, that a high amount of injuries happen during production in the aquaculture industry.

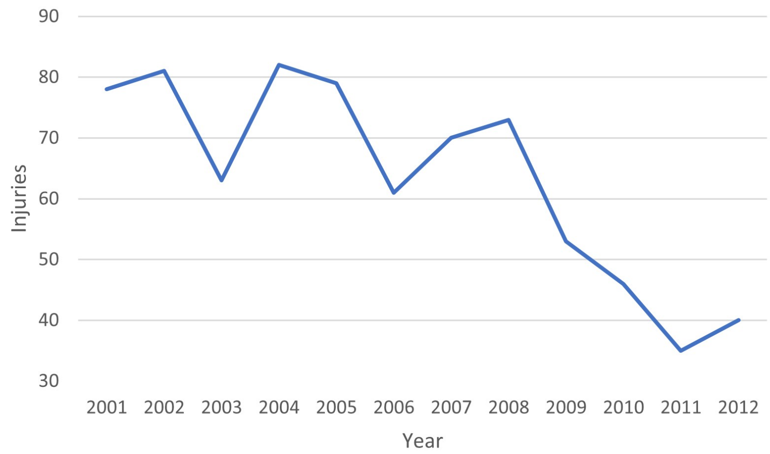

Figure 2.1: Occupational injuries reported to NAV from 2001-2012 [14]

The cause of the different occupational injuries reported to NAV in the period 2001-2012 can be found in Figure 2.2, along with the type of injury. The figure shows that the majority of injuries happen because of fall, which can be divided into two groups: falls to the same level and falls to a lower level [14]. Falls to the same level can involve slipping from a wet or icy surface, often on the deck of a vessel or net cage. The group falls to a lower level, often occur due to movement between vessel and bay, vessel and vessel, vessel and net-cage or vessel and feeder barge. Following are the second and third biggest causes, blow from an object and entanglement or crush. These causes often occur during work operations on a vessel or at the net-cage, mostly in relation to lifting operations with crane and with the use of capstans.

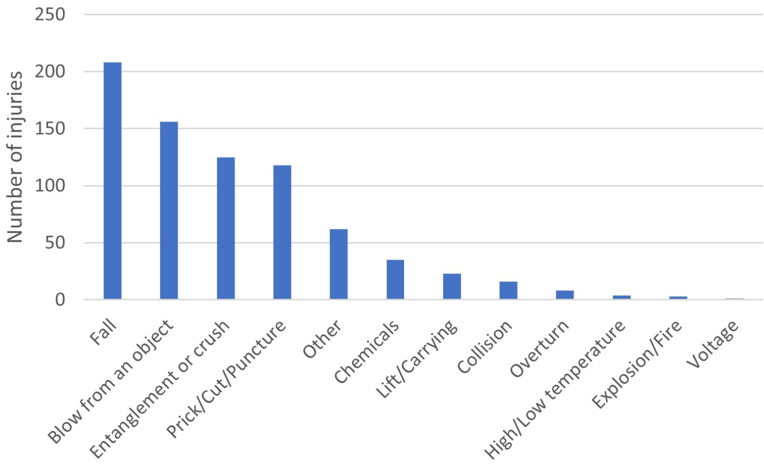

Figure 2.2: Cause and type of occupational injuries reported to NAV from 2001-2012 [14]

As mentioned, the aquaculture industry ranking second when it comes to the risk of fatalities in Norway. This makes it important to understand where and how these fatalities happen, to be able to find risk reduction measures. Data collected from a database at SINTEF Ocean and Barentswatch states that over the period 1982-2018 there have been 36 fatalities in the Norwegian aquaculture industry [10][15]. The data is based on extensive research using networks and media reporting on fatalities in the fish farming industry. Table 2.1, shows that the majority of these accidents (64%) happened on-board work vessels, while 19% occurred in relation to operations at the fish farm. The reason for the high amount of fatalities happen on-board work vessels can be due to the use of over-dimensioned equipment, as well as little focus on safety for personnel.

Table 2.1: Place of fatalities in the Norwegian aquaculture 1982-2018 [10][15]

Place of fatalities	**Number of fatalities**
Work Vessel	23
Fish farm	7
Fish transfer vessel	2
Process facility	1
Smolt facility	1
Truck	1
Pram	1

Figure 2.3, presents an overview of the type of operation that was performed at the time of a fatality. The figure shows that fatalities in the period 1982-2011 happened during transport

operations. These fatalities happen mostly because of capsizing where the vessel is lost and only two fatalities happened due to man overboard. The data shows that no fatalities occurred due to transportation in the period 2012-2018. In recent years it has been common to have several specialized built vessels to perform different tasks such as transport of fodder, transport of equipment and work operations, instead of one vessel designed for everything. This could be a reason for the decrease in fatalities occurring during transportation. The figure shows that the majority of fatalities in present time happens in relation to work operations, mostly because of a blow from an object or crushed between objects during crane operations.

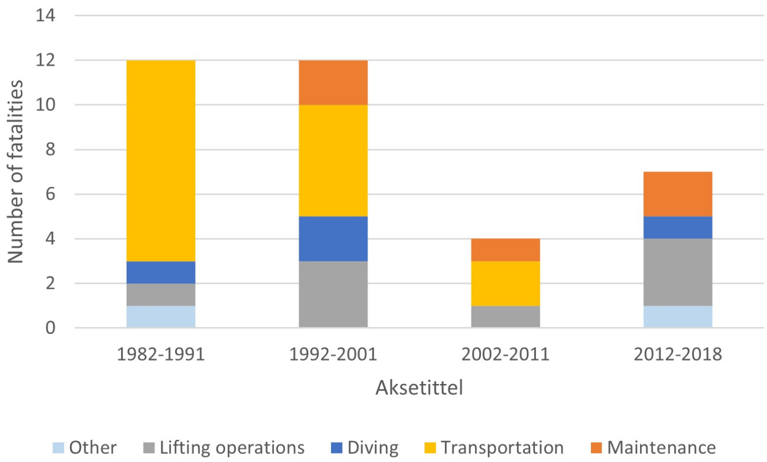

Figure 2.3: Operation types leading to fatalities in Norwegian aquaculture 1982-2018 [10][15]

2.1.2 Risk to environment

Even though occupational safety could be considered the most important part of the industry, little research has been done to prevent occupational accidents from occurring. The focus of the industry has been to decrease risk on the environment by performing structural analysis and investigations on the different farm components, in order to lower the possibility of fish escape [10]. Farmed salmon can be seen as a threat to the wild population since it may transfer diseases that is not normally found in the wild stock, interbreed with wild salmon that leads to breeding fish with bad survival abilities and compete for food and habitat with the wild stock [16]. It is, therefore, important to reduce the possibility of fish escape.

Figure 2.4, shows an overview of reported escaped Atlantic salmon in the Norwegian aquaculture in the period 2001-2020. The data is based on escaped salmon reported to the Norwegian Directorate of Fisheries and statistics from Barentswatch [17][18]. The figure shows that the number of escaped salmon has had a rapid decrease in the period after 2006. This can be due to the increasing focus on reducing the aquaculture impact on the environment.

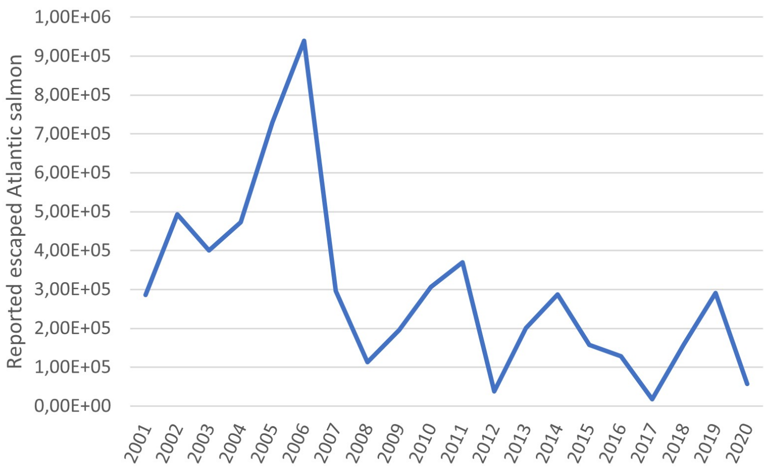

Figure 2.4: Reported escaped Atlantic salmon in the Norwegian aquaculture 2001-2020 [17][18]

Around 76% of the reported escaped Atlantic salmon in the period 2010-2018, escaped because of a hole in the net-cage [19]. As can be seen in Figure 2.5, the weight system is responsible for holes in the net 47% of the time, leaving it to be the main contributor. This can often happen due to handling of the weights, wear from the bottom ring and wear from ropes. Apart from the weight system, holes in the net could occur by conflicts or damage to main farm components (22%). This involves conflicts or damage to the mooring system, feed barge, cage collar that can come from maintenance operations or anchor handling and mooring operations, as well as issues regarding net cage structures and handling of the net. Escapes can also occur due to the collar being below water (16%), where most incidents occur because of conflicts or damage being dealt to the cage collar during work operations.

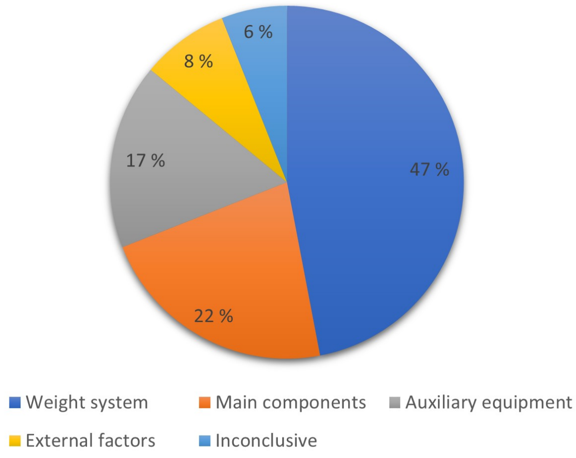

Figure 2.5: Technological causes of hole in cage net related to escape of Atlantic salmon in Norwegian aquaculture 2001-2020 [19]

Technological causes are not the only factors leading to fish escape, underlying human and organizational causes can also lead to escape [20]. Main human factors are lack of competence and experience, which could happen to both new and experienced workers, performance ability being reduced in form of fatigue or reduced concentration and bad communication or misunderstandings. Organizational factors could be bad planning of operations, lack of training for new employees or new equipment, bad management of staffing and working hours and mismatch with requirements or choices.

2.1.3 Risk to fish welfare

Risk to fish welfare is an important aspect of aquaculture production. Bad fish welfare is not only going against what is stated in the Animal Welfare Act., but could influence the quality of the fish and the economy of the industry [21]. The greatest welfare challenges in today's aquaculture industry are all linked to the handling of salmon lice [22]. Today's methods of cleaning fish for lice often require high temperature or rough handling, which can cause different welfare issues such as stress, scale and skin loss, gill hemorrhage and injuries [23]. In this thesis, it is assumed that there will be no need for lice treatments at offshore fish farms.

Salmon can, however, also experience bad welfare during other operations performed on or close to the net-cage. Such operations can be crowding and pumping, which involve creating small spaces and disturbing the fish's normal behavior. These operations can cause stress to the fish and have the possibility to lower the oxygen level in the water, as well as injuries to gills, skin and snout [24]. The stress and low water quality can influence disease outbreaks by compromising fish's immune system functions. Other operations that could influence fish welfare are IMR of net or farm structures close to the net-cage, or handling of weight system or other components of the farm system. This could disturb the normal environment, causing stress to the fish. These operations, especially crowding and pumping, have led to increased levels of mortality during and after operations.

2.2 Rules and regulations

When designing a vessel, is rules and regulations an important tool to set boundaries and requirements for the vessel's construction, stability, fire safety system, equipment, operations that the vessel should perform, machinery systems and others [25]. Considering the fact that this thesis will focus on designing a vessel based on the risk for personnel, environment, material and fish health, some rules and regulations will be presented. It will not go into detail as it falls outside the scope of this thesis.

Rules and regulations by the Norwegian Maritime Authority state that a cargo vessel is defined as "any ship that is not a passenger ship, fishing vessel, barge or pleasure craft" [26]. This definition considers a service vessel in the aquaculture industry to be a cargo vessel and should, therefore, have the same rules and regulations as one. The rules and regulations of a vessel is often based on a vessel's gross tonnage (GT) in tonnes and/or the length of the vessel, the number of passengers intended for, or in which speed level a vessel is designed to operate in. The length referred to can be the vessel's length (L) or the overall length (LOA).

2.2.1 Vessels with LOA above 8 meters, L less than 24 meters, and GT under 500

Vessels with an LOA below 15 meters built before 2015 were not obliged to be certified or approved before being built. This was because there were no specific requirements or regulations for the construction of vessels with an LOA below 15 meters, leading to a large number of vessels being built with this length. This often led to safety concerns as the vessels were designed with a mismatch between dimensions and equipment.

New regulations coming into motion after 2015 stated that all cargo vessels with an L less than 24 meters, an LOA above 8 meters and a GT under 500 tonnes is applicable to "Forskrift om Bygging og Tilsyn av Mindre Lasteskip" (Regulation for Construction and Supervision of Small Cargo Vessels) [27]. This regulation sets requirements to the vessel's stability, construction, equipment, machinery system, fire- and general safety systems and arrangement, documentation, and others. The regulation can refer to standards set by approved classification societies like Det Norske Veritas (DNV), and other approved standards like Norwegian Maritime Authority and Nordisk Båt Standard. The following bullet points present examples of how the regulation can set requirements to the constructions of the vessel, along with equipment requirement in some operations and routines for crew members at a vessel:

- **Chapter 2 §8**
  "*Areas of the hull which may be subjected to increased loads or damage shall be strengthened. Areas which cannot be strengthened shall have an internal watertight barrier preventing further flooding of the ship in the event of damage.*"
- **Chapter 2 §13**
  "*When towing in a trade area greater than protected waters, a complete spare tow connection shall be available. This shall be so arranged that it is readily available for use under all weather conditions.*"
- **Chapter 2 §18 & §15**
  This section sets requirements for dimensioning of equipment and arrangement for towing and anchor handling in small coastings. Small coasting has been defined in regulations on trade areas, "*Voyage on the Norwegian coast where the unsheltered stretches exceed 25 nautical miles, including all more restricted waters, but never farther off the coast than 20 nautical miles from the Base Line*" [28]. Vessels are also obliged to have a safety zone where the crew may stay when anchor handling operations are being performed.

"Skipssikkehetsloven" (Ship Safety and Security Act.)can be used for technical safety rules, for instance, Chapter 3 §9 [29]:

"*A ship shall be so designed, constructed and equipped that it according to its purpose and trade area provides for the satisfactory protection of life, health, property and environment.*"

2.2.2 Vessels with L of 24 meters or above, or with GT of 500 tonnes or above

The regulation "Forskrift om Bygging av Skip" (Regulations for Construction of Vessels), sets requirements to vessel's construction, equipment, stability, safety rules and others [26]. This regulation is applicable for vessels that have an L of 24 meters and above, or GT of 500 tonnes or above. The different sections in the regulation often refer to other regulations and standards for requirements, which can act as the prevailing requirement.

Cargo vessels that have a GT of 500 tonnes and above, and are designed to be engaged on foreign voyages have been applicable under the regulation of the consolidated version of Safety of Life at Sea (SOLAS) edition 2014, chapter II-1 [26]. The regulation sets stricter requirements for the construction, stability and equipment of the vessels, with a special focus on the intact stability, machinery system and safety and fire safety systems. The term foreign voyagers is described in the regulation on trade areas as "*All voyages beyond domestic voyages*", which means all over 20 nautical miles from the Base Line [28]. Cargo vessel with a GT bellow 500 tonnes operating in foreign voyages is applicable for Regulations for Construction of Vessels Chapter 1 §4, "*The requirements of a recognized classification society for construction and maintenance of hull, main and auxiliary engines, electrical installations and automation installation shall apply for the design, construction and maintenance*" [26]. The following bullet point shows more examples of regulations and requirements for the construction of a vessel:

- The stricter requirements set by SOLAS can often lead to high additional costs for vessels designed with a GT of 500 or more, operating in foreign voyages. Vessels are, therefore, often designed with a GT below 500 tonnes, for which requirements set by approved classification societies are the prevailing requirements [25].
- **Chapter 2 §13** in Regulations for Construction of Vessels set requirements to the different equipment needed if a vessel should perform towing and anchor handling operations.
- **Chapter 5 §43** in Regulations for Construction of Vessels set requirements to the load lines and the assignment of freeboard on ships with L of 24 meters or more, operating in foreign voyagers.
- **Chapter 3 §14** in SOLAS set requirements that a rescue vessel should be stowed in a state of readiness for launching not more than 5 min.

2.3 Service vessels characteristics

This section will present an overview of service vessels in the aquaculture industry, which will be grouped into three different groups. In addition, service vessels will be categorized into two categories; multi-purpose vessels and specialized vessels.

2.3.1 Groupings

Based on the regulations and requirements presented in Section 2.2, service vessels can be presented in two main groups:

- Vessels with LOA under 24 meters.
- Vessels with L of 24 meters or more.

The first group is vessels with an LOA under 24 meters, which mostly refers to two types of vessels; vessels with an LOA under and above 15 meters. This group is applicable to the regulation for construction and supervision of Small cargo vessels. The vessels can mostly be found performing operations at sheltered farms located in fjords and locations with little influence of waves. Vessels with an LOA below 15 meters are today the most common service vessels to be found operating in the industry [8]. This trend is the result of the regulations in place before 2015, leading to no regulations for vessels below 15 meters LOA, as mentioned in Section 2.2. These vessels are often designed with a low length to breath ratio, that secures a good deck area and platform with the required size and stability in order for operations to be conducted [25]. Other traits that are typical for the length are restricted draught to avoid interference with the mooring lines, reduced freeboard to ease access for the crew between the deck and the floating collar, and the catamaran hull that increases intact stability and deck work area for the crew.

The changes done to the ship safety and security act. in 2015, mentioned in Section 2.2, opened up to a whole new world of designs for service vessels. Service vessels have been designed with higher safety as the industry required standards for winches and cranes no longer suffer from a mismatch with the service vessel dimensions. This leads to bigger vessels being used for more demanding operations such as anchor handling and mooring operations, while the traditional vessel with a length below 15 meters being used for day-to-day operations.

