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Evaluation and Comparison of Operability and Operational Limits of Service Vessel Designs in Exposed Aquaculture

Øyvind Haug Lund
Trym Sogge Sjøberg

Marine Technology
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Supervisor: Bjørn Egil Asbjørnslett, IMT

Norwegian University of Science and Technology
Department of Marine Technology

Summary

The aim of this thesis is to evaluate and compare the operability and operational limits for three aquaculture service vessels at exposed locations by using a combination of hydrodynamic vessel response analysis and discrete-event simulation. The thesis is motivated by Norwegian aquaculture's gradual move towards more exposed locations due to a lack of available sheltered area. More exposure to winds, waves and currents increases the challenge of safely carrying out operations at sea. Studies have shown that additional insight into the limitations during service operations is needed to create operational decision support tools for exposed aquaculture.

An operational profile for the vessels, two catamarans and one monohull, was created by using information gathered from industry actors and used to construct a simulation model of the service vessels' work cycle. Relevant operational criteria were identified and implemented in hydrodynamic vessel response analysis to determine quantitative operational limits. The simulation model applied the operational limits and wave data from oceanographic buoys to determine the different vessels' long-term operability.

The results show that the operability of the vessels varies when subjected to different incoming wave directions. The design characteristics of the vessels also results in different operational limits and variations of limiting criteria, although roll, motion sickness incidence (MSI) and green water on deck were generally the more limiting criteria for all vessels. The catamarans were more impacted by MSI compared to the large monohull, but achieved a higher long-term operability, mainly due to the increased impact of the roll criteria on the monohull. The effect of different loading conditions was also notable. A study on the effect of wave-induced vessel motions on mooring line tension was also performed, though the tensions were not found to be significant.

The combination of vessel response calculations and discrete-event simulation gave results that demonstrated how the different vessels performed at different exposure, as well as which criteria that dictated their operability. This knowledge can aid the future design of service vessels for exposed aquaculture as well as provide knowledge needed to increase the capacity for operational decision support and planning. The simulation results have been considered to be within the expected range. However, the model and its outputs have not been validated. The results should therefore be interpreted as an indication rather than an exact portrayal of reality. Validation of the results is determined to be an important task for further work. In addition, an analysis of additional vessel designs and the implementation of current and wind effects are also found beneficial.

Sammendrag

Formålet med denne masteroppgaven er å evaluere og sammenligne operasjonsevnen og driftsgrenser for tre akvakulturfartøy på eksponerte lokasjoner ved å bruke en kombinasjon av hydrodynamisk fartøyresponsanalyse og diskret-hendelse simulering. Avhandlingen er motivert av at norsk havbruk gradvis beveger seg mot mer eksponerte lokasjoner på grunn av mangel på tilgjengelig skjermede områder. Økt eksponering fra vind, bølger og strøm øker utfordringen med å utføre operasjoner til sjøs. Undersøkelser har vist at det er behov for ytterligere innsikt i faktorer som begrenser eksponerte serviceoperasjoner for å kunne skape beslutningsverktøy for operasjoner i eksponert havbruk.

Informasjon innhentet fra industriaktører ble brukt til å etablere en operasjonsprofil for fartøyene (to katamaraner og et enkeltskrog), og på bakgrunn av operasjonsprofilen ble en modell av fartøyenes arbeidssyklus konstruert. Relevante operasjonelle kriterier for fartøyene ble funnet og implementert i en responsanalyse for å fastslå kvantitative driftsgrenser. Simuleringsmodellen benyttet driftsgrensene og bølgedata fra oseanografiske bøyer for å bestemme de ulike fartøyenes langsiktige operasjonsevne.

Resultatene viser at fartøyenes operasjonsevne varierer når de blir utsatt for forskjellige innkommende bølgeretninger. Fartøyenes design resulterer også i forskjellige driftsgrenser og varierte begrensende kriterier, selv om rull, forekomst av sjøsyke (MSI) og grønt vann på dekk oftest begrenset operasjonsevnen til fartøyene. Katamaranene ble påvirket av MSI i større grad enn enkeltskrogskipet, men oppnådde en høyere langsiktig operasjonsevne, hovedsakelig på grunn av den økte effekten av rullekriteriet på enkeltskroget. Effekten av forskjellige lastkondisjoner var også merkbart. En studie av effekten av bølgeinduserte fartøysbevegelser på fortøyningsspenninger ble også utført, men resultatene viste at disse spenningene ikke var signifikante.

Kombinasjonen av fartøyresponsberegninger og diskret-hendelse simulering ga resultater som indikerte hvordan de forskjellige fartøyene presterte ved forskjellig eksponering, samt hvilke kriterier som påvirket deres operasjonsevne. Denne kunnskapen kan bidra i den fremtidige utformingen av servicefartøyer for eksponert akvakultur, samt gi kunnskap som er nødvendig for å gi bedre grunnlag til operasjonell beslutningstøtte og planlegging. Simuleringsresultatene har blitt vurdert til å ligge innenfor forventet område. Modellen og dens resultat er imidlertid ikke validert. Resultatene bør derfor tolkes som en indikasjon snarere enn eksakte verdier. Validering av resultatene er derfor foreslått som en viktig del av videre arbeid. I tillegg vil analyser av alternative fartøydesign samt inkludering av strøm- og vindeffekter være fordelaktig i videre arbeid.

Preface

This master thesis is written by Trym Sogge Sjøberg and Øyvind Haug Lund at the Department of Marine Technology at the Norwegian University of Science and Technology. The thesis is written during the spring semester of 2018 in cooperation with SFI-Exposed, a center for research with the goal to develop knowledge and technologies for exposed aquaculture operations, enabling a sustainable expansion of the fish farming industry.

The purpose of this thesis is to use hydrodynamic vessel response analysis in combination with discrete-event simulation to evaluate and compare the operability and operational limits of different service vessel designs at exposed locations. This can in turn help to increase the understanding and knowledge base needed to be able to make educated decisions required for safe operations and aid in future vessel design for exposed aquaculture. It is assumed that the reader of this thesis possesses a basic knowledge of the aquaculture industry in Norway, as well as being familiar with the programming language MATLAB, and the expressions and terms used in the hydrodynamics theory.

We would like to thank our main advisor Professor Bjørn Egil Abjørnslett for his guidance and counseling during the work on this thesis. We would also like to thank our co-supervisor Ørjan Selvik at SINTEF Ocean for his advice and assistance and the other employees at SINTEF Ocean that have supplied us with the help and data necessary to complete this thesis. Thanks also goes out to the personnel that we have contacted in the aquaculture industry for giving us helpful insight into the service vessel industry. Lastly we would like to thank our family, friends and all the other generous people that have helped us along the way.

Trym S. Sjøberg

Trym Sogge Sjøberg

Trondheim 22.06.2018

Place and Date

Øyvind H. Lund

Øyvind Haug Lund

Trondheim 22.06.2018

Place and Date

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Abbreviations

AP	=	Aft Perpendicular
DP	=	Dynamic Positioning
FP	=	Forward Perpendicular
GM	=	Metacentric Height
HDPE	=	High-density Polyethylene
Hs	=	Significant Wave Height
JONSWAP	=	Joint North Sea Wave Project
Kg	=	Kilogram
kN	=	Kilonewton
LFE	=	Longitudinal Force Estimator
LOA	=	Length Over All
MBL	=	Minimum Breaking Limit
MII	=	Motion Induced Interruptions
MSI	=	Motion Sickness Incidence
nmi	=	Nautical Mile
PSV	=	Platform Supply Vessel
RMS	=	Root Mean Square
ROV	=	Remotely Operated Vehicle
Std. Dev	=	Standard Deviation
Tz	=	Zero Crossing Period
WS1	=	Work Station 1
WS2	=	Work Station 2

Symbols

A_{kj}	=	Added mass coefficients
B_{kj}	=	Damping coefficients
C_{kj}	=	Hydrostatic restoring coefficients
F_k	=	Complex exciting forces
∇	=	Del-operator
Δ	=	Mass displacement (kg)
ϕ	=	Velocity potential
u, v, w	=	Velocity in x, y, z direction ($\frac{m}{s}$)
ω_v	=	Vorticity vector
U	=	Ship velocity ($\frac{m}{s}$)
n	=	Normal vector
a_i	=	Acceleration in direction i ($\frac{m}{s^2}$)
g	=	Acceleration of gravity ($\frac{m}{s^2}$)
η_k	=	Ship motion in kth degree of freedom
ρ	=	Density of mass ($\frac{kg}{m^3}$)
p	=	Pressure ($\frac{N}{m^2}$)
T_{ni}	=	Natural period in motion mode i (s)
r_{33}	=	Radius of gyration in heave (m)
r_{44}	=	Radius of gyration in roll (m)
r_{55}	=	Radius of gyration in pitch (m)
ζ_a	=	Wave elevation (m)
$S_{\zeta(\omega)}$	=	Wave spectrum
$H(\omega)$	=	Transfer function
m_k	=	Spectral moment
ϵ	=	Phase shift (rad)
μ	=	Primary wave direction
υ	=	Secondary wave direction
σ	=	Standard deviation & Root mean square
P	=	Probability
A_w	=	Water plane area [m^2]

Chapter 1

Introduction

1.1 Background

The world's population is expected to reach 9 billion in 2050, which in turn will give rise to the need of an increase in food production of at least 70 % to adequately feed the growing population (NUTRECO (2012)). With many global fishery productions being almost static since the 1980s, aquaculture has been the driving factor in the impressive growth in the available supply of fish for human consumption and will continue to be so in the foreseeable future (FAO (2011)).

In the aquaculture industry, Norway is the world's largest exporter of farmed Atlantic salmon as well as a leading actor when it comes to technology and competence (Hersoug and Revold (2012)). Norway had a total production of approximately 1.23 million tonnes in 2016 and a plan to increase the production up to five million tonnes by 2050 (Almås and Ratvik (2017)).

Norwegian fish farming started out in sheltered areas along the coast and in the fjords, but has gradually been moving towards more exposed locations due to a lack of available area. Another factor in the push towards more exposed locations is that The Norwegian Directorate of Fisheries, in response to high rates of salmon lice infestation in Norwegian salmon farming and other environmental issues, has stopped giving out new standard salmon farming permits. To give the industry an incentive to find new ways to combat these problems, The Norwegian Directorate of Fisheries created a system that granted development permits to industry actors who developed technology and solutions that could solve environmental and area challenges within the industry. A significant number of these applications revolve around fish farm designs that will allow for fish farming in areas that are considerably more exposed than what is experienced at the present. Examples of this are the Havfarm, Ocean Farm 1 and Arctic Ocean Farming concepts, from Nordlaks AS, Salmar AS and Aker Solutions ASA respectively. Exposed farming can bring with it many benefits, such as less environmental impact due to increased dispersal of waste products, less conflict concerning limited area along the coast, and better production due to favourable currents allowing increased swimming activity and better oxygen dispersal (Johansson et al. (2014); Fishing and Aquaculture (2008)). Because of these potential benefits, the industry is interested in pursuing this endeavour. There are however new challenges that come with exposed aquaculture. Significant parts of the Norwegian coast are today unavailable to industrial fish farming. Regular as well as infrequent operations are made challenging due to remoteness and exposure to harsh wind, wave, current and ice conditions (Bjelland (2015)). Increased exposure to winds, waves and currents, enhances the challenge of carrying out the required operations for salmon production at sea safely. This includes both the health of personnel and fish in the fish cage, as well as the chances of fish escape. The technology and methods used today limit the degree of work that can be performed in harsh waves and currents, limiting the operational window for important operations (Sandberg et al. (2012)). A survey completed in 2012 found that according to industry actors, one of the key areas that needs to be researched in exposed aquaculture was operational decision support by determining more objective criteria for when a operation can be performed and when it must be stopped. In the present industry, the decision of whether or not to perform an operation or travel out to a location with a service vessel is based on experience and judgment on the person in charge (Sandberg et al. (2012)). An unnecessarily postponed operation can have negative economic impacts and consequences for the health of the fish and the environment. Meanwhile the execution of an operation in unsafe conditions can lead to accidents that can harm the workers, the fish or the integrity of the entire fish farm. With aquaculture being the second most dangerous occupation in Norway, there is a need for a supplementation of knowledge to help decide if an aquaculture service vessel has the ability to perform its assigned tasks at exposed aquaculture locations (Thorvaldsen et al. (2017)).

1.2 State of the Art

At the present, Exposed, a centre for research based innovation at SINTEF, is carrying out eight projects focusing on technology innovation to ensure safe and reliable aquaculture operations and a sustainable expansion of the fish farming industry. The projects of special relevance to the scope of this thesis involve areas such as design of vessels, vessel-structure interactions, safety at sea and electronic infrastructure. In terms of safety, it has been identified that the fish farming industry is the second most risk-exposed workplace in Norway regarding occupational accidents (SINTEF ocean (2017)). The pre-project ”Sustainfarmex” investigates the reported accidents and fatalities in the aquaculture industry (Holen (2017a,b)). The accident report finds that fall and blow from an object is the most common injury modes. The study on fatalities reveals that working operations is the main cause of deaths in the industry since 1992 with blow/crush from an object and man over board being the most frequent death fatality modes. The findings motivate research on the safety aspect of aquaculture, and the project ”Safety at sea” aims to develop good practices for safety and risk management in operations at fish farms as well as implementing safety measures in the industry. A different project, involving electronic infrastructure provides technical measurement devices in order to collect information on both environmental conditions and vessel motions at exposed locations. Oceanographic buoys will collect environmental data such as wind, waves and currents and this will in turn aid in industrial field experiments that will provide a basis for developing new knowledge and new technology. In addition, two catamarans with lengths of 25 [m] and 15 [m] are instrumented with motion response units, wind sensors and GPS units to study motion during operations (SINTEF ocean (2017). The crew onboard the vessels are instructed to log information on aborted operations. This is carried out to eventually provide safe limits for operation based on correlations between the crew logs and measured data such as accelerations and displacements (Selvik (2018)). Furthermore, a number of master theses at NTNU are carried out in cooperation with Exposed. These cover a range of different topics including logistics, risk management and maintenance. Among these, Stemland (2017) studies the long-term operability of a 40 [m] long monohull operating at exposed locations. The long-term operability is found through use of a discrete-event simulation tool. It is found that the method provides increased knowledge of service vessel operations in exposed aquaculture. It is also found that roll motion limits the operation of this specific vessel at the exposed locations.

1.3 Objective

The aim of this thesis is to evaluate and compare the operability for three aquaculture service vessel designs at exposed locations by using a combination of hydrodynamic vessel response analysis and discrete-event simulation. Quantitative operational limits will be determined by analyzing vessel motions with respect to a set of restrictive criteria. A simulation model of a service vessel work cycle will be applied as a way to judge the different vessels capacity to complete their given assignments in the form of their long-term operability. Wave data from oceanographic buoys and the operational limits found in the analysis of the vessels will be used as input in the simulation. Evaluating the operability limits and comparing the different vessels by combining the analysis of vessel motions with a discrete-event simulation model can give an indication of how the three vessel designs perform at different levels of exposure and what the limiting criteria is for the different vessels. This can in turn aid the future design of service vessels for exposed aquaculture as well as provide knowledge needed to increase the capacity for decision support and planning during operations at exposed locations. A set of tasks that shall be carried out to complete the objective of this thesis are presented below.

- Gain an understanding of the relevant operations performed by service vessels in the aquaculture industry.
- Create an operational profile that can be used as a basis for creating a discrete-event simulation that aims to emulate the operations performed by the service vessels of interest.
- Find relevant criteria to use as a basis for evaluating the vessels ability to perform operations in a safe manner at exposed locations.
- Use these criteria to find the operational limits for three different aquaculture service vessels.
- Implement the operational limits into the simulation model to evaluate and compare the operability of the three vessel during operations at two exposed locations.

In addition, an analysis on the effect of wave-induced vessel motions on line tension during anchor deployment operations will be performed in this thesis. If the line tension exceeds the minimum breaking load due to vessel motions the aim is to also implement this as an additional operational limit in the simulation model.

1.4 Report Structure

The remainder of the thesis has the following structure. Chapter 2 consists of the description of the systems of interest in this thesis. This includes the service vessels, operational area details and operations of interest. Following this, Chapter 3 contains an explanation of the problems that are examined in the thesis. Chapter 4 presents related research and previous work that is of relevance to the thesis. Chapter 5 contains the vessel motion theory that is of importance in regards to the analyzes that have been carried out, before Chapter 6 introduces the relevant criteria for assessing vessel operability. Following this, a short introduction to simulation theory is presented in Chapter 7. Chapter 8 explains the methods used to acquire the operational limits from the vessel motion analysis and a detailed description of how the simulation model is constructed and how it functions. In Chapter 9 the results from the VERES calculations are presented, followed by the operability results from the simulation model in Chapter 10. A discussion of the results, methods and validity of the work, followed by a conclusion appear in Chapter 11 and 12 respectively. Finally, Chapter 13 presents recommended further work.

Chapter 2

System Description

The following chapter will detail the real life elements and systems that will be modeled and analyzed in this thesis. The focus revolves around service vessels in the aquaculture industry and the operations they perform on site at exposed aquaculture locations. The software programs Matlab, ShipX, Simulink and SIMA have been used during this thesis and a quick description of these programs can be seen in Appendix D.

2.1 Definition of Exposed Aquaculture

There exists no formal definition of what constitutes exposed sites in the Norwegian aquaculture industry. However the phrase is often used to refer to sites that experience sea states and currents that are more forceful than what is experienced at an average site (Sandberg et al. (2012)). Since this average site exposure has not been objectively quantified, defining what is an exposed site is mostly based on subjective assessments of the given site (Bjelland et al. (2016)). The Norwegian standard on the technical operational requirements for aquaculture sites and structures classification, *(NS9415:2009)*, is often used. It classifies five exposure classes based on a crude distribution of significant wave heights (*Hs*) and peak wave periods (*Tp*), with a similar classification for currents. The largest class known as class *E* is often used to classify an extremely exposed location. A class *E* site is compromised of *Hs* larger than 3 meters, *Tp* from 5.3 to 18 seconds and mid currents above 1.5 m/s. However, this classification does not always provide a sufficient description of the physical environment of a location, as the probability of occurrence of these conditions is also an important aspect for the serviceability and operability of a location (Kristiansen et al. (2017)). There can also be large variations in the exposure at different parts of a site due to varying topography (Kristiansen et al. (2017)). With the trend of moving production to more exposed locations, and new concepts for offshore fish farming being designed for significant wave heights up towards 5 meters such as the Salmar Ocean Farm, the industry needs more precise descriptions of the marine environment. For this thesis, the definition of exposed aquaculture is the same as in the standard *NS9415:2009*. While this classification might not provide a sufficient description for all locations and purposes, it will most likely still be prevalent until newer revised classifications have been established.

2.2 Service Vessels in the Aquaculture Industry

The service vessels of today are used for the day-to-day operation and maintenance of fish farming sites, the construction and deconstruction of new fish farming sites as well as supporting the operations when larger vessels such as well boats visit the sites. Vessels less than 15 meters in length, equipped with high capacity cranes, are the most common service vessels. Among these vessels, catamarans have a dominating position (Bjelland et al. (2016)). Because of the need for the vessels to maneuver throughout the site, the vessels are designed with restricted draught to allow for maneuvering above the mooring frames, as well as having reduced freeboard to allow for easier access to the floating collar at the fish cage. The choice of having service vessels with a length less than 15 meters comes from the fact that former regulations stated that boats in excess of 15 meters required additional crew certification. Because of this, the crane and winch capacities on service vessels increased with the requirements of the industry, while the dimensions lingered to accommodate these regulations. This discrepancy between equipment capacity and vessel dimensions led to dangerous situations that have resulted in loss of life and equipment (Bjelland et al. (2015). However, new legislation on crew certification requirements for vessels over 8 meters took effect at the start of 2018, which could make way for new designs with increased size and capacities (Stautland (2018)). An example of this can be seen in figure 2.1, which is a large catamaran service vessel. The issue of the limiting size of service vessels is a concern for the industry, and projects such as ”Service Fartøy 2010” have looked into how to design the new generation of larger vessels. New vessel types such as the small water plane area twin hull design, (SWATH), have also been put forth as a possible vessel design that can work for exposed aquaculture locations (Bjelland et al. (2016)). Their reduced water plane area give them less accelerations and longer periods in heave and pitch than ships with larger water plane areas (Faltinsen (2006)). Using ballast to achieve lower draught also gives good seaworthiness in rough seas when performing operations. Although none of these vessels are currently in use in aquaculture, they are used extensively in the offshore wind industry.

Figure 2.1: Picture of a large service catamaran. (AQS.no (2018))

2.2.1 Catamaran and Monohull Vessels

A large part of what will be examined in this thesis are the motion characteristics of different vessel designs with respect to a set of limiting criteria. Due to the differences in the hull design of catamarans and monohulls, they will likely behave differently at exposed locations and have both advantages and disadvantages. Firstly, the monohull design has been well tested through use in the offshore industry, and technology such as DP-systems and anti-roll tanks can also be adapted with relative ease for use in monohulls for exposed aquaculture (Bjelland et al. (2016)). The design of the monohull will also potentially allow for a lower metacentric height (GM) than a catamaran, as the second moment of area about the centerline is much lower. As a consequence, a low GM will lead to a longer roll period providing a less stiff behaviour of the vessel. Longer rolling periods will provide a more comfortable sailing and working environment in harsh weather conditions because of less rapid responses due to a reduced restoring moment (Amdahl et al. (2011)). Rapid movements and accelerations in rough seas at zero speed are also pointed out as a disadvantage of catamarans when comparing this design to other possible service vessel designs in the report "EXPOSED - Future Concepts" (Bjelland et al. (2016)). Catamarans can however provide a very stable platform, large working area on deck and flexible arrangement possibilities resulting from the wide beam (Lamb (2003)). The design of a catamaran also allows for increased lifting capacities and reduced draft compared to monohulls with the same length. In combination with the aforementioned regulations on the length of service vessels in the previous section, this may explain the large amount of catamaran in the aquaculture industry today, where the operations are often completed in sheltered locations.

2.3 Description of the Service Vessels of Interest

This section will describe the three vessels that have been analyzed. Due to a desire to keep the identity of the different vessels anonymous, the portrayal will only be a basic description of the vessels. As the analysis has a focus on exposed aquaculture sites, three larger vessels were made available and chosen due to their potential capability of operating in harsh waters. Two of the vessels have a similar design, as both are catamarans of length 25 meters. Despite of this similarity, it is still found interesting to see how small deviations in the design affect the operability of the vessels.

2.3.1 Vessel 1

Vessel 1 is a service catamaran that specializes in heavy operations in the aquaculture industry, such as mooring operations and the construction and deconstruction of fish farming sites. It is equipped with two large deck cranes, three large capstans, one large capacity winch that measures traction, several smaller winches, and specialized facilities for safe and efficient mooring. It also has the ability to be equipped with gear for delousing and is equipped to handle general service work, ROV and diving operations as well as installation of feed barges and fish cages (Contact-1 (2018)). The main dimensions are listed in table 2.1.

Table 2.1: Main particulars of Vessel 1

Vessel 1	
Length overall	25,5 [m]
Breadth	12 [m]
Design water line	2.7 [m]
Depth moulded	3.7 [m]

2.3.2 Vessel 2

Vessel 2 is also a service catamaran specializing in mooring operations and the construction and deconstruction of fish farming sites and is similar in size and capabilities to Vessel 1. It is equipped with two large deck cranes, two capstans, winch for towing as well as a range of smaller winches. The main dimensions of the vessel are listed in table 2.2.

Table 2.2: Main particulars of Vessel 2

Vessel 2	
Length overall	25 [m]
Breadth	13 [m]
Design water line	3.5 [m]
Depth moulded	4.5 [m]

2.3.3 Vessel 3

Vessel 3 is a large monohull service vessel. The vessels' main focus is delousing operations performed with an onboard Thermolicer for mechanical delousing. It is also equipped with large cranes, winches and capstans to be able to complete most other service operations that are needed at aquaculture locations. The main dimensions of the vessel are listed in table 2.3.

Table 2.3: Main particulars of Vessel 3

Vessel 3	
Length overall	40 [m]
Breadth	12 [m]
Design water line	3.6 [m]
Depth moulded	4.5 [m]

2.4 Service Vessel Operations

Service vessels in aquaculture industry are used for a large range of different operations. They play a vital part in the day-to-day operation of a fish farm, including establishing and maintaining the infrastructure. The operations are generally complex and multifaceted, involving several different vessels and crew interactions. This section introduces the different types of operations that service vessels in the aquaculture industry perform. Nekstad (2017) studied how modularization could be used to implement operational flexibility in aquaculture service vessels. As a part of the study, a grouping of the variety of operations was presented. This grouping provides an overview on the operations a service vessel might be required to perform and the operations are listed in figure 2.2. The grouping is based on operations performed by service vessels today, i.e operations performed on sheltered locations. The ensuing section details the operational profile of the vessels, and a short description of a more specific selection of operations based on this profile. The description of the different operations are based on information from the industry contacts as well as information from the master thesis of Nekstad (2017).

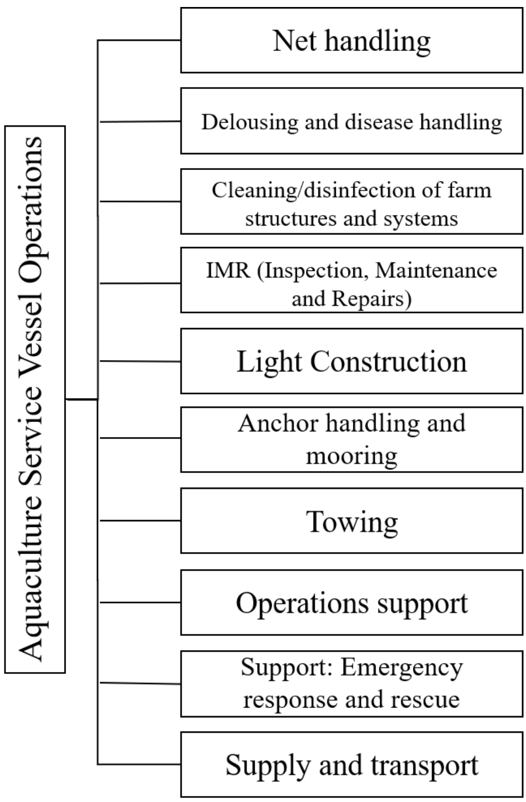

Figure 2.2: Grouping of operations performed by aquaculture service vessels inspired by (Nekstad (2017)).

2.4.1 Operational Profile of Vessels

As stated, service vessels in the aquaculture industry perform a multitude of different complex and multifaceted operations and the vessels examined in this thesis all have the ability to perform a large variety of operations. The main focus of two of the three vessels is heavy lifting operations, so it was decided to contact industry workers with knowledge of these types of vessels. While Vessel 3 is mainly used to perform delousing operations, it still has the capacity to perform heavy lifting operations as well. The operational profile of Vessel 3 is therefore the same as the first two vessels to simplify the process of evaluating and comparing the operability of the three vessels. Through discussions with three different employees from the service vessel industry an approximation of an operational profile was created (Contact-2 (2018); Contact-1 (2018); Contact-4 (2018)).

When a vessel has received an order to perform an operation at a specific site, it will travel to the location and complete the required operations. There is little in regard of operational planning with regard to future weather forecasts as seen in the offshore industry (DNVGL (2011). A vessel will wait for a good weather window to allow for the safe completion of an operation, either on site, moored to the feed barge, or at the nearest port (Contact-1 (2018); Contact-3 (2018). There is however some optimization, as the vessel will attempt to perform multiple operations at one site to reduce travel time (Contact-4 (2018); Contact-3 (2018)). A vessel will also often attempt to visit sites in the most optimal order with respect to distance to reduce total travel time (Contact-4 (2018)).

The industry contacts had difficulties with determining an exact set of operations, but 6 key types of operations were generally presented by all of them. These were; net pen handling, tension of mooring systems, anchor and mooring frame operations, support during delousing operations, facility inspections and towing operations. The focus of this thesis is the operations performed on location at fish farming sites, so towing operations were excluded. Including towing would have necessitated analysis of multi-body systems during forward speed, as well as sea state data from other areas during transit that would go beyond the scope of this thesis. Facility inspection entails a large variety of operations and specifying exactly what this operation entails is difficult. Focus is therefore put on the ROV inspection facet of this operation, as this is performed by all of the vessels.

Vessels that focus on heavy aquaculture operations performs jobs involving the deployment of anchors and mooring frames approximately 10% of the operational time during a year. Tensioning of mooring lines makes up 10%, net pen handling operations account for roughly 30%, inspection operations account for 30%, delousing support 10% and towing operations 10% (Contact-4 (2018)). These types of vessels also have very little down time,

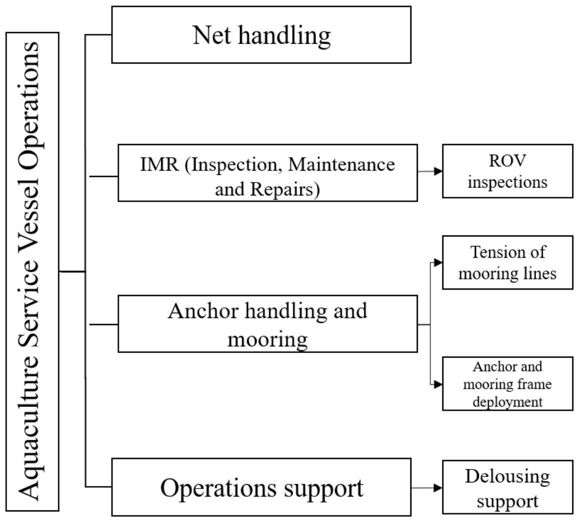

Figure 2.3: Grouping of the 5 operations included in the operational profile.

approximately two weeks in a year. As stated, the towing operations have been excluded from the scope of this thesis. This results in 10% of the operational profile being left out. However, one of the other contacts expressed that their vessel had a larger focus on anchor and mooring frame deployment operations. The percentage of towing operations is therefore moved to this type of operation to give a profile that generally fits the two vessels more evenly. An average operational profile has therefore been made, including five operation types as presented in figure 2.3 and table 2.4.

Table 2.4: 5 operations included in the operational profile of the vessels].

Operation	**Percentage of total operational time**
Anchor and mooring frame	20 %
Tension of mooring lines	10%
Net pen handling	30%
Delousing support	10%
ROV inspections	30%

While the focus is on operations where there is zero forward speed, this is a simplification as certain operations include intervals of forward speed to some degree, mainly anchor and mooring frame operations. The vessel is also simplified as a free floating body, while the vessel would in reality be part of a multi-body system when it is moored to a fish cage or deploying an anchor.

2.4.2 Net Pen Handling

Net pen handling consists of the two similar procedures, installation of and removal of a net pen. There are a number of incidents that can necessitate the need for net pen handling. For example, when installing a new fish farm, net pens must be installed on all of the fish cages at the site. When a fish farm enters its fallowing period it can be necessary to remove the old net pen to decrease the risk of spreading diseases to the new batch of fish that enter the facility after the period is complete. When the fallowing period is over a new ”clean” set of net pens is installed. The need for replacing a net pen can also occur if an ROV or diver can not repair the damages to a net pen due to them being too severe.