The second group consists of vessels with L of 24 meters or more, and a GT below 500 tonnes. These vessels are subject to the regulation for construction and supervision of small cargo vessels, as referred to in Section “the future service vessel”, with SINTEF Ocean and other partners involved in the SFI Exposed project, it is believed that the majority of service vessels operating at an exposed farm will be of group two. Exposed locations are often in the need of enhanced capabilities to maintain a stable work condition during operations in demanding weather. Using vessels with the traditional 15 meter design could reach a risk level that does not meet the regulation standard. Considering that the majority of today’s aquaculture industry is located in sheltered locations, it would be preferable to design a vessel that could operate in both locations. The vessels in group two are preferred to use at offshore farms, although, the vessels also can be used to perform operations at a sheltered location that demands bigger vessels, such as anchor handling and mooring operations. The size of the vessels often makes it hard to maneuver freely around the cages in a sheltered area without interfering with the mooring system or the cages themselves. This often leads to vessels requiring assistance from vessels in the first group, when performing some type of operations at a sheltered location. As mentioned in group one, the catamaran is a favorable design for service vessels in the aquaculture industry, as it allows for increased lifting capacities and reduced draft [30]. Using a catamaran can also lead to a high metacentric height (GM), which could make a vessel’s motion during sailing becoming ”stiff”. This can lead to both discomfort and damage to crew and equipment. “*The effects of a high GM become particularly evident during harsh wave conditions, making catamarans potentially less suitable for operations in exposed sea environments*” [30]. Taking this into consideration, monohulls could be a better option for service vessels at exposed locations. The hull design enables the possibility of a lower GM and, thereby, reduces motion stiffness and creates longer roll periods.

This thesis focuses on the deck platform design of a service vessel for exposed locations. Taking this into consideration, a vessel from group two will be used in the deck design process. The vessel used as a basis for the design process is categorized as a “Macho 40”, built by Møre Maritime AS, illustrated in Figure 2.6. The vessel type is specialized to perform operations in exposed locations and is considered to be the biggest service vessel operational in the aquaculture industry today [31]. It is designed with a monohull and has an LOA of 40 m, it focuses on good crew facilities and operational areas with a good view. According to Stemland’s master thesis, the master on board “Frøy Fighter”, a Macho 40 vessel, states that the vessel shows excellent stability and performance during rough weather [30]. Table 2.2, presents a small summary of different dimensions of the vessel type, see Appendix A, for a detailed description of the vessel. The reason for choosing a vessel with a GT below 500 tonnes comes due to the stricter and additional requirements set by SOLAS, as referred to in Section 2.2.2.

Table 2.2: Macho 40 vessel characteristics

Length overall	40	[m]
Breadth	12	[m]
Gross Tonnage	499	[T]
Deck area	320	[m^2]
Draft	3.7	[m]

Figure 2.6: Illustration of the Macho 40 service vessel [31]

2.3.2 Multi-purpose and Specialized vessels

Apart from the different groupings of service vessels mentioned, service vessels further can be divided into two main types; multi-purpose vessels and specialized vessels. These types often differ in flexibility with regard to the type of operations they can perform [25].

Service vessels defined as specialized vessels are optimized and equipped with the focus of performing one type of operation, or a set of operations that require the same operation related systems and equipment configurations. The specialized vessel is provided with a high operation specific efficiency, but lacks flexibility. Typical operations related to specialized vessels are diving operations, towing, fire and rescue operations, anchor handling and mooring operations, to mention some. Specialized vessels could be defined as light and high-speed vessels compared to a multi-purpose vessel, although, this may vary with the requirement related to an operation the vessel is specialized to perform.

A multi-purpose vessel is, as the name indicates, a vessel that is designed and optimized to perform a set of different operations that require different equipment. The vessel's ability to perform multiple different operations shows that the vessel is designed with high flexibility. This flexibility enables a vessel to adapt to changing demands and needs in the market, although, it also leads to the vessel being less optimal for each, or some, of the operations it is designed to perform. This leads to reduced operation specific efficiency and performance. Multi-purpose vessels are typically designed to accommodate a big variety of different operation related systems and equipment, as they are designed to perform a variety of different operations. This makes them typically larger and more complex to build and design than specialized vessels. If the design of a multi-purpose vessel is not done with focus, a multi-purpose vessel can become multi-useless. This could be a result of the implementation of too much, or the wrong combination of equipment, leading to the vessel becoming so multi-purpose that it is not able to perform the operations it was designed for. This could make it challenging for the vessel to compete in the market. The benefits of having a multi-purpose vessel come with its ability to perform a variety of different operations, making it suitable for adapting to changes in the demands and needs of the market. For example, it would be profitable to design a service vessel that has the flexibility to perform a variety of tasks on farms in both exposed and sheltered locations, rather than having a specialized vessel that will not have the ability to perform other types of operations.

2.4 Service vessel operations

When designing a vessel, it is important to have an understanding of which operations a service vessel could be required to perform. This is important as the capabilities of the vessel should meet the requirements set by the stakeholders, as well as making it able to compete in the market it is designed for. In the following sections, the main operations considered for a service vessel operating at an offshore farm are presented. The uncertainty regarding offshore farming makes it hard to predict what type of operations will be necessary for a service vessel to perform at an offshore location. This can be especially important considering that the pilot projects "Ocean Farm 1" and "HavFarm 1" aim's to be self-sufficient [25]. Due to these uncertainties, this thesis will utilize the operations performed at a sheltered location, as it is assumed that the majority of these types of operations can be performed at an offshore location. Figure 2.7, gives an overview of the operations that are expected to be important for a service vessel.

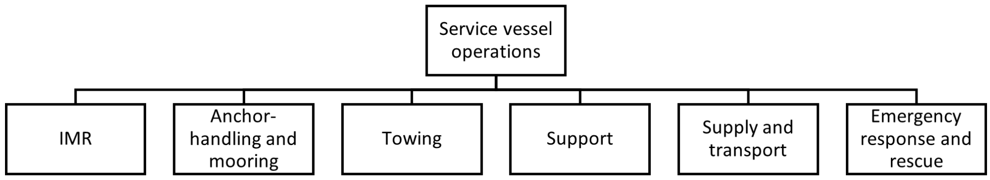

Figure 2.7: Overview of different operations a service vessel could be expected to perform offshore

2.4.1 Inspection, Maintenance and Repair

Inspection, maintenance and repair might be considered as some of the most important operations performed by a service vessel, as it helps reducing risks of material loss and salmon escape, as well as making it safer to perform other operations on the farm. Five bullet points are presented, which provide an overview of the different IMR operations that are expected to be performed.

- Inspection of the farm structures and system, with ROV
- Inspection of the farm structures and system, with divers
- Maintenance and repair of the farm structures and system, using ROV
- Maintenance and repair of the farm structures and system, using divers
- Maintenance and repair of farm structures and system above water

A representative working at an aquaculture service vessel (representative A) commented that "to ensure that the farm structures and systems do not suffer from any damage, wear and tear, or other possible dangers, is inspections performed frequently". It is also important to perform inspections in advance of maintenance and repair operations, in order to safely plan how to proceed. There will, additionally, be a need for inspections after installations of farm components or systems and after maintenance and repair operations. This is to make sure that operations are executed in the way that is wished for and to make sure that no other components are damaged during the operation [25]. Inspections are most commonly performed by the use of ROV or divers. This usually depends on the preference of the company owning the farm or which part of the farm is being inspected. ROV is often used for inspections done at large depths, such as mooring inspections, or if a larger area needs to be covered. For sheltered areas it is common, if possible, to perform inspections with ROV inside the cages because of the mooring wires [30]. Divers are typically used when inspecting a specific part of the farm structure or system. Another method that is being used for inspections of a component is to lift the component on-board the vessel[32].

ROVs and divers can also be used to perform maintenance and repair operations. Being able to perform these operations underwater often saves operational time and expenses, as there would be no need to change or lift the part of the system up from the water, representative A commented. A typical maintenance and repair operation could be to repair holes in the net, fix tubes and wires. If a maintenance and repair job is too extensive to perform underwater, the component or system can be lifted on-board the vessel. This allows for a higher degree of efficiency and precision, however, it is important to plan such operations with focus as it can increase risk if the vessel does not have the right capabilities to have the component lifted on-board.

Nekstad mentions in his master thesis that "it is believable that it will be desirable to minimize the use of divers for diving operations at exposed locations, due to the increased environmental loads, larger areas to cover (due to larger facilities), as well as the increase in water depth" [25]. If this is the matter it can be assumed that the majority of inspection, maintenance and repair operations will be performed with an ROV, which can help reduce the risk to personnel. It will, however, still be necessary to use divers for operations where there is not possible to use ROVs.

To which degree it will be necessary to perform IMR operations with the use of a service vessel, will depend on which degree a farm will be self-sufficient. For example, HavFarm 1 is designed to perform IMR operations without the need for external support, as well as Ocean farm 1 that is designed with autonomous net cleaning [12][11]. During a meeting with SFI Exposed, it was believed that the traditional farm design will be used more in the future at exposed locations. This could lead to a higher demand for service vessels to perform IMR operations.

2.4.2 anchor handling and mooring

A representative working as a vessel manager for Solstad Offshore ASA (Representative B) stated that "anchor handling and mooring can be considered as the most risk influenced operations at a farm". It is, therefore, as mentioned in Section 2.4.1, important to perform extensive inspection beforehand to assist in the planning of anchor handling and mooring operations. These kinds of operations have been separated into the following five bullet points [25]:

- Deployment of anchor bolts, using ROV
- Deployment of anchor bolts, using divers
- Tensioning of mooring and anchor lines
- Maintenance and repair of mooring and anchor system
- Deployment and retrieving of anchor and anchor lines

A service vessel could be required to perform the deployment of anchor bolts, by using ROV and/or divers. Based on what was mentioned in Section 2.4.1, it is believed that the majority of anchor handling operations will be performed by the use of ROV. This is because anchoring at exposed locations often happens at large depths and in areas with increased environmental loads. The vessels could also be tasked with the deployment and retrieving of anchors and anchor lines. The oceanographic of the site often decide whether there will be a need for deployment of anchor bolts and/or anchor [33]. Anchor bolts are used at parts of the seabed where it is difficult to deploy anchors, like areas with hard surfaces. The service vessel could be required to perform tensioning of mooring and anchor lines, as the lines tend to lose their tension over time. In addition to the mentioned, the service vessel will be used for maintenance and repair of the mooring and anchor system.

Which degree a service vessel will be needed to perform the mentioned anchor handling and mooring operations depend on the design of the farm and the capabilities of the vessel. For example, the design of Ocean Farm 1 enables it to use anchoring and mooring systems similar to the offshore industry, representative B stated. Installing this system had to be done with two offshore anchor handling tug supply (AHTS) vessels due to the dimensions of the anchor system. It is believed that such a system is not in the need of periodic tensioning, unlike traditional farms. For a service vessel to be able to perform an operation at this scale would require it to be designed with the same dimensions and capabilities as an offshore AHTS vessel. Due to the development of the offshore industry, there are a large amount of AHTS vessels available [25]. It can, therefore, be more beneficial to use an offshore AHTS vessel, rather than building a dedicated, capital intensive, aquaculture service vessel to perform these operations. As mentioned in Section 2.4.1, it is possible that the traditional farm design will be used at more exposed locations. If this should be the matter, then a service vessel could be a good solution for performing mooring and anchor handling operations. The vessels can also be used to perform similar operations at today's farms in sheltered locations, as these systems do not require a vessel to have the same dimensions as an offshore AHTS vessel.

2.4.3 Towing

"Towing can be required during the launching of a new farm, during the moving of a farm from one location to another, or during the de-commissioning of a farm" [25]. Towing operations can, additionally, be required if mooring systems need to be moved to a new location or if feeding barges need to be relocated. It can also be operations that include towing of other vessels or assisting vessels, such as AHTS vessels, with mooring operations. Towing operations are often performed with the use of tug boats [34]. It can, however, be performed by a service vessel with the proper design and equipment.

During a meeting with SFI Exposed regarding offshore aquaculture service vessels, it was believed that if the majority of offshore farms will be designed at the same scale as Ocean Farm 1, then an aquaculture service vessel might not be the proper use for towing operations. For this to be considered, the vessels would need to be designed with the same capabilities as offshore tugs. It can, however, assist in operations offshore or perform towing operations if traditional farms are moved to exposed locations. Service vessels designed for exposed farming could also perform heavy towing operations at sheltered locations if necessary.

2.4.4 Support

The increased dimensions of the facilities and the increased environmental loads can lead to the need for service vessels supporting operations offshore. Which type of support the service vessel is able or is needed to perform depends on the design of the facility. The majority of supporting operations a service vessel is required to perform is listed as five bullet points [25]:

- General support during well-boat operations
- Diver support during well-boat operations
- ROV support during well-boat operations
- Support during Anchor handling and mooring operations
- Hotel for workers during operations

Service vessels can be used to support well-boat operations by performing inspections with ROVs and/or divers during and after well-boats have finished their given operation. This is to make certain that no components of the farm's system have been damaged during the operation. Well-boat operations involve the well-boat collecting the fish at the end of its production period, or performing de-licing or disease handling of the fish if such should be needed at an offshore facility. A service vessel could also be assigned to perform general support during well-boat operations. This could involve help with lifting up the bottom ring to reduce the volume of the net pen, and deploy the displacement net, which makes it easier for the well-boat to pump the fish up [25].

A Service vessel can further be required to perform support during anchor handling and mooring operations. It can support by performing inspections to help with planning before the operation, as well as during and after the operation, to make certain no damage is done to the system. Service vessels can also be used as a hotel for personnel if required. This can especially be preferable during operations that are performed over several days or if the personnel have to wait for the weather to be better in order to keep up the work.

2.4.5 Supply and transport

As the farms are floating structures, service vessels can be required to perform different transportation operations. The transportation operations a service vessel can be required to perform has been presented with four bullet points:

- Transport of personnel
- Transport of cargo and supplies
- Transport of chemicals and H_2O_2
- Transport of waste

A service vessel can be required to perform transport of personnel working at the farm or from the farm to the mainland. At a sheltered location, this is usually performed by smaller vessels, but as there is an increase in environmental loads at exposed locations, it would be safer to perform such transport with service vessels designed for the environment. The vessel could also be required to transport liquid and dry cargo, such as fuel, oil, feed for the personnel, parts and equipment for the farm, to mention some [25]. A service vessel could also be utilized for transport of chemicals and/or H_2O_2, required for disease handling or de-licing operations if that should be necessary to perform at an offshore facility. If there should be any need of transporting cargo from the facilities, the service vessel is able to perform such operations as well. Typical cargo that needs to be transported from the facilities can be the waste accumulated at the facility, typically garbage, septic water, waste oil, and others.

"As the facilities become more remote, it is believable that transport and supply of cargo, goods, parts and equipment, to and from exposed aquaculture facilities becomes more important" [25]. If this is the matter, service vessels can expect to be required to have an increased capacity for transport of cargo, supplies, waste, parts and equipment. As the cargo transported can be both dry cargo and liquid, there could be a need for service vessels to be able to accommodate tanks that are able to hold both liquid and dry cargo. Cargo can also be accommodated in containers, it would, therefore, be preferable if the service vessel is able to transport containers. As the service vessel will be required to perform transport of personnel due to the increased distance and increased environmental loads, there will be a need for service vessels to be able to accommodate passengers. It should also be equipped with the right systems and equipment that enables safe transfer to/from the facility from/to the vessel.

2.4.6 Emergency response and rescue

As the facilities become more remote and a subject to higher environmental loads, it will be important to ensure the safety of the personnel. The increased distance makes it more demanding and time consuming for specialized rescue vessels to travel from the mainland to the facilities. It would, therefore, be preferable to design a service vessel with some features for emergency response and rescue operations, as it is used at facilities for day-to-day operations. Emergency response and rescue operations can be divided into two bullet points:

- Standby and rescue
- Trawling for escaped fish

It could be required for service vessels to be able to perform standby and rescue operations in case of accidents, structural breakdowns, vessel sinking/capsizing, and so on [25]. Service vessels could be required to inherit some similarities to the systems and equipment of an emergency response and rescue vessel (ERRV). An EERV is a specialized rescue vessel that operates at offshore installations, it has good maneuverability, state-of-the-art navigation/communication equipment and a rescue craft capable of operating in severe weather [35].

2.5 Operation related systems and equipment

This section will present an overview of some examples of operation related systems and equipment that could be utilized at a service vessel for exposed locations, with regard to the operations presented in Section 2.4. Introduction to the systems and equipment, what they can be used for and why they should be used will be presented. To enhance the safety and efficiency of service vessel operations, it is important to focus on finding the right technological components for the vessel.

2.5.1 DP system

A dynamic position (DP) system is a computer-controlled system used to maintain a vessel's position and heading [36]. This allows the vessel to be able to conduct critical activities in a challenging environment without the need for mooring lines and/anchors. The DP system is able to do so by continuously adjusting the direction and thrust of the thrusters and/or propeller, by analyzing the motion of the sea and ship, as well as following specifications given by personnel on board. The DP system will allow a service vessel to maintain its position without the need of mooring to the farm during operations, which could reduce the possible risk of the vessel interacting with the farm or other vessels. The DP system can be divided into three classes; DP1, DP2 and DP3. The classes differ with their redundancy, where DP1 has no redundancy, meaning that loss of position may occur in the vent of a single fault, DP2 has redundancy so that no single fault in an active system will cause the system to fail [37]. The DP3 class is able to withstand fire or flood in any compartment without the system failing. As mentioned in Section 2.4.1, the service vessel will be able to perform IMR operations with the use of ROV and/or divers. For a vessel to be able to perform diving or ROV operations in the offshore industry, ii is required for vessels to be equipped with DP class 2 or 3. It can be assumed that the same regulations will apply for offshore aquaculture [25].

2.5.2 Fore crane and aft crane

Cranes are a common tool in the aquaculture industry as it is a necessary usage for several operations. For vessels operating offshore, it could be beneficial to equip vessels with several cranes, as it allows for higher flexibility. Large service vessels are often equipped with two deck cranes, one positioned aft on the deck and one fore on the deck. The cranes are often placed on the same side, either the starboard or the port side, which lowers the flexibility of how the vessel should be positioned during an operation. In Nekstad's master thesis, the vessel is equipped with two cranes fore (one port side and one starboard side) and two cranes aft (one port side and one starboard side [25]. This allows for more flexibility regarding the positioning of the vessel during an operation, making it possible to position the vessel in a way that is best suited for the execution of the operation.

The cranes used in this thesis will be rotating knuckle-boom cranes. These cranes have the ability to rotate which increases the operational area of the crane. It also has the functionality of the knuckle-boom that allows for the crane to be folded, making it more compact, less space demanding when not in use and lowers the center of gravity (COG).

2.5.3 Crane systems

As the environmental load's increase, so does the possibility of accidents happening during operations. To reduce the risk of possible accidents happening during crane operations, can different crane systems be used:

Active heave compensation system

The active heave compensation system's purpose is to keep the load, lifted by a crane, motionless and to reduce the slack in the line. The system does this by actively compensate for movements created at a specific point, thus eliminating vessel heave motion from the load and decouples load motion from ship heave motion [38]. This system can reduce the risk of vessels or personnel being hit by dangling loads.

Automatic overload protection system (AOPS)

The project thesis supporting this master thesis states that "the AOPS is a safety system that is fully integrated into the crane control system and is designed to meet the specifications (structural capacity) of a crane, to protect personnel or assets against the danger of falling objects" [39]. This system automatically activates when a set of predetermined conditions are met, and if its preset activation limit is exceeded [40]. These predetermined conditions could be the position of the hook, the boom tip, reeving configuration, load on the luffing system and/or the actual load on the hook. If the AOPS activates, it disengages the slewing and hoisting brakes automatically and resets the crane into its initial position. The crane will be operational again once the conditions for activation are met. The benefit of using such a system offshore is that it reduces the risk of personnel or assets being hit by falling objects that comes from critical overload.

Constant tension system (CTS)

The CTS ensures a constant tension between the crane and the lifted object. Prior to the lifting operation is the tension in the line predetermined in the system, which is measured by a load sensor and monitored by the central control system [41]. The system ensures that the tension in the line is maintained by giving out or taking in line, depending on how the tension value differs from the predetermined value. "The benefits of such a system is that it improves operation efficiency, increase the safety of personnel and assets and extend component life, prevents loads bouncing on the deck and helps to maintain tension in the wire in harsh weather and by that enlarges operation weather window" [39].

2.5.4 A-frame

The A-frame is a hydraulic driven crane that is usually placed at the stern side of the vessel. These crane's lifting capacity often range from 1 to 350 tonnes and is used for heavy subsea work in highly corrosive environments [42]. The A-frame allows for stable and controlled launching and retrieving of equipment and tools, as well as performing anchor handling at offshore locations. The benefit of this system is that it can be tilted fort and back over the water and vessel deck, contributing to avoid anchors and other equipment damaging the vessel during launching and retrieving operations [25].

2.5.5 Capstan winch

The capstan winch has a vertical drum that is typically used for hauling and tensioning of lines. It can also be used as a tool to provide pulling power when handling light cargo on deck or as a mooring winch when mooring the vessel. Service vessels are typically equipped with multiple capstan winches that can be found along the port and/or starboard side of the vessel.

For service vessels operating at offshore farms, the capstan winch will most likely not be used for tensioning of mooring lines as the dimensions of the lines do not allow for it to be used, comments Representative A. It can, however, be used at sheltered locations or if traditional farm design is used at exposed locations.

2.5.6 Towing hook

For towing operations, it is common that a vessel is equipped with a towing hook. The hook enables for a quick connection to a tow and reducing the heeling moment on the vessel during ship handling, as well as enabling for safe towing under severe working conditions [43]. The hook can be mounted to a foundation on the work deck, or to a warp winch. During towing operations, the towing line or chain is connected to the towing hook. According to requirements set by the Norwegian Government, vessels that do not have a winch approved for towing operations must be equipped with a towing hook with an emergency release function [25].

2.5.7 ROV systems

The expected increase in the use of ROV for operations at exposed locations will mitigate the risk to personnel. It will, however, give rise to new accident scenarios, such as ROV crashing into the vessel, ROV crashing into the farm, ROV being lost, to mention some. To reduce the possibility of such an event occurring during the launching and retrieving of the ROV, two ROV systems will be presented.

ROV LARS (Launch and Recovery System)
LARS is a crane type that is specialized for launching and retrieving ROV. It can be designed to ensure controlled and secure launching and retrieving of all the largest work classes of ROV, up to a depth of 4000 meters [44]. The benefit of using LARS is that it mitigates the risk of the ROV crashing into the vessel or the farm during launching and retrieving. This enables operations to be performed in a harsher environment, increasing the operational availability of the vessel for operations with ROV. This can be important for exposed locations as the operational weather window is limited and often small [25]. The LARS can, additionally, be used for safe and controlled launching and retrieving of divers.

TMS (Tether Management System)
The TMS can be defined as a garage for the ROV that can be used with most winches and cranes on a vessel, as well as the LARS. The TMS enables for safe and efficient launching and retrieving, as the ROV can be stored in the system during travel. This can protect the ROV and enable for faster deployment to its working depth. During travel, the TMS will "eliminate the effect of drag of the long length of umbilical attached to the ROV" [45]. The system can also, while underwater, be used as a base for the ROV, where it can be parked during different parts of an operation or if challenging weather makes work difficult.

2.5.8 ROV and diving container

For operations where ROV is required an ROV container will be used. The container is accommodated with a control cabin for control of the ROV during launching, operation and retrieving, a hangar for storing the ROV when not in use, as well as a workshop to perform maintenance of the ROV and prepare it for operations [25]. The container, with the mentioned features, will be delivered as a 20-foot container. The benefit of an ROV container is that it allows for efficient transition between system configurations since it can be efficiently equipped.

Similar to the ROV container, a diving container can be used. The diving container comes with a fully functional surface-supplied diving system, which often consists of air-supply systems and other required air-supply systems and equipment for diving operations [25]. A decompression chamber can also be accommodated into the container if wished for. Diving operations over long periods of time and/or at larger depths could require a surface-supplied diving system. It can, therefore, be required to use a 20-feet diving container for diving operations at exposed locations. Similar to the ROV container, allows the diving container for efficient transition between system configuration.

2.5.9 Decompression chamber

After diving over longer time periods and/or diving at large depths, it is necessary for divers to perform decompression stops. These decompression stops can be performed in the water, however, spending long periods in cold water in exposed conditions can lead to an unnecessary increase in risk [25]. It can, therefore, be beneficial to equip vessels with decompression chambers. These chambers allow divers to perform their decompression stops in more controlled environments on a vessel.

In this thesis, it is assumed that the decompression chamber will be a part of the diving container mentioned above. It will, therefore, not be considered as a piece of individual equipment for operations.

2.5.10 Motion compensated gangway

A motion compensated gangway can be expected to be used on future exposed aquaculture vessels that are expected to transfer personnel between the facility and vessels. The gangway provides an alternative method of transferring people, rather than for example helicopters, and consists of three main sub-systems, a skid frame, a motion compensated platform and a gangway [25]. "The motion compensated platform (MCP) is the combination of the transfer deck and compensation mechanism. The MCP connects the gangway to the skid. The transfer deck provides the access route from the vessel onto the gangway and vice versa. The compensation mechanism is designed to compensate ship motions by slewing, rolling and luffing of the gangway" [25].

The gangway is typically accommodated at the center aft of the vessel, and depending of the design of the gangway, can become up to 11.5 meters in length when fully extended. When not in use, the system can be stowed in a 40-feet container or rotated 180 degrees. The footprint loss on the deck of the vessel, experienced when the gangway is not in use, can be seen as a large loss as it renders the area of the deck unusable. This creates some uncertainty to the decision if a service vessel should be used for transporting personnel to the facility, especially if the vessel is required to perform other operations at the same time.

The benefit of using such a system is that it enables a safe and efficient transfer of personnel, as it is designed to compensate ship motions with six degrees of freedom. “The operational limit of the system is set by its ability to compensate for ship motions in sea-states with significant wave heights of up to 2.0 meters, as well as a wind-speed of up to 20 m/s” [25].

2.5.11 Safety and rescue management

As mentioned in Section 2.4.6, a future service vessel might be required to perform different safety and rescue operations. If this should happen, the vessel should be designed with the necessary safety and rescue management systems and equipment to be able to act in these situations.

MOB-boat

Regulations set by the Norwegian Government, states that vessels with a GT higher than 300 and lower than 500 tonnes, operating in trade area 1 to foreign voyages are required to be equipped with a MOB-boat [25]. The MOB-boat is a rescue vessel that is mainly used in man-overboard situations. It can, however, be used for other emergency situations where there is a need for a fast small vessel, with high maneuverability, such as search and rescue operations. As the MOB-boat will be used for rescue operations it is required to be fast and able to be launched and retrieved quickly. It is, therefore, preferable to equip the MOB-boat with its own davit on the port or starboard side of a vessel. The MOB-boat can be regarded as an important part of the operation related systems and equipment if the vessel is required to perform standby/rescue and emergency response operations [25]. If the vessel is assumed to perform the mentioned operations, the vessel could be equipped with a second MOB-boat on the opposite side of the permanently installed MOB-boat. This makes it possible to launch a MOB-boat on the side of the vessel that is most suited, which provides flexibility in case of emergency situations.

Fast rescue craft (FRC)

An FRC could be implemented into the design of a service vessel designed to perform standby/rescue and emergency response operations. These vessels are faster than a MOB-boat and can accommodate more people, as well as being designed for exposed locations. If it is chosen to implement the FCR into the design of a service vessel, it will be accommodated with its own davit [25].

Rescue net

In circumstances where the weather conditions make it difficult to deploy rescue vessels in a rescue situation, a rescue net can be used. The net can be deployed by using one of the cranes mounted on the vessel, where one side is fastened to the crane and the other side of the net is fixed to the bulwark of the vessel [25]. Which side of the vessel the rescue net can be deployed on depends on where a crane is mounted. If the conditions allow it, a smaller version of the rescue net can be deployed, which is a mobile lightweight scramble-net [46]. This version allows for a person to deploy it without a crane, at which side is preferable.

2.6 Service vessel design goals and requirements

Prior to designing a vessel, it is beneficial to understand its expected performance and requirements, as well as its safety goals. A service vessel has several important requirements and functions it is expected to perform. These can be functions and requirements that are related to the operations the service vessel is intended for, as well as general performance. Expected performance can be the ability to sail and perform as required in intended areas and weather conditions [25]. Nekstad presents in his thesis some functions that can be applicable for service vessels:

- "*It is a safe working platform and living quarters for the crew.*"
- "*The vessel provides a stable platform from which one or multiple types of operations can be performed in an efficient manner.*"
- "*It is able to operate and maneuver in the required manner at the farm sites, and in the waters where the farm's sites are located.*"
- "*It is able to sail to the aquaculture facility, perform the operation(s), and sail back to port, or to the next location, with minimum expenditures, in the weather conditions that the vessel is required to operate in.*"

The vessel is required to provide a safe and stable working platform where operations can be executed in an efficient matter, as well as living quarters for the crew. Considering the increased weather conditions that can be expected at exposed locations, compared to sheltered, it is important for the vessel to be able to operate and sail in the weather conditions it might encounter [25]. For this purpose, it is beneficial to be adapted with good stability and seakeeping abilities. Further, the vessel must be able to accommodate the necessary types of operation related systems and equipment that are required to perform the different operations it is designed for. There will also be a need for the vessel to keep stable during the most demanding operations it might encounter, like heavy lifting operations. For this purpose, it will be important for the placement of operation related systems and equipment, as well as the deck arrangement to be designed in such a manner that it allows for efficient execution of operations. It must also provide a safe work environment for the crew and allow for easy cleaning and disinfection, in order to avoid the spreading of diseases between site locations.

The vessel must be designed with maneuverability which allows it to perform the operations it is intended for, in an efficient and safe manner. It must be able to maneuver along the farm cages to position itself, as well as the ability to keep in position during operations, in order to not crashing into the farm cage or other system components [25]. At offshore locations the service vessel might be the first or only vessel present during an accident, the vessel should, therefore, be equipped with sufficient safety equipment to perform rescue operations, like a rescue vessel.

Chapter 3

Methodology

This section will present how the risk-based ship design process has been used to establish a design for a service vessel for exposed aquaculture. The different methods used will be explained, along with the different benefits and weaknesses that follow the methods to justify the choice of methods. An overview of the different risk definitions used, with respect to frequency and consequence, will be presented to understand how the different hazardous events have been ranked.

3.1 Risk definitions

Preliminary to performing risk analysis, it is preferable to get an overall understanding of how the consequence of an accident, based on the different risk categories, have been defined according to the classification of their different degrees of consequence. This section will present which levels of risk acceptance this thesis has used, as well as how the different levels of frequency have been classified.

A consequence involves specific damage to one or more assets and it is, therefore, important to understand the severity of a consequence. As this thesis will focus on four out of the five risk dimensions (personnel, environment, material assets and fish welfare) will four different classifications be used. Figure 3.1, presents the classification of consequences for three of the four risk dimensions focused on; Risk to personnel, risk to environment and risk to material assets.

Table 3.1: Classification of consequences according to their severity [47]

Category	People	Environment	Property
5. Catastrophic	Several fatalities	Time for restitution of ecological resources $\geq 5 years$	Total loss of system and major damage outside system area
4. Severe loss	One fatality	Time for restitution of ecological resources =2-5 years	Loss of main part of the system; production interrupted for months
3. Major damage	Permanent disability, prolonged hospital treatment	Time for restitution of ecological resources $\leq 2 years$	Considerable system damage; production interrupted for weeks
2. Damage	Medical treatment and lost-time injury	Local environmental damage of short duration ($\leq 1 month$)	Minor system damage; minor production influence
1. Minor damage	Minor injury, annoyance, disturbance	Minor environmental damage	Minor property damage

Rausand's book of risk assessment does not cover the different classification of consequence levels involving the severity of fish welfare [47]. It has, therefore, been created, for the purpose of this thesis, a classification of consequence for fish welfare. This classification is based on a working party report from Norecopa (Norwegian Consensus-platform of the Replacement, Reduction and Refinement of animal experts) [48]. Table 3.2, shows the different classification of consequence for fish welfare according to their severity. The severity categories are defined such that a category is approximately 10 times higher than in the preceding category.

Table 3.2: Fish welfare classification of consequences according to their severity [48]

Category	Description
5. Catastrophic	Procedures as a result of which fatalities is inevitable
4. Severe loss	Procedures as a result of which the animals are likely to experience severe pain, suffering or distress
3. Major damage	Procedures as a result of which the animals are likely to experience short term moderate pain, suffering or distress, or long-lasting mild pain, suffering or distress
2. Damage	Procedures as a result of which the animals are likely to experience short term mild pain, suffering or distress
1. Minor damage	Procedure performed entirely under general anesthesia from which the animal shall not recover

To understand the severity of a risk it is just as important to understand the frequency of it happening, as the consequence. Table 3.3, presents the different classifications of frequency that is used. The different categories in the table are set to be about 10 times higher than their preceding category.

Table 3.3: Frequency classes [47]

Category	Frequency [per year]	Description
5. Fairly normal	10 - 1	Event that is expected to occur frequently
4. Occasional	1 - 0.1	Event that happens now and then and will normally be experienced by the personnel
3. Possible	$10^{-}1$ - $10^{-}5$	Very rare event that will not necessarily be experienced by the personnel
2. Remote	$10^{-}3$ - $10^{-}5$	Very rare event that will not necessarily be experienced in any similar plant
1. Improbable	0 - $10^{-}5$	Extremely rare event

By combining the consequence and frequency number that has been assigned a hazardous event it is possible to acquire a risk priority number (RPN). An RPN is a numerical assessment of a risk that is based on the level of consequence and frequency a hazardous event has been given. The RPN is commonly used to evaluate the different risks located and evaluate if the risk should be focused on or is acceptable. The different risks are, based on their RPN, given a level of acceptance. For this thesis has there been focused on three levels of acceptance [47]:

Acceptable
"*The consequence is unlikely or not severe enough to be of concern; the risk is tolerable. However, consideration should be given to reducing the risk further to as Iowa level as reasonably practicable (ALARP), to further minimize the risk of an accident or incident.*"

ALARP
"*The consequence and/or probability is of concern; measures to mitigate the risk to as low as reasonably practicable (ALARP) should be sought. Where the risk is still in the review category after this action, the risk may be accepted provided that the risk is understood and has the endorsement of the person who is ultimately accountable for safety in the organization.*"

Unacceptable
"*The probability and/or severity of the consequence is intolerable. Major mitigation will be necessary to reduce the probability and severity of the consequences associated with the hazard.*"

3.2 Risk-Based Ship design

As mentioned in Section 2.1, the aquaculture industry can be recognized as the second most risk influenced workplace in Norway. Studies have shown that most fatalities occur during transportation and when performing work and MR operations at an operational vessel [10]. With the rising interest in moving the aquaculture industry to exposed locations comes additional requirements to safety. It is, therefore, important to use methods of risk and reliability analysis in various engineering disciplines as decision support tools in engineering applications [49]. As risk is used to measure safety performances, it could be beneficial to implement risk and reliability analysis methods into the design of the vessel. Such a method is called risk-based ship design (RBSD). This method introduces risk analyses into the traditional design process to quantify the risk level of a particular design and its variants. It is expected that implementing safety as an objective into the design optimization process rather than being treated as a constraint, could allow for new technical solutions to be explored. Two clearly distinct motivations for using the RBSD method have been identified:

- If a new transport solution is not approved because it challenges (possibly outdated) rules, risk-based ship design and approval can be used to identify the issues and prove that the new solution is just as safe as required
- Risk-based design can be used in the optimization of a rule-compliant vessel that wishes to increase the level of safety at the same cost or to increase earning potential at the same level of safety

Applications of RBSD are biased towards design concepts with high levels of innovation, which often involves novel or challenging concepts, concepts with large uncertainties or with significant safety trade-offs. This makes it important to use knowledge in all its forms: best practice, engineering judgments, state-of-the-art tools and data; which are all parts of Quantitative Risk Analysis (QRA) [49]. To be able to achieve the explicit, rational and cost-effective treatment of safety that the RBSD method offers, the following principles need to be adhered to:

1. It will be necessary to have a consistent measure of safety, along with a formalized procedure of its quantification (risk analysis). Considering the complexity of what constitutes safety, a clear focus on key safety "drivers" (major accident categories) is necessary for it to be workable. There exist numerous formal procedures for risk assessment, risk quantification and risk management in various contexts. Examples of such a procedure could be a formal safety assessment in rulemaking or a safety case for a specific design/operational solution. The elements of a typical formal safety assessment process are illustrated on the right-hand side of Figure 3.1. This figure shows a high-level framework of the risk-based ship design process.
2. Formal procedures must further be integrated into the design process to allow for trade-offs between safety and other design factors. This can be done by utilizing overlaps between performance, functionality, life-cycle cost considerations and safety. By doing so will provide additional information on safety performance and risk, that will assist in design decision-making and design optimization.

3. The use of parametric models can allow for trade-offs through overlaps at parameter level and access to fast and accurate first-principle tools. This could become necessary, considering the level of computations, to address all pertinent safety concerns, as well as the effect of safety-related design changes on functionality and other performances. This could lead to the design optimization process becoming a typical case of a multi-objective, multi-criteria optimization process. For this process to be conducted efficiently, it could become required for a common ship design model to be managed within an integrated design environment.