When installing a net pen to a cage, the net is first prepared for installation on board the service vessel. It is then positioned in the cage, and the top of the net pen is connected to the floating collar and afterwards the bottom of the net pen is connected to the sinker tube. With the weights connected, the bottom ring and weights are lowered, allowing the net to be stretched to it's desired shape.

Removal of the net pen is similar to the installation, but in reverse. The bottom ring and weights are first lifted up to the surface so that they can be disconnected from the net pen. When this is completed, the net pen is disconnected from the floating collar and subsequently lifted on board the service vessel.

Net handling operations often involve one or more vessels, crane usage and manual labour from personnel on both the service vessel and the floating collar of the fish cage (Contact-4 (2018)). The personnel are also in close proximity to the crane during large parts of the lifting operations. The sinker tube can possibly weigh up to 140 kg/m depending on the conditions at a given site, making it one of the heavier parts of a fish cage. This means that large forces are involved when using the crane to regulate the placement of the sinker tube (Contact-5 (2017)). To lift or lower the sinker tube, the service vessel must move around in the circumference of the fish cage in a step-wise manner, gradually lifting or lowering each lifting line in increments, so that the bottom ring is adjusted evenly. As a result of these factors, the operation can be both time consuming and vulnerable to the conditions at the site of the operation.

2.4.3 Tension of Mooring Lines

The mooring lines at aquaculture sites are generally pre-tensioned to approximately 1 to 1.5 kN (Contact-1 (2018)). The fiber ropes in the mooring lines will in time experience elongation due to creep, and to some degree due to constructional setting and splice slippage. Creep is the length or rate at which the fibers in the rope stretch irreversibly over time when subjected to constant, long-term static loading (SamsonRope (2012)). Consequently, this elongation will in time cause slack. To ensure that the facility is safely moored, the pretension must be reapplied to the lines. When tensioning mooring lines the vessel lifts the line on deck of the vessel with the help of the onboard crane. The mooring line is then fastened to the boat at one end, with the other end fastened to the capstan winch. After this is done, the mooring line is cut and spliced so that the original pretension can be achieved (Contact-1 (2018)).

2.4.4 ROV Inspections

ROV inspections are a sub-group of the main group ”Inspection, maintenance and repair” which includes a variety of different operations. Inspection operations are performed on a regular basis at fish farming sites to ensure that the farm can operate successfully without breakdowns. When performing inspections, the ROV is used to observe the cage and other farm structures for damage. The vessel will also often lift the connector plates for a more meticulous up-close inspection. The comprehensiveness of inspections can vary from shorter one-day inspections to full facility inspections that can take up to 3 days. The heavy operation vessels mainly inspect the mooring lines and anchors with the on board ROV, and if they locate damages or wear that is not too extensive during the inspection they will normally perform corrective maintenance (Contact-4 (2018)).

2.4.5 Delousing Support

When the amount of salmon lice per fish in a fish cage exceeds the limit sett by the Norwegian authorities, a delousing procedure is required. This limit is set to an average of 0.2 or 0.5 adult female salmon lice per fish, depending on the time of the year and the location of the fish farming site (Lovdata (2018)). Salmon lice has been one of the largest issues to face the industry in recent years, and accounts for a large amount of the operations performed by service vessels in the aquaculture industry. Delousing with chemicals and tarpaulin has been the most common method (Lusedata.no (2018). However, new methods have been introduced in recent years, such as mechanical, thermal and fresh water delousing, which are all increasing in popularity.

Operations labelled as delousing support includes missions where the service vessel is required to support well-boats or other vessels during delousing operations. During these operations a service vessel maneuvers itself next to the fish cage where the delousing is to be performed. The service vessel might be required to use its cranes to help lift the bottom ring of the net to reduce the volume of the net-pen and crowd the salmon, as well as navigating sweep-nets or ”kulerekker” to help with the horizontal crowding of the salmon. Furthermore, the service vessel might be required to perform inspections using divers or ROVs after the operation to ensure that the net or other parts of the net pen did not get damaged. As seen in figure 2.4, the operations can be quite complex, involving many different cranes, ropes and workers on the floating collar.

Figure 2.4: A vessel with an onboard Thermolicer system performing a delousing operation, supporting service vessel is seen to the right. (TU.no (2018))

2.4.6 Anchor Handling and Mooring Frame Deployment

This operation group contains the operations required to establish the anchor and mooring systems on a fish farm. This includes deployment and setting of anchors, deployment of buoys, coupling plates, mooring lines and mooring frames and in addition, tensioning of the anchor lines and the mooring system. In the event of a rock bottom, anchor bolts are usually deployed in the bottom using divers or an ROV instead of an anchor (Contact-1 (2018)). When deploying the anchor the fiber rope mooring line is first fastened to the the onboard winch and to the anchor chain. The anchor chain is then connected to the anchor. When the vessel has positioned itself in the correct position the anchor is hoisted off the aft of the service vessel with the help of a crane, before being lowered to the seabed with the help of the winch system. The vessel then relocates itself so that the mooring line has sufficient length, in general 3 times the depth of the location (Høy and Martinsen (2010)). When this position is reached the vessel increases its bollard pull to sett the anchor and make sure it can endure the forces it is required to withstand based on calculations that have been performed when projecting and designing the fish farming site. 4 main mooring lines are first deployed, before the mooring frame is built on board the service vessel. This mooring frame is then connected to these 4 main mooring lines, before the rest of the anchors and mooring lines are deployed and connected to the mooring frame. The operations involve high loads and tension, and are considered risk exposed operations both with respect to personnel and equipment (Bjelland (2015)).

2.5 Fish Farming Site Details

2.5.1 Location of Fish Farming Sites

The geographical location of two real world fish farming sites located off the coast of Sør-Trøndelag are used as the two destinations in the simulations, as seen in figure 2.5. Both of these locations are focus areas for SINTEF Exposed and are both considered exposed aquaculture locations. Each location is accompanied by a oceanographic buoy in close proximity to the site that collects a multitude of data on the environmental condition of the site. This data is important to be able to create a representative description of the environmental conditions experienced at present exposed locations, and other future exposed locations. The use of real world data and locations also allows for realistic sea state values that can increase the validity when evaluating vessel performance. Due to small islands, reefs and local bathymetry in proximity of near-shore sites, the local wave conditions are affected through refraction, diffraction and scatter effects, which can result in a large range of variable wave conditions (Kristiansen et al. (2017)). This means that the conditions on near-shore sites can be substantially different from conditions experienced offshore (Kristiansen et al. (2017)). Site 1 is surrounded by a large amount of skerries and underwater rocks. These outcroppings can provide shelter from ocean waves, but not from wind exposure so the effect of wind could be a significant contribution to operational difficulties at this site.

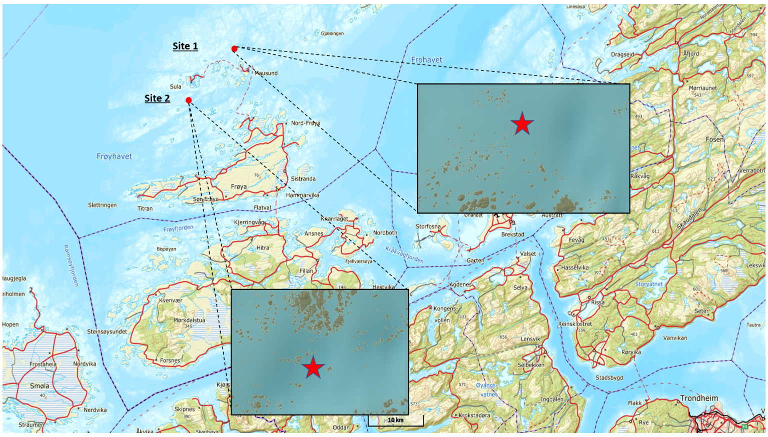

Figure 2.5: Location of the Site 1 and Site 2, including a close up of each location. Map image collected from (Norgeskart.no (2018))

In reality, service vessels in the aquaculture industry have a very large area of operations, and operate at a large variety of different sites, often traveling long distances to arrive at the next site where their services are needed (Contact-1 (2018)). However, due to data being available for two locations, the simplification of using data from two locations was selected.

Hitra Kysthavn Josnøya is the corresponding port chosen to accompany the sites. This is the port closest to the two sites that is used regularly as a port for ships in the aquaculture industry. The service vessel will return to the port after each completed operation, as well as having an extanded stay when changing crew. The two routes chosen can be seen in figure 2.6, and the distances from port to each site can be seen in table 2.5. The approximate distances were measured with the help of Google's map tool. There are a multitude of different routes that can be used to arrive at one of two locations. However, the focus of this thesis is on the operations performed at the fish farm sites and not the transit between locations. Because of this, the sea states and vessel motions are not taken into account along the routes, and it is assumed that the ship always uses the same routes.

Distance from port to site		
Site 1	32.4	[nmi]
Site 2	35.6	[nmi]

Table 2.5: Distances from port to sites

(a) Route from port to Site 1

(b) Route from port to Site 2

Figure 2.6: Routes from Hitra Kysthavn Josnøya to sites. Map image collected from (Google (2018)

2.5.2 Oceanographic Seawatch Buoys and Scatter Diagrams

The oceanographic buoys at the two locations are of the type SEAWATCH Midi 185 Buoy. The buoys collect a multitude of different data with the help of sensors equipped on the buoy. This includes current velocity profile, directional waves, wind, temperature and salinity. By utilizing FOAS Wavesense 3m, wave elevation, wave period and wave propagation direction are measured. These measurements are based on a measurement sequence of 17 min duration per hour. (Kristiansen et al. (2017)). Using these measurements, wave parameters like significant wave height, maximum wave height and mean zero-crossing period are calculated. Focus has been put on the data regarding the significant wave height (Hs), mean zero-crossing period (Tz) and mean spectral wave direction (μ). There is however great value in all of these other measurements in regard to the safety of workers during operations and the health of the fish at the site.

Scatter diagrams of the two sites based on the oceanographic buoy data are presented in figure 2.7 and 2.8. The scatter diagrams provide informative tables on the most frequent combinations of Hs and Tz. It can easily be seen from the tables that Site 2 is characterized by both higher Hs and Tz than Site 1. In addition it can be seen in the diagrams that the highest wave heights are encountered in the mean zero-crossing period interval between 4-7 seconds.

Hs \ Tz	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	Sum
0-0.5	0	0	19	5032	1665	77	16	9	1	0	0	0	0	0	0	6819
0.5-1	0	0	3	3172	1706	51	5	2	0	0	1	0	0	0	0	4940
1-1.5	0	0	0	250	771	8	0	0	0	0	0	0	0	0	0	1029
1.5-2	0	0	0	0	73	3	0	0	0	0	0	0	0	0	0	76
2-2.5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
2.5-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	**0**	**0**	**22**	**8454**	**4215**	**140**	**21**	**11**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	12865

Figure 2.7: Scatter diagram of Site 1, a more frequent Tz is indicated by a darker red.

Hs \ Tz	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	Sum
0-0.5	0	0	8	528	3391	2479	601	198	76	22	6	4	2	0	0	7315
0.5-1	0	0	1	463	2868	2049	457	188	101	72	43	32	20	8	9	6311
1-1.5	0	0	0	6	892	1400	456	107	51	19	12	6	2	3	1	2955
1.5-2	0	0	0	0	241	756	207	37	10	3	1	0	0	0	0	1255
2-2.5	0	0	0	0	5	399	107	12	1	0	0	0	0	0	0	524
2.5-3	0	0	0	0	0	77	98	3	0	0	0	0	0	0	0	0
3-3.5	0	0	0	0	0	1	14	2	0	0	0	0	0	0	0	0
3.5-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	**0**	**0**	**9**	**997**	**7397**	**7161**	**1940**	**547**	**239**	**116**	**62**	**42**	**24**	**11**	**10**	18555

Figure 2.8: Scatter diagram of Site 2, a more frequent Tz is indicated by a darker red.

2.5.3 Layout of Fish Farming Sites

The fish farming sites are assumed to be a regular generic circular HDPE fish cage site in a $4 \cdot 2$ layout. The sites are orientated with the short sides towards the north and south and the long sides orientated towards the east and west as seen in figure 2.9. The sites have a total of 16 mooring lines each, connected with anchors. In reality the layout, orientation and number of mooring lines are based on the requirement of a given location and can therefore vary. The number of mooring lines are often increased based on the need for extra holding capacity in certain directions where the current forces are strongest. Current forces often account for up to 70-75 % of the total forces on a typical medium sized fish cage and these forces are transferred to the mooring lines (Cardia and Lovatelli (2015)). This is also the case for the orientation and the layout of the site, as the net pens in the fish cages cover a large area, resulting in a large drag forces.

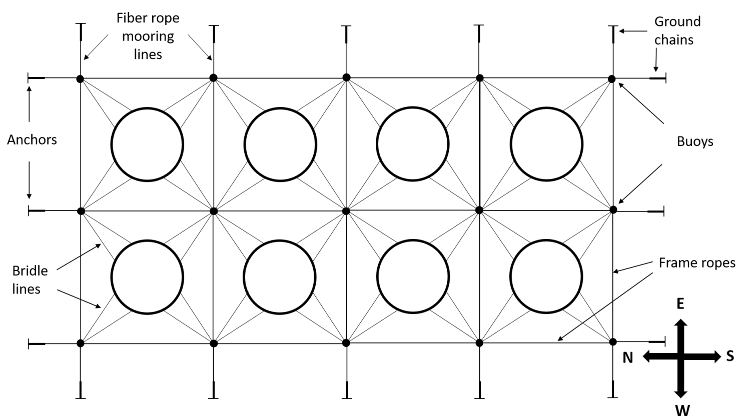

Figure 2.9: Layout of fish farming site. Orientation of site in right corner

Chapter 3

Problem Description

In this chapter, a detailed description of the problem investigated in this thesis will be explained. From 2000-2009 the aquaculture industry in Norway was the occupation with the second most registered accidents leading to deaths per employee (Thorvaldsen et al. (2017)). Holen (2017b) investigated 34 fatalities in the aquaculture industry in the period 1982-2012 finding that 60% of the fatalities were related to work on board working vessels. Many of the accidents before 1992 were related to transportation, while fatalities related to vessel operations have been the main cause since 1992. Following the growth of the industry, an improvement of the vessel design have been evident in the later years. New legislation's towards the size of the vessels as well as demands from large scale sites have led to a new generation of larger vessels of various designs.

Due to environmental issues such as lice and pollution, there is a lack of capacity inside the fjords limiting the expansion of the industry in sheltered water. Following an increased demand for seafood, the industry is looking towards exposed waters to expand the industry. A substantial part of Norway‘s coastline is today unavailable for aquaculture due to harsh weather conditions, strong winds and currents. From a safety perspective, an expansion of the industry towards more exposed waters will require more robust vessels to be able to perform vessel operations. In the light of the industry's reputation of being a hazardous occupation, an effort should be put forth to ensure the safety of the workers as the industry expands its area of operation.

This thesis aims to evaluate and compare different service vessel designs with respect to operability and operational limits at exposed aquaculture sites. The operability will be evaluated in terms of the vessels capabilities to perform their operations safely and effectively. Furthermore, the main focus will be on the operations of a service vessel when the vessel is on site at zero forward speed. A quantification of the operability can be found by evaluating the motions of the vessel in exposed waters with respect to a set of limiting criteria for ship motions found in literature. The vessel criteria will give insights into how the vessel performs for a given wave spectrum with an associated significant wave height and zero-crossing period. In order to assess the long term operability of a vessel a discrete-event simulation tool, Simulink is utilized to create a model that replicates a service vessel work cycle. Compared to traditional methods of calculating the operability of a vessel, a simulation model allows for the inclusion of operation specific details such as varying wave directions, duration and operational methods. To enable a simulation of the vessels performance, an operational profile of the vessels will be established based on information gathered from industrial contacts. Given time series wave data for two exposed locations, the vessels will be set out to operate in the locations on an hour to hour basis. The results from the long term performance of the vessels can provide insights into which factors that have the largest impact on different vessel operability. This can in turn aid in future design of service vessels, as well as increase the industry's capacity for decision support and planning during operations at exposed locations.

As a step in achieving a deeper understanding of the limiting criteria that can be used to evaluate service vessel operability, a side study consisting of an analysis of a specific possible issue during anchor deployment operations is conducted using the software SIMA. When deploying plough anchors there is a need for the anchors to burrow in to the sea bottom, and to confirm that it has sufficient holding power. This operation is carried out by making use of service vessel to plough the anchor at a sufficient bollard pull. There has been put forth a concern that the wave-induced surge motions of the vessel can lead to variable tensions in the fiber rope mooring line that exceed the minimum breaking load (*MBL*) of the line (Selvik (2018)). A broken anchor line imposes a danger to the crew, as there are large forces at work. The snapped mooring line might strike personnel, damage equipment or give rise to excessive motions of the vessel. The analysis showed that the tension in the lines would not be exceeded unless exposed to extreme conditions that were not experienced at any of the two locations of interest. As such, these results were not included in the simulation or in the main body of this thesis. A presentation of the work done in this analysis can be found in appendix A.

Chapter 4

Related Research

This section will provide an overview on previous research concerning the main aspects considered in this thesis, including health and safety during aquaculture operations, research on vessel operability and discrete-event simulations of marine operations.

4.1 Health and Safety in Aquaculture Operations

From 2000 to 2009, the aquaculture industry in Norway was the occupation with the second most registered accidents leading to deaths per employee. It also had the second most registered injuries per employee, only beaten by the fishery industry (Thorvaldsen et al. (2017)). This has motivated studies with respect to safety in the aquaculture industry, especially in relation to the fact that the industry is moving towards exposed locations.

SustainFarmEx was a project lead by SINTEF with the goal of developing knowledge that enables safe, reliable and profitable production and operation at exposed aquaculture facilities. The project was divided into four parts called work packages. Work package 1 (WP1) focused on identifying risk factors for exposed aquaculture operations and guidelines to design safe work places (Holen (2015)). This was achieved by performing interviews, inspections and a work shop. WP1 concluded that exposed sea states, wind and current affected work to a large degree. Crane operations were pointed out as critical regarding operability and safety. Moreover, Holen (2017a) provided an overview on the reported accidents in the Norwegian aquaculture industry during a period from 2011 to 2014. It was found that the most common mode of injury was blow from an object with one third of these injuries involving the use of a crane and objects falling from the crane.

Crush and fall are found to be the second and third most common injury mode, and it is argued that the working vessels unstable nature as well as a slippery surface gives a major contribution to these injury modes. In addition Holen (2017b) studied the 34 fatalities in the Norwegian aquaculture industry in the period 1982 to 2015. 60 % of these fatalities were related to work on board working vessels. It should be mentioned that the category ”working vessels” includes a range of different vessels as there has been a development in the design and technology of these vessels since 1980. Transportation was found to be the main cause of fatalities before 1992 while fatalities in relation to work operations has been the main cause since 1992. The most common modes of fatalities has been found to be loss of vessel, man over board and blow from an object.

4.2 Vessel Operability

There exists a lot of research on operability of ships in literature. However, the research is often concerned with operability of larger vessels in the offshore industry or commodity and passenger transport. In terms of operability of smaller vessels, there are some studies carried out, mostly concerned around fishing vessels. Studies carried out on operability of fishing vessels are somewhat similar to service vessels, considering the vessels size and that their operational area is found in coastal areas similar to exposed aquaculture locations. Fonseca and Soares (2002) studied the availability of a container-ship and a fishing vessel with respect to a range of different seakeeping criteria. The result of the study is given as an operability index indicating the percentage of time the vessels were able to perform their mission. For the fishing vessel, the operability was considered both using coastal wave climate statistics and offshore wave climate statistics. It was found that the operability was mostly limited by seas at a $90°$ wave heading. The operation of the fishing vessel was mostly limited by the roll criterion of $4°$. A large difference in operability, 0.93 in coastal areas and 0.76 in offshore areas, showed that it is important to have local and accurate wave statistics when considering small vessels operability in a coastal area. The study was also motivated by the fact that there is a large uncertainty on the definition of the seakeeping criteria since the criteria are based on different authors judgment and experience from operation. Therefore, an investigation of the influence of varying different seakeeping criteria was carried out indicating that the sensitivity of the operability index with respect to varying the values of the seakeeping criteria was small. Another study carried out by Tello et al. (2011) investigated the seakeeping performance of 11 fishing vessels of different dimensions ranging from 13-46 meters of length. The aim was to identify which seakeeping criteria and vessel condition that limits the operability of the fishing vessels in certain sea states. It was found that the roll and and pitch motion criteria were the most often exceeded criteria having root mean square limits of 6° and 3° respectively. In addition the report emphasized the importance of paying attention to the location of working stations on board when designing a vessel as these are critical to the crews performance as well as the operability of systems onboard the vessel.

4.3 Simulation of Marine Operations

Several studies on marine operations using simulation models have been performed. These are however mostly focused on logistical aspects such as fleet sizing optimization and operational planning support, and not as a tool for evaluating the operability of vessel designs. No published reports with a focus on operations in aquaculture have been found, though findings in these other areas of study can be of relevance. There is however a relevant master thesis using discrete-event simulation of aquaculture operations that will also be presented below.

A simulation model study on the ferry traffic in the Aegean Islands performed by Darzentas and Spyrou (1996) had the the aim of creating a decision aiding system for regional development. Due to the complex layout of the Aegean Islands and the large population varieties, designing and controlling this ferry transportation system is complicated. The model considerations included vessel types, harbour layouts, weather conditions and operational time and demands. The results produced in the study were used as an indication of the model's potential as a decision aid. The necessity of usability for the end user of a product was emphasized, and was dealt with by implementing a graphical interface to the simulation. It was also concluded that careful and time consuming data collection is necessary when using the simulation for evaluation purposes of future scenarios and vessel types.

By utilizing a discrete-event simulation model, Maisiuk and Gribkovskaia (2014) examined the problems that arise when planning supply vessel operations at offshore oil and gas installations. The model was used to evaluate alternative fleet size configurations by considering the uncertainty in weather windows and the future spot rates for the vessels. The hiring of supply vessels in the offshore industry is expensive, and deciding the required number of vessels in advance can have a strong effect on the total annual cost. Careful planning is needed to determine the optimal fleet size as the operations are complex, and impacted by weather condition uncertainties and the spot rates for the vessels fluctuate. This makes the system decidedly stochastic in nature. Due to the unfeasibility of describing and modeling the stochastic system analytically, discrete-event simulation modeling was presented as a good method of approach for such a system. Another study was conducted on resource sharing in the logistics of offshore wind farm installations using a discret-event simulation by Beinke et al. (2017). The model took into consideration simultaneous installation of wind farms, the impact of weather restrictions on operations, as well as the impact of the implementation of resource sharing. The study was motivated by the large amount of wind farms that will be installed in the future, as well as economic benefits that might be attained through resource sharing. The results showed that weather restrictions have a significant impact on installation times, time usage of resources and the utilization rate of the resources. Resource sharing was also shown to have notable savings potential for this industry. While the focus of these studies was of an economic character, the use of weather data to model the duration and pose restrictions on operations and sailing based on significant wave height, wave direction and wind speed can also be used when modeling operations of service vessels in the aquaculture industry.

As stated in section 1.2, Stemland (2017) studied the long-term operability of a 40 meter long monohull operating at exposed aquaculture locations for his master thesis. The long-term operability was found through use of a discrete-event simulation tool, and real time series data from oceanographic buoys was used to model the sea states, though the short length of the time series were presented as issue. Stemland (2017) emphasized that the method allows for an increase. It was also found that roll motion limits the operation of this specific vessel at the exposed locations. The validity of the simulation model and output were not tested or verified, but the results were explained to provide increased knowledge of service vessel operations in exposed aquaculture and the vessels sensitivity to wave headings and long-term operability.

Using a discrete-event simulation model to evaluate the operability of different vessels in the aquaculture industry is not a common approach according to the literature found. The master thesis of Stemland (2017) is an exception, although he used this process to examined one specific vessel. The method incorporated in this thesis is therefore quite a novel approach to the subject matter.

Chapter 5

Vessel Motion Theory

In order to calculate the motion responses of the three different vessels subjected to the analysis in this thesis, the vessel response program VERES has been used. This chapter is devoted to describe the fundamental theory behind the numerical calculations carried out in VERES. The theoretical framework on which VERES is developed, is based on the traditional two-dimensional strip theory developed by Tuck et al. (1970). The chapter will not go into detail on how the resulting ship motions are found for every degree of freedom of the vessels, but rather give an overview on central terms and equations used to find motion responses of the vessels. The theoretical framework presented in this section is mostly found from ”Sea Loads on Ships and Offshore Structures” (Faltinsen (1990)).

5.1 Strip Theory

Strip theory is a computational method by which the forces on and motions of a three-dimensional floating body can be determined using results from two-dimensional potential theory. In strip theory, the 3-dimensional ship is considered made up by a series of 2-dimensional strips where each strip closely resembles the segment of the ship it represents (Journe and Massie (2001)). Each strip has associated hydrodynamic properties, i.e added mass, damping and stiffness, which contribute to the coefficients for the complete hull in the equations of motions. The calculations for each strip assumes that the hydrodynamical properties are the same as would be experienced if the strip were part of an infinitely long cylinder. The principle of the partitioning of the ship hull is given in figure 5.1

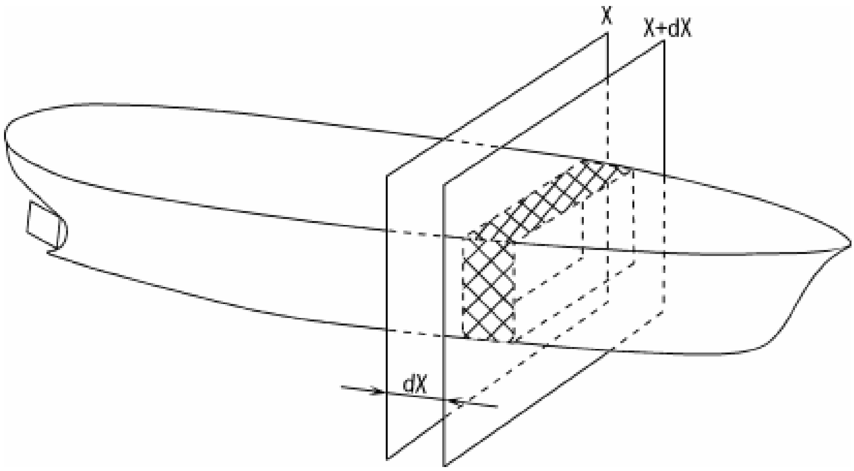

Figure 5.1: 2-dimensional ship segment (Okumoto et al. (2009)).

5.2 Potential Theory

VERES makes use of potential theory for the fluids interacting with the vessels. By that it follows that the fluid is assumed to be homogeneous, incompressible, inviscid and irrotational. A brief explanation of the properties of a potential flow as well as the boundary conditions that has to be satisfied in order to solve potential flow problems follows. Using a Cartesian coordinate system, one can describe the fluid motion by a velocity potential, ϕ. The velocity potential has the property that the velocity component in a point in the fluid can be found as the derivative of the potential function in that specific point and direction (Journe and Massie (2001)). The velocity vector can then be written as in 5.1, with i,j,k being unit vectors along the x-,y- and z axes respectively.

$$V = \nabla\phi = \frac{\partial\phi}{\partial x}i + \frac{\partial\phi}{\partial y}j + \frac{\partial\phi}{\partial z}k \tag{5.1}$$

From the assumption that the water is incompressible, i.e no change in mass in a flow into and out of a control surface, it follows that the velocity potential has to satisfy the Laplace equation given in 5.2.

$$\nabla^2\phi = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{5.2}$$

In addition to satisfying the continuity equation, all potential theory solutions must fulfill the non rotation condition given in 5.3. The fluid is irrotational when the vorticity vector is zero everywhere in the fluid.

$$\omega_v = \nabla^2 \times V = 0 \tag{5.3}$$

For a fixed body in a moving fluid there will be no flow through the surface of the body. This condition represents the impermeability of the body and can be expressed as in 5.4.

$$\frac{\partial \phi}{\partial n} = 0 \tag{5.4}$$

While equation 5.4 expresses the impermeability of a fixed body, e.g the seabed with n representing a normal vector pointing from the seabed and out in the fluid, an equation for a moving body with a velocity U can be generalized as in 5.5.

$$\frac{\partial \phi}{\partial n} = U \cdot n \tag{5.5}$$

Under the assumption of small waves, the fluid particles on the surface is assumed to stay on the free-surface. This is known as the kinematic free-surface condition. Furthermore, the dynamic free-surface condition states that the water pressure is equal to the constant atmospheric pressure on the free surface. By using linear theory under the assumption of small waves, zero current and zero forward speed of the body one can obtain simplified and linearized kinematic, (5.6) and dynamic, (5.7), free-surface conditions.

$$\frac{\partial \zeta}{\partial t} = \frac{\partial \phi}{\partial z} \quad on \quad z = 0 \tag{5.6}$$

$$g\zeta + \frac{\partial \phi}{\partial t} = 0 \quad on \quad z = 0 \tag{5.7}$$

These equations can be combined to obtain the linearized free surface condition as in equation 5.8.

$$\frac{\partial^2 \zeta}{\partial t^2} + g\frac{\partial \phi}{\partial z} = 0 \quad on \quad z = 0 \tag{5.8}$$

5.3 Responses in Regular Waves

The superposition principle makes it possible to obtain reasonable results in irregular seas, by adding linear responses from regular waves Faltinsen (1990). The linearity of the responses indicate that the forces on the ship are proportional to the wave amplitude. Furthermore, it is assumed no transient effects, meaning that the floating structure will harmonically oscillate with the same frequency as the incident waves. Hydrodynamic problems in regular waves are usually dealt with as two sub-problems. These problems involve the *excitation forces* and the *added mass, damping and restoring forces* respectively Faltinsen (1990). For a ship in a seaway, the oscillatory motions will consist of three translations in the x-,y- and z-direction and three rotations about the x-, y- and z-direction respectively. The coordinate system is fixed with respect to the mean position of the ship and η_j represents the motion in each degree of freedom. The coordinate system as well as the translatory and angular displacement conventions are shown in figure 5.2.

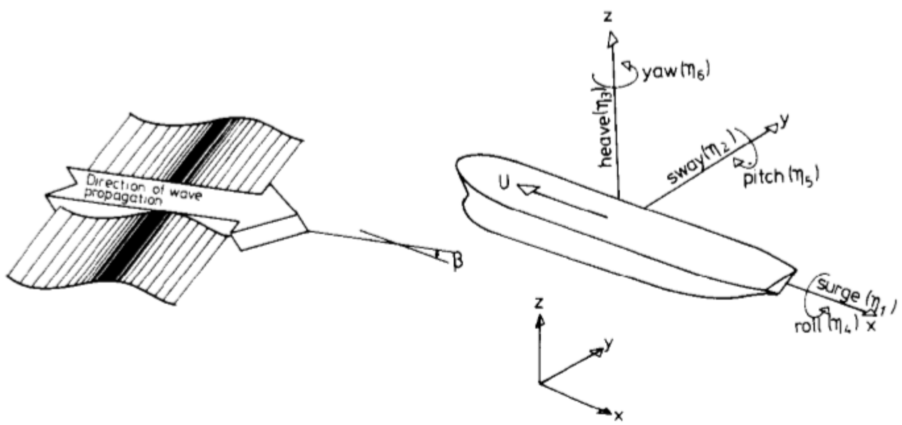

Figure 5.2: Sign conventions for translatory and rotational displacements (Faltinsen (1990)).