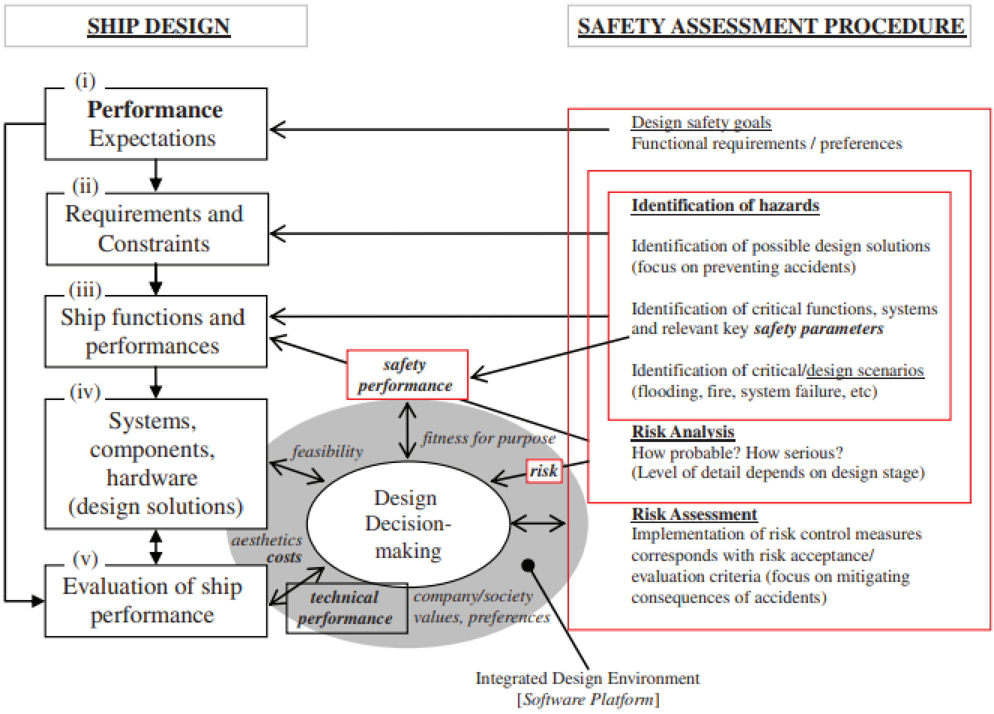

Figure 3.1: High level framework for risk-based design [49]

According to Papanikolaou, "*key to understanding RBD is the integration of risk assessment in the design process and decision-making towards achieving the overall design goals but also as part of a parallel (concurrent) iteration within the safety assessment procedure to meet safety-related goals/objectives*" [49]. For this purpose, a flowchart has been created, see Figure 3.2. This flowchart shows how risk assessment has been implemented into traditional design methods for this thesis and the process leading up to the end result.

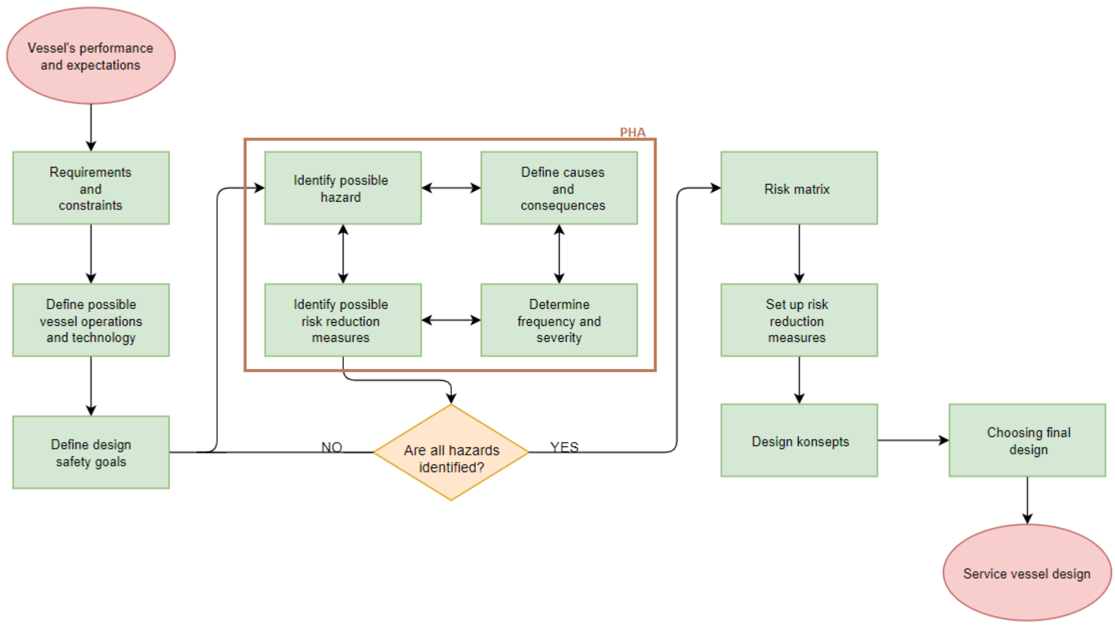

Figure 3.2: A flowchart illustrating the RBSD process performed in this thesis

The start of a design project is commonly associated with uncertainty, where the level of uncertainty depends on whether something similar has been done before or not. For this purpose, is it beneficial to map the performance expectations of the new design. This mapping allows for a better understanding of the new design as it gives an overview of what is expected by the vessel, in terms of capabilities and operational purpose. This gives an indication of what the vessel will become.

When familiar with what is expected by the new design it is beneficial to map the owner's operational and functional requirements and constraints related to the vessel. The vessel's requirement will be based on the operational capabilities and functions related to the expected performance of the vessel. Constraints on the other hand are derived from rules and regulations on vessel design. Similar to the performance expectations, the mapping of the requirements and constraints related to the vessel will be used as a guide through the design process. It will keep the process on track and make certain that it does not move outside the bounds of what is legal and possible.

To support the mapping of requirements and constraints, a study of service vessel operations and operation related systems and equipment has been performed, see Section 2.4 and 2.5. The study shows possible operations that a service vessel for offshore aquaculture can be expected to perform, as well as associated systems and equipment. There has also been created an overview of different rules and regulations on vessel design, see Section 2.2. The overview presents different rules and regulations for cargo vessels with L under 24 meters and above, as well as with a GT under 500 tonnes. This is done to create constraints to focus on during the design process.

In addition, to the mapping of requirements and constraints for the design of a service vessel, could it be favorable to define safety goals related to the design. safety goals are, as other design goals, related to the ship's operations and purpose [49]. Safety goals can be categorized into two categories; top-level goals and specific technical goals. The top-level goals are safety goals that have a high priority (e.g. low impact to the environment, no accidents leading to total ship loss, etc.), while specific technical goals relate to the design of the vessel (e.g. ship able to withstand all foreseeable loads during its lifetime, high passenger comfort, etc.). The benefit of establishing safety goals for a design is that it shows what is expected performance related to safety.

As presented in the flowchart, there has been performed a preliminary hazard analysis. This is a method that is often used in the early stages of a design process to identify hazards and potential accidents, as well as determine the cause and consequences of a hazardous event. Rausand states that "*The overall objective of a PHA is to reveal potential hazards, threats, and hazardous events early in the system development process, such that they can be removed, reduced, or controlled in the further development of the project.*" [47]. Figure 3.3, illustrates the structure of the PHA used in this thesis. The operation performed during the time of the accident is followed up by two sub-categories for a better and more detailed explanation of the accident. There has also been added a section that describes which risk category each accident belongs to.

The motivation for using the PHA method is that it only requires expert judgment [50]. Expert judgment is a method for obtaining data directly from experts in response to a specified problem, and can often involve only one or a group of individuals. For this thesis, there has been used available data (Section 2.1), own knowledge and expert judgment from Representatives. This is beneficial as there is little data on accidents for offshore aquaculture where a service vessel is involved.

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
Emergency response and rescue	Standby and rescue	6.1.1	Slow response time when accident occur	Personnel in water struggles for too long	- Lack of training - Lack of fast deployment mechanism of rescue vessel	Personnel drowning	2	4	6	Better routines and training on rescue operations (emergency plans) Equip the vessel with a dedicated davit for the use of MOB-boat only Depending on the weather on the time happening and severity of the accident could it be beneficial to also have a fast rescue vessel on board, with its own davit	Personnel
		6.1.2	Bad weather during man overboard rescues	Personnel not able to get onboard	- Lack of sufficient rescue equipment onboard vessel	Personnel drowning	3	4	7	A rescue net can be used to enable for a faster rescue of personnel Depending on the weather on the time happening and severity of the accident could it be beneficial to also have a lightweight scramble-net on board, as it allows for faster deployment and flexible rescue	Personnel

Figure 3.3: A part of the PHA to illustrate the structure and use of the method

After every hazardous event is identified and the frequency and consequence are determined, the different accidents will be evaluated in a risk matrix. A risk matrix is a tabular illustration of the frequency and consequence of hazardous events and accidents [47]. It is used to rank the different hazardous events and accidents that are identified through the PHA identify which events that should be of focus for mitigation. They are ranked in accordance with the three levels of acceptance, mentioned in Section 3.1. Since the hazardous events and accidents have been categorized in accordance with their respective risk category, there has been created four different risk matrices, one for each risk dimension. This shows which risk category that needs to be of focus when designing the vessel.

Each event located in the risk matrices is ranked by their given RPN, which is determined in the PHA. This number is given by adding the consequence and frequency of a risk. It has in this thesis chosen to add the consequence and frequency together, rather than multiplying, which is a common approach to finding the RPN. The reason for this can be explained by looking at the RPN as a logarithmic value. Adding shows that the different RPN values differ only by one logarithmic value while multiplying would make the RPN values vary different even though the risk is the same. It would, therefore, be easier to evaluate the different risks if the RPN were found by adding. The risks with the highest RPN (mostly located in the red and yellow area) will be of priority for mitigating and risk-reduction measures for each risk will be determined. This will be used to determine which service vessel design that would be most suitable for offshore aquaculture.

Chapter 4

Results

This chapter gives an overview of the result found by the PHA, as well as presenting the proposed design concepts. A summary of the PHA will be presented, along with risk matrices for the four risk dimensions to rank the different hazardous events and accidents based on their consequence and frequency. There will also be created risk-reduction measures for the events with the highest risks, to be used to determine the best suited service vessel design for offshore farming.

4.1 Risk picture for operations with exposed aquaculture service vessel

The frequency and consequence of the different hazardous events identified in the PHA have been mapped into four different risk matrices to understand their risk level, in accordance with the four risk categories, as can be seen in Figure 4.1. All the identified events correspond with the three levels of acceptance, which were described in Section 3.1. The line separating the acceptable area from ALARP and the unacceptable area illustrates which hazardous events are focused on in this thesis. It has been chosen not to focus on the hazardous events in the acceptable area, as it would be more beneficial to focus on mitigating the hazardous events in ALARP and the unacceptable area.

Figure 4.1: Risk matrices for the hazardous events in the four risk dimensions

Figure 4.1, shows that the majority of the different hazardous events identified are located in the personnel risk category. It is, therefore, important to focus on finding good risk-reduction measures for personnel in the design process of the vessel. The hazardous events identified as ALARP in the risk matrices for material assets, environment and fish health will be necessary to reduce if it is feasible and beneficial to do so.

Notice that the gathered sum of the hazardous events in the four risk matrices is lower than the total number of hazardous events identified in the PHA. This is because several hazardous events occurring from the same sub-operation share the same frequency and consequence. This can be illustrated by looking at event number 2.2.2 in the PHA, found in Appendix B. It is here identified two hazardous events in the personnel risk category with the same frequency and consequence, making them only registered once in the personnel risk matrix. For more detailed risk matrices that show which hazardous event is registered in the different risk levels, see Appendix C.

Figure 4.2, presents a summary of the performed PHA. This summary shows the different hazardous events that occurred in the different sup-operations. The hazardous events have been separated into their respective risk category and presented by their given level of acceptance. There were identified a total amount of 98 potential hazardous events for the different operations focused on. 26 events are located in the Acceptable area, 61 events are defined as ALARP and the remaining 11 events are located in the Unacceptable area. As mentioned, the majority of the identified hazardous events are in the personnel risk category, making it beneficial to mitigate risk in this category. This is especially important as 69% of the hazardous events identified as a risk to personnel are located in the ALARP area. The category is also subject to 100% of the events in the Unacceptable area.

Operation	Sub-operation	No.	Totall	Personnel			Materiall assets			Environment			Fish health			%OK	%ALARP	%Not OK
				OK	ALARP	Not OK	OK	ALARP	Not OK	OK	ALARP	Not OK	OK	ALARP	Not OK			
IMR	Inspection with ROV	1.1	5	0	0	0	0	1	0	1	2	0	0	1	0	4	7	0
	Inspection with divers	1.2	9	2	5	0	1	0	0	0	0	0	1	0	0	15	8	0
	Maintenance and repair using ROV	1.3	6	0	0	0	2	1	0	0	2	0	1	0	0	12	5	0
	Maintenance and repair using divers	1.4	8	2	5	0	1	0	0	0	0	0	0	0	0	12	8	0
	Maintenance and repair over water	1.5	6	0	3	2	1	0	0	0	0	0	0	0	0	4	5	18
Anchor-handling and mooring	Deployment of anchor bolts, using ROV	2.1	3	0	0	0	1	1	0	0	1	0	0	0	0	4	3	0
	Deployment of anchor bolts, using divers	2.2	5	1	3	0	1	0	0	0	0	0	0	0	0	8	5	0
	Maintenance and repair of mooring and anchor system	2.3	12	0	3	3	2	2	0	0	2	0	0	0	0	8	11	27
	Deployment and retrieving of anchor and anchor lines	2.4	6	0	2	2	1	1	0	0	0	0	0	0	0	4	5	18
Towing	Towing of farms	3.1	6	1	5	0	0	0	0	0	0	0	0	0	0	4	8	0
	Towing of vessels	3.2	4	1	2	0	0	1	0	0	0	0	0	0	0	4	5	0
Support	General support during well-boat operations	4.1	6	0	1	2	0	0	0	0	1	0	0	2	0	0	7	18
	Diver support during well-boat operations	4.2	3	1	2	0	0	0	0	0	0	0	0	0	0	4	3	0
	ROV support during well-boat operations	4.3	2	0	0	0	2	0	0	0	0	0	0	0	0	8	0	0
	Support during anchor-handling and mooring operations	4.4	3	0	1	0	1	1	0	0	0	0	0	0	0	4	3	0
Supply and transport	Transport of personnel	5.1	4	0	4	0	0	0	0	0	0	0	0	0	0	0	7	0
	Transport of cargo and supplies	5.2	6	0	3	2	1	0	0	0	0	0	0	0	0	4	5	18
Emergency response and rescue	Standby and rescue	6.1	4	1	3	0	0	0	0	0	0	0	0	0	0	4	5	0

Figure 4.2: Summary of the preliminary hazard analysis

4.2 Analysis of the result from the PHA

A distinct similarity between most of the different operations is the hazardous events occurring due to lifting operations, which is the reason for 100% of the unacceptable events. Lifting operations are performed in every operation category except for towing and emergency response and rescue, leading to some similarities in the risk-reduction measures.

The IMR operations consist of several sub-operations that contribute to high risk of personnel, such as lifting operations and diving. Lifting operations and diving during IMR operations, are the main contributors to the high amount of ALARP events in the personnel risk category, being responsible for 31% of the total amount of ALARP events in the category and 18% of the unacceptable events. The operation category, additionally, often consists of operations where an ROV is required. The use of an ROV in this category has contributed to 50% of the total ALARP events in the environmental risk category.

The majority of anchor handling and mooring operations consist of heavy loads lifting operations and high tension cables, which often sets requirements for the stability of the vessel. Performing such operations in a challenging environment makes this operation category the most risk influenced of the six categories. The category also involves the use of divers and ROV to perform inspections during operations and to perform deployment of anchor bolts, all of which increase the risk to personnel and material assets. anchor handling and mooring operations stand for 25% of the hazardous events ranked as ALARP and 45% of all the unacceptable events. It is also responsible for a high amount of hazardous events in the ALARP region for material assets (50%) and the environment (38%), making it important to establish risk reduction measures if the operation is to be performed.

Towing operations have shown to be subject to high risk. Even though there were only identified 10 hazardous events in this category has 80% shown to be in the ALARP area, hence contributing to 13% of the overall hazardous events ranked as ALARP. The majority of the hazardous events identified for towing operations are located in the personnel risk category, making it beneficial to locate risk-reduction measures to reduce the overall risk to personnel. Risk-reduction measures for this operation category mostly focus on improving organizational factors, such as training of personnel and planning of operations.

Service vessel support of operations is an operation category that is almost certain to be performed at an exposed location, making it an important subject of risk reduction. The identified hazardous events in this category have shown to contribute with 13% to the overall events located in the ALARP region, and 10% of the personnel risk category. This is mostly due to the need of performing lifting operations and the use of divers which has shown leading to high risk. These types of operations also lead to 67% of the hazardous events located in the ALARP area in the fish health risk category.

For supply and transport in exposed locations, there have been identified 10 hazardous events, where seven of these accidents are located in the ALARP area. Two of these events are located in the unacceptable area, contributing 18% to the overall amount of events located in this area. The consequence of most of the identified hazardous events evolves around personnel falling overboard, vessel capsizing or personnel injured during lifting operations. This has made it important to establish risk reduction measures that focus on personnel safety.

There are only identified four hazardous events related to emergency response and rescue operations, but three of the four are ranked as ALARP, making it an operation with high risk. The operation is also an operation of importance as some of its sub-operation follows requirements stated in the Regulations of Construction of Vessels, as mentioned in Section 2.2.2. This type of operation is required during and after an accident has occurred, making it beneficial to locate good reactive reduction measures which allow for fast activation in the time of a crisis.

To reduce the consequence and/or frequency of the different identified hazardous events, there have been established different risk-reduction measures for the identified hazardous events for each operation category. The risk-reduction measures are divided into proactive and reactive barriers. This is done to gain a better understanding of which measure that is installed to prevent an accident from happening (proactive), and which activates in the time of an accident to prevent the following sequence of events from happening (reactive).

Proactive measures:

Table 4.1, presents the different proactive risk-reduction measures adapted to the identified hazardous events for the different operations. The goal of these measures is to reduce the frequency and/or the consequence of a hazardous event to lower the total risk picture for aquaculture service vessels operating offshore. The table shows which operations each risk-reduction measure is applicable for, where the operations are categorized in accordance with Figure 4.2.