5.3.1 Excitation Forces

Assuming the structure is restrained from oscillating and there are incident regular waves, one can find the wave excitation loads which are composed of the Froude-Kriloff forces and diffraction forces. The Froude-Kriloff force can be found from 5.9 considering an undisturbed pressure field caused by the waves. Here, $p = -\rho\frac{\partial\phi}{\partial t}$ is the pressure of a pressure field caused by an undisturbed wave, and n is a unit vector normal on the structure surface defined as positive pointing into the fluid. The Froude-Kriloff is found by integrating the pressure over the mean wetted surface of the body.

$$F_{FK} = -\iint_S pnds \tag{5.9}$$

If one only consider the Froude-Kriloff force there will be a fluid flow through the surface of the body. The diffraction forces are a result of the fact that the pressure field is changed due to the presence of the structure in the fluid. The boundary condition from equation 5.5, tells us that the normal derivative of the diffraction potential has to be opposite and of equal magnitude as the normal velocity of the undisturbed wave system. Assuming a slender structure and long wave lengths, this force can be written as in 5.10. Here, $a_{1,2,3}$ is the acceleration along the x, y- and z-axes of the undisturbed wave field and A_{ij} is the added mass in $i = 1, 2, 3$ from motion in $j = 1, 2, 3$ with reference to the sign convention in figure 5.2.

$$F_{Diffraction} = A_{i1}a_1 + A_{i2}a_2 + A_{i3}a_3 \tag{5.10}$$

5.3.2 Added Mass, Damping and Restoring Terms

Assuming the structure is forced to oscillate with the wave excitation frequency one can find the hydrodynamic loads identified as the added mass, damping and restoring forces and moments. The oscillated motion of the body will generate outgoing waves. The forced motion results in oscillating fluid pressures on the body surface. Integration of the fluid pressure forces over the structure surface gives resulting forces and moments on the body (Faltinsen (1990)). The hydrodynamic added mass and damping loads can be written as in equation 5.11 with A_{kj} as the added mass coefficient and B_{kj} being the damping coefficient.

$$F_k = -A_{kj}\frac{d^2\eta_j}{dt^2} - B_{kj}\frac{d\eta_j}{dt} \quad k, j = 1, 2....6 \tag{5.11}$$

In this equation, A_{kj} and B_{kj} are defined as added mass and damping coefficients respectively. The indexes refer to force in k direction resulting from motion in j direction. The added mass term can be understood as an additional force necessary to accelerate the fluid surrounding the body. As the body oscillates in the water the whole surrounding fluid will also oscillate with different particle amplitudes throughout the fluid (Faltinsen (1990)). The potential damping, B_{kj} origins from wave generation as the body oscillates in the water and the radiated waves withdraws energy from the motion of the vessel.

The restoring forces results from the body not being in equilibrium with respect to the hydrostatic mass force and the buoyancy. Whenever the body is out of its equilibrium position, $\eta \neq 0$, one will have a force acting on the structure as given in 5.12. C_{kj} is the restoring coefficient. For motion in heave this restoring coefficient can be approximated as the change in buoyancy resulting from the ships vertical motion. In pitch and roll restoring forces are dependent on GM_L and GM_T respectively.

$$F_k = -C_{kj}\eta_j \tag{5.12}$$

5.3.3 Viscous Effects in Roll

As described, potential theory assumes the fluid to be homogeneous, non-viscous and incompressible. Viscous effects are in other words not accounted for and the absence of these will induce large roll motion even in small sea states if the potential damping is low. In roll, viscous effects *should* be accounted for since the potential damping from radiated waves is small (Fathi (2017)). For a ship, the roll damping is usually a combination of potential damping from radiated waves and viscous damping resulting from friction on the hull as well as viscous effects due to pressure distributions around the ship (Faltinsen (1990)). For a monohull the pressure distribution around the ship is usually significantly increased with the presence of a bilge keel as this component induce drag forces acting in the opposite direction of the roll movement (Fathi (2017)). In general a catamaran will roll less than a monohull. The roll motion of a catamaran is characterized as one hull heaving up while the other hull heaves down. The transverse motion of the water relative to the hull will therefore be in a vertical direction instead of a radial direction as in the case of the monohull. Fitting bilge keels on a catamaran may therefore not significantly reduce the roll motion (Lamb (2003)).

5.3.4 Equation of Motion

Having established all the force terms and contributions one can finally put them all together to present the equation of motion of the ship. The equation of motion is given as in 5.13 with mass, added mass, damping and restoring forces on the left side and the exciting forces on the right side. The exciting forces are given as the real part of the complex function $F_j e^{i\omega t}$. There will in total be six linear coupled differential equations in accordance with the six degrees of freedom the ship is moving in.

$$\sum_{k=1}^{6} \left[\left(M_{jk} + A_{jk}\right)\ddot{\eta_k} + B_{jk}\dot{\eta_k} + C_{jk}\eta_k = F_j e^{i\omega t} \quad j = 1, ..., 6 \tag{5.13}$$

5.3.5 Natural Periods

When considering motion of a ship in a seaway, the natural periods are important parameters to consider. Large motions can occur if the oscillation periods of the incident waves are close to the natural period of the structure. When assessing the seakeeping and operability of a given ship the combined effect of sea states and ship resonance periods is of interest. In general, there are no uncoupled resonance periods for an unmoored ship in surge, sway and yaw. The uncoupled natural period in heave, pitch and roll is given as in 5.14, 5.15 and 5.16.

$$T_{n3} = 2\pi\sqrt{\frac{M + A_{33}}{\rho g A_w}} \tag{5.14}$$

$$T_{n5} = 2\pi\sqrt{\frac{Mr_{55}^2 + A_{55}}{\Delta g GM_L}} \tag{5.15}$$

$$T_{n4} = 2\pi\sqrt{\frac{Mr_{44}^2 + A_{44}}{\Delta g GM_T}} \tag{5.16}$$

Here, A_{jj} refer to added mass in motion mode j, r_{jj} is the radius of gyration with respect to an axis on which the structure is rotating, and GM_L and GM_T refer to the longitudinal and transverse metacentric height respectively. It is a common design recommendation for ships to select natural periods in roll larger than 10 seconds to make sure that rolling is not a problem in small and moderate seas (Faltinsen (1990)). The natural period in roll is largely dependent on the metacentric height, GM_T and will decrease with a larger second area of moment of the waterline of a hull. The second moment of area is usually significant larger for catamarans compared to monohulls due to the large spacing between the hulls. Therefore, the natural period in roll is usually longer for a monohull compared to a similar sized catamaran.

5.4 Wave Statistics

Irregular waves can be seen as a superposition of a series of sinusoidal waves. The wave elevation of a long-crested irregular sea, propagating along the positive x-axis can be written as the sum of a large number of regular wave components as in 5.17. Furthermore, the instantaneous wave elevation at a given time t is supposed to be Gaussian distributed with zero mean.

$$\zeta(t) = \Sigma\zeta_{a_n} cos(k_n x - \omega_n t + \epsilon_n) \tag{5.17}$$

The irregular wave history, $\zeta(t)$, can be expressed via Fourier series as a sum of a large number of regular wave components, each with its own frequency, amplitude and phase in the frequency domain (Journe and Massie (2001)). This is the basis for the wave energy spectrum where each step in the frequency domain is expressed as in 5.18, with $\Delta\omega$ being a constant difference between successive discrete frequencies. One can multiply this expression with ρg to obtain the energy per unit area of the wave.

$$S_\zeta(\omega_n)\Delta\omega = \frac{1}{2}\zeta_{a_n}^2 \tag{5.18}$$

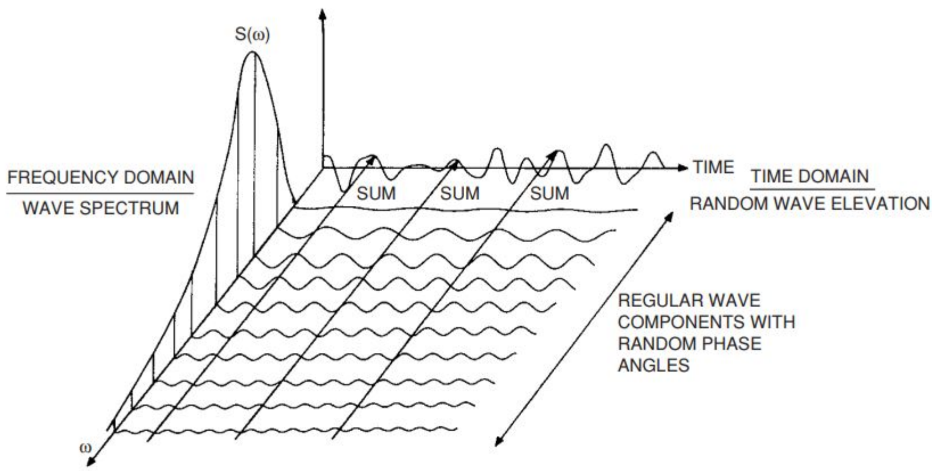

Figure 5.3: Relationship between a random wave elevation in the time domain and the regular wave components in the frequency domain. The sum lines represent how the regular wave elevation at different frequencies add up to give the irregular wave elevation at a time instant (Faltinsen (2006)).

An irregular sea state may be characterized by a standard wave spectrum which can be estimated from wave measurements. A standard wave spectrum assumes that one can describe the sea as a stationary random process, which is a good assumption given that the sea states have the tendency to vary slowly with time. Time periods are usually taken to be between one half and up to ten hours (Faltinsen (2006)). In the literature, there exists a number of different standard spectra that can represent different ocean areas. A brief overview of the different wave spectra available in the software VERES are presented (Fathi (2017)).

The Pierson Moskowitz Spectrum: This spectrum is suitable for a fully developed sea, meaning that the wind has been blowing long enough over a sufficiently open stretch of water, so that the high frequency waves have reached equilibrium.

The Torsethaugen Spectrum: Torsethaugen is a two peaked spectrum which includes both wind generated sea and swell. It includes one peak at a low frequency originating from swell aswell as one peak at a ”normal” frequency from wind generated waves.

The JONSWAP spectrum: JONSWAP is assumed to be especially suitable for the North Sea, and does not represent a fully developed sea state. The JONSWAP spectrum is a generalization of the Pierson-Moskowitz spectrum by inclusion of a ”peak enhancement” factor, γ, which determines the concentration of the spectrum around the peak frequency.

The long-crested irregular wave from 5.17 is rarely encountered at sea. Instead, a certain wave spreading is frequent and interactions between several wave systems coming from different directions results in alternating enhancements and cancellation of wave crests and troughs (Fathi (2017)). The directional wave spectrum can be written as in 5.19, where a cosine power spreading function is added to the spectrum formulation.

$$S_{\varsigma}(\omega, \upsilon) = Dcos^{m}(\frac{\pi}{2\upsilon_{max}}(\upsilon - \mu)S_{\varsigma}(\omega)) \tag{5.19}$$

Here, m is the wave spreading index, as m is increased, the energy concentrates about the primary wave direction. Furthermore, υ represents the wave direction and μ is the predominant wave direction.

5.5 Response Statistics

From the equation of motion in equation 5.13, one can obtain transfer functions by solving for the particular solution of the second order differential equations. This function can be found by solving the equations numerically for $\eta_k = \tilde{\eta_k} e^{i\omega t}$, where $\tilde{\eta_k}$ is the complex motion amplitude (Fathi (2017)). The transfer function is expressed as the ratio of response amplitude per amplitude of excitation as a function of the wave frequency. It is given as in 5.20.

$$|H(\omega)| = |\frac{\eta_k}{\zeta_a}(\omega|) \tag{5.20}$$

The linear theory used to calculate the ship response assumes that the wave-induced motion and load amplitudes are linearly proportional to the wave amplitude, ζ_a. This is useful as one can obtain results in irregular seas by adding together results from regular waves of different amplitudes, wavelengths and propagation directions (Faltinsen (1990)). Having found both the transfer function and the wave spectrum, one combine them as in equation 5.21 to obtain the response spectrum of the vessel in a given degree of freedom as a function of the wave frequency. The figure in 5.4 shows the transition from a wave spectrum and a transfer function to a response spectrum. The last figure gives the response for all frequencies in the wave spectrum. The responses will be high when the peak frequency of the wave spectrum is close to or matches the peak frequency of the transfer function. The peak of the transfer function corresponds to the natural frequency of the vessel and the transition underlines the importance of considering the natural frequencies when designing a vessel for specific sea areas.

$$S_R(\omega) = |H(\omega)|^2 S_\zeta(\omega) \tag{5.21}$$

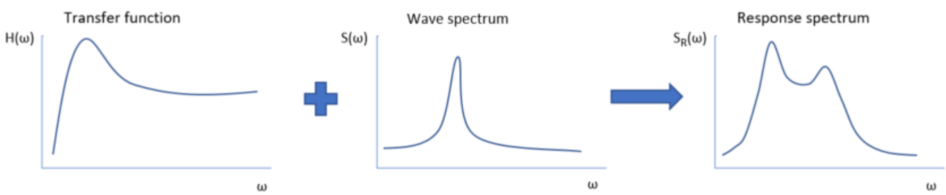

Figure 5.4: Principle procedure to obtain the response spectrum $S_R(\omega)$.

From the response spectrum one can calculate spectral moments to obtain statistical properties of the spectrum. The square root of the zeroth order moment of the response spectrum, m_0^η, corresponds to the standard deviation of the response, σ, and is equal to the root mean square (RMS) of the response for a zero mean process (Fathi (2017)). The RMS of velocity and acceleration are found from the square root of the second and fourth order moment of the response spectrum. The equation for calculating the moments of the response spectrum is given in 5.22.

$$m_k^\eta = \int_0^\infty |\omega|^k |H(\omega)|^2 S_\zeta(\omega) d\omega \qquad k = 0, 2, 4.. \tag{5.22}$$

Chapter 6

Principles for Assessing Vessel Operability

Service vessels for the aquaculture industry are historically designed to operate in a protected environment inside the fjords. As the recent expansion of the aquaculture industry leads the industry into more harsh and hostile waters, it follows that requirements given to vessels in order to successfully perform operations are sharpened. According to Fonseca and Soares (2002), the operability of a ship can be defined as the ships ability to carry out its intended operation safe and effectively. In this context, the operability of the ship in still water is taken as the standard of reference, and the amplitude of motions and accelerations resulting from wave motions degrade the vessels probability of successfully completing its operation. The requirements of a ”safe and effective” operation can differ depending on which requirements are set for each specific operation. Of primary importance for a service vessel for the aquaculture industry is the efficiency and safety of personnel and equipment. As a service vessel in the aquaculture industry has a limited number of personnel, any reduction in performance capabilities of either personnel or equipment will significantly reduce the vessels operational effectiveness.

The design of service vessels in the Norwegian aquaculture industry is in general covered by the Norwegian Maritime Authority, through the *Regulations on construction and supervision of small cargo ships* (Lovdata (2015)). The regulation sets requirements on the vessels construction, stability criteria and documentation, freeboard, machinery and electrical installations, fire safety and supervision during construction, reconstruction and comprehensive repairs. Meanwhile the safety of the personnel is covered by *Arbeidsmiljøloven* as aquaculture involves a combination of both work on land as well as work sea (Arbeidstilsynet (2014)). These regulations do however not require an operability analysis in the context analyzed in this thesis, and it is not within the scope of this thesis to take these regulations into account.

To assess the vessels operability, the vessels capabilities to perform operations can be evaluated by considering the ship motion with respect to different motion limits. Several criteria are proposed in literature based on different responses such as displacements, velocities and accelerations of the vessels motion in its six degrees of freedom. These criteria are based on general experience, good practice or/and systematic trials. "Seakeeping Performance of Ships", a joint Nordic research project coordinated by NORDFORSK (1987), aimed at establishing a Nordic standard for seakeeping criteria and methods to evaluate motion characteristics. The intention was to make it possible to compare different designs and to improve their seakeeping characteristics. The project presents a variety of different criteria either found from previous research and in some cases from research performed by the participants during the project. A review of the different criteria available in literature is presented in the next section.

6.1 Relevant Criteria

In this section, different criteria for ship motion are presented. In addition, theory on how they are calculated as well as comments on how they can impact an aquaculture operation are included. The implementation as well as the choice of final limits will be presented in chapter 8.

6.1.1 Relative Motions Between the Ship and the Wave

When assessing the seakeeping qualities of a ship, deck wetness and bottom slamming are important factors to take into account. The occurrence of these events are directly governed by the relative motion between the vessel and the free surface motion of the seas. The relative motions at a position (x, y, z) on the vessel are calculated as in 6.1 where η_{3r} is the complex amplitude of the relative motion, $\eta(x, y, z)$ is the complex amplitude of the vessel motion and $\zeta(x, y)$ is the undisturbed wave elevation at the given position (Fathi

(2017)).

$$\eta_{3r}(x,y,z) = \eta_3(x,y,z) - \zeta(x,y) \tag{6.1}$$

Deck wetness: Deck wetness, also known as green water, is defined to take place when at a particular station the amplitude of vertical relative motion between the deck and the waves exceeds the freeboard of the vessel. When the wave exceeds the freeboard, an amount of sea water might flow on to the deck. This causes interruptions to the work carried out on deck, and might impose danger both with respect to personnel and equipment. Deck wetness is calculated as a limiting significant wave height, H_s^{lim}, due to the probability of green water on deck as in equation 6.2. Here, P_{dw} is the permissible probability of deck wetness, F is the freeboard at the point of interest and g_r is the RMS value of the relative vertical motion per meter significant wave height.

$$H_s^{lim} = \frac{F}{g_r\sqrt{-2ln(P_{dw})}} \tag{6.2}$$

Slamming: The phenomenon of bottom slamming occurs when a ship bottom hits the water with a high velocity. This causes impulse loads with high pressure peaks, introducing hazards related to ship hull (Fathi (2017)). The probability of slamming is highest in the fore part of the ship where the relative velocity between the ship and the waves is largest (Faltinsen (1990)). From NORDFORSK (1987) the criterion is defined as a permissible probability of occurrence based on an Ochi type (Ochi (1964)) critical re-entry velocity as given in equation 6.3. Here g is the acceleration of gravity and L is the length of the ship. The limiting significant wave height is calculated as in equation 6.4, with P_s being the permissible probability of slamming, d is the local draft at the specified measuring point and g_r and g_{rv} is the relative vertical motion and velocity respectively.

$$V_{cr} = 0.093\sqrt{gL} \tag{6.3}$$

$$H_s^{lim} = \sqrt{\frac{1}{2ln(Ps)}\Big(\frac{d^2}{g_r^2} + \frac{V_{cr}^2}{g_{rv}^2}\Big)} \tag{6.4}$$

6.1.2 Human performance

Depending on the mission of the ship, the ability of the personnel to carry out a particular job may be critical for the operability of the ship. For calculating the operational index, it is assumed the work is discontinued when the ship motion exceeds a certain limit (Fonseca and Soares (2002)). In literature, there exists different limiting criteria with regard to safety and working efficiency of personnel on board. For a service vessel, these criteria will be defined from the point of view of safety, comfort and working efficiency of personnel.

6.1.3 Roll, Vertical Acceleration and Lateral Acceleration

Translatory and rotational motion may cause danger to crew or lead to damage on equipment on board a vessel. When evaluating the different criteria in relation to service vessels in the aquaculture industry, it is not only human aspects such as manual work that has to be considered. Rapid movements or large displacements will also cause trouble for cranes and equipment on board a vessel. The general criteria regarding roll, vertical acceleration and lateral acceleration are given in table 6.1.

Table 6.1: General motion criteria according to NORDFORSK (1987)

Vertical acceleration	Lateral acceleration	Roll	Description
0.20 g	0.10 g	6.0°	Light manual work
0.15 g	0.07 g	4.0 °	Heavy manual work
0.10 g	0.05 g	3.0°	Intellectual work
0.05 g	0.04 g	2.5°	Transit passengers
0.02 g	0.03 g	2.0°	Cruise liner

These motion limits are recommended based on the RMS of the response of the vessel, σ_R. From the response spectrum in a given sea state the maximum significant wave is calculated as in equation 6.5, with $g_x = \frac{\sigma_i}{H_s}$ being the short term statistical value of response per meter wave height (Fathi (2017)).

$$H_{S_{max}}(T_z, \beta) = \frac{\sigma_{cr}}{g_x} \tag{6.5}$$

6.1.4 Motion Sickness

The term ”motion sickness”, in a ship context known as sea sickness, is understood as a sickness due to ship motions that result in physical discomfort with related symptoms such as irregular breathing, nausea, fatigue and vomiting, consequently leading to performance degradation (Cepowski (2012)). The reason behind sea sickness is believed to be lack of conformity between different stimuli, eye signals and the labyrinth (inner ear), received by the human brain. Pioneering work on the topic of motion sickness by O‘Hanlon and McCauley (1974) found that periodic vertical motion was the main sickness cause. In the context of operability of ships it is critical that the personnel has the ability to carry out their work properly, thus motion sickness incidence should be kept to a minimum.

Motion sickness is believed to take place at frequencies below $0.5Hz$ and findings in the report of O‘Hanlon and McCauley (1974) has indicated that even moderate accelerations at a frequency of $0.2Hz$ should be avoided as these produces the highest incidence of motion sickness. According to ISO 2631-1:1997 (1997), the probability of occurrence of motion sickness symptoms increases with increasing duration of motion exposure up to several hours. Over longer periods adaption to the motion occurs.

In ISO 2631-1:1997 (1997), motion sickness incidence (MSI) is measured from a motion sickness dose value which is defined such that higher values correspond to a greater incidence of motion sickness. The motion sickness dose value is estimated from the frequency weighted RMS value of vertical accelerations multiplied with the square root of the exposure duration as in 6.6. The frequency weighting accounts for the fact that motion sickness is occurring more often at certain frequencies.

$$MSDV_z = a_{zw}\sqrt{T_0} \tag{6.6}$$

$$MSI = K_m \cdot MSDV_z \tag{6.7}$$

The motion sickness is defined in ISO 2631-1:1997 (1997) as the percentage of people who may vomit and is given as in 6.7. Here, K_m is a constant which may vary depending on the exposed population. For a mixed population of unadapted male and female adults, $K_m = 0.33$.

6.1.5 Motion Induced Interruptions

A motion induced interruption, (MII), is defined as an incident where the accelerations due to the ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their task to make a postural adjustment in order to remain upright (Crossland and Rich (1998)). The criterion is both relevant for safety with respect equipment as well as personnel during operations. The motion induced interruptions is calculated as in 6.8 using the concept of a lateral force estimator (LFE), which is the lateral acceleration perceived in the plane of the ships deck by an object or a person (Fathi

(2017)). In the formula, $\ddot{\eta_2}(x, y, z)$ is the vessel acceleration in sway, and $g\eta_4$ represents the acceleration of gravity induced by the inclination, η_4 of the vessel in roll. As a result the LFE can be seen as a combination of deck inclination due to roll and lateral acceleration.

$$LFE(x, y, z) = -\ddot{\eta_2}(x, y, z) - g\eta_4 \tag{6.8}$$

In order to quantify MII as a seakeeping criterion, Graham (1990) suggested that a limit number of motion induced interruptions per minute during deck operations was most suitable. The MII risk levels are included in table 6.2.

Table 6.2: MII risk levels

Risk Level:	1.Possible	2.Probable	3.Serious	4.Severe	5.Extreme
MII‘s per minute:	0.1	0.5	1.5	3.0	5.0

6.2 Long-term Operability of a Vessel

In numerical terms, the operational effectiveness can be described as the *”proportion of time the ship can successfully accomplish its mission in a given combination of sea areas and seasons”* (LLoyd (1989)). The quantitative measurement is commonly given as a percentage of time of operation known as the operational index (NORDFORSK (1987)). Following the procedure of last section, the operational capability is given in terms of ship motion limits. When the ship responses exceed the limiting criteria the operations cease. The limits are however based on short term statistics of the response and is based on a given sea state. The duration of a given sea state is usually taken to be in between one half and up to ten hours (Faltinsen (1990)). In order to calculate long term statistics of a vessels operability one can make use of scatter diagrams in order to have information on how the sea state changes over time. The scatter diagram provides the joint probability of significant wave heights and characteristic periods over a long period, ranging from a season and up to several years. If the response functions are known for several speeds and headings, one can include a scatter diagram to calculate the long term operability of a vessel. In the end one can find the percentage operability for a given speed (V) and heading (μ) in accordance with equation 6.9 .

$$P_o(V, \mu) = \Sigma P(T_j; V, \mu)(Q(T_j)) \tag{6.9}$$

Here, P is the probability of significant wave height not exceeding the operability limiting value. $P(T_j; V, \mu)$ is the joint probability of successfully operating in a sea state with period T_j and wave direction μ at the given speed V, and Q is the percentage of wave observations with period T_j. The method allows for a weighting of wave headings to account for probabilities regarding the expected headings of the waves in the sea areas of interest. The method described is implemented in the VERES post-processor. This method can be suitable for a merchant ship, sailing a pre-desired route in a specific sea area. In that case, the probabilities and weightings are easily obtainable based on expected wave headings for the specific route of focus. However, in order to better capture operation specific details of an aquaculture operation, the analysis in this thesis is carried out using a discrete-event simulation tool. In the discrete-event simulation, the operation of the vessels are simulated on an hour to hour basis considering location specific time series data as well as the pool of operations presented in section 2.4.1. Distinctions between each operation can be made by including duration, orientation towards the wave and speed for each operation. In the next chapter, the underlying simulation theory will be presented, while the implementation of specific operation in the simulation model will be presented in chapter 8.

Chapter 7

Simulation Theory

A simulation is the process of using a computer to imitate the operation of various real-world facilities or processes, called a system, which in this thesis, is the work flow of a service vessel in the aquaculture industry. To study the system and it's behaviour scientifically, a set of assumptions on how it works must be made that together constitute a model. A simulation evaluates a model numerically, and gathers data in order to estimate the true characteristics of the model. A simulation is useful when the complexity of the system in question is of such a degree that the model must be based on too many assumptions for there to be a mathematical method that can obtain the exact information of interest, called an analytically solution. This accounts for most real-world systems, and a simulation is therefore often needed (Law and Kelton (2007)).

The applicable areas of simulations are numerous and varied. With some of the areas presented bellow (Law and Kelton (2007)):

- Design and analysis of manufacturing systems
- Evaluation of new military weapon systems and tactics
- Designing and operating transportation facilities such as ports, freeways, subways and airports
- Analyzing financial and economic systems

The collection of variables necessary to describe a system at a given time, in regard to the objectives of a study constitutes the state of a system. Law and Kelton (2007) categorizes systems into two types, *discrete* and *continuous*. A discrete system is a system where the state variables change instantaneously at separated points in time. A continuous system on the other hand is a system where the state variables change continuously with respect to time. There are few systems that are fully discrete or fully continuous which also applies to the system examined in this thesis, but a system can usually be classified as one or the other since one is often more dominant. They further divide simulations into three other dimensions.

- Static vs Dynamic Simulation Models: In a *static* simulation model, time does not influence the model. A *dynamic* simulation model however, changes over time.
- Deterministic vs Stochastic Simulation Models: If a system implements random variables, it will be a *stochastic* simulation model, while the opposite(no random variables) will define a *deterministic* simulation model.
- Continuous vs Discrete Simulation Models: The difference between these two simulation models can be made in accordance with the definition of continuous and discrete systems stated above. However a discrete system does not necessarily need to be modeled as a discrete model, and vice versa. This depends on the specific objective of a given study.

When creating a simulation model it is also important to attempt to validate the model as a simulation is an attempt to imitate an actual system (NTNU (2016)). If possible, the system should be compared to the real system it is trying to simulate. By changing certain parameters one can see if the output also changes as expected. The data supplied to the model also has to be reliable, and improper statistical distributions can lead to unreliable data. As Campuzano and Mula (2011) put it: A model cannot be better than the information entering it. Campuzano and Mula (2011) also mention other important aspects of simulation modeling:

- Do not construct a complicated model but a simple one that works.
- A model must never be put under pressure to do, or be criticized for not doing, that which it has never been devised for.
- A model must never be considered literally.
- Models cannot replace decision makers.

Regarding the model created in this thesis, the model can be viewed as a dynamic, and discrete, often referred to as a discrete-event simulation. The model is also stochastic due to the implementation of stochastic variables that govern the rate of the generation of service vessel operations. A discrete-event simulation is defined as the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time (Law and Kelton (2007)). These points are referred to as an *event*. This representation is evidently an approximation of reality, since real physical variables cannot change instantaneously. Discrete-event models is however efficient in making the model more manageable and to speed-up the simulation significantly (Murray-Smith (2015)).

Chapter 8

Methodology

This chapter presents the methodology used to evaluate and quantify the operability of the three different vessels presented in chapter 2. The procedure of calculating short term statistics and obtaining operability limiting curves from VERES is presented in section 8.1. This includes specification of vessel particulars as well as quantification of seakeeping criteria. In section 8.2 the method of approach to obtain the long term operability will be presented. This includes a description of the input data and a detailed run-through of the simulation model.

8.1 Seakeeping Performance Calculations in VERES

The calculations of motion characteristics have been carried out in VERES. The basic calculation procedure follows the steps in figure 8.1 and the calculations generally follow the theoretical framework presented in chapter 5. The next section will give a detailed overview on the calculation steps carried out in order to obtain operability limiting boundary curves in VERES. It should be mentioned that VERES is suited for motions of free floating bodies, and a simplification is therefore made so that any mooring or towing gear will not change the motion characteristics of the vessel. Furthermore, the program is based on the linear strip theory presented in chapter 5 and does not take into account the effects of wind and current in the analysis. Lastly, the vessel motions are only calculated for zero forward speed.

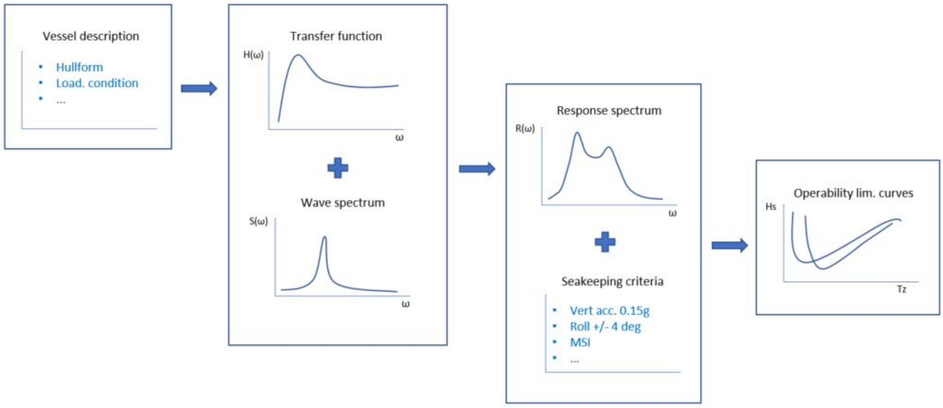

Figure 8.1: General procedure to find operability limiting boundaries in VERES.

8.1.1 Vessel Description

Before running computations in VERES a set of vessel parameters have to be specified. For the three vessels subjected to this analysis, three geometry files are collected and imported to the program. These do not include the loading conditions of the ship, and these are specified based upon data collected from stability reports for Vessel 2 and 3 and information from co-supervisor Ørjan Selvik for Vessel 1. The loading conditions for Vessel 2 and Vessel 3 are specified as ”ballast loading condition”, a loading condition close to the design water line. Meanwhile only the condition ”Max load” was supplied for Vessel 1. The particulars of the vessels in their given loading conditions are as presented in table 8.1.