Table 4.1: Proactive barriers for risk-reduction of operations

No.	Measures for	Operations	Risk-reduction measure
P-1	Launching/retrieving of ROV	1,2,4	Implementation of a ROV LARS system to the design of the vessel, to ensure safe launching and retrieving
P-2	Launching/retrieving of ROV	1,2,4	Use a TMS during launching/retrieving of the ROV to protect it against impact damage
P-3	Crane operations	1,2,4,5	Implement an active heave compensation system into the crane system, to eliminate ship motion in the crane
P-4	Training of personnel	1,4	Improve training of personnel operating ROV to lower the possibility of ROV damaging farm structure or being damaged
P-5	Operations planing	1,2,3	Improve planning of operations with respect to the weather to ensure sufficient operational time window
P-6	Diving	1,2,4	Start using a diving container equipped with diving equipment, air-supply system and decompression chamber, to ensure for sufficient equipment

P-7	Lifting operations	1,2,4	Equip the vessel with an A-frame to perform heavy lifting in a highly corrosive environment, to could lower the possibility of the vessel capsizing during lifting and objects damaging the vessel
P-8	Crane operations	1,2,4,5	Implement a constant tension system into the crane system to ensure constant tension in lifting wire, lowering the risk of a lifted object bouncing on the deck
P-9	Personnel safety	1,2,3,4,5	Have given safety zones on deck where personnel can be stationed during operations
P-10	Crane operations	1,2,4,5	Implement an automatic overload protection system into the crane system, to make the system shut down if given operational limits are exceeded, increasing the safety of personnel and material assets
P-11	Training of personnel	1,2,4,5	Better safety training of personnel on how to perform operations harsh weather
P-12	Aborting operations	1,2,4,5	Having set operational limit for aborting operation, to prevent any unpredicted events to occur
P-13	Maintenance and repair of ROV	1,2,4	Implement use of ROV container for storing, repairing and maintaining ROV
P-14	Training of personnel	3,5	Better safety training of personnel on how act during sailing
P-15	Vessel position planing	1,2,4	Better planning of how the vessel should be positioned during operations to reduce the risk of fish being stressed
P-16	Personnel transfer	5	Implement a motion compensated gangway in the design of the vessel to allow for a safe and efficient transfer of personnel
P-17	Mooring	1,2,4	Implement capstan winches into the design of the vessel to enable for fast and safe mooring of the vessel to the farm and other vessels
P-18	Inspection of cargo fastening	5	Better procedures on checking the fastening of cargo and others, to lower the possibility of personnel being hit by moving cargo

P-19	Training of personnel	6	Better training of personnel on how to act during rescue operations
P-20	Rescue operations	6	Having established emergency rescue plans for rescue operations

Reactive measures:

Table 4.2, presents the different reactive risk-reduction measures adapted to the identified hazardous events for the different operations. The goal of these measures is to reduce the frequency and/or the consequence of a hazardous event to lower the total risk picture for aquaculture service vessels operating offshore. The table shows which operations each risk-reduction measure is applicable for, where the operations are categorized in accordance with Figure 4.2.

Table 4.2: Reactive barriers for risk-reduction of operations

No.	Measures for	Operations	Risk-reduction measure
R-1	Recovering man overboard	All	Equip the vessel with a rescue net to allow for easier rescue during man overboard
R-2	Recovering man overboard	All	Depending on the severity and place of the accident and the weather during the accident, it could be beneficial to use a lightweight scramble-net for the rescue of man-overboard, as it allows for faster and more flexible deployment
R-3	Releasing towing line	3	Implement the use of a towing hook with an emergency release function, allowing for fast release of the towing line in case of unpredicted events
R-4	Rescue of personnel	6	Equip vessel with MOB-boat to allow for fast rescue of personnel during an accident
R-5	Emergency response	6	Equip the vessel with an FRC as it can ensure a fast rescue with higher maneuverability and capacity than the MOB-boat
R-6	Deployment of MOB and FRC	6	Equip the vessel with a dedicated davit for MOB-boat or FRC, to be used for fast and safe deployment
R-7	Protective equipment	All	Good procedures for personnel to use adequate protective gear

4.3 Design concepts for aquaculture service vessel

The uncertainty of which role an aquaculture service vessel will have at exposed locations makes it difficult to know for certain how the design of the vessel will be. For this purpose have there been established three design concepts that differ in the operations they are designed to perform and their operation related systems and equipment. The goal is to find a design that is able to perform its operations with as low risk as possible with respect to the four risk categories, with a special focus on reducing personnel risk.

The different design concepts are established with respect to the identified risk-reduction measures. This is done to reduce the impact of the hazardous events that were identified in the PHA. The following sections present the different proposed design concepts; the goal and purpose of the design, the operations it is designed to perform and its operation related systems and equipment. Each design is also presented with a mapping of the advantages and disadvantages of the design.

Table 4.3, gives an overview of the operation related systems and equipment that is shared between the three concepts, as well as non-technological risk-reduction measures. Similar to aquaculture in sheltered areas, the service vessel will be required to perform lifting operations, which ranked as the major contributor to hazardous events in the unacceptable area. Hence, the cranes on each vessel will be installed with an active heave compensation system, constant tensioning system and automatic overload protection system, to lower the frequency of hazardous events related to lifting operations. The organizational risk-reduction measures (training, planning, procedures) are expected to be followed when operating in exposed aquaculture, which is the reason for them to be presented as a shared feature for the concepts. Similar to lifting operations, all three concepts will be designed to perform ROV operations, making it beneficial to implement an ROV container and the tether management system into the design, to reduce the frequency and consequences to material assets. As mentioned in Section 2.5.1, it is assumed that offshore aquaculture service vessels performing diving or ROV operations are required to be equipped with a DP system of class 2 or 3. The concepts will, therefore, be equipped with a DP system of class 2, as there is no need for a class 3 for offshore fish farming. The same goes for the implementation of the MOB-boat and its dedicated davit, regulation set by the Norwegian Government stated that vessel with a GT lower than 500 tonnes operating in foreign voyages is required to be equipped with a MOB-boat, as mentioned in Section 2.5.11. All three concepts will also be equipped with both a rescue net on the starboard side and a lightweight scramble-net to increase the flexibility of where the net can be deployed.

Based on the role of today's aquaculture service vessels for sheltered locations and what roles it can be expected to have for exposed locations, will all three design concepts be required to perform some similar operations; IMR, Support, supply and transport and emergency response and rescue. There will, however, still be some differences in their role in each operation category.

Table 4.3: Shared features between the three purposed design concepts

Risk-reduction measure	No.	Motivation
Tether management system	P-2	Protecting the ROV during launching/retrieving
Active heave compensation system	P-3	Eliminate ship motion in a crane during lifting operations, reducing the risk of personnel being hit by lifted objects
Training in ROV handling	P-4	Improving personnel handling of ROV to reduce risk to material assets and/or environment
Planing of operations	P-5	Improving planning of operations to ensure sufficient operational weather window
Constant tension system	P-8	Ensuring constant tension in the lifting wire, reducing the risk of personnel being hit by lifted objects
Safety zones	P-9	By having given safety zones on the vessel where personnel can be stationed during operations/sailing will reduce the overall risk to personnel
Automatic overload protection system	P-10	Shutting down the system if given operational limits are exceeded will reduce the frequency of hazardous events occurring
Training in safety	P-11 & P-14	Improving safety training and procedures will reduce the frequency of personnel experiencing hazardous events
Operational limits for aborting operations	P-12	By setting operational limits makes personnel able to abort operations if the limits are exceeded, reducing the possibility of hazardous events to occur

ROV container	P-13	The container increases the flexibility of performing maintenance and repair of the ROV, which can reduce the frequency and consequence of hazardous events effect on risk to material assets
Planing for positioning of vessel	P-15	Good procedures on how the vessel should be positioned during operations will reduce the Impact of the DP system on the fish
Capstan winches	P-17	Designing the vessel with capstan winches to enable for fast and safe mooring
Good procedures for inspection of cargo fastening	P-18	Establishing good procedures for cargo fastening will reduce the possibility of personnel being hit by moving cargo or experiencing cargo overboard
Training of rescue operations	P-19 & P-20	Improving rescue training and procedures to reduce the consequences following some hazardous events
Rescue nets	R-1 & R-2	Having a rescue net ready on the starboard side of the vessel and a lightweight scramble net onboard the vessel at all times will increase the flexibility of rescuing man-overboard and reduce its consequences
MOB-boat	R-4 & R-6	Having a standby MOB-boat fastened to its own davit at the top port side will reduce the consequences of hazardous events
Protective equipment	R-7	There will be required for all personnel to always use sufficient protective equipment for the operation performed, reducing consequences of hazardous events
DP system class 2	-	The DP system will allow for the personnel to maintain the vessel's position and heading, increasing the safety when performing operations
Aft and fore crane	-	Using two cranes aft and fore on the vessel enable higher flexibility and control during lifting operations

4.3.1 Concept 1

The first concept is established by the motivation of finding a design that is able to perform a large variety of operations with as low risk as possible. This concept is equipped with equipment and systems to be able to perform a variety of the operations focused on in this thesis; IMR, anchor handling and mooring, support, supply and transport and emergency response and rescue.

The operation related equipment used for the deck platform design for this concept is schematically illustrated in Figure 4.3. The figure presents a draft of the Macho 40 and how the equipment will be distributed around the deck of the vessel. As mentioned in Table 4.3, is the aft and fore crane systems installed with an active heave compensation system, constant tension system and an automatic overload protection system. The vessel will also be equipped with four capstan winches on the starboard and port side of the vessel, to enable for higher flexibility of which side the vessel can perform mooring from. Note that mooring on the port side of the vessel will not be possible on every occasion because of the MOB-boat on the side of the vessel. The MOB-boat must either be lifted on-board the vessel or the personnel must be certain that the MOB-boat is not damaged during mooring. To perform heavy lifting operation during anchor handling and mooring operations or lifting farm components on-board the vessel for IMR, has the vessel been equipped with an A-frame at the aft side of the vessel. The A-frame would, as mentioned in Section 2.5.4, allow for stable and controlled lifting of objects away from the vessel side, possibly reducing the frequency of the lifted object being damaged or damaging vessel sides. It will, additionally, be used for deployment and retrieving of ROV. The rescue net is placed on the starboard side of the vessel and the fore crane will be used for deployment of the net when necessary. The net will be connected to the crane hook during sailing to enable faster deployment if man-overboard situations should occur. The lightweight scramble net will be stored in the personnel safety zone at the vessel deck to allow for flexible rescue during man-overboard situations.

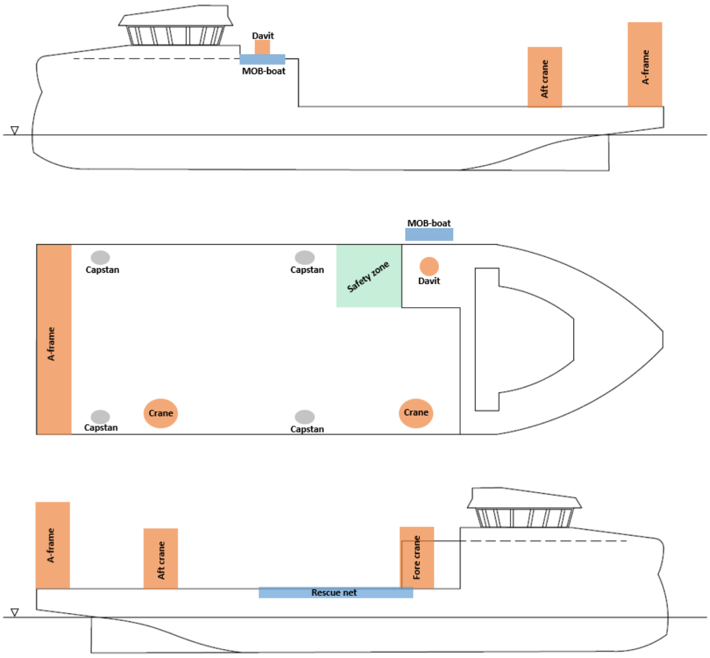

Figure 4.3: Schematic illustration of concept 1 with all the operation related systems

Table 4.4, presents the equipment for concept 1 that is not shared between all the concepts. The concept can be required to perform diving operations at the fish farm, it will, therefore, be equipped with a diving container. The diving container will be equipped with necessary diving equipment, an air supply system and a decompression chamber. This container will not be a permanent accessory at the vessel, it will be lifted onto the vessel deck when a diving operation is required. Similar to the diving container, will an ROV container and a tether management system be adapted to the vessel when an ROV operation is required.

Table 4.4: Operation related equipment for concept 1 that is not shared between the concepts

Risk-reduction measure	No.	Motivation
Diving container	P-6	The diving container contains the necessary equipment for a diving operation and could flexibly be equipped to the vessel when a diving operation should be performed
A-frame	P-7	The A-frame will allow for heavy lifting in a highly corrosive environment, as well as reducing the frequency of vessel capsizing or lifted objects coming in contact with vessel sides

The focus of establishing a new design is to enhance the features of its predecessors. The advantages of concept 1 have, therefore, been mapped and are presented in Table 4.5. A new design can also give rise to new potential hazardous events, for this reason, there has been performed a mapping of the disadvantages following the concept, as can be seen in Table 4.6.

Table 4.5: Advantages by implementing design concept 1

No.	Advantages
C1-A1	Implementing the risk-reduction measure P-7, improves the vessels ability to perform heavy lifting operations and makes it safer to deploy/retrieve a ROV compared to doing with the starboard cranes. It also reduces the risk of the vessel capsizing or lifted object damaging the vessel or being damaged if impact with the vessel should occur.
C1-A2	Being able to perform a variety of different operations could lower the possibility of the vessel being stationed away during downtime in production.
C1-A3	Implementing risk-reduction measures P-3, P-8 and P-10, reduces the frequency of hazardous events related to lifting operation from occurring. This could lead to a big reduction in the risks occurring when performing lifting operations, making it safer for personnel.
C1-A4	The design implements the risk-reduction measure P-6, improves the flexibility of storing the diving equipment away when not in use and makes it easier to equip the vessel with the necessary equipment when required to perform diving operations. The diving container provides an alternative way to perform decompression stops by storing a decompression chamber, which lowers the possibility of divers experiencing diving sickness if not able to decompress during ascending to the surface. It also lowers the risk of oxygen depletion as it comes with an air-supply system.
C1-A5	The design implements the risk-reduction measure P-13, improves the flexibility of storing and equipping the vessel with the necessary ROV equipment. The ROV container will also reduce the consequences of postponing an operation because of damage dealt to the ROV during operations as it enables for maintenance and repair of the ROV.
C1-A6	The decision of not using the vessel for towing operations eliminates the hazardous events caused to personnel.
C1-A7	The vessel is able to perform emergency response and rescue operations with the implementation of risk-reduction measure R-4. This will make it possible to lower the consequences of a hazardous event.
C1-A8	The implementation of risk-reduction measure R-6 will make it possible to perform a fast deployment of the MOB-boat and ensure that it is always ready to be deployed. This also follows the regulation set by SOLAS that the rescue vessel must be equipped in a way that it is ready for use within 5 minutes after an accident has occurred, as mentioned in Section 2.2.2.
C1-A9	The implementing risk-reduction measure P-9 will reduce the frequency of personnel being influenced by hazardous events during operations, this is especially important in lifting operations.
C1-A10	The implementation of risk-reduction measures R-1 and R-2, allows for fast and flexible rescue of man-overboard hazardous events.

Table 4.6: Disadvantages by implementing design concept 1

No.	Disadvantages
C1-D1	There might be a possibility that by designing it to become multi-purpose it can end up as multi-useless.
C1-D2	Since the Macho 40 is much smaller than an AHTS vessel designed to perform anchor handling and mooring of offshore structures, could present new hazardous events if the Macho 40 is intended to perform anchor handling and mooring operations.
C1-D3	The DP system installed in the vessels system could have a negative impact on fish health as it could stress the fish if not used properly.

4.3.2 Concept 2

anchor handling and mooring operations were defined as the most risk influenced operation category out of the six presented, as could be seen in Figure 4.2. The motivation for designing concept 2 is, therefore, to eliminate the risk following anchor handling and mooring operations. Concept 2 has been equipped with operation related systems and equipment to perform IMR, towing, support, supply and transport and emergency response and rescue operations.

Similar to concept 1, there is created a schematic illustration of how the operation related equipment for concept 2 is distributed along the deck of a Macho 40, see Figure 4.4. The vessel will only be equipped with two capstan winches located on the starboard side of the vessel. The reason for this is that it would be more beneficial for the vessel to be moored at the starboard side, as it would allow the FRC to be deployed if an accident should occur, even if the vessel is moored. The FRC is located on the port side of the vessel, close to the safety zone for the personnel to allow for faster use of the craft if an accident should occur. Different from the MOB-boat, the FRC will be stationed in a davit on the inside of the vessel, in such a way that it can quickly be lifted and deployed overboard if necessary. The reason for the position of the FRC is the 3,7m draft of the Macho 40. Since the vessel is designed to perform towing operations, it will be equipped with a towing hook at the center aft side, so that no other equipment at the deck will experience impact damage from the towing line during towing. The hook used will be in accordance with risk-reduction measure R-3, it will be installed with an emergency release function so that it can quickly be released if an accident should occur. This will lower the risk to personnel and material assets, as well as lowering the frequency of the vessel capsizing due to towing. The concept will also be equipped with an aft and fore crane that has the risk-reduction measures P-3, P-8 and P-10 installed in its system. The cranes will be used for common lifting operations and deployment and retrieving of the ROV if it should be required. The fore crane will also be used to deploy the rescue net, located on the starboard side if a man-overboard accident should occur. The net will be fastened to the crane during sailing to enable faster deployment of the net. Similar to concept 1, a lightweight scramble net will be stored in the personnel safety zone to reduce the time it takes to deploy.

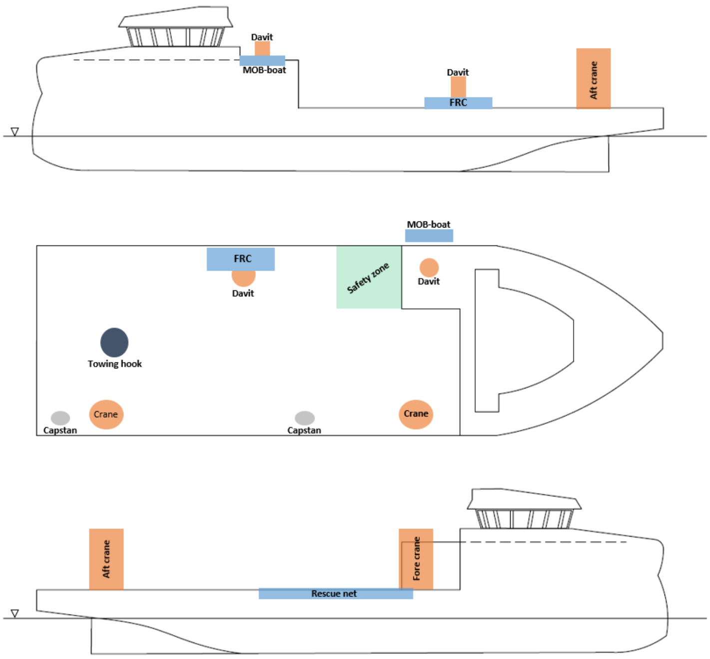

Figure 4.4: Schematic illustration of concept 2 with all the operation related systems

Table 4.7, presents the operation related equipment for concept 2 that is not shared between all the concepts. Similar to concept 1, can concept 2 be equipped with a diving container and/or an ROV container and a TMS if diving and/or ROV operations are required to be performed.