Table 8.1: Vessel particulars at loading condition ”ballast departure” for Vessel 2 and Vessel 3 and loading condition ”Max load” for Vessel 1

Vessel:	**Vessel 1**	**Vessel 2**	**Vessel 3**
Lpp	24.370 [m]	24.99 [m]	37.870 [m]
Breadth	11.920 [m]	12.99 [m]	12.0 [m]
Draught	2.70 [m]	3.399 [m]	3.335 [m]
Mass	393 [t]	475 [t]	929 [t]
VCG	4.358 [m]	4.496 [m]	3.021 [m]
GM_T	5.134 [m]	5.810 [m]	3.528 [m]

In addition, Vessel 2 has been evaluated at two additional loading conditions seen in table 8.2. Evaluating and comparing different loading conditions for all three vessels would be preferable, Vessel 2 was however the only vessel where stability reports at different loading conditions were available. As the only loading condition for Vessel 1 was "Max load" this is included in the additional loading conditions to make a comparison more impartial.

Table 8.2: Additional loading conditions for Vessel 2

Loading condition	**Max load**	**No Load**
Draught	3.698 [m]	2.870 [m]
Mass	536 [t]	368 [t]
VCG	4.325 [m]	4.107 [m]
GM_T	5.321 [m]	7.78 [m]

The mass moment of inertia of the vessels are specified by the radii of gyration about the center of gravity. These are not known beforehand for the ships in this analysis. The values are specified in accordance with table 8.3. According to Fathi (2018), both the radius of gyration in pitch and yaw have typical values of $0.25L_{pp}$ for catamarans and monohulls. Furthermore, the radius of gyration in roll is recommended to be $0.45B$ for a catamaran and $0.35B$ for a monohull. The larger radius of gyration for the catamarans is a result of the large spacing between the hulls of a catamaran.

Table 8.3: Typical values for the radius of gyration

Value	**Description**	**Typical values**
r_{44}	Radius of gyration in roll [m]	0.3B-0.45B
r_{55}	Radius of gyration in pitch [m]	$0.20L_{pp} - 0.30L_{pp}$
r_{66}	Radius of gyration in yaw [m]	$0.20L_{pp} - 0.30L_{pp}$

8.1.2 Transfer Function

Having imported ship geometries and defined all relevant ship parameters, a calculation of all relevant ship response transfer functions can be carried out. The responses found here are for regular waves, and the transfer functions are calculated for all wave directions

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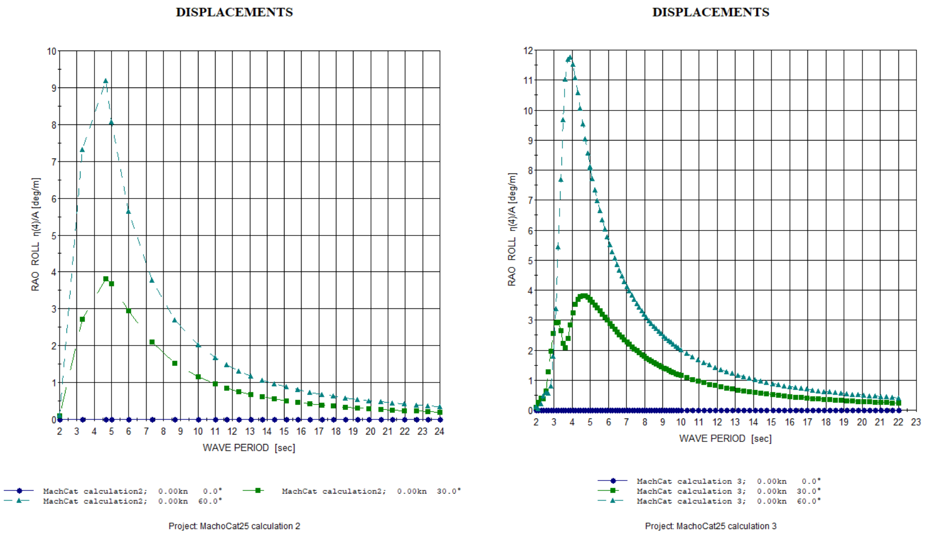


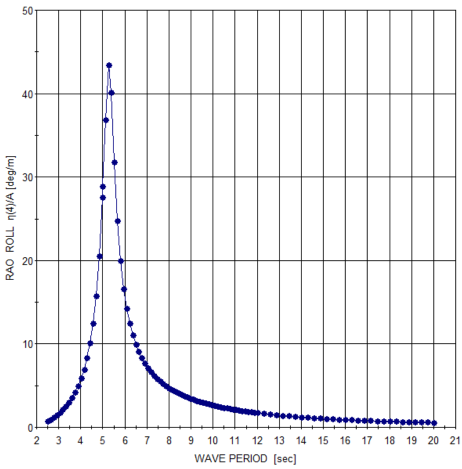
(a) Roll motion with low resolution

(b) Roll motion with high resolution

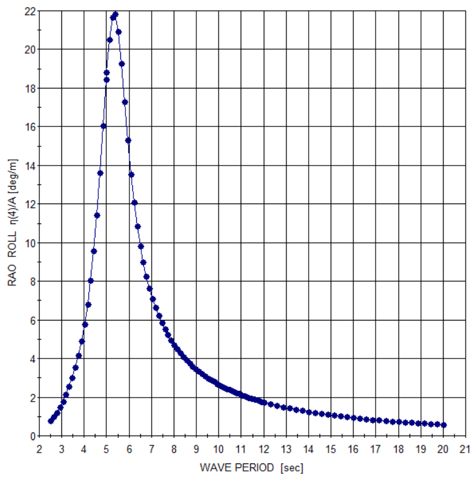
Figure 8.2: Wave period resolution

between head seas and following seas. In order to calculate the responses in a precise manner it is important that the wave period resolution is sufficiently good. This is especially important in wave periods close to the natural period of the ship where one can have resonant periods. This is exemplified in figure 8.2, where a case of too few wave periods is compared with a case of sufficient number of wave periods. It is evident from the figure that when the wave period is at approximately 4 seconds, there is a cancellation effect occurring at a heading of 30°. Due to the low wave period resolution in figure 8.2a this effect is ignored, while it is evident in figure 8.2b. The interval between each wave period has therefore been set higher close to the resonance periods of the vessel in order to capture such effects.

In addition, as the potential damping in roll is low, especially for the monohull, it is of importance to include viscous effects in order to get reasonable results. This is possible for both the monohull and the catamarans in VERES. For Vessel 3 which is a monohull, bilge keels should also be included to present a more accurate representation of the vessels performance in roll. The locations of the bilge keels for Vessel 3 were selected based upon 3D drawings from Autocad, and then created using the built-in auto generate function for placing bilge keels in VERES. As is evident from figure 8.3, the effect of including viscous effects and bilge keels reduces the roll motion approximately 50 % at resonance periods in the case of Vessel 3.



(a) Without bilge keels



(b) With bilge keels

Figure 8.3: Roll motion of Vessel 3 with and without bilge keels

8.1.3 Wave Spectrum

The regular waves on which the transfer functions are based will not exist in a sea environment. Both the wave amplitude and the wave period will vary and change over time and is referred to as irregular waves. The sea state is usually characterized by a standard wave spectrum and the wave spectrum expresses the distribution of wave energy at different frequencies. In literature there exists a variety of different spectra for different sea areas and a short description of the spectrum available in VERES can be found in section 5.4. The seakeeping analysis is carried out for two sites located in coastal areas considered as somewhat protected waters with limited fetch. According to Australian Defence Force (2003), the JONSWAP spectrum is considered to be suitable for coastal operations, given that the spectrum represents conditions that may be encountered in sea areas with limited fetch. The same recommendation follows from ANEP-11 (1983), recommending the JONSWAP spectrum with a peak enhancement factor, $\gamma = 3.3$ and a spreading function of $90°$. For calculating short term statistics, it is important to make sure that a sufficient number of wave headings are applied to give a good resolution of the wave spreading function. In consistency with this, a wave spreading of $15°$ has been applied in the analysis. The spectrum parameters applied in the calculations are listed in table 8.4.

Peak enhancement factor γ	3.3
Wave spreading angle	$\pm 90°$
Resolution between wave headings	$15°$

Table 8.4: Wave spectrum input parameters.

8.1.4 Seakeeping Criteria

Location of working stations and measuring points

Criteria of acceptable levels of ship motion are set at specific locations on the ship and the locations have different requirements according to the subsystem of the ship at focus. It is considered convenient to have a "standard" set of working stations and measuring points established on all three vessels for the calculations to be comparable. On the ships there have been defined two locations to evaluate the responses on the working deck, one point on midship side and one point at the forward perpendicular. According to the master on Vessel 1 (Contact-1 (2018)), there is no specific location on the working deck where most of the operations take place, so it has been decided to evaluate these two distinct locations far off the center of gravity, where one can expect that high responses are taking place. In addition, one working station is located on the bridge. While these locations represent working locations of the crew, other points have been applied to capture the incidence of green water and slamming. The evaluated points and their corresponding seakeeping criteria as well as a figure showing the locations are found in table 8.5 and figure 8.4 and 8.5.

Table 8.5: Location of points and corresponding criteria

Working station	**Location**	**Criterion**
WS1 (1)	Midship side	Heavy manual work, MII & MSI
WS2 (2)	AP side	Heavy manual work, MII & MSI
Bridge (3)	Bridge	Light manual work & MSI
Midship side (4&5)	Midship SB/PS bulwark	Green water
AP (6)	AP Working deck	Green water
FP (7)	FP baseline	Slamming

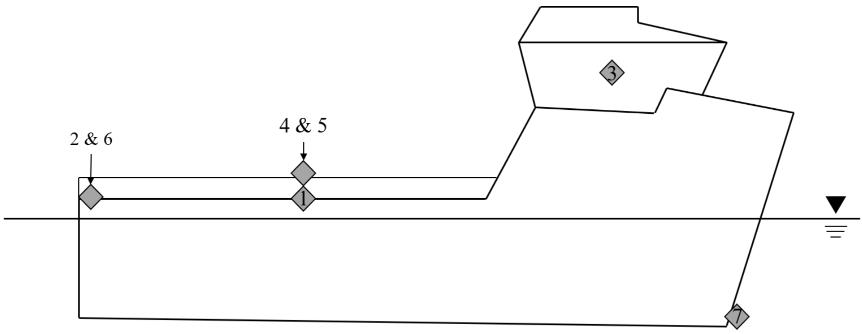


Figure 8.4: Starboard side view of the locations of the evaluated points on a generic vessel.

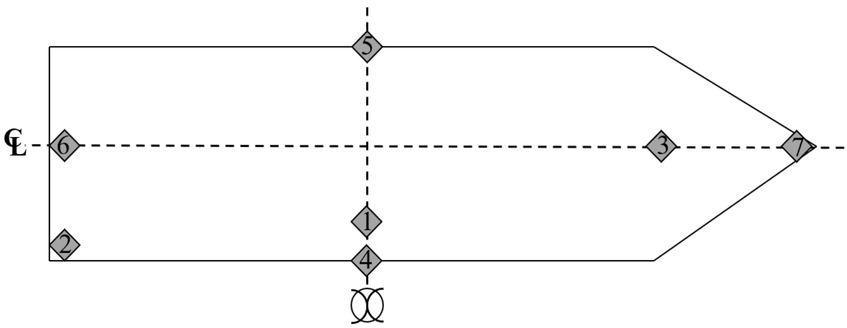


Figure 8.5: Birds eye view of the locations of the evaluated points on a generic vessel.

Criteria

In order to assess the seakeeping performance of the vessels, the criteria defined in section 6.1 are quantified and applied to all ships in the comparative study. The criteria are quantified in compliance with recommendations found in literature, although some subjective considerations based on conversations with industry contacts have been made for some criteria. The criteria applied to the vessels will essentially be the same but some minor considerations with respect to the specific design will be pinpointed. During operations there will be made no distinction between each criteria, meaning that all criteria are equally weighted and of equal importance when investigating the total operability of the vessels.

The criteria for **slamming and green water** follow the recommendations proposed in NORDFORSK (1987), i.e having a probability of 0.03 and 0.05 respectively. These criteria should be treated with care, as their validity are related to the position where they are measured. This is a result of the fact that they are measured as a relative motion between the ship and the wave and that the presence of the wave distorts the wave as it passes through the ship. The slamming criteria is measured at the forward perpendicular (FP), and is mostly relevant in head sea. The green water criteria is measured at three different positions on Vessel 2 and Vessel 3, at midship on both port- and starboard side and at the aft perpendicular. On Vessel 1, green water is only measured at port side and aft perpendicular due to a superstructure on starboard side providing a much higher freeboard.

Further criteria regard seakeeping limits related to crew performance on deck and on the bridge. The service vessels unstable nature impose danger to the crew and as found in Holen (2017a), crane operations, crush and fall were the most common sources of injury modes. This underlines the importance of applying accelerations and displacements as criteria for service vessel operations. A variety of different criteria related to crew operations are presented in section 6.1.4. **The lateral accelerations, vertical accelerations and roll** in the working stations on the working deck, WS1 and WS2, are chosen in accordance with the NORDFORSK (1987) criteria for heavy manual work on board fishing vessels. For the bridge, NORDFORSK (1987) recommends applying criteria in accordance with limits set for intellectual work on the bridge. However, the intellectual work criteria is considerably lower compared to heavy manual work and will consequently give lower operability of the ship. Interviews with the master on board Vessel 1 revealed that the masters role during an operation at zero forward speed was mostly limited to supervision (Contact-1 (2018)). Based on this information the criteria for acceleration and displacements on the bridge is set to be in compliance with the criteria for light manual work. The numerical RMS limitations for accelerations and roll displacements at different locations on the ship are presented in table 8.6.

Table 8.6: Vertical acceleration, lateral acceleration and roll limits

Criterion	**Location**	**RMS**
Vertical acceleration	WS1 and WS2	$0.15g$
	Bridge	$0.20g$
Lateral acceleration	WS1 and WS2	$0.07g$
	Bridge	$0.10g$
Roll	WS1 and WS2	4°
	Bridge	6°

The motion sickness incidence (MSI) criteria according to ISO 2631-1:1997 (1997) depends on three parameters. The first parameter is the exposure time of the operation. This has been set under an assumption that a crew member will remain in the same location for maximum 3 hours for each operation. Furthermore, one has to determine the percentage of crew who is seasick after this exposure period. STANAG 4154 (2000) recommends that the limit is set to be 20% for navy personnel, although it is stated in the standard that acclimated crew will experience less motion sickness. From section 6.1.4, the constant K_m is 0.33 based on a mixed population of unadapted male and female adults. To account for possible habituation and adaptability of the crew, this limit is set to be 0.2 in the VERES calculations.

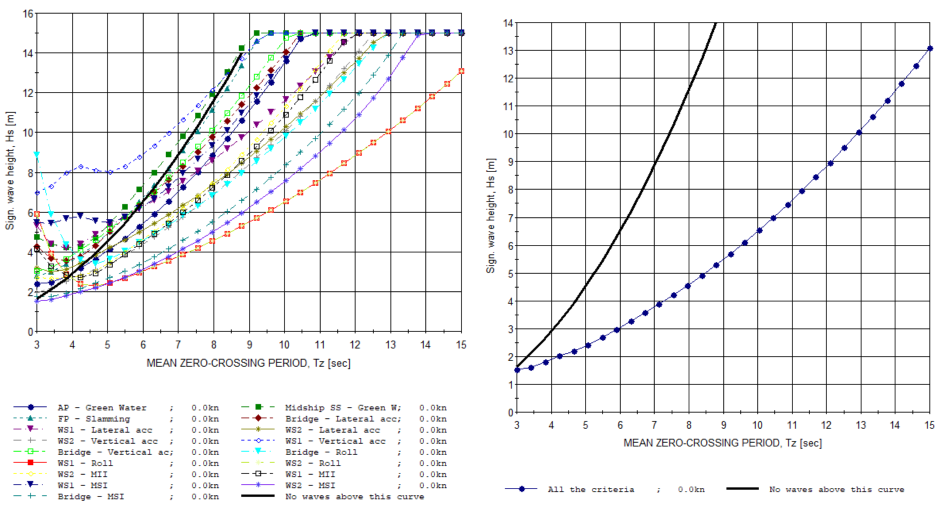
Table 8.7: MSI parameters

Exposure time	3 hours
Seasickness limit	20 %
K_m	0.2

Although criteria regarding ship motions like roll, vertical and lateral acceleration has been used in seakeeping for a long time, they do not necessarily describe the motion and forces a person experience correctly. **Motion induced interruptions** (MII) takes into account the combined effect of ship motions and gravity. Graham (1990) found that a limiting number of MIIs during a specific deck operation was a good criterion for measuring operability with respect to crew performance. In the article he proposes that a deck operation is substantially degraded when the number of MIIs exceed one per minute. This recommendation has been used in the calculations.

8.1.5 Operational Limiting Boundaries

From the short-term statistics one can derive displacements, velocities and accelerations on different positions of the ship. Combining these with the seakeeping criteria from the previous sections will yield the operational limiting boundaries. These data are presented as limiting significant wave height [Hs] as a function of the mean zero-crossing period [Tz] and can be found for all headings specified in the program. The figure in 8.6 shows an example when all criterias are applied, (8.6a), and the resulting operability limiting boundary, (8.6b), based on all the applied criteria. The plots with the resultant criteria provide the input for the calculation of the long term operability and based on these the vessel can be in one out of two possible states; operable or in-operable. The area under the graph corresponds to an operable state while the area over the graph corresponds to an in-operable state. The black line evident in both figures corresponds to the theoretical limit of breaking waves.



(a) All criteria

(b) Resulting criteria

Figure 8.6: All criteria and resulting criteria for Vessel 1 at 45° wave heading.

8.2 Simulink Simulation Model

This section will go into detail of how the discrete-event simulation model created in Simulink is set up, how entities flow through the system, and how the inputs and outputs to and from the system are handled. This section will generally follow the same order as seen in figure 8.7. First showcasing the input data and how the different operations are emulated, followed by a detailed run-through of the simulation, and then presenting information regarding the output from the model. A high-level overview of the work flow in the simulation is however presented first so that the reader can put the model information into context. The following explanations will include terminology that requires some prior knowledge of Simulink or other similar programs. Readers inexperienced with Simulink are encouraged to read appendix G for a basic recap of Simulink terminology relevant to the model created in this thesis.

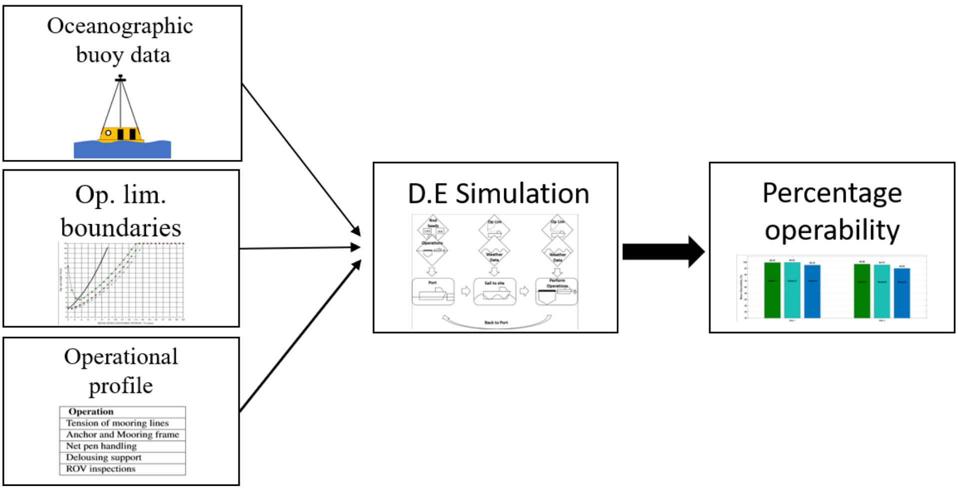


Figure 8.7: Graphical illustration of how the flow of data culminates in operability results.

8.2.1 Overview of Simulation

The model aims to simulate the hour-to-hour work flow of a service vessel in the aquaculture industry over a given time interval. The operability of the given vessels is examined by taking into account given operational limits of the service vessel produced in VERES. These limits are cross-referenced with the conditions received from the oceanographic buoys at the site at a given time.

To simplify the explanation of the system, a high level illustration has been created, shown in figure 8.8 below. The large squares in the illustration represent the three main processes that take place, while the diamond shapes represent the input data used to complete these actions. By implementing different service vessels into the simulation model, the long term operability of the different vessels can be determined and compared.

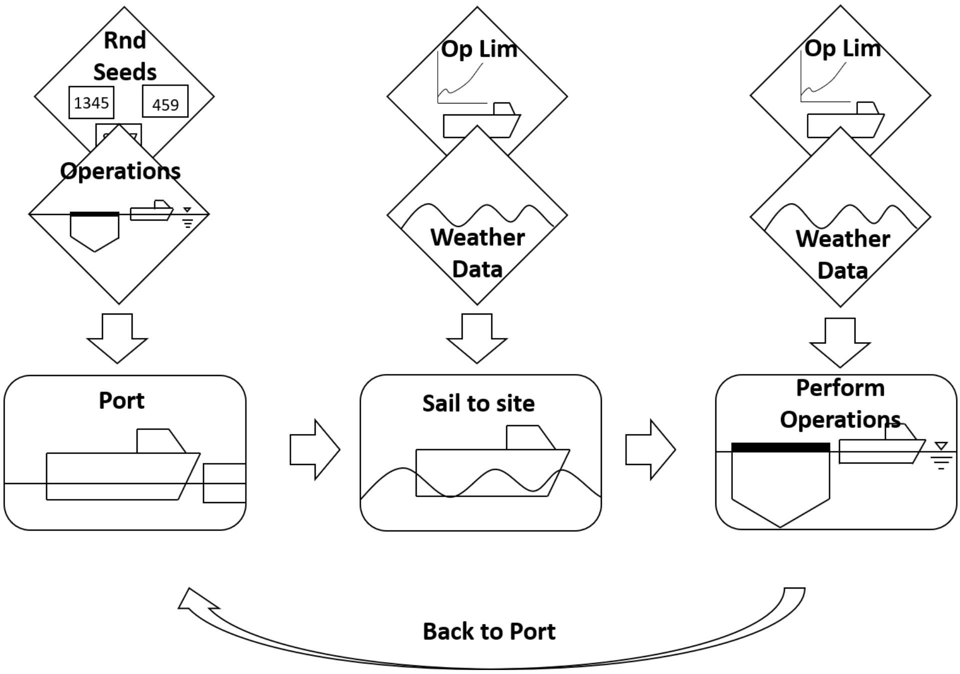


Figure 8.8: High level illustration of the work flow of the simulation, showcasing the main processes and input data for each of these

At the start of the simulation, an *entity* representing the service vessel is generated and sent to **Port**. The entity will wait at port until a job at the site of interest is received. When the job is received the entity moves on to the next square, **Sail to site**.

In this process the simulation checks the weather at the specified site. If the weather at the site is within the operational limits of the entity, it will sail out to the site. If the weather is outside of the entity's operational limits, it will wait for one time step, i.e one hour, and then check again until the weather has calmed down enough so that the operation can be performed, moving to the **Perform Operations** square.

When the entity arrives at the given location, the conditions at the location is once again checked. Like before, if the operational limits of the entity are exceeded at the site, the entity will wait for one time step until the job can be started. If the limits are not exceeded, the operation will start. The simulation will check the weather for each hour that passes, and will postpone the assignment one hour if the limits are exceeded during the operation. This act is continued until the job is completed. With the requested job completed, the entity will sail back to port to receive a new operation. This continues until the desired amount of simulation steps have passed.

8.2.2 Input Data

Sea state data from Oceanographic buoys

When the data was received 20.04.2018, the Site 2 buoy had collected data since 03.02.2016, and Site 1 had collected data since 09.03.2016. The data is however incomplete at certain intervals for both buoys due to maintenance. Site 2 was in maintenance for almost two months, from 30.06.17 to 24.08.17. To account for the missing data and allow for a continuous supply of data throughout the simulation, the values from the same time interval in 2016 was inserted to replace the missing data. This gives Site 2 a total of 18557 measurements that can be used, meaning a little over two years. Site 1 had maintenance from 02.09.2017 to 04.04.2018 and was later moved to another location. Therefore this site's buoy has a total of 12865 measurements, approximately 1.5 years. The data from the two sites is exported into two excel documents with three columns, consisting of data on Hs,Tz and wave direction (θ) for every hour. For every time step in the simulation, corresponding data from the correct site is read from excel and used to evaluate the current sea state at the given location.

Operational limits from VERES

The operational limits for the 24 wave headings with 15°intervals produced in VERES are imported from an Excel document that is exported from the VERES post processing. The operational limits are exported for Tz values from 3 to 20 seconds, with intervals of 0.58 seconds, each with a corresponding maximum Hs limit. For each wave heading, the excel document has a numerical representation of the graph shown in figure 8.6b. Depending on which vessel is specified the correct Excel document will be read and used in the simulation.

The wave heading convention from VERES is zero degrees for head waves, 90 degrees for portside beam waves and 180 degrees for following waves, and this same convention will be used when describing how the wave direction is used to determine the correct operability limits to utilize. There are 24 incoming wave headings that have been analyzed in

VERES, while the wave directions can be any direction in the interval of 0°to 360°. Because of this a simplification was determined to be necessary, as evaluating every heading would require a very large amount of calculations, and provide diminishing returns. To account for this, it was decided to evaluate each of these headings as a sector of 15°instead of an exact heading, each sector being the given heading +- 7.5°, as seen in figure 8.9. When a vessel entity arrives at a location to perform an operation, an initial heading position will be set. How this position is set will depend on the operation being performed and is detailed further in section 8.2.4. A new sea state with a certain wave direction will be read from Excel for each time step (one hour). A Matlab script in the entity server will evaluate which sector this wave direction, relative to the vessels heading coincides with. This will continue until the operation is completed. The operational limits from VERES are given as discrete values so interpolation is therefore used to find the limiting Hs for the specific vessel at a given Tz.

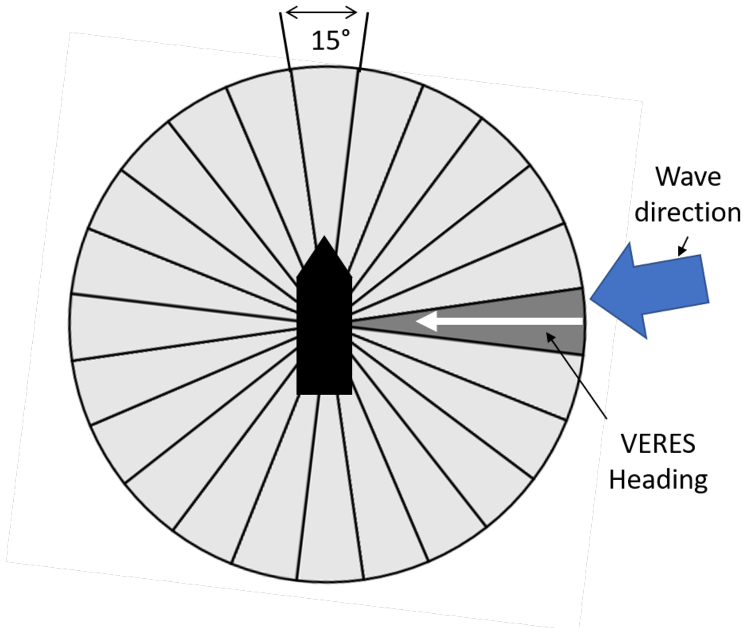


Figure 8.9: Orientation of all 24, 15°sectors used in the simulation. Showing how the incoming wave direction translates to a VERES-heading.

8.2.3 Operational Profile Distribution

Using the information of the operational profile of heavy operations service vessels in section 2.4.1, and the approximate duration of the different operation, an iteration process was performed to find the correct distribution to use for the operational profile. The distribution shown in table 8.8 resulted in roughly the operational profile explained by (Contact-4 (2018)) when running the simulation.

The discrete-event model will use one location as a basis for the environmental conditions and distance to port throughout the simulation, however the operational profile of the vessels are based on the operations completed during a year at a large variety of sites. This means that the simulations will in effect be simulating a system where there is a large number of sites located with the same distance from each other and with the same environmental conditions.

Table 8.8: Frequency and duration of the different operation categories, values are given in hours. Normal distribution values presented as:[mean(standard deviation)].

Operation	Frequency[h]	Duration[h]
Tension of mooring lines	280(28)	16
Anchor and Mooring frame	360(36)	54
Net pen handling	280(28)	64
Delousing support (high season)	700(70)	96
Delousing support (low season)	2500(250)	96
ROV inspections	48	280(28)

Distribution of operations frequencies

The frequency of the operations are based on a normal distribution and a given standard deviation set as 10% of mean of the normal distribution to emulate the uncertainty in the operation frequency, as well as allowing operations to occur at different time intervals when running new iterations of the simulation.

In reality there can also be large variations in the duration of these operations. Deploying an anchor can for example take much longer depending on the depth at a location, with the deployment of a single anchor possibly taking up to six hours if the location is in a deep fjord (Contact-2 (2018)). This is not taken into account in the simulation and the duration of the operations are constant. This simplification was needed as the model is constructed in a way that requires the operational time to be divided into certain constant intervals.

Delousing support stands out from the rest of the operations since it has been given a high and a low season that changes the frequency of delousing support operations at certain times of the year. The press of sea lice varies greatly with geographical location and seasonal variation. Barentswatch records the reports from fish farming sites on the salmon lice count, temperature and delousing measures taken to battle raised salmon lice levels (Barentswatch (2018). By examining the data for Sør-Trøndelag, a graph can be created that shows when the sea lice levels are at their highest. The graph in figure 8.10, created by (Næstvold (2017)), shows that the high season for sea lice is in the months of July, August and September, which is applied in the model.

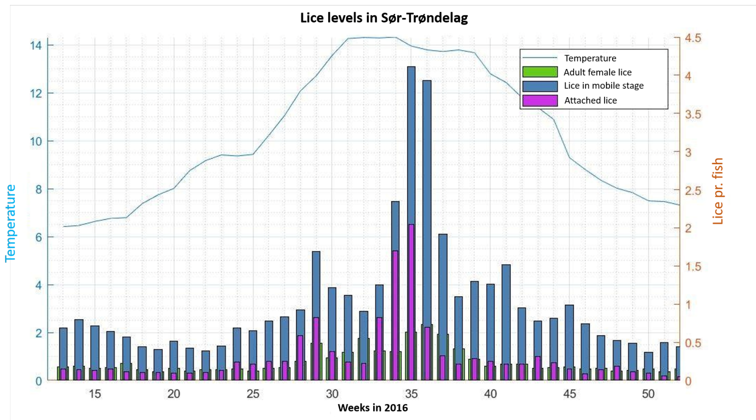


Figure 8.10: The variation of sea lice during 2016 in Sør-Trøndelag. (Næstvold (2017))

Seeds for generating operations

Simulink is designed in such a way that it will use the same seed for the generation of the stochastic variables with every new simulation iteration. The seed is the number used as the basis for the generation of random numbers in Simulink. This means that during the simulation, the stochastic variables will behave as intended, but when a new run is started, the same pattern of randomly generated numbers will occur. This can be favorable if the intention is to examine how the simulation results vary with respect to time. However this is not desirable when the intention is for the stochastic variables to vary with every new run. To circumvent this, a new seed is used in the generation of each stochastic variable with each new run. This is achieved by creating an excel document with a large amount of random numbers generated in MATLAB. A MATLAB script reads a new set of numbers each time the simulation is started, allowing for the entity generators to use a unique seed when the simulation starts. This results in different outcomes for each new run of the model as the operations will be performed at different times, and consequently, different sea states.