Table 4.7: Operation related equipment for concept 2 that is not shared between the concepts

Risk-reduction measure	No.	Motivation
Diving container	P-6	The diving container contains the necessary equipment for a diving operation and could flexibly be equipped to the vessel when a diving operation should be performed
Emergency release towing hook	R-3	Implementing the use of a towing hook with an emergency release function will reduce the risk of performing towing operations, as the towing line can be released from the towing hook if an accident should occur.

Fast rescue craft	R-5	The use of an FRC will enhance the ability to perform emergency response and rescue operations as it has a higher capacity and manoeuvrability and is able to travel faster than a MOB-boat.
Davit for FRC	R-6	By implementing a davit dedicated to the FRC, ensures that the craft is always on standby and enhances fast deployment (not more than 5 minutes).

Similar to concept 1, the advantages and disadvantages for concept 2 has been mapped. The advantages of design concept 2 are presented in Table 4.8. The disadvantages of the concept have also been mapped and can be found in Table 4.9.

Table 4.8: Advantages by implementing design concept 2

No.	Advantages
C2-A1	Implementing risk-reduction measures P-3, P-8 and P-10, reduces the frequency of hazardous events related to lifting operation from occurring. This could lead to a big reduction in the risks occurring when performing lifting operations, making it safer for personnel.
C2-A2	The design implements the risk-reduction measure P-6, improves the flexibility of storing the diving equipment away when not in use and makes it easier to equip the vessel with the necessary equipment when required to perform diving operations. The diving container provides an alternative way of decompression by storing a decompression chamber, which lowers the possibility of divers experiencing diving sickness if not able to decompress during ascending to the surface. It also lowers the risk of oxygen depletion as it comes with an air-supply system.
C2-A3	The design implements the risk-reduction measure P-13, which similar to the diving container improves the flexibility of storing and equipping the vessel with the necessary ROV equipment. The ROV container will also reduce the consequences of postponing an operation because of damage dealt to the ROV during operations since it delivers an area for maintenance and repair of the ROV.
C2-A4	The vessel is well equipped to perform emergency response and rescue operations with the implementation of risk-reduction measures R-4 and R-5. This will make it possible to lower the consequences of a hazardous event.
C2-A5	The implementation of risk-reduction measure R-6 makes it possible to perform a fast deployment of the MOB-boat and the FRC to ensure that they are always on stand by. This follows the regulation set by SOLAS that rescue vessels must be equipped in a way that it is ready for use within 5 minutes after an accident has occurred, as mentioned in Section 2.2.2.

C2-A6	The implementing risk-reduction measure P-9 will reduce the frequency of personnel being influenced by hazardous events during operations, this is especially important in lifting operations.
C2-A7	The decision of not designing the vessel to perform anchor handling and mooring operations will eliminate the high risk to personnel that followed the operations
C2-A8	The implementation of risk-reduction measure R-3, will reduce the frequency of hazardous events occurring in relation to towing operations.
C2-A9	The implementation of risk-reduction measures R-1 and R-2, allows for fast and flexible rescue of man-overboard hazardous events.

Table 4.9: Disadvantages by implementing design concept 2

No.	Disadvantages
C2-D1	The DP system installed in the vessels system could have negative impact on fish health as it could stress the fish if not used properly.
C2-D2	The design will need to perform launching/retrieving of the ROV with the aft or fore crane. This sets stricter requirements to the weather ROV operations can be performed in and the ROV has a higher risk crashing into a vessel or farm structures in the process or deploying/retrieving than an ROV LARS.
C2-D3	The placement of the towing hook could restrict the available space for cargo at the deck.

4.3.3 Concept 3

The goal for establishing design concept 3 is to focus on reducing the risk to personnel. The concept is, therefore, not designed to perform anchor handling and mooring operations and towing operations, which have shown to be operations with high risk to personnel. The vessel will focus on IMR, support, supply and transport and emergency response and rescue operations. It could be seen in the PHA summary, Figure 4.2, that diving operations are a subject of high risk for personnel. Concept 3 has, therefore, not been designed to perform diving operations.

A schematic illustration of the operation related equipment and their position at the vessel for design concept 3 is presented in Figure 4.5. Similar to concept 1, concept 3 will be equipped with four capstan winches, two on the starboard side and two on the, which enables for higher flexibility when mooring. The vessel will, additionally, be equipped with an aft and fore crane that has risk-reduction measures P-3, P-8 and P-10 implemented into its system, to reduce the frequency and consequence of hazardous events related to lifting operations. The fore crane will, similar to concepts 1 and 2, be used to deploy a rescue net, located on the starboard side of the vessel. The rescue net reduces the consequences related to man-overboard situations and will be equipped to the fore crane hook during sailing to enable faster deployment. A lightweight scramble net will be stored in the personnel safety zone to allow for easy use if required. One of the main operation for concept 3 will be to perform IMR operations with the use of an ROV. The vessel is, therefore, equipped with a Launching and retrieving system for ROV, which is a crane specialized for this purpose. This system enhances the operational weather limit for using ROV, as it ensures controlled and safe launching and retrieving.

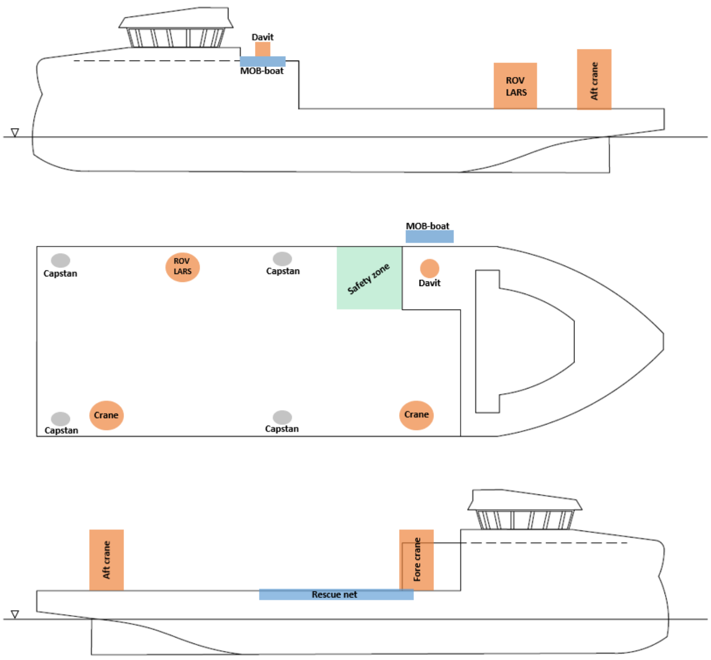

Figure 4.5: Schematic illustration of concept 3 with all the operation related systems

Operation related equipment that is not shared between the concepts is presented in Table 4.10. When the vessel is required to perform operations with an ROV, can it be equipped with an ROV and a TMS, which is stored in a container at land to prevent the equipment from taking space at the vessel when not in use. If the vessel should be required to perform the transfer of personnel to a farm/other vessels, it is possible to equip the vessel with a motion compensated gangway. The gangway is stored in a 40 inch container, making it easy to equip to the vessel when required and storing it at land when not in use. When in use it will be equipped at the center aft side of the vessel, enabling easy transfer.

Table 4.10: Operation related equipment for concept 3 that is not shared between the concepts

Risk-reduction measure	No.	Motivation
LARS ROV	P-1	The implementation of a LARS ROV system will enable for controlled and secure launching and retrieving of ROV in harsher environments then by crane.
Motion compensated gangway	P-16	The gangway will make it safer to transfer people between the vessel and farm/other vessels as it compensates the ship motion with six degrees of freedom. Reducing the frequency of hazardous events related to transferring of personnel.

Similar to concepts 1 and 2, has the advantages and disadvantages for concept 3 been mapped. Table 4.11, presents a list of advantages established for concept 3, while Table 4.12, shows the disadvantages.

Table 4.11: Advantages by implementing design concept 3

No.	Advantages
C3-A1	Implementing risk-reduction measures P-3, P-8 and P-10, reduces the frequency of hazardous events related to lifting operation from occurring. This could lead to a big reduction in the risks occurring when performing lifting operations, making it safer for personnel.
C3-A2	The design implements the risk-reduction measure P-13, which similar to the diving container improves the flexibility of storing and equipping the vessel with the necessary ROV equipment. The ROV container will also reduce the consequences of postponing an operation because of damage dealt to the ROV during operations since it delivers an area for maintenance and repair of the ROV.
C3-A3	The vessel is able to perform emergency response and rescue operations with the implementation of risk-reduction measure R-4. This will make it possible to lower the consequences of a hazardous event.
C3-A4	The implementation of risk-reduction measure R-6 will make it possible to perform a fast deployment of the MOB-boat and ensure that it is always ready to be deployed. This also follows the regulation set by SOLAS that the rescue vessel must be equipped in a way that it is ready for use within 5 minutes after an accident has occurred, as mentioned in Section 2.2.2.
C3-A5	The implementing risk-reduction measure P-9, will reduce the frequency of personnel being influenced by hazardous events during operations, this is especially important in lifting operations.

C3-A6	The implementation of risk-reduction measure P-1 enhances the operational limit for launching and retrieving of ROV, as it offers a controlled and safe launching and retrieving. This will reduce the frequency of hazardous events where the ROV crashes into the vessel or other farm components.
C3-A7	The decision of not performing anchor handling and mooring, diving and towing operations will have a major impact on the risk to personnel as it eliminates the hazardous events identified for these operations.
C3-A8	The implementation of risk-reduction measure P-16, increases the safety of transferring personnel between the vessel and farm/other vessels. Hence, reduces the frequency of hazardous events where personnel falls overboard during moving between the vessel and farm/other vessels.
C3-A9	The implementation of risk-reduction measures R-1 and R-2, allows for fast and flexible rescue of man-overboard hazardous events.

Table 4.12: Disadvantages by implementing design concept 3

No.	Disadvantages
C3-D1	The DP system installed in the vessels system could have negative impact on fish health as it could stress the fish if not used properly.
C3-D2	The vessel's lack to perform diving operations will require specialized diving vessels to be used if it is not possible to use an ROV. This could lead to loss in time.

Chapter 5

Discussion

The motivation for this thesis has been to find a suitable design for the deck platform for a service vessel for offshore farming, that operates with as lows risk as possible. The fact that Norwegian aquaculture only has two projects for offshore farming, could be the reason for the lack of information on how the offshore aquaculture industry will become. There are uncertainties on whether the design of the farms should become rigid structures with design traits from the offshore oil and gas industry, or the traditional design of farms should be altered to endure the increased loads offshore. This has, further, lead to some uncertainties on the design of the future aquaculture service vessel; what operations it could be expected to perform offshore, as well as what operation related equipment and systems it should be equipped with.

It would be beneficial to have the vessel perform as many operations as possible, to reduce the need of other vessels at the farm, lowering operational costs in the industry and reduce the downtime of the service vessel. This could, unfortunately, render the vessel to become multi-useless since it would have been able to perform several operations but none of them very well. Even though it would have been beneficial to implement all the operation related systems and equipment mentioned in this thesis to make the Macho 40 able to perform all the focused operations, it would render it to become multi-useless and possibly create new hazardous events. Some operations have also shown to be a subject to high risk, like anchor handling operations. It could, therefore, be a better solution to not design the service vessel to perform such operations, eliminating some of the risks related to the operation category. This again depends on how the design of offshore farms will be and what anchor and mooring system will be required. If an anchor and mooring system is to become similar to what the oil platforms use, like the system

Ocean Farm 1 uses, it could be safer to use a specialized AHTS vessel that has a more rigid design than the Macho 40. If the anchor and mooring system required would be similar to what is used for traditional farms, the Macho 40 vessel could be suitable to perform the operations. Some similarities can be experienced with the decision if the service vessel should be equipped to perform towing operations, or if specialized tug boats should be required to perform such operations.

The aquaculture industry has shown to be ranked as one of the most risk influenced occupations in Norwegian industry. There has, however, shown to be little information and research on the different accidents related to personnel, material assets, environment and fish health. This has created some limitations on which risk analysis method that is possible to use. The preliminary hazard analysis method used, does not rely on statistical possibilities for previous accidents, making it a suitable method for analyzing the risk of operations performed with a service vessel. The method is commonly used in the early stages of a design process to identify hazards and potential accidents with the use of expert judgment. This makes the method a subject to some uncertainty, but it will still deliver a good indication of the frequency and consequences of the identified hazardous events. To strengthen the decision of choosing a design it could be beneficial to use other risk analysis methods (BBN, event three, fault three, etc.) after establishing a final design with the PHA method. Even though, the use of risk analysis methods is a good approach to establishing a deck platform design that focuses on reducing the risk to personnel, material assets, environment and fish health, does it not evaluate if the design is favorable in terms of cost. For this purpose, it would have been beneficial to conduct a cost-benefit analysis, to see if the chosen concept is beneficial in terms of cost. With all said, the use of the PHA is still a good starting point for developing a design concept that reduces the risk to the four risk categories focused on.

After a PHA was conducted and all the hazardous events were identified, was three different concepts established, as could be seen in Chapter 4. The first concept was established to find a design that is able to perform a large variety of operations with low risk. It is designed to perform a variety of operations, among these are anchor handling and mooring operations. As mentioned above, could the vessel become a subject to increased risk if it is designed to perform anchor handling and mooring with the current design of the Macho 40. It will, therefore, be more beneficial to use specialized AHTS vessels to perform these operations, even though the operational cost will be larger since there will be a need for other vessels performing the operations. This can be especially important if the future design of offshore farms would require the same rigid anchor and mooring system as the one Ocean Farm 1 uses. Even though concept 1 is not the best concept for a service vessel for offshore farming, the A-frame used at the vessel could be a good accessory for IRM of farm components on the deck of the vessel. Especially since it is able to perform heavy lifting and at the same time reduce the possibility of capsizing or component hitting the hull of the vessel.

Concept 2 is designed to eliminate the risk related to anchor handling and mooring operations and, therefore, will not perform such operations. It is, however, designed to perform towing operations, which has shown to have high consequences if a hazardous event should occur. To reduce the consequence of an accident was the towing hook implemented with an emergency release function. The position of the towing hook renders the deck area around it to become unavailable. This could limit the use of the aft crane a little since the crane is located next to the towing hook. It could, therefore, be more beneficial to not be designed with a towing hook at this position or to not perform towing operations at all, eliminating the risk related to the operation. It can be valuable to notice that towing operations are not something that happens too often in the aquaculture industry, especially not with the use of service vessels. In addition, there is a high amount of specialized tug boats available for towing operations, which is designed to perform these types of operations as safely as possible. Considering this it could be more beneficial to design a service vessel that focuses on other operations than towing. It could, however, be designed to perform emergency towing of the farm if such should be necessary, but this again depends on the design of offshore farms. The bigger the farm, the more dangerous it is to perform towing. The decision of not to perform towing operations will increase the need of hiring other vessels to perform the operations. This will lead to additional operational costs for the industry, making it a matter of cost-benefit decisions. Concept 2 is also equipped with an FRC and a MOB-boat, making it an excellent design for performing emergency response and rescue operations. This could be important since emergency response and rescue operations could be of great importance for offshore production since the facility usually is located far from land and the service vessel is most likely the closest vessel to a possible accident. The vessel should, therefore, be equipped with an FRC to strengthen its ability to perform emergency response and rescue operations.

The last concept that has been considered focuses on reducing risk to personnel. Concept 3 will, therefore, not perform towing and anchor handling and mooring operations, eliminating the high risk to personnel experienced in these operations. The vessel will also not perform diving operations, which increases the amount of vessel needed at the farm during operations.

This will, as mentioned, increase operational costs as specialized vessels would be required for these operations. Diving operations could be seen as an operation with high risk for personnel and it will be more dangerous to use divers at offshore locations, than at sheltered locations because of higher environmental loads. This increases the focus of using ROV to perform as many operations as possible, hopefully reducing the need for divers. If the use of ROV is to be increased, these types of operations will be important for this concept, which is why the vessel has been equipped with a LARS ROV to ensure safe launching and retrieving. The location of the LARS ROV makes it difficult for the vessel to be equipped with an FCR, to enhance its ability in emergency response and rescue operations. The FCR would need to be located close to the sides of the vessel to allow for fast deployment. This makes it difficult to equip the FCR to the deck in concept 3 without it being at risk of experiencing impact damage during lifting operations, or for it to lower the availability to other equipment.

The high amount of hazardous events for risk to personnel, shown in Figure 4.2, has a major influence on the decision of choosing a final design. Based on this, design concept 3 will be the best design for the deck platform for the Macho 40. The elimination of diving, towing and anchor handling and mooring operations will have a big influence on reducing the overall risk to operations offshore with an aquaculture service vessel. The decision of not performing these operations will, however, lead to the need of having other vessels perform the operations and letting them adopt the risks following the operations. This is will be a better solution since the vessels required to perform these operations usually is specialized to perform an operation. This can lead to vessels being able to perform these operations with less risk than they would with a service vessel. The need of hiring specialized vessels to perform the operations will lead to higher expenses for the industry than if a service vessel should be able to perform the operations. Considering that anchor handling and mooring and towing operations are not performed that often these expenses will not become too high, making it beneficial to use specialized vessels for these operations rather than service vessels. Concept 3 will also reduce the risk to material assets, as it focuses on improving operations with ROV. This will, additionally, influence the reduction of risk to the environment. Even though concept 3 is the best design concept for the deck platform of the Macho 40, it could be further improved if some changes were done to the hull design. By expanding the top deck on the starboard side, similar to the port side where the davit for the MOB-boat is located, would allow for an FCR with its own davit to be stationed. Hence, increasing its ability to handle emergency response and rescue operations.