8.2.4 Simulation of Operations

This section will present how the simulation aims to emulate the work process of the five different operations in the model by using knowledge of the different operations acquired throughout the work on this thesis. The MATLAB scripts utilized when simulating these operations can be seen in appendix H. For a description of how the operations are performed in real life, see section 2.4. The operations are performed on the generic HDPE farm layout presented in section 2.5.3.

An essential factor when emulating the different operations is whether or not the vessel has the ability to change its heading during the operation. Table 8.9 shows which operations allow for a change of heading during the operation and which ones are ”locked” based on information from Contact-3 (2018). For most of the operations, the vessel heading will be ”locked” during the operation. For ”tension of mooring lines” and ”anchor and mooring frame” operations, the heading will depend on the layout of the site, and consequently the mooring line directions. When performing net pen handling operations and delousing support, the vessel can attempt to position itself in the most optimal manner around the fish cage before starting the operation. Inspections with ROVs will be the only operation where the vessel will be able to change its heading throughout the duration of the operation, as the vessel will follow the target while on DP.

Table 8.9: Which operations that allow for variable vessel heading.

Operation	Change heading	Comment
Tension of mooring lines	Not possible	Dependant on anchor line orientation.
Anchor and Mooring frame	Not possible	Dependant on anchor line orientation.
Net pen handling	Not possible	Choose position when starting Op.
Delousing support	Not possible	Choose position when starting Op.
ROV inspections	Possible	Follow target on DP.

Net pen handling and Delousing support

The operations ”net pen handling” and ”delousing support” are based on the same approach during the simulation, only differing with regard to time usage. The operations will emulate the removal or delousing of all of the 8 net pens at a generic fish farm. When the vessel entity arrives at the site to perform its operation, the current wave direction will be used to set the initial position of the vessel so that the vessel has the waves towards the bow as this has been stated as generally being the preferred heading. The operation lasts for 8 or 12 hours to emulate the removal of one net pen or delousing of one fish cage. To emulate the start on a new net pen, the wave direction will again be used to set the new position of the vessel. This process will be repeated six more times for a total of 64 hours for net pen handling and 96 hours for delousing support.

Tension of mooring lines and Anchor and mooring frame operations

When performing this type of operation, the master of the vessel will in reality have the option of choosing which mooring line to work on depending on the current environmental conditions on site. The master will often try to choose the line which will allow for the weather to approach from the bow of the ship (Contact-4 (2018)). This would however demand a very complex script to emulate. To save time and increase efficiency of the simulation, it was decided to perform this operation in the same order each time.

When tensioning the mooring lines the vessel will always start with the mooring lines located on the east side of the generic fish farm. It will then complete the mooring lines on the west side before working on the south and then the north side. Each individual line takes 1 hour to tension, for a total of 16 hours.

Anchor and mooring frame operations are used to simulate the process of deployment of plough anchors and mooring lines as well as constructing the mooring frame. Mooring lines in the four corners of the fish farm are first deployed. After this, an additional six hours will imitate the construction of the mooring frame between these corners. During this operation, the vessel will keep a south-facing heading to mimic the construction of the mooring frame in the longitudinal direction, from north to south. When this is completed the remaining 12 mooring lines will be deployed and fastened to the mooring frame in the same orderly fashion of working on one side at a time as when performing the tension of mooring lines operation. The deployment of each individual anchor and mooring line takes 3 hours.

ROV Inspections

The ROV inspection operation is recreated quite simply in the simulation, as this operation allows for the vessel to continuously change its heading by using its dynamic positioning system. When this operation is started, the vessel will continuously keep the incoming weather towards the bow of the ship until the operation is completed. As stated before, this has been mentioned as the most favourable heading.

8.2.5 Detailed Run-through of the Simulation

To streamline the detailed run-through of the simulation each of the following sections will detail a certain simulation part as shown in figure 8.11. The parts are divided in such a way that each part focuses on a certain aspect of the simulation.

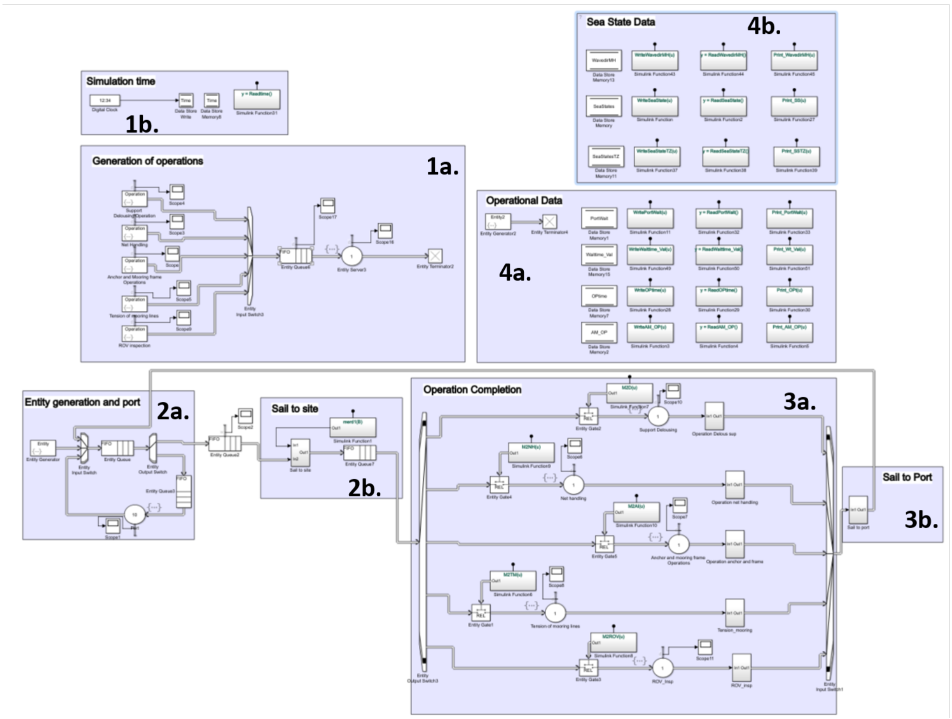


Figure 8.11: The whole simulation model, with numbering of each distinct part.

Part 1 - Generation of Operations

Part 1a. generates the operations that are to be performed during the simulation. Each operation is generated in its dedicated *Entity Generator* at different frequencies as explained and presented in section 2.4.1 and table 8.8. Due to attributes given in each entity generator, the entity will move on to the *Entity Server* block where the server reads the entity attributes and opens the *Entity gate* that coincides with this operation located in **Part 3.** of the simulation. The *Entity* will then be terminated in the *Entity terminator*. A close-up of **Part 1a.** can be seen in figure 8.12.

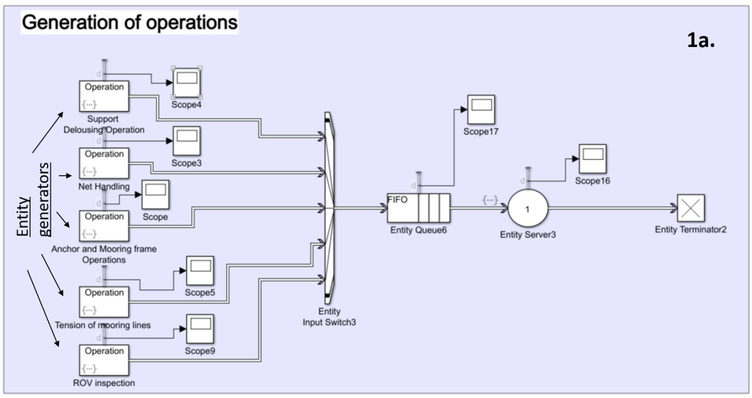


Figure 8.12: Part 1a. of the simulation - Generation of operations.

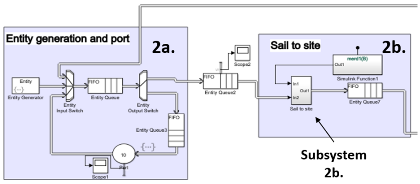
Part 1b.

This small part seen in the top left in figure 8.11 is used as a way to control the time that has passed during the operation. This timekeeping is used to let the generation of delousing operations know when it is high or low season.

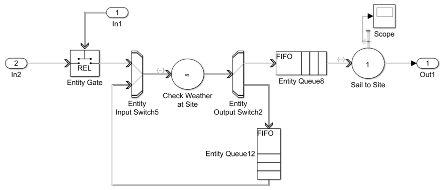
Part 2 - Entity generation and port, Sail to site

Part 2a. consists of the Entity generator for the vessel as well as the port. The Entity generator creates the entity that will represent the service vessel during the simulation, as well as applying the necessary entity attributes it uses to communicate with the different *Blocks*.

When a signal has been received from one of the operations from **Part 1a.**, the entity travels to **Subsystem 2b.** In this subsystem the conditions at the site are checked and evaluated in the *Check Weather* server. If the conditions are too harsh, the entity will wait at port for one hour, before checking again. The vessel then moves on to the *Sail to Site* server, where the distance to the site and the service speed of the vessel is used to calculate the transit time.



(a) Part 2. of simulation



(b) Subsystem 2b.

Figure 8.13: Part 2 of simulation. Generating vessel entity and sailing to site

Part 3 - Operation completion and Sail to port

When entering **Part 3a.** the entity follows the path that relates to the entity gate opened in **Part 1a**. The entity will then enter the subsystem for the specific operation seen in figure 8.15.

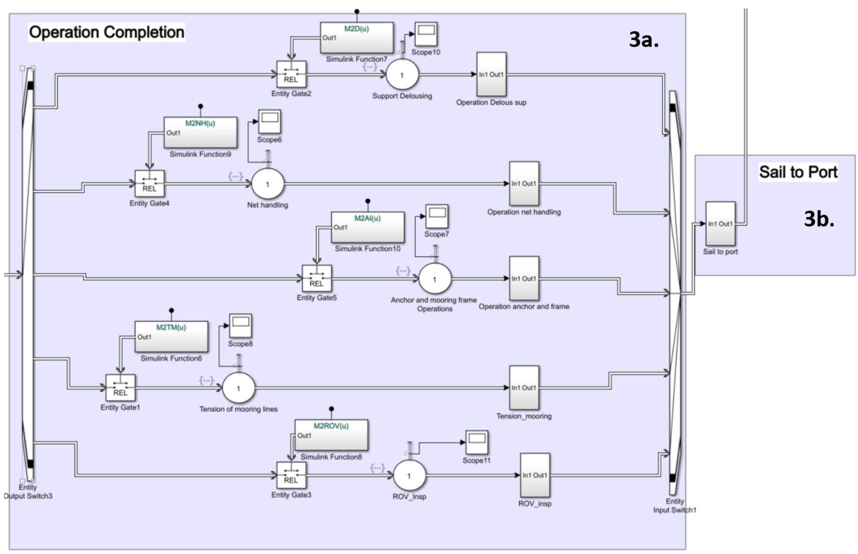


Figure 8.14: Part 3 of the simulation - Operation completion.

In this subsystem the *Check Weather* entity server checks to see if the limits allow the vessel to complete the operation in time steps of one hour. If it can, the vessel travels to the entity server *Opstep* where one hour of the operation is completed, if it can't, it travels to the entity server *WaitOP* where it waits for one hour. The entity then travels back to the *Check weather* entity server. This continues until the total time of the operation is completed and the vessel will then move on to **Part 3b.**.

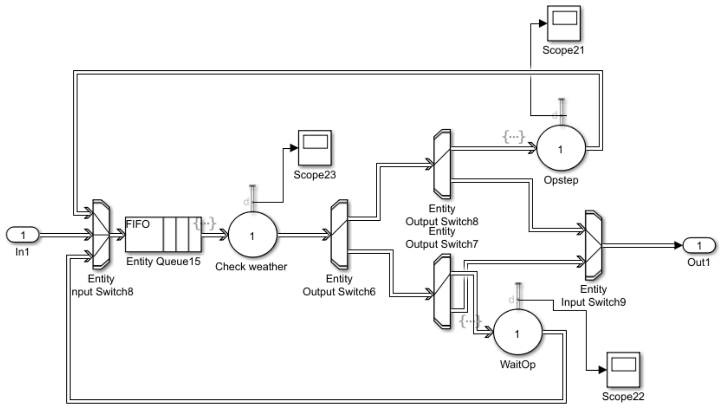


Figure 8.15: Subsystem in Part 3a for executing operations.

Figure 8.16 shows the subsystem that sends the entity back to port. In the two *Entity servers* the distance to the port and the service speed of the vessel is again used to calculate the transit time. An additional 2 hours is also applied to mimic the disinfection of the vessel which is required when traveling between sites (Contact-1 (2018)). The entity gate on the upper path is opened when three weeks have passed. This will make the entity stay in port for an extra 2 hours to allow for changing of crew. According to Contact-1 (2018) crew change is generally every 3 weeks.

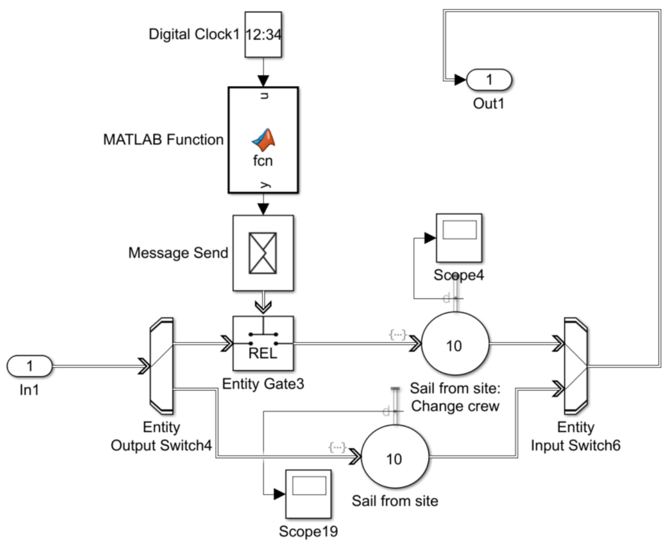
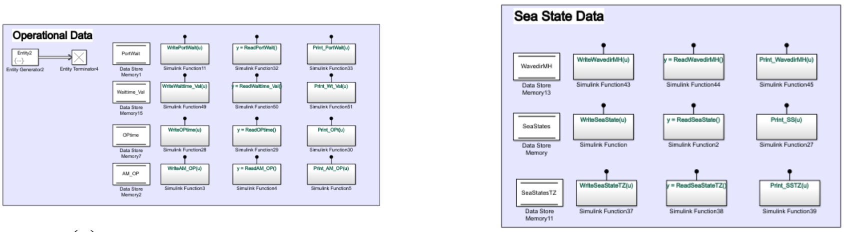


Figure 8.16: Subsystem in Part 3b Sailing to port.

Part 4. Global Variables - Operational data and Sea state data

The *Data store memory* blocks and *Simulink function* blocks seen in figure 8.17 are the global variables used to allow for communication between the different blocks in the model, as well as sending data out to the MATLAB work space for post-processing. The data that is processed in MATLAB is the total number of operations performed, total operational time, total waiting time when performing operations and total waiting time in port.



(a) Operational data storage

(b) Sea state data storage

Figure 8.17: Part 4. Global Variables - Operational data and sea state data.

8.2.6 Defining Operability in the Simulation Model

Through conversations with industry contacts, it became clear that service vessels will rarely completely abort a mission when it has been initiated. They will instead attempt to moor the vessel to the feed barge at the fish farm location, or travel to the nearest harbour to wait for the conditions to improve (Contact-1 (2018); Contact-3 (2018)).

Therefore, the operability from the model is not presented as a relationship between the amount of operations completed and not completed, but rather in the two ways presented in equation 8.1 and 8.2. In the first approach the operability is calculated as the relationship between the amount of operations completed and the amount of operations where there was a need to wait for the conditions to improve. The second approach calculates the relationship between the total operational time and the time spent waiting for the conditions at the site to improve during the course of a simulation.

$$Operability\, N = \frac{Total\, delayed\, operations}{Total\, operations\, performed} \tag{8.1}$$

$$Operability\, T = \frac{Total\, delay\, time}{Total\, operational\, time} \tag{8.2}$$

Even though this constitutes that there are no cancelled operations, it is still important to be able to complete the desired operations in the allocated time frame (Contact-1 (2018)). Failing to do this can lead to interference with other operations that should be performed. Many of the operations are also necessary to complete for the sake of the well being of the fish at the fish farm, and postponing these operations can have a negative effect on the fish in the fish cage. For example, during the event of fish crowding in the net pen, the fish density is drastically increased, going from the industry standard of 25 kg/m^3 to values up to 500 kg/m^3 in a couple of hours (Espmark (2009)). Therefore, it is a recommended practice that the operation does not exceed 2 hours, which can be an issue if the operation must be postponed (RSPCA (2018)) .

8.2.7 Required Iterations

The results from the simulations are a product of stochastic variables that control how often and when different operations occur and these variables change with each simulation. Because of this it can be difficult to decide how many iterations are necessary before a reliable mean result for the two operability approaches are achieved. A simple but effective qualitative approach has been performed to help in this decision-making process using the cumulative mean. For iteration n the cumulative mean is calculated as in equation 8.3. Here, p_{n-i} is the result from operation $n-i$ and n is the total number of iterations performed.

$$CM_n = \frac{1}{n}\sum_{i=0}^{n} p_{n-i} \tag{8.3}$$

The cumulative mean for each successive run of the simulation is calculated and plotted in a graph. By examining the graph it is possible to make out when the cumulative means start to approach a certain value. This means that the inclusion of a new simulation result will not significantly impact the cumulative result, and the required number of iterations has been found. An example of this effect can be seen for Vessel 1 at Site 2 in figure 8.18, though in this case it is evident the simulations could effectively have been ended at around 80 iterations. In general, 80-100 iterations produced satisfactory results.

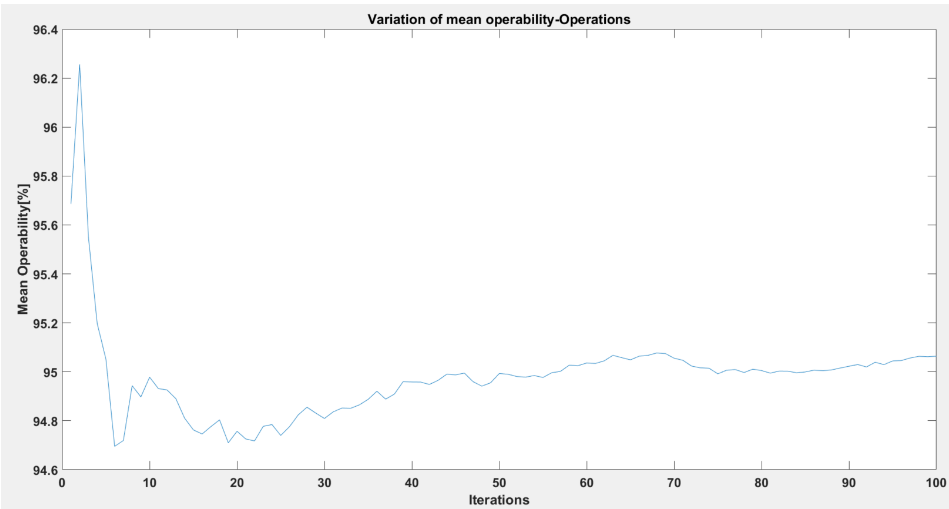


Figure 8.18: Variation of mean operability for Vessel 1 at Site 2 for 100 iterations.

Chapter 9

Results - Operability Limits and Criteria

This chapter presents the results from the vessel response calculations performed in VERES. The chapter is divided into two parts; section 9.1 shows the natural periods of the vessels based on the transfer functions in heave, roll and pitch. Section 9.2-9.4 presents the *limiting criteria* as well as the *limiting significant wave height* for each vessel.

The limiting criteria are presented based on the operability limiting curves from VERES. As both the limiting curves and the limiting criteria will differ based on the mean zero-crossing periods the vessels are subjected to, only the limiting criteria in the period range 4-7 seconds will be presented. This interval represents the zero-crossing periods where the vessels will most likely encounter a *Hs* large enough to impact the vessel operability at the locations of focus. It is found by examining the the scatter diagrams in section 2.5.2. The main limiting criteria is shown in the inner circle and the secondary in the outer circle. The secondary limiting criteria will be included when there are two criteria limiting the operation in the period range, with the second criteria limiting the operability in the shortest interval. It should be noted that the limiting criteria are presented for 30°intervals, and not for all of the 15°intervals used in the VERES analysis. This simplifies the presentation of the results while still giving a good indication of which criteria limit the operability.

The limiting significant wave height will be presented as polar plots showing the limiting significant wave height for wave headings between 0°-360°. The polar plots are found from the same wave period interval, i.e 4-7 seconds. This gives an indication on how the operability changes for different angles of encounter for the three vessels. It should be noted that the polar plots will change depending on the wave periods, and these plots show the *lowest* permissible Hs in the interval 4-7 seconds. Although a variety of different results can be presented based on calculations in VERES, only a selection of the most relevant and limiting criteria will be presented in this chapter. Criteria that do not occur unless large sea states are encountered are therefore excluded in this chapter. The reader is encouraged to visit appendix E for a more comprehensive outline on the different criterion's impact on the operability of the vessels.

9.1 Natural Periods from Transfer Functions

From the transfer functions one can find the wave periods that gives the largest motions for the ship. This is of interest when assessing the operability of the ships in a certain sea area as the wave period that coincides with the natural period of the vessel might cause resonance and large responses. The natural periods of the vessels are found from the peaks of the transfer functions and are listed in table 9.1. An example showing the transfer function in roll for all vessels at 90° is found in figure 9.1. A rather interesting outcome from the transfer function in roll is the roll period of the monohull, Vessel 3, compared to the roll periods of the catamarans, Vessel 1 and Vessel 2 at the given loading conditions. As a contradiction to the theory found on monohulls compared to catamarans in section 5, Vessel 3 has a lower period in roll compared to Vessel 1 and Vessel 2.

Table 9.1: Natural periods

Motion mode	Vessel 1	Vessel 2	Vessel 3
Heave [sec]	4.0	4.4	5.2
Pitch [sec]	4.2	4.5	5.7
Roll [sec]	5.9	5.7	5.3

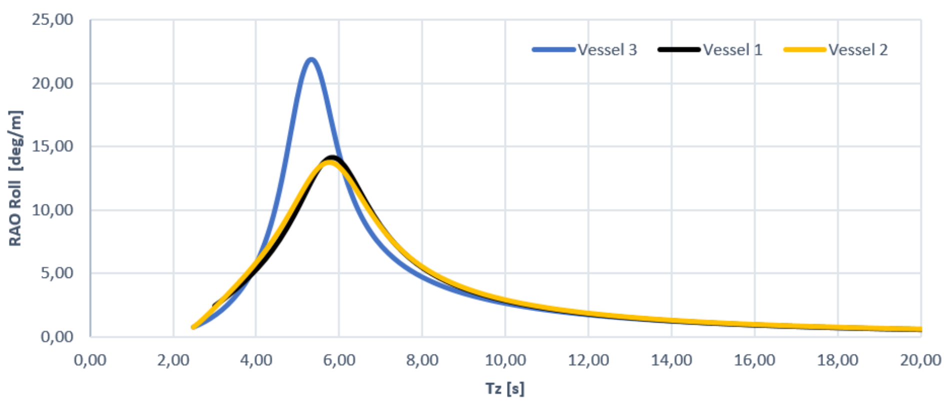
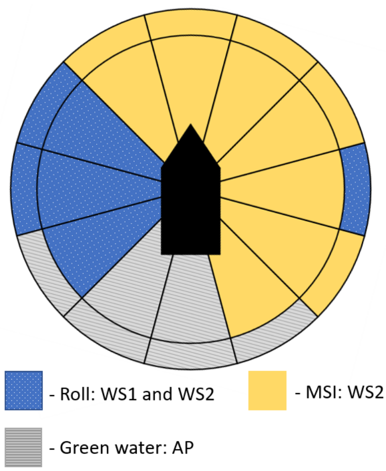


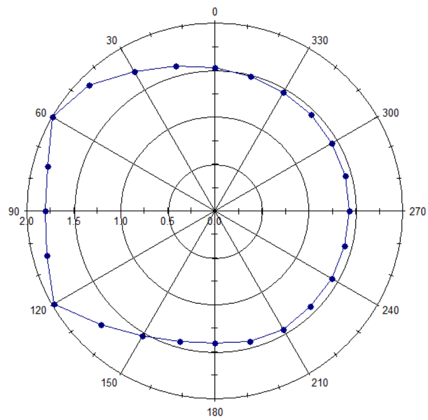
Figure 9.1: Transfer function in roll for all vessels.

9.2 Vessel 1

Figure 9.2a show that motion sickness incidence at work station 2 (WS2) is the main criteria that limits the operation of Vessel 1 for most headings. In addition, in following seas the limiting criteria is found to be green water on deck at aft perpendicular measuring point (AP Center). Furthermore, roll at WS1 and WS2 is the main limiting criteria when the incoming waves come in from the port side of the vessel. The polar plot in figure 9.2b show that the operability is asymmetric with respect to the angles of encounter and it is in general better for beam and quartering waves on port side of the ship compared to starboard side. This is a result of how the working stations are defined on the vessel, with both working stations located on starboard side. The limiting significant wave height is generally found between 1.4-2.0 [m].



(a) Main and secondary limiting criteria.

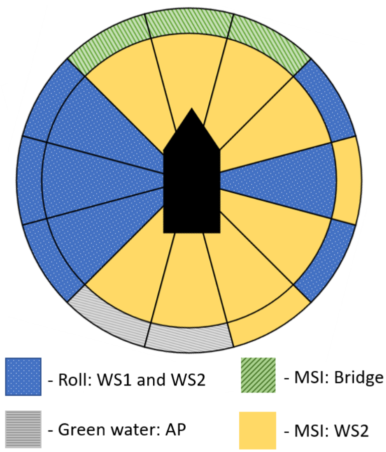


(b) Polar plot of the limiting Hs.

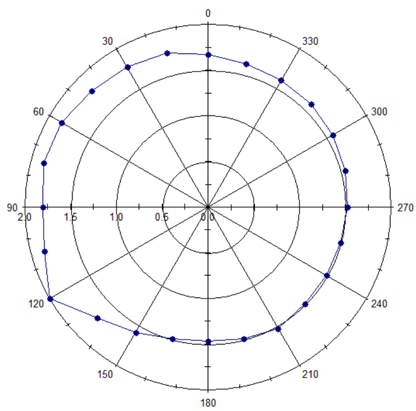
Figure 9.2: Limiting criteria and Hs of Vessel 1 in Tz range of 4-7 seconds. In (a), the inner circle is the main limiting criteria, the outer circle is the secondary limiting criteria.

9.3 Vessel 2

A range of criteria limit the operation of Vessel 2. Figure 9.3a shows that in head and following seas the primary limiting criteria is found to be MSI on WS2. On starboard side, the limiting criteria for beam sea is roll. In quartering and beam waves, the limiting criteria is roll for WS1 and WS2 for port side waves. Other criteria affecting the operability is found to be green water in following waves as well as MSI on the bridge in head seas. Figure 9.3b show that the operability for Vessel 2 is better for beam and quartering seas on port side. As for Vessel 1, the location of WS2 and the MSI criteria is assumed to be the reason behind the asymmetric operability. The operability is slightly better for beam and head seas compared to Vessel 1. The limiting significant wave height is generally in the range 1.5-2.0 [m].



(a) Main and secondary limiting criteria.

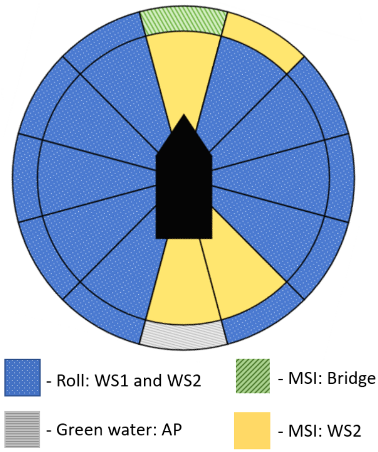


(b) Polar plot of the limiting Hs.

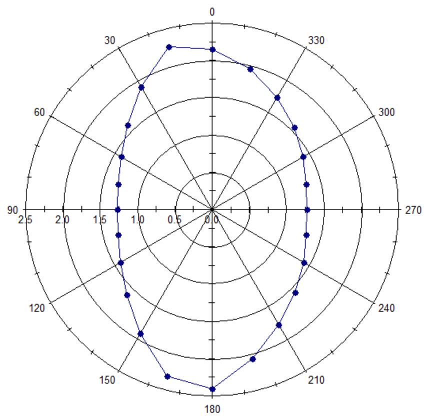
Figure 9.3: Limiting criteria and Hs of Vessel 2 in Tz range of 4-7 seconds. In (a), the inner circle is the main limiting criteria, the outer circle is the secondary limiting criteria.

9.4 Vessel 3

As is evident in figure 9.4a, roll motion in WS1 and WS2 is the limiting criteria for most sectors for Vessel 3. Exceptions are found for head and following seas where MSI on WS2 and the bridge are found to be limiting criterias. The vessel is also affected by green water at the aft perpendicular on the working deck in following waves. From the polar plot in figure 9.4b it is evident that the operability of the vessel is clearly better in head and following waves compared to both Vessel 1 and Vessel 2. For beam and quartering seas the operability is generally lower due to roll motion. The limiting significant wave height is found in the interval 1.3-2.4 [m].



(a) Main and secondary limiting criteria.



(b) Polar plot of the limiting Hs.

Figure 9.4: Limiting criteria and Hs of Vessel 3 in Tz range of 4-7 seconds. In (a), the inner circle is the main limiting criteria, the outer circle is the secondary limiting criteria.

Chapter 10

Results - Long-term Operability from Simulation Model

This section will present the results found from the Simulink model which simulates the work cycle of a service vessel on an hour-to-hour basis. The long-term operability for all three vessels locked at 12 specific wave headings of 30° intervals will be presented first to get an insight into how a certain wave heading can affect the operability of the different vessels. As in the preceding chapter, using 30°intervals gives a good indication of how the vessels perform, while still allowing presentable and interpretable tables. In section 10.2, the results from a more realistic approach of evaluating the long-term operability will be presented. This approach includes the different methods of simulating operations presented in 8.2, subsequently leading to varying wave headings throughout the simulation cycle. This approach also includes all 24 headings analyzed in VERES. Finally, results showing how different loading conditions can impact the operability of service vessels will be presented. As a reminder, the two versions of operability are calculated by using equation 8.1 and 8.2.