To get an illustration of how the implementation of deck design concept 3 will influence the overall risk for offshore operations performed with an aquaculture service vessel, has Figure 5.1 been presented. The result in this figure is based on the risk-reduction measures implemented in the deck platform design, it is assumed that the organizational risk-reduction measures are followed. With the elimination of towing, diving and anchor handling and mooring operations, it can be seen that the total amount of hazardous events has had a major reduction. Many of the hazardous events have been improved from the ALARP area to the acceptable area. The hazardous events related to crane handling have been improved from not acceptable to ALARP, this is because further analysis of the risk related to lifting operations is required to say for certain. Since the vessel will be designed with a level 2 DP system, there will still be a possibility that it will affect the fish health and will, therefore, still be located in the ALARP area. A specific analysis of how the DP system affects fish health needs to be performed to find good risk-reduction measures to reduce this impact.

Operation	Sub-operation	No.	Totall	Personnel			Materiall assets			Environment			Fish health			%OK	%ALARP	%Not OK
				OK	ALARP	Not OK	OK	ALARP	Not OK	OK	ALARP	Not OK	OK	ALARP	Not OK			
IMR	Inspection with ROV	1.1	5	0	0	0	1	0	0	3	0	0	1	0	0	19	0	0
	Inspection with divers	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Maintenance and repair using ROV	1.3	6	0	0	0	3	0	0	2	0	0	1	0	0	23	0	0
	Maintenance and repair using divers	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Maintenance and repair over water	1.5	6	2	3	0	1	0	0	0	0	0	0	0	0	12	5	0
Anchor-handling and mooring	Deployment of anchor bolts, using ROV	2.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Deployment of anchor bolts, using divers	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Maintenance and repair of mooring and anchor system	2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Deployment and retrieving of anchor and anchor lines	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Towing	Towing of farms	3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Towing of vessels	3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Support	General support during well-boat operations	4.1	6	1	2	0	0	0	0	1	0	0	1	1	0	12	5	0
	Diver support during well-boat operations	4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ROV support during well-boat operations	4.3	2	0	0	0	2	0	0	0	0	0	0	0	0	8	0	0
	Support during anchor-handling and mooring operations	4.4	3	1	0	0	2	0	0	0	0	0	0	0	0	12	0	0
Supply and transport	Transport of personnel	5.1	4	4	0	0	0	0	0	0	0	0	0	0	0	15	0	0
	Transport of cargo and supplies	5.2	6	3	2	0	1	0	0	0	0	0	0	0	0	15	3	0
Emergency response and rescue	Standby and rescue	6.1	3	3	0	0	0	0	0	0	0	0	0	0	0	12	0	0

Figure 5.1: Illustration of how the implementation of design concept 3 affects the PHA

Chapter 6

Conclusion and further work

6.1 Conclusion

The results provided from the preliminary hazard analysis showed that the majority of all the identified hazardous events were located in the personnel risk category. This led to the decision that the personnel risk category should be of focus for risk reduction, as it would have a great impact on the overall risk for service vessel operations. Among the operations focused on in this thesis, is anchor handling and mooring operations regarded as the major contributor to the identified hazardous events. This is a result of heavy lifting operations that can challenge the vessel's stability, as well as the risk to personnel while performing lifting operations. These operations often consist of diving operations, which has shown to be a leading contributor to personnel risk in many of the operations a service vessel can be expected to perform, due to the high environmental loads experienced offshore. Similar to diving, lifting operations are required in many of the different operations. It is, however, also responsible for a high amount of hazardous events and the key contributor to hazardous events ranked as unacceptable, making it an important focus for risk reduction. The identified hazardous events for the six operation categories have all been analyzed to establish technological (systems and equipment) and organizational risk-reduction measures.

With the established risk-reduction measures, concept 3 is chosen to be the final design for the deck platform of the Macho 40. The concept is chosen based on its motivation for reducing the overall risk to personnel. The vessel is equipped with different operation related systems and equipment to perform IMR, supply and transport, support during operations and emergency response and rescue operations. Its elimination of anchor handling and mooring and towing operations has shown to have a significant reduction to the overall risk. Concept 3 focuses on increasing the safety of material assets and the environment, by implementing equipment to improve ROV operations. In addition, technological and organizational risk-reduction measures have been implemented to reduce the risk related to lifting operations.

6.2 Further work

With the aquaculture industry looking to expand production to more exposed locations and the uncertainty related to this expansion, it is hoped that this thesis will encourage further study in this area. A study for understanding a service vessel's role in exposed aquaculture and establishing a deck platform design that focuses on safety for a service vessel will have a great impact on reducing the overall risk in the industry. Some examples of further work for this study will be presented if it should be of interest to continue the work performed in this thesis.

As the final design is chosen it is important to perform a new analysis of the risk related to the new deck platform design. This is to ensure that the new deck design is able to make a difference to the risk and not give rise to new hazardous events. With the PHA being a method that is preferably used in the early stages of a design process and is solely based on expert judgment, it could be beneficial to use other risk analysis methods to validate the data. Risk analysis methods that could be preferred are BBN, event three and/or fault three.

BBN, event three and fault three, all rely on statistical probabilities for that a hazardous event should occur. It can, therefore, be focused on further work to perform a more detailed study of the probabilities of the hazardous events identified in the PHA.

With crane operations being a major risk contributor to the aquaculture industry, it will be beneficial to perform a more detailed study of risk related to hazardous events for lifting operations. There is just so much that can be covered for each operation when several operations are to be covered. It could, therefore, be interesting to perform a risk study solely on reducing lifting operations, which could lead to a set of new risk-reduction measures being established.

As the final deck design is established, further work for the design process could be to establish a design for the vessel itself and not just the deck platform. This would make it possible to implement more of the risk-reduction measures, such as the FRC, and improve the position of the operation related equipment.

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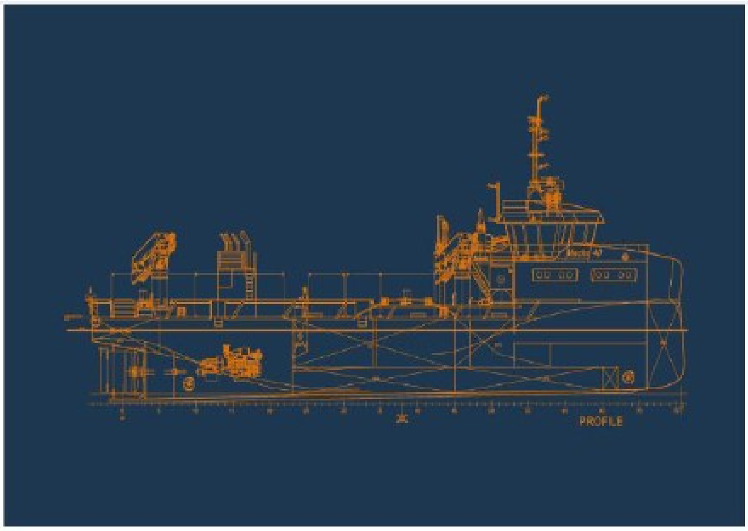
Appendix

A Vessel Specifications - Macho 40



Main Designer:	**More Maritime AS**
Length overall:	**40 m**
Breadth:	**12 m**
Gross tonnage:	**499 T**
Bollard pull:	**17 T**
Depth to main deck:	**4,5 m**
Draft:	**3,7 m**
Service speed:	**10 kn**

Capacity	
Fuel Oil	80.0 m³
Fresh water	60.0 m³
Cargo hold	370.0 m³
Deck area	320.0 m²
	12 containers [20"]
Water ballast	250.0 m³

Machinery	
Main engines	1 x Cummins, 1000 bhp
Bow thr.	1 x MB, 320 bhp
Aft thr.	1 x MB, 250 bhp
Propellers	1 x Finnøy CP incl. Nozzle
Rudders	1 x Becker, off flap
Diesel generators	2 x Scania DI, 376 bkW

Lifesaving equipment	
Life rafts	2 x 8 persons
MOB craft	1 x 6 persons
Immersion suits	10

Deck equipment	
Windlasses	2 x hydraulic, 2 x chain
Anchors	2 x 900 kg

Accomodation	
Berths	8
Galley	1
Ventilation systems	Central/electrical

Navigation/communication	
Radars	1
Gyro	1
Autopilot	1
GPS	1
AIS	1
Echo sounder	1
VHF Radio	2
UHF Radio	2

Vessel specification of Macho 40 ([30] and [51])

B Preliminary Hazard Analysis

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk: Freq.	Risk: Cons.	Risk: RPN	Risk-reduction measure	Risk category
	Inspection with ROV	1.1.1	Launching/retrieving ROV in water with crane	ROV crashing into vessel	- Lack of planning - Lack of sufficient equipment	Damaging equipment	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of TMS to protect ROV during launching and retrieving Implementation of active heave compensation system to eliminate ship motion in the crane If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets
				ROV crashing into net cage	- Lack of planning - Lack of sufficient equipment	Damaging net, could lead to fish escape	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery. Implementation of active heave compensation system to eliminate ship motion in the crane	Environment
		1.1.2	ROV performing net inspection	Net gets caught in the ROV	- Bad driving of ROV - Not sufficient circumstances for use of ROV	Making a hole in the net, leading to fish escape	2	3	5	Improve training of ROV drivers The use of AUVs could lower the risk of human errors being made	Environment
			ROV performing inspections inside net	ROV interacts with fish inside cage	- Lack of planning - Bad driving of ROV	Fish stressed by the ROV	4	2	6	Improve training of ROV drivers The use of AUVs could lower the risk of fish being stressed during net inspection	Environment

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
		1.1.3	Using ROV in rough weather	Losing control of ROV	- Lack of planning - Sudden change in weather	Damage to equipment or farm structure, could lead to fish escape	3	3	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations The use of a tether management system can work as base for the ROV if bad weather should occur If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Environment
	Inspection with divers	1.2.1	Divers performing long dives or diving at large depths	Proper decompression not performed while traveling to surface	- Lack of planning - Lack in diving training - Lack of sufficient equipment	Possibility of experiencing diving sickness	4	2	6	A decompression chamber could be used if divers are not able to perform decompression in the water	Personnel
				Diver suffer from lack of oxygen	- Lack of planning - Lack in diving training - Lack of sufficient equipment	Diver suffocate	2	4	6	Better planning of diving operations could ensure that sufficient oxygen is present during the operation Have set operational limits for starting and aborting operations A diving container equipped with the necessary equipment and air-supply system could be used	Personnel
		1.2.2	Performing diving during rough weather	Divers hitting farm component or other	- Sudden change in weather - Bad planning of operation	Losing consciousness	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk Freq.	Risk Cons.	Risk RPN	Risk-reduction measure	Risk category
				Divers being dragged by the sea currents	- Sudden change in weather - Bad planning of operation - Lack in diver training	Lost at sea	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel
		1.2.3	Deployment or retrieving of divers with crane	Divers hitting the vessel during launching or retrieving	- Waves causing big motions in crane - Equipment not suited for purpose	Losing consciousness	2	2	4	Implementation of ROV LARS can also ensure safe launching and recovery of divers Implementation of active heave compensation system to eliminate ship motion in the crane	Personnel
				Divers hitting the vessel during launching or retrieving	- Waves causing big motions in crane - Equipment not suited for purpose	Damaging equipment	2	2	4	Implementation of ROV LARS can also ensure safe launching and recovery of divers Implementation of active heave compensation system to eliminate ship motion in the crane	Material assets
				Divers not able to proper decompress because of fast retrieving	- Lack in planning - Rescue operation - Bad driving of crane	Possibility of experiencing diving sickness	4	2	6	Use personnel with sufficient training/knowledge of crane operation, with respect to diving A decompression chamber could be used if divers are not able to perform decompression in the water	Personnel
		1.2.4	Inspection inside net cage	Diver is pushed down by fish	- Lack in planning - Lack in training	Light pain or stress	2	2	4	The use of AUV or ROV for inspection inside fish cage could lower risk to divers	Personnel
				Diver interacts with the fish	- Lack in planning - Lack in training	Stressing fish	3	2	5	The use of AUVs instead of divers could lower the risk of fish being stressed during net inspection	Fish welfare

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
IMR	Maintenance and repair using ROV	1.3.1	Launching/retrieving ROV in water with crane	ROV crashing into vessel	- Lack of planning - Lack of sufficient equipment	Damaging equipment	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of TMS to protect ROV during launching and retrieving Implementation of active heave compensation system to eliminate ship motion in the crane If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets
				ROV crashing into net cage	- Lack of planning - Waves creates crane motion	Damaging net, could lead to fish escape	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of active heave compensation system to eliminate ship motion in the crane	Environment
		1.3.2	Performing MR of farm structure	ROV damage's structure component during MR	- Bad driving of ROV	Damaging material	3	2	5	Improved training for ROV operator	Material assets
				ROV crashing into structure components, damaging ROV	- Strong currents - Bad driving of ROV	Damaging equipment	2	2	4	Improved training for ROV operator If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets
		1.3.3	Performing MR of net cage	ROV interacts with fish during MR	- Bad driving of ROV	Injured fish	2	3	5	Improved training of ROV operator Divers can used to perform MR operations inside farm cage to enable for higher precision and gentle care of fish, unless it is possible to perform operation on the outside of cage net	Fish welfare

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
		1.3.4	Using ROV in rough weather	Losing control of ROV	- Lack of planning - Sudden change in weather	Damage to equipment or farm structure, could lead to fish escape	3	3	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed The use of a tether management system can work as base for the ROV if bad weather should occur Have set operational limits for starting and aborting operations If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Environment
	Maintenance and repair using divers	1.4.1	Divers performing long dives or diving at large depths	Proper decompression is not performed	- Lack of planning - Lack in diving training - Lack of sufficient equipment	Possibility of experiencing diving sickness	4	2	6	A decompression chamber could be used if divers are not able to perform decompression in the water	Personnel
				Diver suffer from lack of oxygen	- Lack of planning - Lack in diving training - Lack of sufficient equipment	Diver suffocate	2	4	6	Better planning of diving operations could ensure that sufficient oxygen is present during the operation Have set operational limits for starting and aborting operations A diving container equipped with the necessary equipment and air-supply system could be used	Personnel
		1.4.2	Performing diving during rough weather	Divers hitting farm component or other during MR	- Sudden change in weather - Lack in planning	Losing consciousness	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk Freq.	Risk Cons.	Risk RPN	Risk-reduction measure	Risk category
				Divers being dragged by the sea currents	- Sudden change in weather - Lack in planning	Lost at sea	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel
		1.4.3	Deployment or retrieving of divers with crane	Divers hitting the vessel during launching or retrieving	- Waves causing big motions in crane - Equipment not suited for purpose	Losing consciousness	2	2	4	Implementation of ROV LARS can also ensure safe launching and recovery of divers Implementation of active heave compensation system to eliminate ship motion in the crane	Personnel
				Divers hitting the vessel during launching or retrieving	- Waves causing big motions in crane - Equipment not suited for purpose	Damaging equipment	2	2	4	Implementation of ROV LARS can also ensure safe launching and recovery of divers Implementation of active heave compensation system to eliminate ship motion in the crane	Material assets
				Divers not able to proper decompress because of fast retrieving	- Lack in planning - Rescue operation - Bad driving of crane	Possibility of experiencing diving sickness	4	2	6	Use personnel with sufficient training/knowledge of crane operation, with respect to diving A decompression chamber could be used if divers are not able to perform decompression in the water	Personnel
		1.4.4	MR inside net cage	Diver is pushed down by fish	- Lack in planning - Lack in training	Light pain and stress	2	2	4	The use of AUV or ROV for inspection inside fish cage could lower risk to divers	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
	Maintenance and Repair above water	1.5.1	Lifting farm components by crane	Vessel experiences high amount of heeling	- Lack in planning - Equipment/vessel not dimensioned for lifting the components required -Lack in training/knowledge of vessel stability and factors which influence stability	Vessel capsizing	2	5	7	Better planning of lifting operations with regard to the characteristics of the lifted object and the capacity of the crane The vessel could be equipped with a A-frame that is often used for heavy subsea work in highly corrosive environment. Installing it at the stern side of the vessel lowers the possibility of the vessel capsizing during lifting	Personnel
				Personnel being hit by lifted object	- Lack in personnel training - waves leads to high vessel motion	severe injury or fatality	4	4	8	Implementation of active heave compensation system to eliminate ship motion in the crane Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel
				Lifted object falling on personnel	- Lack in training - Lack in planning - Capacity of equipment is not sufficient for lifting component - wear on wire	Severe injury or fatality	4	4	8	Implementation of an automatic overload protection system for cranes to lower the possibility of falling objects Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
				Vessel is hit by lifted object	- Lack in training - waves leads to high vessel motion	Damaging vessel	3	2	5	Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Implementation of active heave compensation system to eliminate ship motion in the crane The vessel could be equipped with a A-frame that allows for stable and controlled launching and retrieving of equipment	Material assets
				Personnel crushed between objects	- Lack in training - waves leads to high vessel motion	Severe injury or fatality	3	4	7	Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Implementation of active heave compensation system to eliminate ship motion in the crane Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel
		1.5.2	Deck is covered in water	Slippery on deck	- Lack in training - Bad weather	Personnel falling overboard	3	4	7	Better safety training of personnel on how to work with slippery deck If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
	Deployment of anchor bolts, using ROV	2.1.1	Launching/retrieving ROV in water with crane	ROV crashing into vessel	- Lack of planning - Lack of sufficient equipment	Damaging equipment	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of TMS to protect ROV during launching and retrieving Implementation of active heave compensation system to eliminate ship motion in the crane If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets
				ROV crashing into net cage	- Lack of planning - Rough weather - Lack of sufficient equipment	Damaging net, could lead to fish escape	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of active heave compensation system to eliminate ship motion in the crane	Environment
		2.1.2	Using ROV in rough weather	Losing control of ROV	- Lack of planning - Sudden change in weather	Damaging equipment	3	2	5	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed The use of a tether management system can work as base for the ROV if bad weather should occur Have set operational limits for starting and aborting operations If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
	Deployment of anchor bolts, using divers	2.2.2	Performing diving during rough weather	Divers hitting ground or anchor components	- Sudden change in weather - Lack in planning	Losing consciousness	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel
				Divers being dragged by the sea currents	- Sudden change in weather - Lack in planning	Lost at sea	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel
		2.2.3	Deployment or retrieving of divers with crane	Divers hitting the vessel during launching or retrieving	- Waves causing big motions in crane - Equipment not suited for purpose	Losing consciousness	2	2	4	Implementation of ROV LARS can also ensure safe launching and recovery of divers Implementation of active heave compensation system to eliminate ship motion in the crane	Personnel
					- Waves causing big motions in crane - Equipment not suited for purpose	Damaging equipment	2	2	4	Implementation of ROV LARS can also ensure safe launching and recovery of divers Implementation of active heave compensation system to eliminate ship motion in the crane	Material assets