10.1 Fixed Wave Directions

The simulations with fixed wave directions assume that all operations are performed with a fixed incoming wave direction during all operations throughout the simulation. This may not be a realistic case, but the results can help to determine which directions are the most critical for each vessel. *Operability N* is shown in this section, while the results considering *Operability T* can be found in appendix F, as similar conclusions can be drawn from both versions. Due to the large amount of operational time compared to waiting time, the *Operability T* tables are also generally more laborious to examine when comparing results. In addition to the mean percentage of operability, a cross reference with the results from the vessel responses have been made in order to create a table showing the limiting criteria for each sector. The limiting criteria are only shown in cases where *Operability N* is below 99%.

The results from Site 1 are presented in table 10.1 and table 10.2 and the result from Site 2 are presented in table 10.3 and table 10.4. When reading the results, the convention is that 0°-180° corresponds to port side and 180°-360° corresponds to starboard side.

10.1.1 Fixed Wave Direction Operability for Site 1

Table 10.1: Mean Operability N for all vessels at **Site 1** for fixed wave directions, from 0°to 330°

Mean Operability N, Site 1						
Wave direction	**Vessel 1 [%]**	**st. dev [%]**	**Vessel 2 [%]**	**st.dev [%]**	**Vessel 3 [%]**	**st.dev [%]**
0°	98.3	0.54	100	0	100	0
30°	100	0	100	0	100	0
60°	100	0	100	0	92.9	0.97
90°	99.4	0.33	99.6	0.27	87.9	1.17
120°	100	0	100	0	92.9	0.96
150°	98.5	0.48	100	0	100	0
180°	95.2	0.90	100	0	100	0
210°	96.5	0.77	98.7	0.40	99.6	0.28
240°	95.4	0.88	97.3	0.65	92.6	1.01
270°	95.4	0.88	98.2	0.43	87.4	1.35
300°	96.6	0.78	98.7	0.40	92.6	1.01
330°	96.5	0.82	99.4	0.31	100	0

In table 10.1 it is shown that all vessels achieve a high operability for Site 1. Vessel 1 tends to be more affected by following waves and beam as well as beam quartering waves on starboard side. For Vessel 2, the operability is, as for Vessel 1, generally more affected by starboard and starboard quartering waves. Finally, Vessel 3 shows lower operability when it is subjected to beam waves on both starboard and portside. For all vessels, the operability tends to be more affected by waves from starboard side, consequently giving the vessels an asymmetric operability with respect to the centerline of the vessels. This is a result from how the working locations are defined in VERES. Table 10.2 presents the different criteria limiting the operability of the vessels. For Vessel 1 it is evident that the main criteria affecting the operability are MSI at working station 2 for starboard side waves, as well as green water at the AP measuring point for following waves. The impact of MSI at working station 2 is also evident for Vessel 2 but the severity of the criterion is less compared to Vessel 1. For Vessel 3, roll in both starboard and port side waves limit the vessels operation.

Table 10.2: Criteria affecting the operability from 0°to 330°for Site 1

Mean Operability			
Wave direction [%]	**Vessel 1 Limiting Criteria [%]**	**Vessel 2 Limiting Criteria [%]**	**Vessel 3 Limiting Criteria**
0°	MSI - WS2	-	-
30°	-	-	-
60°	-	-	Roll
90°	-	-	Roll
120°	-	-	Roll
150°	GW - AP	-	-
180°	GW - AP	-	-
210°	MSI - WS2	MSI - WS2	-
240°	MSI - WS2	MSI - WS2	Roll
270°	MSI - WS2	Roll	Roll
300°	MSI - WS2	MSI - WS2	Roll
330°	MSI - WS2	-	-

10.1.2 Fixed Wave Direction Operability for Site 2

Table 10.3: Mean Operability N for all vessels at **Site 2** for fixed wave directions, from 0° to 330°

Mean Operability N, Site 2						
Wave direction	**Vessel 1 [%]**	**st. dev [%]**	**Vessel 2 [%]**	**st.dev [%]**	**Vessel 3 [%]**	**st.dev [%]**
0°	91.3	0.81	99.5	0.28	100	0
30°	97.3	0.57	100	0	99.8	0.19
60°	93.4	0.80	93.7	0.77	82.6	1.07
90°	87.6	1.06	87.9	0.97	77.2	1.31
120°	93.5	0.80	93.4	0.81	82.6	1.08
150°	97.1	0.63	100	0	99.8	0.19
180°	90.6	0.74	99.2	0.33	100	0
210°	85.6	1.14	91.1	0.83	97.3	0.58
240°	84.3	0.86	96.3	1.13	82.6	1.07
270°	84.9	0.94	86.0	1.06	77.2	1.31
300°	86.3	1.10	92.8	0.73	82.6	1.07
330°	89.4	1.01	97.1	0.63	99.8	0.19

As can be seen in table 10.3, all vessels show a lower operability on Site 2 compared to Site 1. This is expected as the sea states at Site 2 are characterized by higher significant wave heights. The trends in the results are also similar to Site 1, with Vessel 1 and Vessel 2 showing a decrease in operability for starboard waves compared to port side waves. The wave directions that limit the operability of Vessel 1 the most are wave headings from 180°-360°. For Vessel 2, the operability is mostly limited by beam waves on both starboard and port side. The same result is evident for Vessel 3, but the beam waves tend to give a lower operability for Vessel 3 compared to both Vessel 1 and Vessel 2. However, Vessel 3 proves to have best operability for both head and following waves.

Table 10.4 shows the criteria limiting the operability for each wave direction. As for Site 1, MSI and green water limit the operability of Vessel 1 in waves on starboard side and following waves respectively. Roll also has an impact on the operability of Vessel 1 as the sea states are rougher at Site 2. Vessel 2 is mostly limited by roll on port side and MSI on starboard side. The operation of Vessel 3 is, as in Site 1, mainly limited by roll in beam seas in direction towards both sides of the vessel.

Table 10.4: Criteria affecting the operation from 0° to 330°

Mean Operability			
Wave direction [%]	**Vessel 1 Limiting Criteria [%]**	**Vessel 2 Limiting Criteria [%]**	**Vessel 3 Limiting Criteria**
0°	MSI - WS2	-	-
30°	MSI - WS2	-	-
60°	Roll	Roll	Roll
90°	Roll	Roll	Roll
120°	Roll	Roll	Roll
150°	GW - AP	-	-
180°	GW - AP	-	-
210°	MSI - WS2	MSI - WS2	MSI - WS2
240°	MSI - WS2	MSI - WS2	Roll
270°	MSI - WS2	Roll	Roll
300°	MSI - WS2	MSI - WS2	Roll
330°	MSI - WS2	-	-

10.2 Operation Specific Headings and Variable Wave Directions

The following results are based on a model that takes into account the complexities of the service vessel operations such as navigational limitations during operations and incoming wave directions to achieve a more realistic operability result.

By running the simulations, the key values found in table 10.5 can be extracted. Because none of the operations are cancelled, only delayed, all three vessels are able to complete the total number of operations that are generated. It is important to note that Site 1 has a lower number of operations due to the shorter length of the simulation run. As expected, Site 2 has the highest total number of delayed operations. Vessel 2 has the lowest amount of delays for both sites, and Vessel 3 has the most delayed operations, which is also reflected in the total delay time. Regarding the mean time of the delays, Site 1 also has shorter delay times than Site 2.

Table 10.5: Key values from simulations.

	Site 1			**Site 2**		
Mean values	Ves.1	Ves.2	Ves.3	Ves.1	Ves.2	Ves.3
Completed operations	175	175	175	255	255	255
Delayed operations	4	1.3	9.5	24.9	13.6	29
Total delay time [h]	10.2	2.6	31.8	133.5	63	240
Duration of delays [h]	2.5	1.9	3.3	5.4	4.6	8.3

The bar plots in figure 10.1 below present the mean long-term operability for all three vessel at Site 1 and Site 2 by using equation 8.1. Both of the catamarans are able to complete the majority of the operations without delays during the operations at Site 1, although Vessel 2 achieves a slightly higher operability. Meanwhile, Vessel 3 has the lowest percentage, completing 94.56% of the operations without delay.

For Site 2 the the mean long-term operability is lower for all three vessels compared to Site 1, which is understandable since this location is characterized by higher significant wave heights. With a mean operability of 88.62% Vessel 3 is again the vessel with the lowest operability. Vessel 1 experiences the largest decrease in operability when comparing the results from Site 1 and 2. Meanwhile Vessel 2 attains the highest percentage with 94.67%.

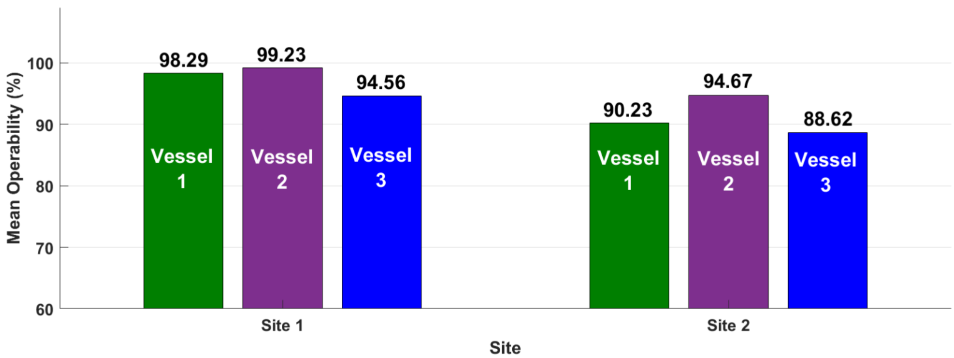


Figure 10.1: Mean operability N for the three vessels at Site 1 and Site 2. Operability calculated as: (Number of delayed operations/ Total number of operations).

While figure 10.2, shows the same general distributions between the vessels and sites, it is interesting to see how the total operational time compares to waiting time. Many of the operations last across 2 or 3 days and the waiting time is generally in smaller increments with only a few going past the 8 hour mark. This difference effects *Operability N* to a larger degree than *Operability T*. When examining *Operability T* it can be seen that for both sites and all three vessels the operability is high, over 99% in the majority of the cases except for Vessel 1 and 3 at Site 2, which is goes below 99 % with the operability of 98.89% and 98.02% respectively.

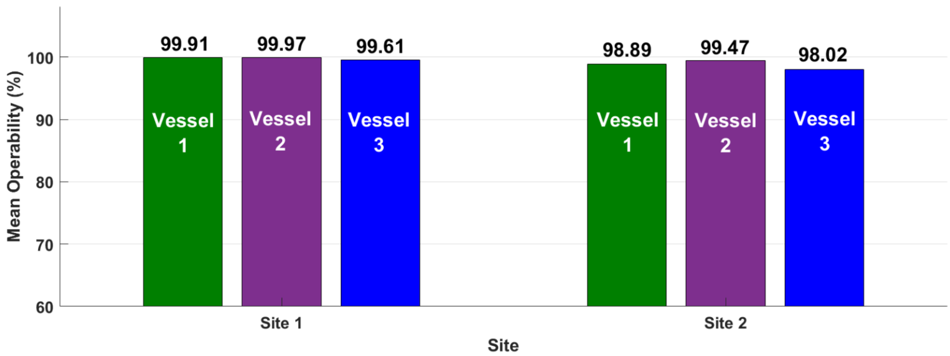


Figure 10.2: Mean operability T for the three vessels at Site 1 and Site 2. Operability calculated as: (Total delay time/ Total operational time).

10.2.1 Effect of Loading Conditions

As Vessel 1 has a different loading condition compared to Vessel 2 and Vessel 3 in the analysis above, simulations were also performed for Vessel 2 at two additional loading conditions. This will provide information that makes it possible to compare the operability of Vessel 1 and Vessel 2 in a fair manner. In addition a comparison of different loading conditions can give insight in how the long-term operability changes with different displacements of the vessels. The loading conditions are:

- No load departure.
- Ballasted departure, same loading condition used in the other results.
- Maximum load departure, same loading condition used for Vessel 1.

Figure 10.3 shows the operability of Vessel 2 for different loading conditions for a simulation with operations specific headings and variable wave directions. From the figure, it is evident that the operability is highest in the ballasted loading condition at both Site 1 and Site 2. The maximum load condition gives lowest operability and compared to the results for Vessel 1 in figure 10.1 the difference in operability between the vessels is lower for the same loading condition.

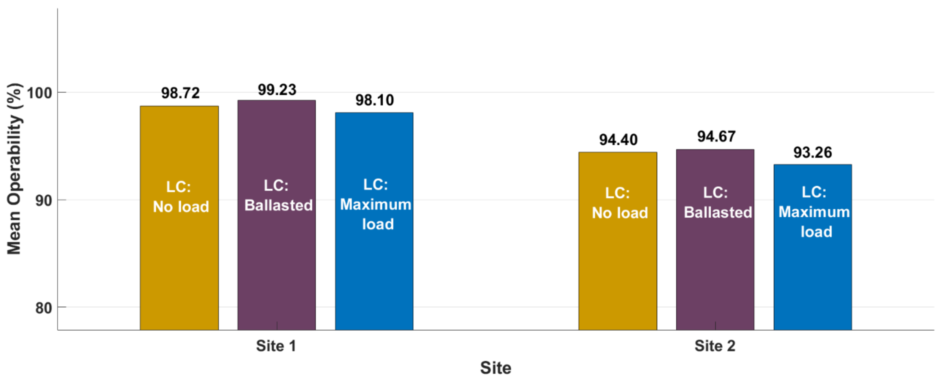
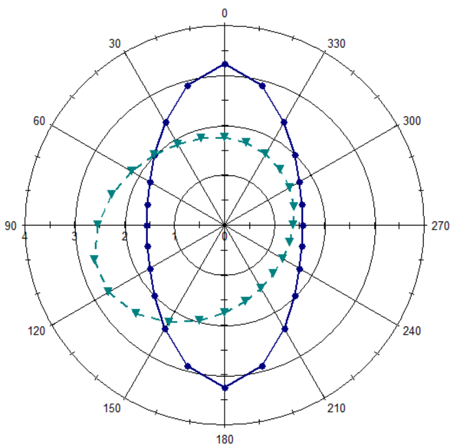
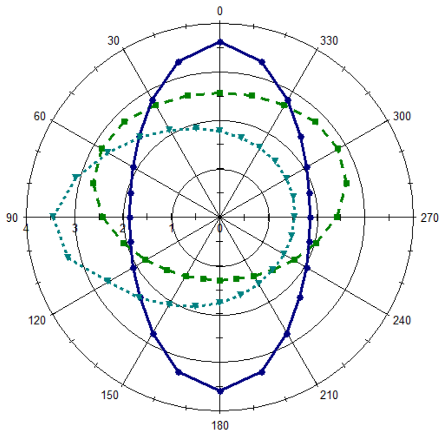


Figure 10.3: Mean operability N at different loading conditions for Vessel 2).

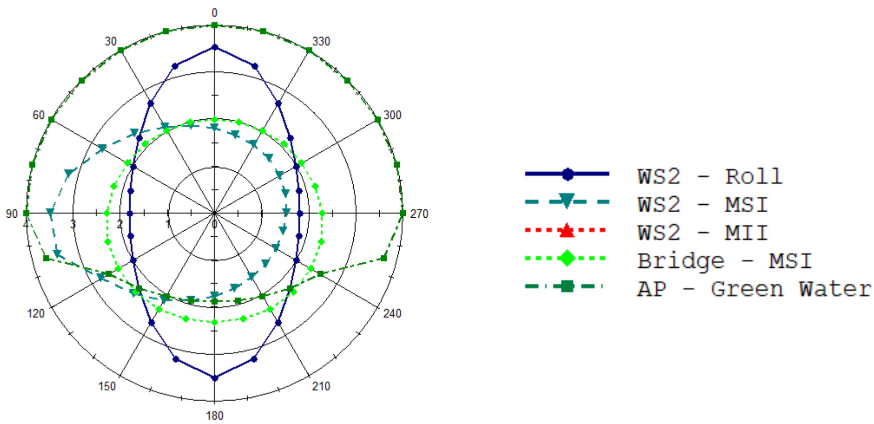
The impact of various criteria on different loading condition can be studied using polar plots. In figure 10.4 polar plots showing the limiting criteria for all loading conditions are shown. It is evident that the "No load" condition gives lower operability with respect to roll motions. However, the operability of Vessel 2 at "No Load" is not limited by green water on AP, whereas this criterion has an effect the "ballasted" and a large effect the "Max Load" loading condition in following waves. MSI tends to have a similar effect on all loading conditions, and gives lowest operability for starboard beam waves.



(a) Limiting criteria of Vessel 2: No load



(b) Limiting criteria of Vessel 2: Max load



(c) Limiting criteria of Vessel 2: Ballasted

Figure 10.4: Limiting criteria for Vessel 2 at different loading conditions for Tz 4-7s.

10.3 Key findings

Before the discussion in the next chapter, it is considered convenient to list the key findings from the results.

- All vessels show better operability for Site 1 compared to Site 2. This is expected since Site 2 is characterized by higher significant wave height.
- The operability of the vessels is dependent on the incoming wave direction and the wave directions impact the vessels differently.
- Vessel 2 generally exhibits the best operability. The operability of the vessel is mostly limited by beam and quartering seas while the operability is generally good in head and following seas.
- Vessel 2 is mostly limited by roll motion and MSI at WS2.
- Vessel 1 presents the second best operability. The operability is generally more affected by beam waves on starboard side.
- The main criteria affecting the operability of Vessel 1 are found to be MSI on WS2, roll and green water on AP working deck.
- Vessel 3 shows the lowest operability. The operability is generally limited by beam and quartering waves, and the operability is found to be good in head and following seas.
- The main criteria affecting the operability of Vessel 3 are found to be roll on WS1 and WS2.
- The loading condition effects the operability of Vessel 2. The ”No load” and ”Max load” condition gave reduced operability compared to the ”Ballasted” condition.
- Using the ”Max load” condition on Vessel 2 resulted in operability closer to what was seen for Vessel 1, which also has this loading condition. There is however still a disparity, likely due to the different design of the two vessels.

Chapter 11

Discussion

This chapter will discuss the results and findings that have been put forth in chapter 9 and 10, how these results reflect the objectives of this thesis, and the method used to aquire these results. Furthermore, the validity of the results and methods used will be discussed in detail.

11.1 Operability from VERES and Simulation Model

The main objective of this thesis has been to evaluate and compare the operability and operational limits for three aquaculture service vessel designs at exposed locations. For such a comparative study to be carried out, the assumptions made for all vessels should be the same. It is therefore emphasized that the loading condition of Vessel 1 is different from the loading condition of Vessel 2 and Vessel 3. Consequently this introduces factors that make a direct comparison impossible. An analysis of Vessel 2's operability has however been performed for two other loading conditions, one of which is the same as for Vessel 1. A direct comparison of these vessels can therefore be made.

In general, all vessels show satisfying operability with a small mean downtime, (figure 10.2), ranging from 0.53% to 1.98% for all vessels at Site 2. In terms of delayed operations, (figure 10.1), the percentage of delayed operations are found to be in between 5.33% and 11.38%. The difference in these results comes from the fact that the duration of the delays are small compared to the average length of each operation. The results from the fixed wave direction simulations show that the long-term vessel operability for all of the vessels is dependent on the direction of the incoming waves and that the wave directions impact the vessels differently. The standard deviation of the fixed wave heading results also show a trend of being larger when the mean operability is decreased. This can indicate that these headings are generally more impacted by variations of the sea state than the headings showing a high mean operability. Although it is found that all vessels show generally appreciable operability when operating at the exposed sites, it is of interest to investigate criteria that limit the operation of each vessel.

In general, Vessel 2 showed the best operability for fixed headings seen in table 10.1 and 10.3 and during operations with specific headings seen in figure 10.1. A direct comparison with Vessel 3 is possible due to the similar loading conditions of the two vessels. The vessels both show satisfying operability in head and following seas, but Vessel 3 is subjected to larger roll motions consequently surpassing the limit in roll for WS1 and WS2 in beam and beam quartering seas when the wave heights are large. The large roll motion of Vessel 3 can be explained considering two factors. The first factor is the natural period in roll, found to be 5.3 seconds based on the transfer functions found in section 9.1. The sea states encountered at Site 1 and in particular at Site 2 have a large portion of their zero-crossing periods in the interval 5-6 seconds. The vessel is therefore often found in situations where the sea state can trigger resonance motions. However, the roll periods of the catamarans are found in the same interval without having the roll motion exceeding the criteria limit as frequently. An explanation of this comes from the second factor, the amplification factor in roll, especially around resonance periods. As is stated in the theory section in 5.3.3, the amplitude in roll is dependent on the damping level. This is found to be significantly lower for the monohull compared to both catamarans, thus limiting the operation of Vessel 3, especially in beam and beam quartering seas. This is also evident from figure 9.1, showing the transfer function in roll at 90° for all three vessels. The problem of roll motion on monohulls is currently being addressed by one of the engineering companies in the industry, Møre Maritime, by introducing anti-roll tanks for monohull service vessels (SINTEF ocean (2017)).

From section 9.1, it is evident that the catamarans have lower natural periods in pitch and heave compared to the monohull and by that generally experienced higher accelerations. As a consequence, the operability of Vessel 1 and Vessel 2 was found to be mostly limited by the motion sickness incidence criteria. The effect of this criteria is strongly correlated with vertical accelerations at the location they are measured, and they were found to be limiting for WS2 located on the aft perpendicular side. Site 1 and Site 2 both experience significant amounts of Tz in the range 4-7s, and according to the standard, ISO 2631-1:1997 (1997), MSI is more prevalent at frequencies close to 0.2 Hz, i.e in periods close to 5 seconds. Large accelerations is a well known problem for catamarans and the problem was also identified in the report, Future Concepts (Bjelland et al. (2016)), arguing that one of the main disadvantages regarding catamarans are motions and accelerations in rough seas at zero forward speed. For ships, large water plane areas compared to displacements will result in greater heave restoring forces, and thus shorter natural periods. In the offshore wind industry, this problem has been overcome by introducing small water plane service catamarans (SWATH) that experience lower accelerations and longer periods in heave and pitch due to a reduced water plane area (Faltinsen (2006)).

The operation of Vessel 1 was found limited by the ”green water” criteria in directions in the interval $150°$-$210°$, i.e following waves. The incidence of green water is highly dependent on the height of the freeboard as well as the relative motion between the ship and the waves. As the specified loading condition for Vessel 1 was ”Max load” it gave less clearance between the waterline and the AP centerline working deck. The same result was also evident when examining the effect of different loading conditions for Vessel 2, as the operation was more impacted by the green water criteria in the ”Max load” condition compared to the other loading conditions. It also achieved a long-term operability more similar to Vessel 1 when having this loading condition. For Vessel 3 the freeboard in the ”ballast loading” condition is found to be higher compared to both Vessel 1 and Vessel 2, thus making the green water criterion less prevalent for this vessel.

The long-term operability was generally appreciable for all three vessels at both sites. These results can be considered to be within the range of what one could expect. This is because all three vessels were built with a mindset of designing a vessel that could operate in harsher sea states, mainly due to their increased size compared to the standard industry service vessels. Had the long-term operability been poor, it could have been an indication that the operability criteria were set too harsh, or that certain calculations had been performed incorrectly.

11.2 Methodology

The objective of this thesis was to evaluate and compare the operability and operational limits for three aquaculture service vessel designs at exposed locations by using a combination of hydrodynamic vessel response analysis and discrete-event simulation. As the literature review showed, this is a novel approach for comparing and evaluating different vessels, it has however produced results that indicate differences between the three vessels operability and limiting criteria.

As the analysis has a focus on exposed aquaculture sites, three larger vessels were made available and chosen due to their potential capability of operating in harsh waters. Two of the vessels have a similar design, as both are catamarans of length 25 meters. Despite this similarity, it is still found interesting to see how small deviations in the designs affect the operability of the vessels.

The information regarding the service vessel industry has been obtained first hand by conversations with industry actors who have given estimates on the time usage and frequency of the operations based on their educated guesses. There is therefore an inherent uncertainty regarding this data as it is based on assumptions and not quantitative values. It must however be pointed out that the information is received directly from industry actors experienced with service vessel operations which increases the validity of this information.

The operability of each vessel was evaluated in terms of criteria found in the literature which are largely based on experience and trials on vessels from other industries such as offshore, fishery and naval vessels. The criteria were in other words not specifically made for aquaculture vessels, but the relevance of the criteria is still valid considering the fact that they are based on vessels operating in the same environment as vessels in the aquaculture industry. Furthermore, there was made no consideration towards which criterion is most important during each specific operation, the focus was rather on finding criteria that reflected the aquaculture vessels nature as an unstable working platforms.

The ShipX package VERES was chosen to carry out the calculations of ship motions as well as determine the operability limiting significant wave heights. The code of the program is based on linear strip theory and should provide accurate results in moderate seas with moderate resulting ship motions. The approach of using strip theory is widely recognized for calculating seakeeping capabilities of ships and was used by both Tello et al. (2011) and Fonseca and Soares (2002) to evaluate seakeeping characteristics of fishing vessels. Thus, for free-floating bodies with limiting motion criteria the predictions from VERES should provide results that approach the real case. However, VERES does not allow for including interaction between the vessel and towing gear as well as crane gear during operations such as mooring frame deployment or tensioning of mooring lines, details that can change the motion characteristics of a vessel. In addition, it has been reported, both from industry contacts and reports (Holen (2015)), that wind and currents often impose safety risks when carrying out aquaculture operations. Utilizing a program such as SIMA or the WASIM package could have allowed for a more in depth analysis, including more operational aspects such as wind and currents.

To calculate the long-term operability of the vessels, a discrete-event simulation made in Simulink has been used. Simulink's graphical block-diagram environment for event driven system models allows for a visualization of the path an entity takes throughout the model, making it an intuitive and effective model construction tool. The graphical interface is also important for the usability of a model according to Darzentas and Spyrou (1996). Due to the graphical nature of Simulink, making changes is not complicated, however extensive changes can be time-consuming as they are often characterized by manual changes to the blocks in the system. Multiple similar models were also created for different evaluations. This approach simplifies the individual models, however making changes is cumbersome as a simple fix must often be done on all models. Even though it would have made the models more complicated, an increased merging of the models would have been preferable. The models have also been set up in such a way that other sites and vessels can be evaluated without difficulty if operational limits and weather data are implemented in the same format that was used in this thesis.

Real measurements from oceanographic buoys located by both sites are used as input for the models instead of a combined hindcast data and Markov chain approach. Due to small islands, reefs and local bathymetry, it is hard to estimate the conditions on near-shore sites, and the conditions can be substantially different from conditions experienced offshore(Kristiansen et al. (2017)). The choice to use real world data from real locations might therefore increase the reliability of the results. There is however a lack of observation points. When creating long-term predictions, a reliable scatter diagram is typically in the order of 100 000 observations according to Faltinsen (2006). A large set of observations makes it possible to capture changes in weather from year to year. Compared to the proposed number of observations necessary to obtain a reliable scatter diagram, the number of observations used in the simulations in this thesis is rather limited. For the longest interval there were 18557 observations, corresponding to approximately 2 years of measurements. These observations also include a repeat of certain months to allow for continuous time series because of service down times of the buoy, so it is in reality less.

While the simulation is still only an imitation of reality, it gives a good indication of the operability achieved by the different vessels. Further improvements can also be made that can lead to an even more detailed representation of service vessel operations. The method used to obtain the results is therefore a good steppingstone in the pursuit of determining the true operational limits of aquaculture service vessels and how different designs affect long-term operability.

11.3 Validity of Vessel Response Calculations

This section will discuss the validity and uncertainties in the vessel response calculations. The aim is to identify factors that might influence the final results but the discussion will not attempt to quantify the uncertainty.

11.3.1 VERES

As outlined in chapter 5 the calculations carried out in VERES are based upon linear strip theory. This means that the ship motions are supposed to be small, as large ship motions might introduce non-linearities to the calculations. As the waves encountered at Site 1 and Site 2 were relatively small this was not considered to introduce any large errors in the calculations. In addition, as the objective was to study motions in relation to seakeeping criteria based on a limiting RMS of the response, which imparted a limitation on the induced vessel motions well below motions induced by extreme sea states.

11.3.2 Criteria

When evaluating operability of ships it is important that the criteria applied are relevant and reflect the vessels operations. This is especially important when comparing different vessel designs, as the effect of changing one criterion might have a large influence on the percentage of operability found in the analysis, thus other interpretations of the criterion might lead to different results. Although the criteria applied in this analysis are well established and based on previous research, it is still found important to discuss the validity and uncertainty inherent in the criteria. The results from the simulation does not explicitly show which criterion that limits the operation, but based on the scatter diagrams and the operability boundary curves, it was possible to get an impression of which criteria governed the operability of the ship. It was found that the main limiting criteria for the vessels at the given sites were MSI, roll and green water on deck.

There will always be some uncertainty in the calculation of **MSI** due to the definition of the criterion. The criterion according to ISO 2631-1:1997 (1997), applied in this operability assessment, attempts to predict the percentage of personnel that are motion sick after a given exposure time. It is obvious that this calculation will be influenced by the physiology of the personnel of the vessels, i.e it will differ in accordance with individual receptivity in a population. This is accounted for in the formula by introducing a constant, K_m, which may vary depending on the exposed population. However, the standard only propose one value of K_m and this represents a mixed population of unadapted male and females, thus not representable for a crew on a service vessel. A lower value has been applied to account for the effects of adaptability of the crew based on a subjective considerations. In addition, the duration of the criterion is set to three hours. Considering the fact that many of the operations specified in this thesis lasts for a much longer time, this might also introduce a certain error in the calculation. However, both WS1 and WS2 will give conservative operability limits based on their location on the vessels, i.e away from the center of gravity, and it is assumed that the workers at max, stay in one position for three hours.

Roll was found to be a limiting criterion in beam and beam quartering seas and the limit of $4°$ is considered a standard criterion for operations requiring personnel to carry out heavy manual work. Graham (1990), however, questions the applicability of this criterion, considering the fact that operations are not limited by the deck inclination itself, but rather the combination of deck inclination with lateral as well as vertical accelerations which may cause personnel to lose balance. Graham (1990) further suggested that MII is a better criterion for operations, as it is more dependent on the location, whereas roll is the same anywhere on the vessel. In the calculations, both criteria were applied and it was found that roll consequently limited the operations before MII. However, the intention of this thesis is not to define which criterion that provides the most accurate operability, but rather to evaluate and compare vessels in terms of relevant and acknowledged criteria found in literature. The discussion here however, underlines the importance of providing standard and accurate limits when evaluating operability for vessels in a hazardous occupation such as aquaculture.

Green water on deck is calculated based on the relative motion between the hull and the wave. As pointed out in section 6.1, both slamming and green water on deck are criteria that should be treated with care as their validity depend on heading of the wave towards the point of interest. The incident wave field will experience distortions resulting from diffracted and radiated waves making the assumption of an undisturbed wave field invalid.

However, the distortion of the wave is larger as the wave pass over the hull, and the green water criteria was found to be limiting for the operations mostly when the wave heading is directly towards the point of interest, hence the criteria has been considered valid for the analysis carried out in this thesis.

11.3.3 Location of Working Stations

The master of Vessel 1 identified the whole working deck as locations on which operations take place. In order to capture the most severe motions of the vessels, two working stations located at locations far off the center of gravity were found convenient. As the locations were both located on starboard side, the calculations consequently gave an asymmetric operability with respect to the centerline of the vessels, especially for location dependent criteria such as MSI, MII and vertical acceleration. This introduces an error in the exact quantification on the operability of the vessels. However, as the working stations are located in a standard manner for all vessels, it is possible to make qualitative conclusions.