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk Freq.	Risk Cons.	Risk RPN	Risk-reduction measure	Risk category
				Divers not able to proper decompress because of fast retrieving	- Lack in planning - Rescue operation - Bad driving of crane	Possibility of experiencing diving sickness	4	2	6	Use personnel with sufficient training/knowledge of crane operation, with respect to diving A decompression chamber could be used if divers are not able to perform decompression in the water	Personnel
		2.3.1	Tensioning of mooring and anchor lines	Tensioned lines breaks and hits personnel with high force	- The lines are not able to withstand the amount of tension - Lack in personnel training	severe injury or fatality	4	4	8	Better safety training of personnel on how to work when tensioning mooring and anchor lines Close observation/analysis of the wire tension when using a capstan winch for tensioning	Personnel
				Personnel squeezed between two tensioned lines	- Lack in personnel training - Lack in planning	severe injury or fatality	2	4	6	Better safety training of personnel on how to work when tensioning mooring and anchor lines Close observation/analysis of the wire tension when using a capstan winch for tensioning	Personnel
				Tear on net cage when lifting lines	- Lack in planning - Wear on the net	Creating hole in net, leading to fish escape	4	3	7	Perform inspections of farm structures before performing lifting of mooring and anchor lines	Environment
				Personnel hit by lifted objects	- Lack in personnel training - waves leads to high vessel motion	severe injury or fatality	4	4	8	Implementation of active heave compensation system to eliminate ship motion in the crane Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
Anchor-handling and mooring	Maintenance and repair of mooring and anchor system	2.3.2	Lifting farm components by crane	Vessel experiences high amount of heeling	- Lack in planning - Equipment/vessel not dimensioned or lifting the components required -Lack in training/knowledge of vessel stability and factors which influence stability	Vessel capsizing	2	5	7	Better planning of lifting operations with regard to the characteristics of the lifted object and the capacity of the crane The vessel could be equipped with a A-frame that is often used for heavy subsea work in highly corrosive environment. Installing it at the stern side of the vessel lowers the possibility of the vessel capsizing during lifting	Personnel
				Personnel hit by lifted object	- Lack in personnel training - waves leads to high vessel motion	severe injury or fatality	4	4	8	Implementation of active heave compensation system to eliminate ship motion in the crane Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel
				Crane wire breaking during lifting	- Lack in planning - Capacity of equipment is not sufficient for lifting component - wear on wire	Object lost	3	3	6	Implementation of an automatic overload protection system for cranes to lower the possibility of falling objects Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Material assets

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
				Vessel hit by lifted object	- Lack in personnel training - waves leads to high vessel motion	Components damaging vessel	3	2	5	Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Implementation of active heave compensation system to eliminate ship motion in the crane The vessel could be equipped with a A-frame that allows for stable and controlled launching and retrieving of equipment	Material assets
		2.3.3	Deck is covered in water	Slippery on deck	- Lack in training - Bad weather	Personnel falling overboard	3	4	7	Better safety training of personnel on how to work with slippery deck If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
		2.3.4	Launching/retrieving ROV in water with crane	ROV crashing into vessel	- Lack of planning - Lack of sufficient equipment	Damaging equipment	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of TMS to protect ROV during launching and retrieving Implementation of active heave compensation system to eliminate ship motion in the crane If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
				ROV crashing into net cage	- Lack of planning - Rough weather - Lack of sufficient equipment	Damaging net, could lead to fish escape	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of active heave compensation system to eliminate ship motion in the crane	Environment
		2.3.5	Using ROV in rough weather	Losing control of ROV	- Lack of planning - Sudden change in weather	Damaging equipment	3	2	5	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed The use of a tether management system can work as base for the ROV if bad weather should occur Have set operational limits for starting and aborting operations If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets
	Deployment and retrieving of anchor and anchor lines	2.4.1	Lifting operation	Lifted object falling on personnel	- Lack in planning - Lack in training - Capacity of equipment is not sufficient for lifting component - wear on wire	severe injury or fatality	4	4	8	Implementation of an automatic overload protection system for cranes to lower the possibility of falling objects Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
				Personnel hit by lifted object	- Lack in personnel training - waves leads to high vessel motion	severe injury or fatality	4	4	8	Implementation of active heave compensation system to eliminate ship motion in the crane Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel
				Wire breaking during lifting	- Lack in planning - Capacity of equipment is not sufficient for lifting component - wear on wire	Object lost	3	3	6	Implementation of an automatic overload protection system for cranes to shut down the system if any pre-determined conditions is met. Lowering the possibility of objects falling Better planning and inspection of equipment before performing operation	Material assets
				Vessel hit by anchor during lifting	- Lack in training - waves leads to high vessel motion - Lack in planning	Damaging vessel	2	3	5	Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Implementation of active heave compensation system to eliminate ship motion in the crane The vessel could be equipped with a A-frame that allows for stable and controlled launching and retrieving of equipment	Material assets

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
				Personnel crushed between objects	- Lack in training - waves leads to high vessel motion	severe injury or fatality	3	4	7	Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Implementation of active heave compensation system to eliminate ship motion in the crane Better safety training of personnel on how to act during lifting by cranes, have given safety zones on deck	Personnel
		2.4.2	Deck is covered in water	Slippery on deck	- Lack in training - Bad weather	Personnel falling overboard	3	4	7	Better safety training of personnel on how to work with slippery deck If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
	Towing of farms	3.1.1	Fast tensioning of wire because of fast acceleration	Personnel hit by wire	- Lack in training	Personnel falling overboard	2	4	6	Better safety training of personnel on how to act during towing Having a safety area for personnel during operations If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
				Personnel hit by wire	- Lack in training	Personnel injured	2	3	5	Better safety training of personnel on how to act during towing Having a safety area for personnel during operations, safety zone on deck	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
Towing		3.1.2	Vessel turning to fast, making the farm continue in its path forward	The farm makes vessel heeling	- Lack in training - Lack in planning	Vessel capsizing	2	5	7	Better training of personnel operating the vessel Implement the use of a towing hook with an emergency release function, allowing for fast release of towing line if necessary	Personnel
		3.1.3	Farm becomes unstable during towing, affecting the vessel	The farm makes vessel heeling	- Bad weather - Lack in planning	Vessel capsizing	2	5	7	Better planning of operation, with respect to weather and the amount of vessel performing the towing	Personnel
				Personnel affected by vessel motion	- Bad weather - Lack in planning	Man overboard	2	4	6	Better planning of operation, with respect to weather and the amount of vessel performing the towing If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
		3.1.4	Personnel working/staying on deck during transport	Personnel affected by the vessel motion	- Lack in training	Man overboard	3	4	7	Having a safety area for personnel during sailing Better safety training of personnel on how to act during sailing If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
	Towing of vessel	3.2.1	Drive-off	Towed vessel collides into towing vessel	- Lack in training	Damaging vessel	3	3	6	Better training of personnel operating vessel	Material assets
		3.2.2	Personnel working/staying on deck during transport	Personnel affected by vessel motion	- Lack in training	Man overboard	3	4	7	Having a safety area for personnel during sailing Better safety training of personnel on how to act during sailing If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
		3.2.3	Fast tensioning of wire because of fast acceleration	Personnel hit by wire	- Lack in training	Personnel falling overboard	2	4	6	Better safety training of personnel on how to act during towing Having a safety area for personnel during operations If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
				Personnel hit by wire	- Lack in training	Personnel injured	2	3	5	Better safety training of personnel on how to act during towing Having a safety area for personnel during operations	Personnel
	General support during well-boat operations	4.1.1	Lifting the bottom ring	Tearing the net	- Wear on net - Lack in planning - Lack in training	Creating a hole in the net, leading to fish escape	4	3	7	Perform inspections of farm structures before performing lifting of bottom ring	Environment
				Net interacts with fish, creating less volume to swim	- Lack in planning	Stressing the fish	4	3	7	Better planning and preparation before performing the operation to lower the risk of fish being affected	Fish health
		4.1.2	Lifting objects	Personnel hit by lifted object	- Lack in training - waves leads to high vessel motion	severe injury or fatality	4	4	8	Implementation of active heave compensation system to eliminate ship motion in the crane Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk Freq.	Risk Cons.	Risk RPN	Risk-reduction measure	Risk category
		4.1.3	Crane wire breaking	Object falling on personnel	- Lack in planning - Capacity of equipment is not sufficient for lifting component - wear on wire	severe injury or fatality	4	4	8	Implementation of an automatic overload protection system for cranes to lower the possibility of falling objects Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes Have given safety zones on deck	Personnel
		4.1.4	Vessel using DP system to hold location	DP system affecting the fish	- Not sufficient distance to farm net - Lack in planning	Stressing the fish	4	2	6	Better planning of how the vessel should be positioned during operation Vessel could be positioned further away from the net cage Be moored to the farm itself to lower the need of DP	Fish health
		4.1.5	Deck is covered in water	Slippery on deck	- Lack in training - Bad weather	Man overboard	3	4	7	Better safety training of personnel on how to work with slippery deck If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
	Diver support during well-boat operations	4.2.2	Performing diving during rough weather	Divers hitting farm component or other	- Sudden change in weather - Bad planning of operation	Losing consciousness	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
				Divers being dragged by the sea currents	- Sudden change in weather - Bad planning of operation - Lack in diver training	Lost at sea	2	4	6	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed Have set operational limits for starting and aborting operations If it is necessary to perform the operation during rough weather could it be preferable to use a ROV, rather than divers	Personnel
		4.2.3	Lifting operations performed with diver in the water	Diver hit by lifted objects	- Lack in training - Personnel operating the crane is not observant of diver in the water	Severe pain and injury	2	3	5	Better training of divers on how to act during lifting of components on the water, keep distance during lifting	Personnel
Support		4.3.1	Lifting operations performed with ROV in the water	ROV hit by lifted objects	- Lack in training - Personnel operating the crane is not observant of ROV in the water	Damaging equipment	2	3	5	Better training of ROV operators on how to act during lifting of components on the water, keep distance during lifting	Material assets
	ROV support during well-boat operations	4.3.2	Using ROV in rough weather	Losing control of ROV	- Lack of planning - Sudden change in weather	Damaging equipment	3	2	5	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed The use of a tether management system can work as base for the ROV if bad weather should occur Have set operational limits for starting and aborting operations If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk Freq.	Risk Cons.	Risk RPN	Risk-reduction measure	Risk category
	Support during anchor-handling and mooring operations	4.4.1	Launching/retrieving ROV in water with crane	ROV crashing into vessel	- Lack of planning - Lack of sufficient equipment	Damaging equipment	3	3	6	Implementation of ROV LARS to ensure safe launching and recovery Implementation of TMS to protect ROV during launching/retrieving Implementation of active heave compensation system to eliminate ship motion in the crane If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets
		4.4.2	Using ROV in rough weather	Losing control of ROV	- Lack of planning - Sudden change in weather	Damaging equipment	3	2	5	Improve planning of an operation, ensuring that the operational time window is sufficient for the operation to be performed The use of a tether management system can work as base for the ROV if bad weather should occur Have set operational limits for starting and aborting operations If ROV is damaged during an operation, could it be beneficial to use an ROV container which include a working space for maintenance and repair of ROVs	Material assets
		4.4.3	Supporting operation with low-capacity crane	Vessel experience rapid heeling during lifting	- Crane not dimensioned to lift required object - Lack in planning -Lack in training/knowledge of vessel stability and factors which influence stability	Vessel capsizing	2	5	7	Better planning of lifting operations with regard to the characteristics of the lifted object and the capacity of the crane The vessel could be equipped with a A-frame that is often used for heavy subsea work in highly corrosive environment. Installing it at the stern side of the vessel lowers the possibility of the vessel capsizing during lifting	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
Supply and transport	Transport of personnel	5.1.1	Personnel walking on deck during transport	Personnel affected by vessel motion	- Lack in training	Man overboard	3	4	7	Having a safety area for personnel during sailing Better safety training of personnel on how to act during sailing If a person should fall overboard the vessel could be equipped with a rescue net that allows easier rescue of the person	Personnel
		5.1.2	Personnel moving between vessel and farm/other vessels	Falling between the vessel and farm/other vessels	- Rough sea - Big gap between the vessel and farm/other vessels	Fatality	3	4	7	A motion compensated gangway can be used to enable for a safe and efficient transfer of personnel Use a capstan winch for mooring with the farm/ other vessels	Personnel
		5.1.3	Transport during bad weather	Vessel experience sudden heeling	- Lack of planning -Lack in training/knowledge of vessel stability and factors which influence stability	Vessel capsizing	2	5	7	Have set operational limits for starting and aborting operations	Personnel
				Personnel affected by the vessel movements	- Lack of training - Personnel on deck during sailing	Man overboard	3	4	7	Better training for personnel on how to act during sailing	Personnel
		5.2.1	Lifting cargo with crane	Personnel hit by lifted object	- Lack in training - waves leads to high vessel motion	severe injury or fatality	4	4	8	Implementation of active heave compensation system to eliminate ship motion in the crane Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
	Transport of cargo and supplies	5.2.2	Transport during bad weather	Vessel experience sudden heeling	- Lack of planning -Lack in training/knowledge of vessel stability and factors which influence stability	Vessel capsizing	2	5	7	Have set operational limits for starting and aborting operations	Personnel
				Personnel affected by the vessel movements	- Lack of training - Personnel on deck during travel	Man overboard	3	4	7	Better training for personnel on how to act during sailing	Personnel
		5.2.3	Crane wire breaking	Object falling on personnel	- Wear on wire - Lack of planning - Wire not classified for lifting the object	severe injury or fatality	4	4	8	Implementation of an automatic overload protection system for cranes to lower the possibility of falling objects Implementation of Constant tension system to ensure constant tensioning in the lifting wire, lowering the possibility of lifted object bouncing on deck Better safety training of personnel on how to act during lifting by cranes	Personnel
		5.2.4	Cargo not fastened during transport	Cargo or supply falling overboard	- Lack of training - Lack of planning	Loss of material	2	3	5	Training personnel to always check that cargo and other is fastened and ready for sailing	Material assets
				Sliding across deck and hitting personnel	- Lack of training - Lack of planning - Personnel on deck during travel	severe injury or fatality	3	4	7	Training personnel to always check that cargo and other is fastened and ready for sailing Having a dedicated safety area for personnel on board the vessel, where people can be safe during travel	Personnel

Operation category	Operation	No.	Event	Hazardous event	Cause	Consequence	Risk			Risk-reduction measure	Risk category
							Freq.	Cons.	RPN		
Emergency response and rescue	Standby and rescue	6.1.1	Slow response time when accident occur	Personnel in water struggles for too long	- Lack of training - Lack of fast deployment mechanism of rescue vessel	Personnel drowning	2	4	6	Better routines and training on rescue operations (emergency plans) Equip the vessel with a dedicated davit for the use of MOB-boat only Depending on the weather on the time happening and severity of the accident, it could be beneficial to also have a fast rescue vessel on board, with its own davit	Personnel
		6.1.2	Bad weather during man overboard rescues	Personnel not able to get onboard	- Lack of sufficient rescue equipment onboard vessel	Personnel drowning	3	4	7	A rescue net can be used to enable for a faster rescue of personnel Depending on the weather on the time happening and severity of the accident could it be beneficial to also have a lightweight scramble-net on board, as it allows for faster deployment and flexible rescue	Personnel
		6.1.3	Vessel not able to manoeuvre between obstacles in searching area	Personnel in water not found	- Not sufficient equipment on-board to perform rescue missions	Personnel not found	2	4	6	A vessel should be equipped with a MOB-boat for fast rescue in though terrain Depending on the weather on the time happening and severity of the accident could it be beneficial to also have a fast rescue vessel on board, as it is faster and can accommodate more people than the MOB	Personnel
		6.1.4	Fast and uncontrolled deployment of rescue vessel	Vessel experiences rapid heeling when deployed	- Lack of training - Lack of sufficient deployment equipment	Vessel capsizing	2	1	3	Better training on fast and controlled deployment of MOB-boat and FRC Having a dedicated davit for the deployment and retrieving of MOB-boats and FRC	Personnel

C Risk matrix

Personnel					
Frequency / Consequence	1 Improbable	2 Remote	3 Possible	4 Occasional	5 Fairly normal
5 Catastrophic		5.1.3, 5.2.2, 1.5.1, 2.3.2, 3.1.2, 3.1.3, 4.4.3			
4 Severe loss		1.2.1, 1.2.2, 1.4.1, 1.4.2, 2.2.2, 2.3.1, 3.1.1, 3.2.3, 4.2.2, 6.1.1, 6.1.3	1.5.1, 1.5.2, 2.3.3, 2.4.1, 2.4.2, 3.1.4, 3.2.2, 4.1.5, 5.1.1, 5.1.2, 5.1.3, 5.2.2, 5.2.4, 6.1.2	1.5.1, 2.3.1, 2.3.2, 2.4.1, 4.1.2, 4.1.3, 5.2.1, 5.2.3	
3 Major damage		3.1.1, 3.2.3, 4.2.3			
2 Damage		1.2.3, 1.2.4, 1.4.3, 1.4.4, 2.2.3		1.2.1, 1.2.3, 1.4.1, 1.4.3, 2.2.3	
1 Minor damage		6.1.4			

A risk matrix for accidents on personnel risk, based on the PHA

Material assets					
Frequency / Consequence	1 Improbable	2 Remote	3 Possible	4 Occasional	5 Fairly normal
5 Catastrophic					
4 Severe loss					
3 Major damage		2.4.1, 4.3.1, 5.2.4	1.1.1, 1.3.1, 2.1.1, 2.3.2, 2.3.4, 2.4.1, 3.2.1, 4.4.1		
2 Damage		1.2.3, 1.3.2, 1.4.3, 2.2.3	1.3.2, 1.5.1, 2.1.2, 2.3.2, 2.3.5, 4.3.2, 4.4.2		
1 Minor damage					

A risk matrix for risk on material assets, based on the PHA

Environment					
Consequence \ Frequency	1 Improbable	2 Remote	3 Possible	4 Occasional	5 Fairly normal
5 Catastrophic					
4 Severe loss					
3 Major damage		1.1.2	1.1.1, 1.1.3, 1.3.1, 1.3.4, 2.1.1, 2.3.4	2.3.1, 4.1.1	
2 Damage					
1 Minor damage					

A risk matrix for Environmental risk, based on the PHA

Fish health					
Consequence \ Frequency	1 Improbable	2 Remote	3 Possible	4 Occasional	5 Fairly normal
5 Catastrophic					
4 Severe loss					
3 Major damage		1.3.3		4.1.1	
2 Damage			1.2.4	1.1.2, 4.1.4	
1 Minor damage					

A risk matrix for risk on fish health, based on the PHA