11.4 Validity of the Simulation Model

11.4.1 Model Simplifications

When constructing a simulation model it is important to not construct a too complicated model, but a simple one that works for its intended purpose(Campuzano and Mula (2011)). This mindset was used when developing the Simulink model in this thesis as a perfect imitation of a system is not feasible, making simplifications necessary. Certain simplifications have therefore been implemented in the model which are a simplistic imitation of the real world system. These simplifications can to some degree effect the validity of the simulation results, and it is therefore important that they are presented.

The inherent characteristic of discrete-event simulations means that the variables are assumed to take place instantaneously and in a discontinuous fashion at specific moments in time. In reality the operations are a continuous process with frequent evaluations taken throughout their duration. As such, there could in reality be important events that take place in between the one hour time steps used in this model that could lead to different results. The delaying of operations is also instantaneous, while in reality the time used to temporarily abort different parts of an operation could vary. Some segments of an operation might also be more difficult or serious to postpone. For example, if the fish are already crowded during a delousing support operation, postponing this operation due to harsh sea states could have a negative impact on the wellbeing of the fish in the crowded net pen.

The five operation types used in the simulation are modeled as one steady operation that lasts as long as this operation type takes to complete. In reality the operations are an amalgamation of several sub-operations, each with their own limitations and restrictions. The model does however attempt to partition these operations to some degree by varying the direction of the vessel when certain circumstances are met, though the criteria for operability does not change throughout the operation.

When assessing if an operation can be performed the model checks to see if the current weather is too demanding one hour in advance based on the data from the oceanographic buoys. A more authentic approach would be to implement some form of a weather forecast which would allow for a more consistent and safe evaluation for larger time frames into the future. However, conversation with industry actors presented in section 2.4.1 revealed that a vessel will often travel out to a site wait for an appropriate weather window, which makes this simplification somewhat consistent with reality.

The operational profile that decides the operational frequency is based on information about the real frequencies of operations experienced by service vessels in the aquaculture industry. In reality a service vessel will perform operations at considerably varied locations, both geographically and with respect to exposure, whereas the simulation model evaluates the operability based on only a specific site. Service vessels will also often collaborate with other service vessels when performing certain operations and attempt to complete multiple operations when visiting a site. The simulation however, only evaluates one vessel performing one operation at a time. This causes a mismatch between the way the vessels operate in real life compared to the model. The introduction of other sites with accompanying sea state information would however not be difficult to implement within Simulink if the necessary data was available. Since creating an excessively complicated simulation can lead to problems, the main focus of the thesis, which was evaluating the operability of the three vessels at exposed locations was put in the forefront, and the model as it is now allows for this evaluation.

11.4.2 Data Supplied to the Model

As Campuzano and Mula (2011) put it, *a simulation model cannot be better than the information entering it*. This means that the Simulink simulation model is dependent on reliable data from the VERES calculations, the information attained about aquaculture service vessel operations, and the operational profile that determines the generation of operations in the simulation. The validity of the VERES calculations has however already been discussed in detail, and will not be discussed further here.

The operational profile used in the simulation is an interpretation of the information attained through conversations with industry contacts making educated guesses, and therefore contains some uncertainty. The operational profile is also based on service vessels with a focus on heavy operations, and fits better for the two catamarans, Vessel 1 and Vessel 2, compared to Vessel 3 which is not primarily used for these types of operations. Vessel 3 does however have the capacity to perform these operations, and to simplify the process of evaluating and comparing the operability of these three vessels, this approach was adopted. This means that the results attained for Vessel 3 could be seen as more unreliable than for the two catamarans.

As was also stated in section 11.2, the time series data of sea states used in the simulation are approximately 1.5 years for Site 1 and 2 years for Site 2. This amount of observation points can be considered too short for a reliable evaluation of the long-term operability of the vessels.

11.4.3 Validation of the Model

There have been performed numerous tests to confirm that the model works as intended during its development. This has been done mainly by changing different values and aspects of the model and examining how this impacts the model. Using the output from the scope blocks in Simulink has been the main approach, as this is the most convenient way to evaluate that the entity traverses the model in the intended way. The output was also examined to make sure the delivered results are of a logical nature. The model has therefore been verified with respect to the fact that it works for the intended purpose it was constructed for. It is however important to point out that there could still be small errors in the code that can cause issues, though these have not been detected when verifying the model, or when using the model to acquire the results.

A model should also, if possible, be validated by comparing it to the system that it is designed to emulate. The intended purpose of the simulation is to evaluate the ability of service vessels to operate safely when the vessel operates at exposed locations. Considering no published reports on the long-term operability of aquaculture service vessels at exposed locations were available, validating the results by comparing them to real life systems is not possible. A master thesis by Runar Stemland in 2017 did however evaluate the operability of the Macho 40 service vessel design by combining vessel response calculations with a discrete-event simulation (Stemland (2017)). The results from his thesis were comparable to the results found for Vessel 3, however his model also lacked sufficient validation, which makes the validity of this comparison uncertain. SINTEF Ocean has an ongoing project which aims to examine the operability of service vessels by implementing accelerometers and sensors that measure ship motions on a number of different service vessels in the industry Selvik (2018). These measurements will then be combined with operational logs that indicate when and why operations have been cancelled. Utilizing the results from this project could allow for a validation of both the input to the simulation model, and the results from the simulation.

Chapter 12

Conclusion

The aim of this thesis was to evaluate and compare the operability and operational limits for three aquaculture vessel designs operating at exposed locations by using a combination of hydrodynamic vessel response analysis and discrete-event simulation. An operational profile for aquaculture service vessels has been created based on information gathered from conversations with industry actors. The operational profile has been used as a basis for creating a discrete-event simulation in Simulink which emulates the service vessel work cycle. Relevant operational restrictive criteria was found from literature and implemented in VERES to find operability limits for the three vessels. These limits, together with the operational profile and wave measurement data were used as input in the simulation model. The simulation model was used to evaluate the long-term operability of the three vessels, both at fixed wave directions and operations specific vessel headings with variable wave directions. The combination of short-term and long-term vessel response gave insight in to which criteria affect the different vessels, how different loading conditions affect the operability and a quantification of the operability of the vessels.

The results from the short-term statistics as well as transfer functions for each vessel revealed that the different designs were limited by different criteria. For the monohull, Vessel 3, the operability was mostly limited by roll motion. Both catamarans, Vessel 1 and Vessel 2, were often limited by MSI at WS2. Due to how the working stations were defined, the operability was found to be asymmetric with respect to the centerline of the vessels, especially for the catamarans. The long-term operability of the vessels revealed that the operability of the vessels at exposed locations in general is appreciable. Vessel 2 exhibited the best operability at both locations, with Vessel 3 showing the lowest operability. The low operability of Vessel 3 is a result of roll motion, which is often found to limit the operation of the vessel in beam seas. Vessel 1, which has a similar design to Vessel 2, was analyzed for a different loading condition compared to Vessel 2 and Vessel 3. This can explain the difference between Vessel 1 and Vessel 2 in the long-term operability analysis. When evaluating Vessel 2 for the same loading condition as Vessel 1, the long-term operability became comparable, but there were still some differences. The three vessels also performed noticeably better at Site 1, where the sea states were milder compared to Site 2, showing the effect of rougher sea states.

The combination of vessel response calculations and discrete-event simulation gave results that demonstrated how the different vessels performed at different exposure, as well as which criteria dictated their operability. The simulation results have been considered to be within the expected range. However, the model and its outputs have not been validated leading to uncertainty regarding the results. The results should therefore be interpreted as an indication rather than an exact portrayal of reality. Despite this uncertainty, the results show how different vessels perform at different exposure and allows for a comparison of the three vessels' operational limits and long-term operability, and the objective of this thesis is therefore realized. This knowledge can aid the future design of service vessels for exposed aquaculture as well as provide knowledge needed to increase the capacity for operational decision support and planning.

Chapter 13

Further Work

The study performed in this thesis gives a good indication of the operability of different service vessel designs in the aquaculture industry at exposed locations. There are however certain aspects that could lead to improved outcome quality if worked on further. In the following, other directions of interest for further research are also identified.

The vessels analyzed in this thesis have proven to have generally good operability on the sites of focus. However, the operability limits were exceeded in some sea states, and MSI, green water and roll were generally the limiting criteria. It could therefore be of interest to include additional designs in a future comparative study. As mentioned in section 2.2, SWATH vessels have been put forth as a possible vessel design for exposed locations because of their positive motion characteristics in rough seas. Such a design is already operating in the wind industry in the same length interval as the designs considered in this thesis.
Another design aspect of further work is with respect to roll motions. The criterion of a limiting RMS of $4°$ had a big impact on the monohull in beam and beam quartering seas. It could therefore be of interest to look into the effect of possible design features such as stability tanks to reduce the roll motion around resonance periods.

Although the seakeeping criteria applied in this thesis are based on acknowledged research and experience, there exist no standard tailor-made seakeeping criteria for the aquaculture industry. Therefore, the criteria applied in this thesis are taken from standards based on experience and research from other industries such as fishery and offshore and are all equally weighted for the operations carried out. SINTEF Ocean is currently conducting a projects which aims to examine the operability of service vessels by implementing accelerometers and sensors that measure ship motions on a number of vessels. Combining these measurements with operational logs that indicate when and why operations have been cancelled. Utilizing these findings could allow for a more in depth understanding of what leads to abortion of each specific operation. In light of this, it has also been reported that wind and current often impose troubles to the operations carried out by the service vessels. As these effects are not taken in to account in the analysis in VERES, it is recommended to use hydrodynamic solvers such as WASIM and WADAM for a more comprehensive analysis of the operability.

The side study performed in SIMA showed that the increased mooring line tension from wave-induced vessel motions would not be an issue during anchor deployment operations. The act of carrying out an in depth analysis of specific problem areas of concern during service operations is however important. It would therefore be interesting to identify and examine other such areas to achieve a more detailed understanding of the operability limits in exposed aquaculture. Examples could be crane wire tension during net pen handling operations and an analysis of the structural integrity of a fish farm facility during vessel collision.

Regarding the simulation model, further work could be performed to make it more comprehensible and detailed so that it can imitate the real world system to a higher degree. Possible issues with the simulation model derived from simplifications and other factors were presented in section 11.4 that could all possibly be addressed. Most important of these would be to partition the operation groups into smaller sub operations with their own limitations based on the current mission parameters. Having longer time series of sea state data would also give more reliable results of the long-term operability of the different vessels. It would also be interesting to see how these vessels would perform at even more exposed locations, since the development permit concepts revolving around very exposed aquaculture, such as Havfarm and Arctic Offshore Farming will be located in areas that will experience new levels of exposure for the industry. Doing this would also require an investigation into which operations are necessary to perform at these locations, as these concepts are constructed differently and have different operational needs than the standard circular HDPE cages. Lastly the model and its outputs have not been validated, when the necessary data needed to perform an evaluation of the validity of the model is available, for example through the ongoing SINTEF Ocean project detailed above, this should be a priority.

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Appendix A

Side Study - Analysis of Mooring Line Tensions

A.1 Anchor Deployment Operations

A more in depth analysis of a possible issue during anchor deployment operations has been performed. During this operation there has been put forth a concern regarding the holding capacity of the mooring line, as wave-induced motions of the vessel can lead to variable tensions in the line that might exceed the minimum breaking load (*MBL*) of the line (Selvik (2018)). A snapped mooring line imposes danger to the crew, as there are large forces at work. The snapped line might strike personnel, damage equipment or give rise to excessive motions of the vessels.

A typical mooring line for aquaculture purposes consists of an anchor, a chain and a synthetic fiber rope. The most common choice of anchor for a sandy/muddy sea bottom is a plough anchor which is burrowed in to the sea bed. The chain serves as a link between the anchor and the synthetic fiber rope and provides weight to the mooring line in order to keep the angle between the rope and the seabed within a desired range (Cardia and Lovatelli (2015)). In addition, the chain prevents the synthetic fiber rope from experiencing wear from sharp edges along the sea bottom. A typical length for a chain for the intended purpose is given as 27.5 meters according to co-supervisor Selvik (2018). Furthermore, according to Høy and Martinsen (2010), it is a common rule of thumb in the industry to apply a rope length of three times the water depth at the location of deployment. Based on information collected from interviews with Contact-1 (2018) and Contact-2 (2018) it has been found that the bollard pull of a service vessel during an anchor deployment operation is generally in a range between 8-12 tons. This is however dependant on the required load the mooring line and anchor should be able to withstand based on the site specifications. A figure showcasing the layout of the system is given in A.1.

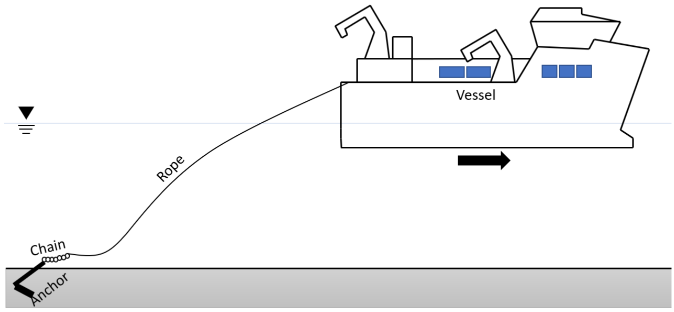

Figure A.1: Showcase of anchor deployment operation

A.2 Modeling of Anchor Deployment Operation

In order to model the operation, a set of first order transfer functions for all vessels were imported from VERES. The bollard pull is modelled by giving the mooring line a pre-tension equivalent to the bollard pull of the respective vessels. Furthermore, the anchor point is set to be fixed at a given position on the flat sea bottom. In accordance with the short-term operability calculations in VERES, a three parameter JONSWAP spectrum has been considered appropriate for the locations at focus. In order to get maximum values for the response, the vessels are subjected to head waves, which after comparison with following seas consequently gave higher tension in the mooring line. Figure A.2 showcases the SIMA model used in the analysis.

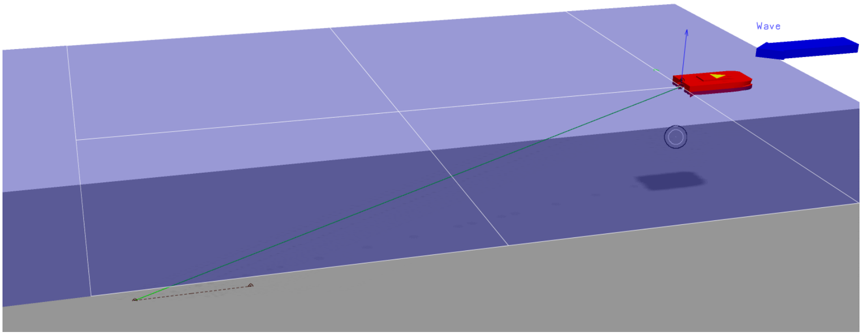

Figure A.2: 3D model from the SIMA analysis showing the fixed anchor point, mooring line, vessel and wave direction

The simulation length has been set to 3600 seconds with a time step of 0.02 seconds. While this specific operation is generally performed for approximately 20 minutes (Contact-1 (2018)), the simulation length was increased in order to have a sufficient number of incoming waves, as the wave generation is based on a spectrum of waves that change over time. To avoid transient motions at the start of the simulation, the sampling of data starts at 60 seconds. For every run, the recorded maximum, mean and minimum tension experienced in the mooring line is sampled with the help of the post processor in SIMA. As long periods gave rise to larger tension in the mooring line, a combination of the highest spectral peak (*Tp*) and significant wave height (*Hs*) for both sites have been used to generate the JONSWAP spectrum in the analysis, seen in table A.1.

Table A.1: Highest measured combination of Hs and Tp at both sites.

Site	Hs [m]	Tp [s]
Site 1	1.87	22.27
Site 2	4.57	24.9

The fiber ropes used in the analysis are of the type Supertec 8-strand polypropylene ropes (Haug.no (2018)). They were chosen because they are a rope type often used by vessels during these operations (Selvik (2018)). Polypropylene ropes have elongation at MBL in the range of 18-22 %, and a conservative estimate of 18% was chosen for the ropes (SamsonRope (2018)). According to requirements from NS 9415 (2003), the maximum load for the mooring line should be calculated as in equation A.1, with γ_f and γ_m being the load and material factor respectively.

$$F\gamma_f \leq \frac{R}{\gamma_m} \tag{A.1}$$

F is the load experienced by the mooring line, while R is the limit of the respective mooring line, in this case the MBL. The value for the material factor is set to be 1.5 for a proven and documented rope. The load factor is set to be 1.15 in accordance with the recommendations for an unmanned dynamic analysis. Table A.2 details the two different fiber ropes and the chain used in the analysis.

Table A.2: Properties of chain and fiber ropes used in SIMA analysis

Parameter	**Chain**	**Fiber rope 1**	**Fiber rope 2**
Diameter [mm]	50.7	36	72
Minimum Breaking Load [kN]	[-]	277.6	1034.9
MBL with material factor [kN]	[-]	185.1	689.3
Mass coefficient [kg/m]	15.84	0.58	2.34
Axial stiffness [N]	[-]	$1.54 \cdot 10^6$	b3
Elongation at MBL	[-]	0.18	0.18

The analysis carried out in SIMA gives different statistical properties. In figure A.3 the maximum, mean and minimum tension in the fiber rope is plotted against the bollard pull of the vessel. The minimum breaking load is represented by the horizontal line. This serves as an illustrative case and the sea state in this example represents an extreme sea state which was never encountered in the measurements from the oceanographic buoys. The max tension in the fiber rope represents the effect of the dynamic motion of the vessel when it is subjected to head waves.

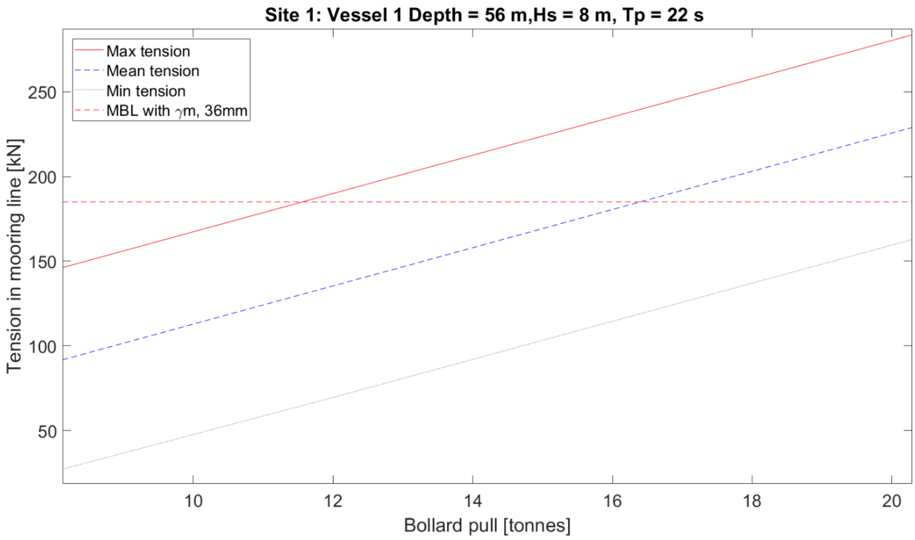

Figure A.3: Tension in line for Vessel 1 at Site 1, horizontal line is MBL for 36 mm fiber rope

The model is an approximation of reality as a set of simplifications have been made. Firstly, the transfer function from VERES only considers first order motions. Furthermore, no current or wind effects are taken into consideration. As the anchor has been modelled as a fixed point in the analysis, no consideration has been made towards the holding power of the anchor.

A.3 Results

The following results investigate the effect of changing different parameters in the analysis. The main objective is to find different parameters relevant to the two sites and vessels that cause the fiber rope to exceed its minimum breaking load.

A.3.1 Different Vessels

Figure A.4 shows the maximum experienced tension in the mooring line fiber rope for the three different vessels at Site 1. In the figure it can been seen that Vessel 2 experiences the largest tension, but there is not a substantial difference between the vessels. A similar plot for Site 2 can be found in Appendix B, with similar results with regard to the differences between the vessels.

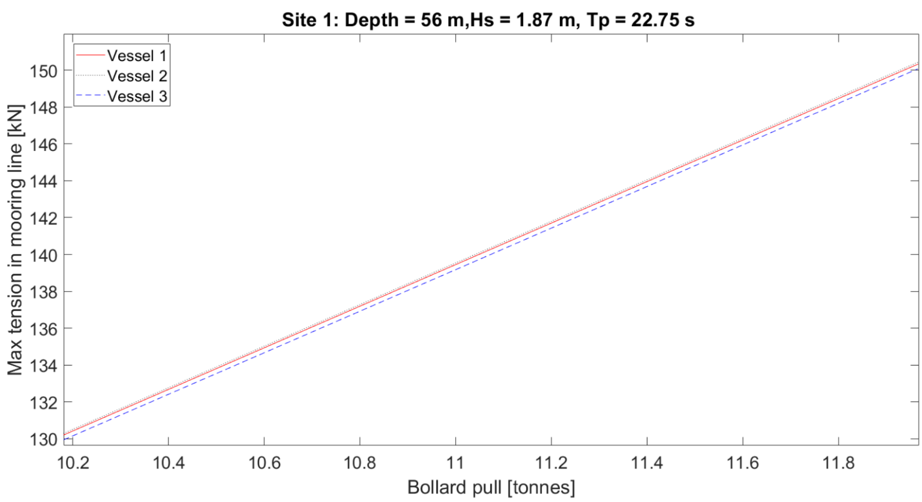

Figure A.4: Effect of vessel design on line tension at Site 1

A.3.2 Effect of Different Water Depths

The two different locations, have different water depths at 127 meters and 56 meters respectively, roughly found through the use of Kartverket's map tool (Kartverket (2018)). The effect of deploying the anchor in shallow water compared to deep water shows that the tension in the anchor line is larger in shallow waters, seen in figure A.5. This is an expected result when considering that the rope is much longer in the deep water case. By making a simple physics consideration, Hooke‘s law tells us that the force applied on the rope is given as $F_r = kx$, where k and x is given as the stiffness and the elongation of the rope respectively. Now, x can be written as $\frac{s}{L}$ with s being the fractional static elongation and L the total length of the rope. Therefore, it is evident from equation A.2 that a shorter rope will imply a larger force given the same fraction of elongation and stiffness.

$$F_r = k\frac{s}{L} \tag{A.2}$$

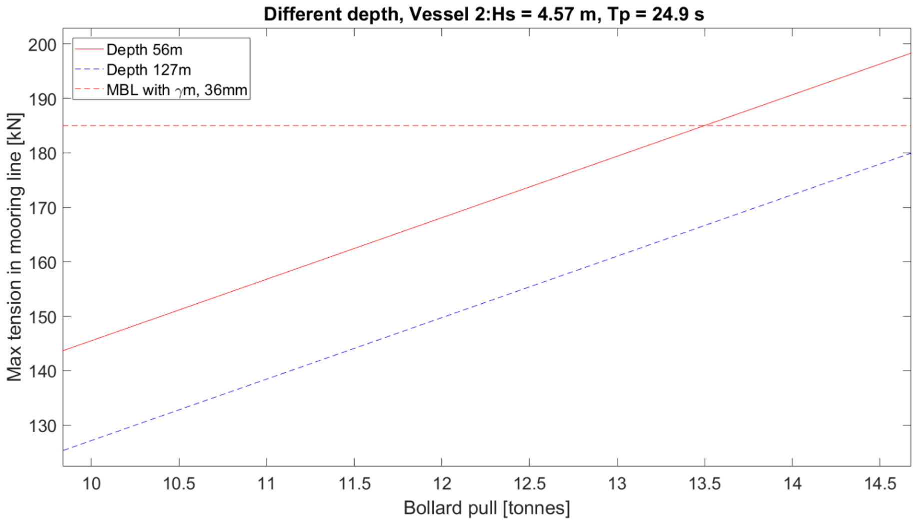

Figure A.5: Effect of water depth on line tension

A.3.3 Minimum Breaking Load

In figure A.6, the minimum breaking load (MBL) is compared to a typical range of bollard pull for the vessels. The general range of bollard pull from a service vessel is highlighted by the grey area. As is evident in the figure, the tension in the mooring line at a typical range of bollard pull is far from reaching the material factor minimum breaking load. A similar graph for the 72 mm found in Appendix B also shows that the maximum tension in this rope will not exceed the MBL unless a significant bollard pull is applied to the rope, far higher than the average of 10-12 tonnes.

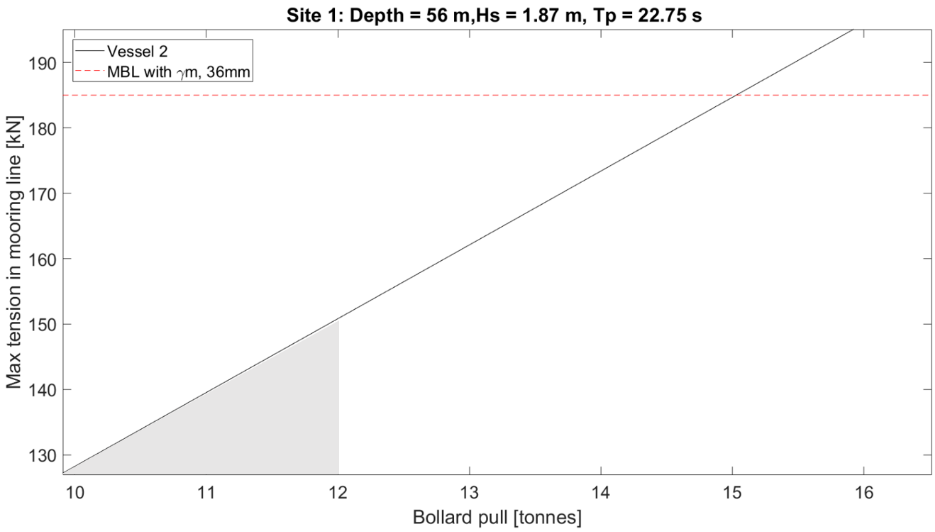

Figure A.6: Bollard pull vs Max tension in mooring line. MBL indicated as dotted line. The typical bollard pull range from the vessels is marked in grey.

A.4 Discussion

From the results in section A.3 it is shown that shallower waters will give rise to higher tension in the mooring line when deploying an anchor due to the elastic properties of shorter fiber ropes. However, even when considering the highest significant wave height and spectral periods, both polypropylene ropes were still far from reaching the minimum breaking loads at both locations. Furthermore, as expected, the fiber rope with the smallest diameter is closest to reaching its minimum breaking load due to its much lower MBL. There was also small differences in maximum tension when analyzing the different vessels, with Vessel 2 experiencing the largest tensions. These were however deemed not to be particularly consequential due to small differences and the simplifications used during the analyzes. While there was a desire to implement these results into the Simulink simulation, it is clear that the environmental conditions encountered at the two sites of interest will not cause the tension in the mooring line to exceed the MBL. Other operability limits set during the VERES analysis presented in section 6.1 of the main thesis body will also be exceeded before the MBL of the lines is surpassed.

Høy and Martinsen (2010) reported on the holding power of different types of anchors in the aquaculture industry, indicating that anchors will often slip in the range of 10-25 tonnes. This indicates that there is a good chance for the anchor to loose traction before exceeding the MBL in the fiber ropes. This is however dependant on the seabed conditions, as rocky seabeds will often hinder the traction of the anchor. This problem did not arise during this specific analysis, due to the anchor being modelled as a fixed point. Vessel instability and minor deviations in the direction of traction due to wind, current and waves are also discussed as issues during anchor operations, and the effects of this could also impact the ability to perform this operation safely.

Only using the input from the first order transfer functions from VERES was deemed necessary due to the lack of full 3D models of the vessels. By using 3D models of the vessels in a program such as WASIM, a more comprehensive analysis of the individual vessels could have been performed. Using this as input into SIMA would allow for the inclusion of wind and current, wave drift forces and other factors that would have an effect on the vessel motions as well as the mooring line. This would in turn give the results a higher reliability, as well as possibly giving a larger difference between the three vessels as their hydrodynamic properties could be modeled more comprehensively.

A.5 Conclusion

Through the analysis of line tensions during anchor deployment operations performed in SIMA, a distinct evaluation of a specific possible issue was performed. However, the results showed that the sea states experienced at the sites would not cause the tension to exceed the MBL of the mooring line. As a first approximation to the problem at hand, the approach of only including first order linear motions from VERES was considered sufficient as the calculated tension in the mooring lines were far from the minimum breaking load. The act of carrying out an more in depth analysis of specific problem areas of concern when performing service operations is however important. The results from multiple analyzes of operations such as this can result in a more detailed and in depth understanding of the operability limits in exposed aquaculture. If these limits are implemented into a model, they can provide more accurate and reliable results of the long-term operability of service vessels in the aquaculture industry.

A.6 Further work

Further work on this issue, if more exact results are of interest, should entail the use of vessel kinetics from full 3D models analysis from programs such as WASIM and not only the first order motions of the vessel imported from VERES. The further use of SIMA or other similar tools as a way to evaluate more specific issues faced in exposed aquaculture is an important step in the goal of establishing reliable quantitative limits that can be used as input when deciding if an operation can be safely executed. Such calculations are relevant both as an input for a simulation and also for real life decision making.

Appendix B

Auxiliary Results from Mooring Line Analysis

B.1 Different rope diameters

Fiber ropes at both ends of the spectrum, with the diameters of 36mm and 72mm were analyzed. The 72 mm rope experiences a larger tension than the 36 mm at the same bollard pull. However, the difference in MBL between the ropes is large, and the 36 mm reach its MBL limit at a much lower bollard pull compared to the 72 mm.

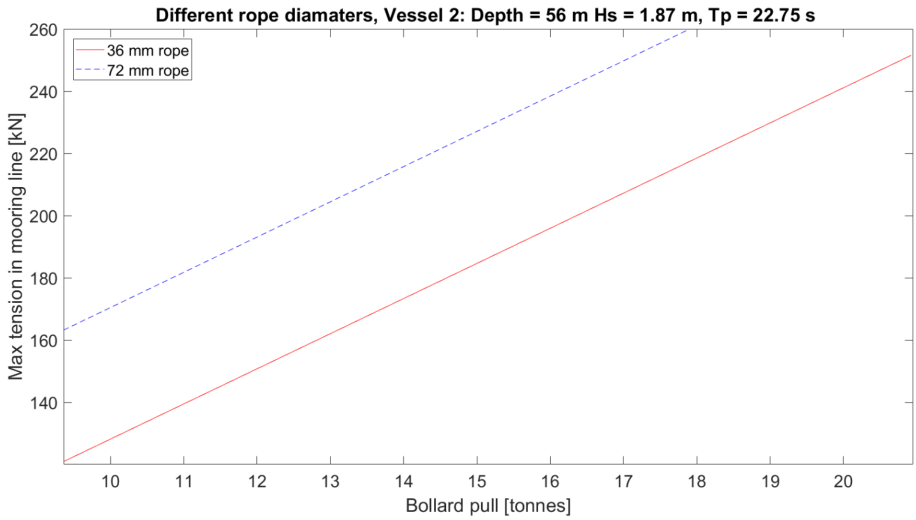

Figure B.1: Effect of rope diameter on line tension.

B.2 Effect of vessel design on line tension at Site 2

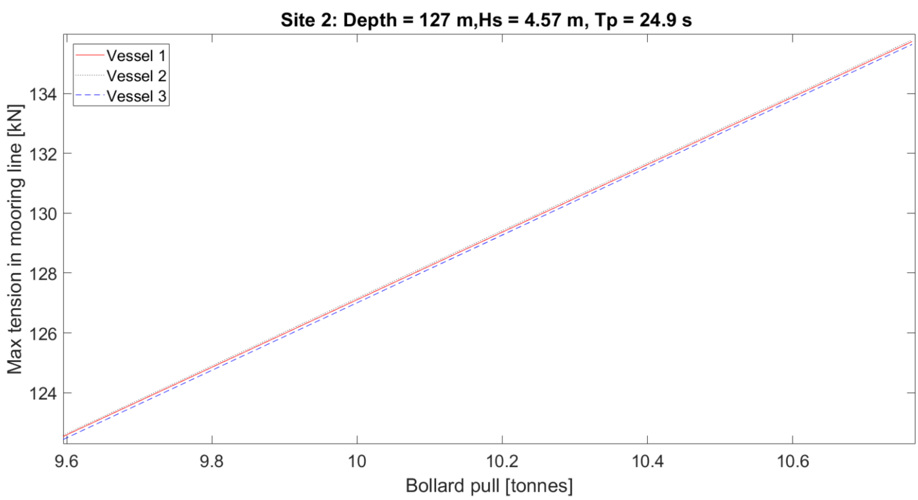

Figure B.2: Effect of vessel design on line tension at Site 2. As seen, the differnce is small.

B.3 Maximum tension in 72 mm fiber rope at Site 2

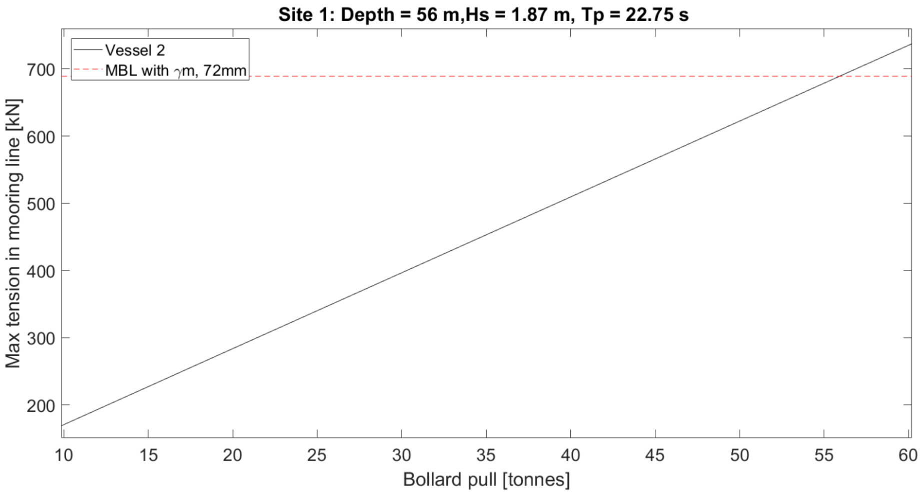

Figure B.3: Maximum tension in fiber rope with increased bollard pull. MBL of 72mm rope seen as horizontal line at the top.

Appendix C

Task Description

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2018

For stud.techn.
Trym Sogge Sjøberg, Øyvind Haug Lund

Evaluation and comparison of operability and operational limits of service vessel designs in exposed aquaculture

Background
The world's population is expected to reach 9 billion in 2050, which in turn will give rise to the need of an increase in food production of at least 70 % to adequately feed the growing population. With many global fishery productions being almost static since the 1980s, aquaculture has been the driving factor in the impressive growth in the available supply of fish for human consumption and will continue to be so in the foreseeable future.

In the aquaculture industry, Norway is the world's largest exporter of farmed Atlantic salmon as well as a leading actor when it comes to technology and competence. Norway had a total production of approximately 1.23 million tonnes in 2016 and a plan to increase the production up to five million tonnes by 2050. Norwegian fish farming started out in sheltered areas along the coast and in the fjords but has gradually been moving towards more exposed locations due to a lack of available area. Another factor in the push towards more exposed locations is that The Norwegian Directorate of Fisheries, in response to high rates of salmon lice infestation in Norwegian salmon farming and other environmental issues, has stopped giving out new standard salmon farming permits. To give the industry an incentive to find new ways to combat these problems, The Norwegian Directorate of Fisheries created a system that granted development permits to industry actors who developed technology and solutions that could solve environmental and area challenges within the industry. A considerable number of these applications revolve around fish farm designs that will allow for fish farming in areas that are considerably more exposed than what is experienced at the present. Examples of this are the Havfarm, Ocean Farm 1 and Arctic Ocean Farming concepts, from Nordlaks AS, Salmar AS and Aker Solutions ASA respectively.

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Exposed farming can bring with it many benefits, such as less environmental impact due to increased dispersal of waste products, less conflict concerning limited area along the coast, and better production due to favourable currents allowing increased swimming activity and better oxygen dispersal. Because of these potential benefits, the industry is interested in pursuing this endeavour. There are however new challenges that come with exposed aquaculture. Significant parts of the Norwegian coast are today unavailable to industrial fish farming. Regular as well as infrequent operations are made challenging due to remoteness and exposure to harsh wind, wave, current and ice conditions. Increased exposure to winds, waves and currents, enhances the challenge of carrying out the required operations for salmon production at sea safely. This includes both the health of personnel and fish in the fish cage, as well as the chances of fish escape.

The technology and methods used today limit the degree of work that can be performed in harsh waves and currents, limiting the operational window for important operations. A survey completed in 2012 found that according to industry actors, one of the key areas that needs to be researched in exposed aquaculture was operational decision support by determining more objective criteria for when an operation can be performed and when it must be stopped. In the present industry, the decision of whether or not to perform an operation or travel out to a location with a service vessel is based on experience and judgment on the person in charge. An unnecessarily postponed operation can have negative economic impacts and consequences for the health of the fish and the environment. Meanwhile the execution of an operation in unsafe conditions can lead to accidents that can harm the workers, the fish or the integrity of the entire fish farm. With aquaculture being the second most dangerous occupation in Norway, there is a need for a supplementation of knowledge to help decide if an aquaculture service vessel has the ability to perform its assigned tasks at exposed aquaculture locations.

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Objective

The aim of this thesis is to evaluate and compare the operability and operational limits for three aquaculture service vessel designs at exposed locations by using a combination of hydrodynamic vessel response analysis and discrete-event simulation. Quantitative operational limits will be determined by analysing vessel motions with respect to a set of restrictive criteria. A simulation model of a service vessel work cycle will be applied as a way to judge the different vessels capacity to complete their given assignments in the form of their long- term operability. Wave data from oceanographic buoys and the operational limits found in the analysis of the vessels will be used as input in the simulation. Evaluating the operability limits and comparing the different vessels by combining the analysis of vessel motions with a discrete-event simulation model can give an indication of how the three vessel designs perform at different levels of exposure and what the limiting criteria is for the different vessels. This can in turn aid the future design of service vessels for exposed aquaculture as well as provide knowledge needed to increase the capacity for decision support and planning during operations at exposed locations

Tasks

The candidate is recommended to cover the following parts in the project thesis:

a. Gain an understanding of the relevant operations performed by service vessels in the aquaculture industry.
b. Create an operational profile that can be used as a basis for creating a discrete event simulation that aims to emulate the operations performed by the service vessels of interest.
c. Find relevant criteria to use as a basis for evaluating the vessels ability to perform operations in a safe manner at exposed locations.
d. Use these criteria to find the operational limits for three different aquaculture service vessels.
e. Implement the operational limits into the simulation model to evaluate and compare the operability of the three vessels during operations at two exposed locations.
f. State a set of recommended tasks for further work.

In addition, an analysis on the effect of wave-induced vessel motions on line tension during anchor deployment operations will be performed in this thesis. If the line tension exceeds the minimum breaking limit due to vessel motions the aim is to also implement this as an additional operational limit in the simulation model.

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

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Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverable

- The thesis shall be submitted in two (2) copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:
Main supervisor:
Bjørn Egil Asbjørnslett

Co-supervisor:
Ørjan Selvik

Deadline: 25.06.2018

Appendix D

Software Programs Description

The programs utilized in the thesis were ShipX, SIMA and Simulink in combination with MATLAB. MATLAB will however not be further explained as it is assumed this is prior knowledge obtained by the reader. ShipX with the VERES package is used to examine the hydrodynamic vessel responses for the three ships. SIMA is used utilized in order to examine how the surge motions of the different vessels impacts the tension experienced in a mooring line during anchor handling operations. Finally Simulink was used to create the discrete-event simulation models that were used to evaluate the operability of the different vessels.

ShipX/ VERES

ShipX is a platform that integrates a variety of different hydrodynamic analysis into an integrated design tool. With the help of ”Plug-ins” advanced functions can be added as an addition to the basic functions of hull geometry manipulation and database operations built into ShipX. The *VERES* ”Plug-in” used in this thesis adds ship motion and global load calculations to the platform.

SIMA/ SIMO and Riflex

SIMA is a streamlined graphical interface platform with 3D visualization for simulation and analysis of marine operations and floating systems. SIMA incorporates both *Riflex* and *SIMO* as underlying numerical programs and can use the programs individually or in coupled analysis using both programs. Riflex is tool for advanced static and dynamic analysis of slender marine structures, such as mooring lines and risers. SIMO is a time domain simulation program used to study marine operations.

MATLAB

MATLAB is a numerical computing program and programming language. MATLAB allows for matrix manipulations, plotting of functions and data as well as a range of other computation techniques. MATLAB is primarily used for numerical computing, but also allows for symbolic computing.

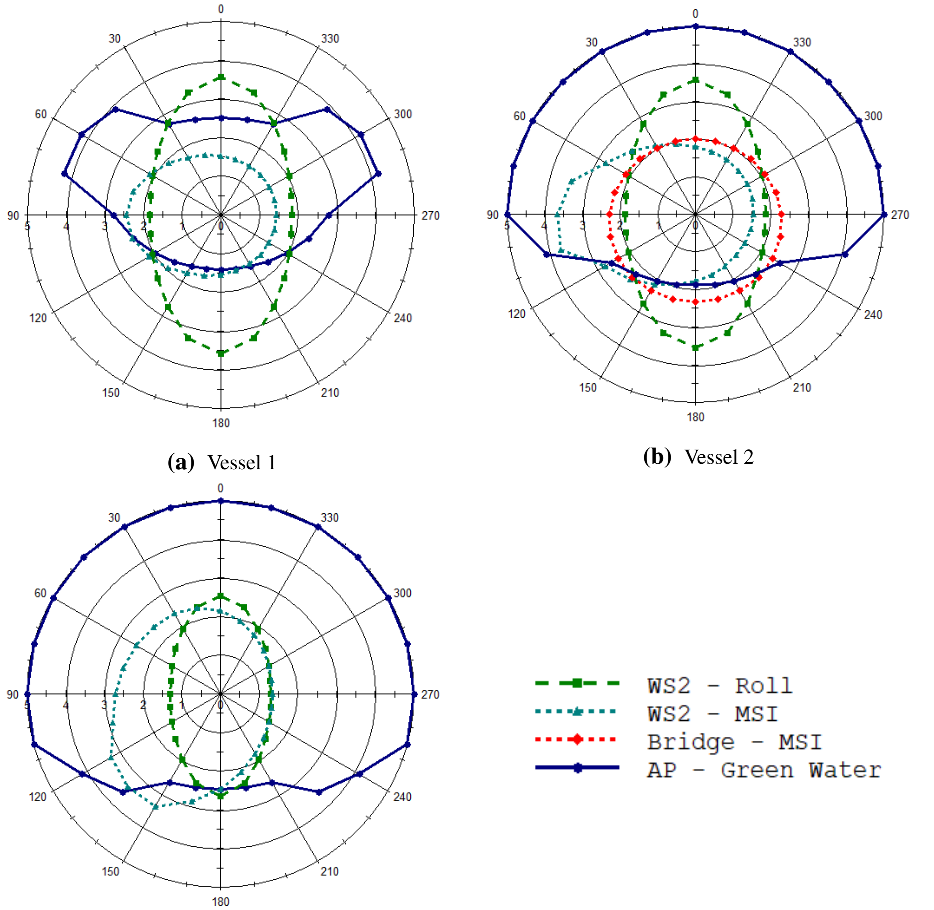
Simulink/ SimEvents

Simulink is a graphical block-diagram environment for modeling, simulating and analyzing multi-domain dynamical systems. Simulink is integrated into MATLAB, and can therefore seamlessly incorporate MATLAB algorithms, as well as export results directly to MATLAB for further analysis. *SimEvents* is a discrete event simulation engine that adds a component library for event-driven system models to the Simulink environment.

Appendix E

Operability Plots from VERES

From VERES a range of different plots are available. The following polar plots presents the effect of all criteria applied in the operability calculations of the three vessels analyzed in this thesis. In accordance with the rest of the analysis as well as all figures presented in this thesis, the plots are based on short-crested seas and a JONSWAP spectrum with a cosine-squared spreading function. The limiting values are selected within a crossing period from 4 [s] to 20[s]. As a remainder of the direction convention, zero degrees correspond to head seas and 90 degrees corresponds to port side waves. In addition it is emphasized that all calculations are given at zero forward speed for all vessels. Lastly, the operability will be asymmetric with respect to the centerline of the vessels for vertical acceleration, MSI and green water on deck. This is a result from how the working stations are defined on the vessels.

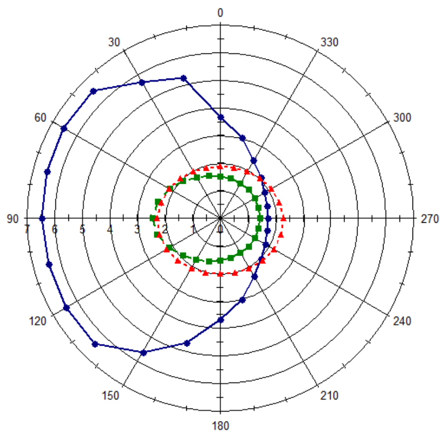


(a) Vessel 1

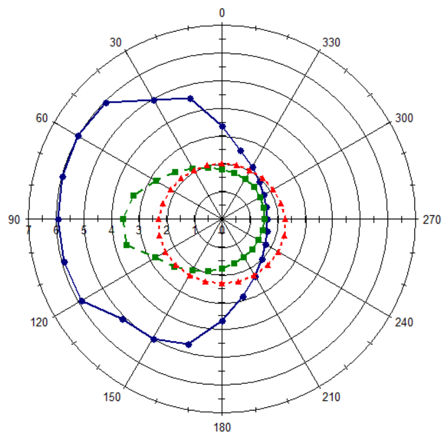
(b) Vessel 2

(c) Vessel 3

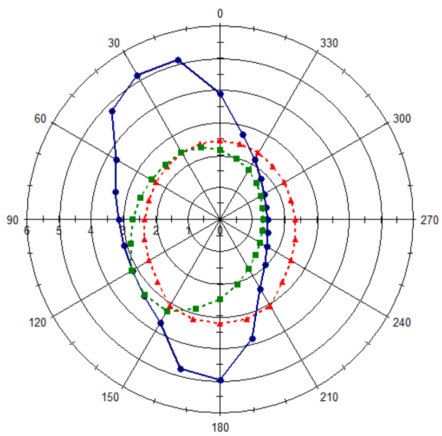
Figure E.1: Resulting limiting criteria for all three vessels. It is clear from the figures that Vessel 3 shows greater operability in head and following waves compared to Vessel 1 and Vessel 2. Both Vessel 1 and Vessel 2 are clearly limited by MSI on WS2 for starboard, and head waves. Vessel 1 and Vessel 2 are also more impacted by green water on AP center. The operability of Vessel 3 is generally limited by roll especially in beam waves.



(a) Vessel 1



(b) Vessel 2



(c) Vessel 3

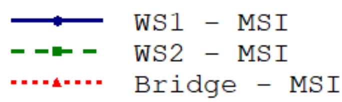
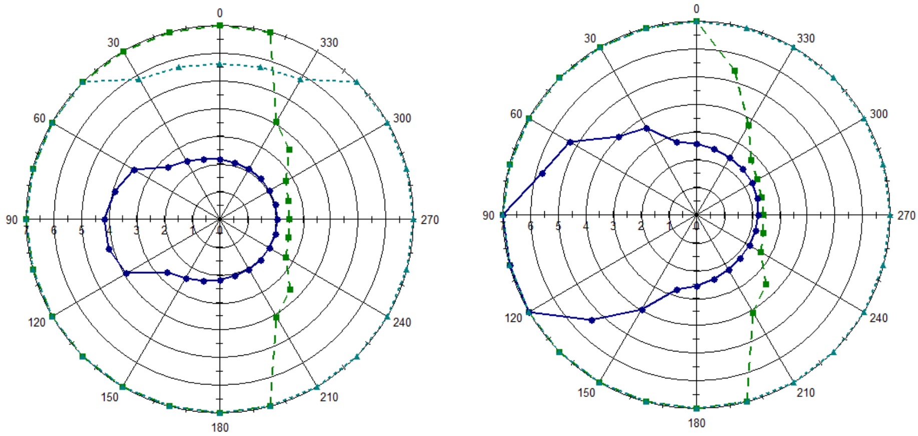
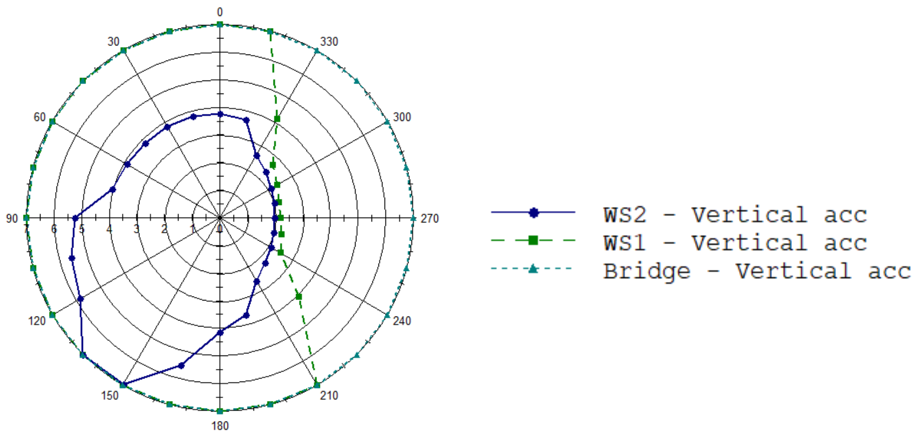


Figure E.2: Effect of MSI on all three vessels. From the figure one can see that MSI at Working station 2 in particular limit the operability of the vessels. Compared to Vessel 3, both Vessel 1 and Vessel 2 are more limited by the MSI criteria, especially in head and following waves.

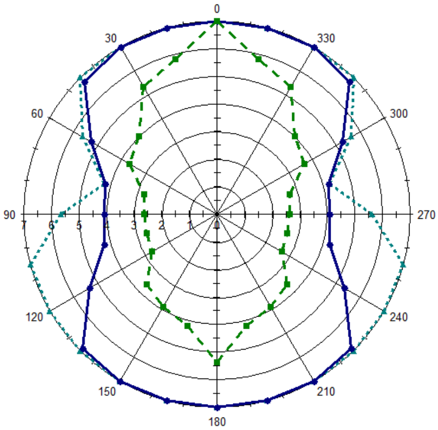


(a) Vessel 1 **(b)** Vessel 2

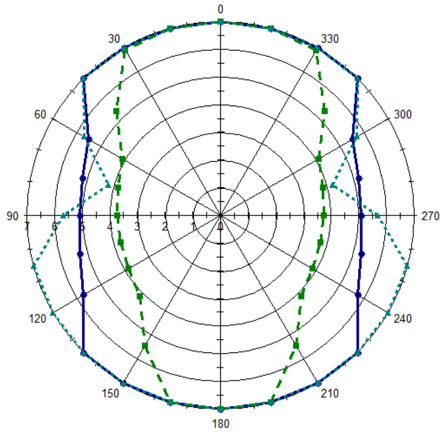


(c) Vessel 3

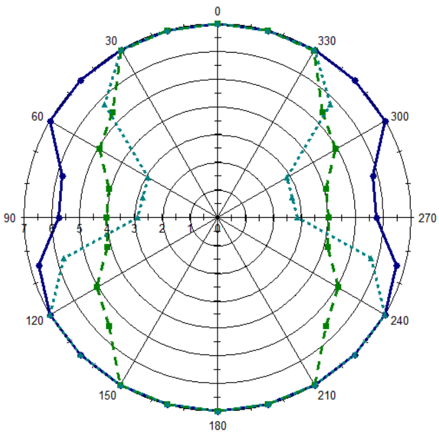
Figure E.3: Effect of vertical acceleration on all three vessels. In beam waves on starboard side there are only small deviations between the vessels, but Vessel 3 shows better operability in head and following waves compared to Vessel 2 and in particular Vessel 1.



(a) Vessel 1



(b) Vessel 2



(c) Vessel 3

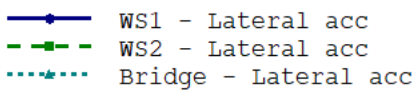
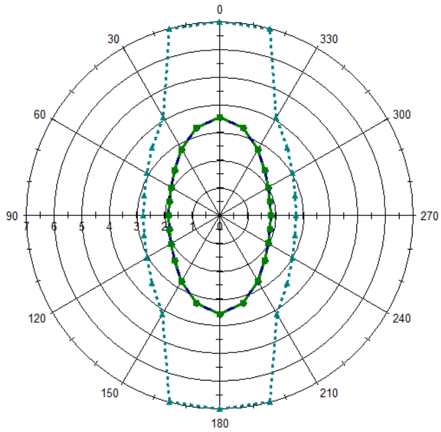
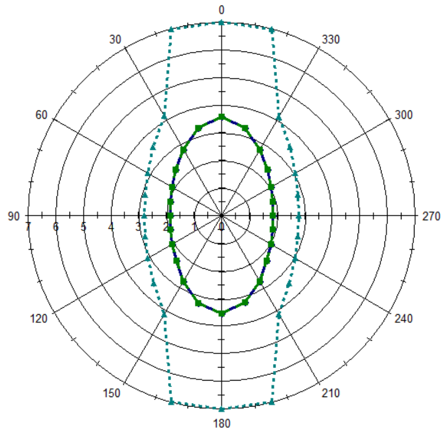


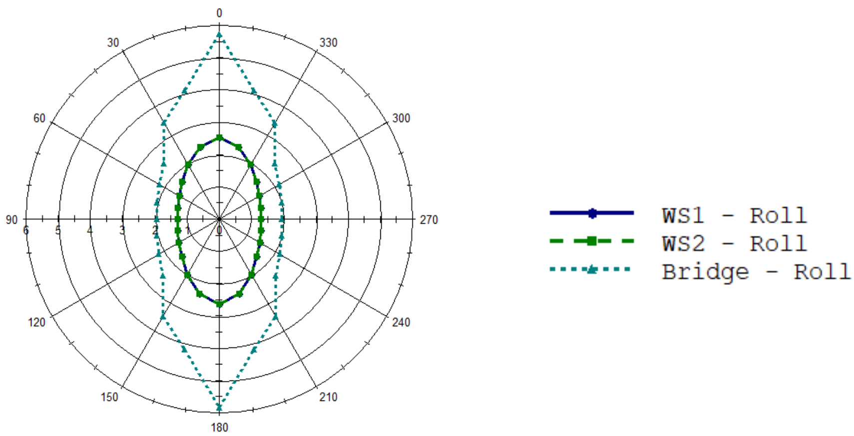
Figure E.4: Effect of lateral acceleration on all three vessels. In general all vessels have appreciable operability with respect to this criteria at the sites considered in this thesis. Vessel 1 tend to be generally more affected, especially on working station 2.



(a) Vessel 1

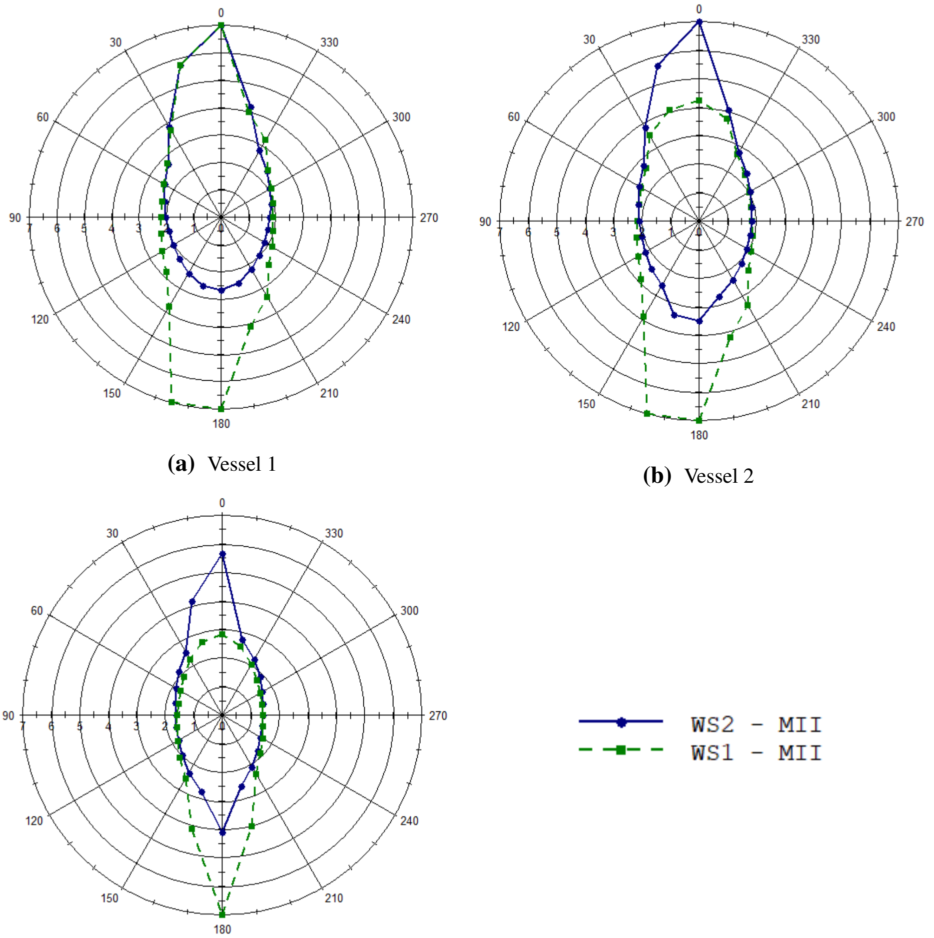


(b) Vessel 2



(c) Vessel 3

Figure E.5: Effect of roll on all three vessels. As is evident in the figure, roll motion limit the operability of Vessel 3 more compared to both Vessel 1 and Vessel 2 and the effect is as expected more prevalent in beam seas. As the roll motion is the same on all locations on the vessel WS1 and WS2 coincides in the plots. At the bridge the limit was set to 6° and on WS1 and WS2 4°.

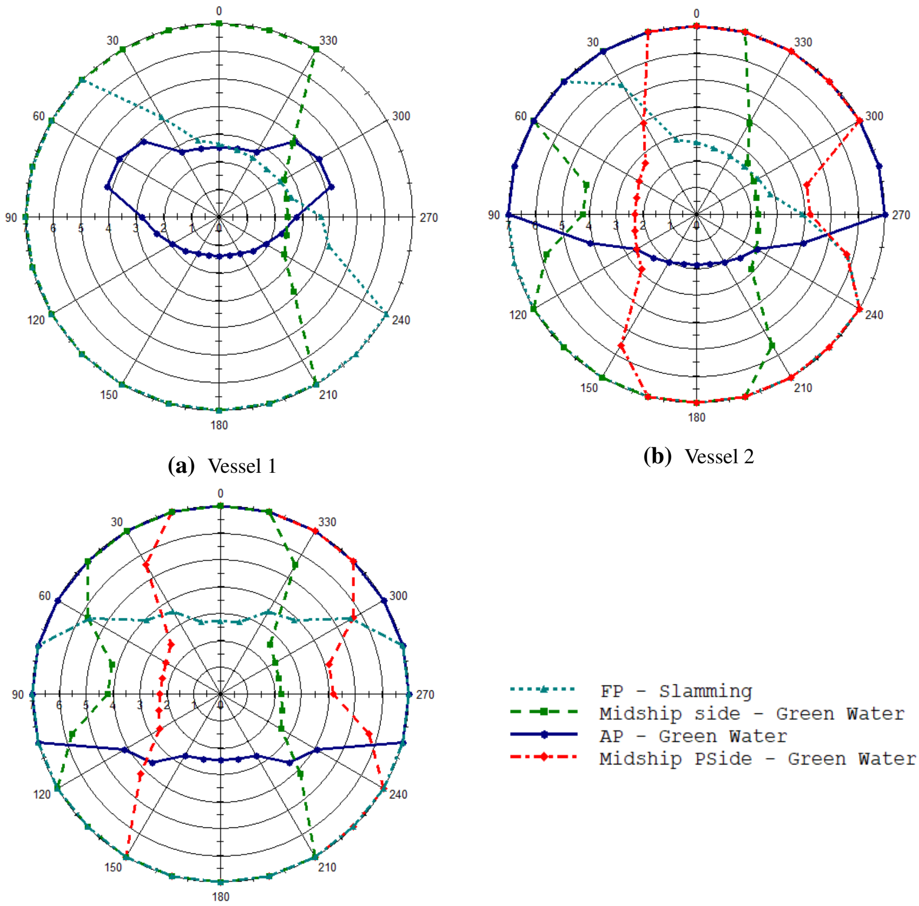


(a) Vessel 1

(b) Vessel 2

(c) Vessel 3

Figure E.6: Effect of MII on all three vessels. Motion induced interruptions limit the operation more for Vessel 3 compared to Vessel 2 and Vessel 1. This is not surprising given that the incidence of MII is strongly correlated with roll motion. Roll motion consequently surpassed the limit before MII in the analysis.



(a) Vessel 1

(b) Vessel 2

(c) Vessel 3

Figure E.7: Effect of relative motion criteria on all three vessels. Relative motion include both slamming and green water on deck. Green water limited the operation of Vessel 1 and Vessel 2 to a larger degree compared to Vessel 3. It is assumed that the larger freeboard of Vessel 3 gives the vessel a better operability with respect to this criteria.

Appendix F

Operability T - Different Wave Directions

The mean *Operability T* for all three vessels at fixed wave headings from 0°-330°is shown for Site 1 in table F.1 and Site 2 in table F.2. The operability is generally high at both sites. 91.82 % is the lowest operability that occurs, when Vessel 3 is at Site 2, with waves coming in at 270°.

Table F.1: Mean Operability T for all three vessels at fixed wave headings, from 0°to 330°for Site 1

Wave direction	**Vessel 1**	**Vessel 2**	**Vessel 3**
0°	99.91	100	100
30°	100	100	100
60°	100	100	99.26
90°	99.95	99.97	98.10
120°	100	100	99.26
150°	99.94	100	100
180°	99.61	100	100
210°	99.68	99.92	99.99
240°	99.58	99.76	99.25
270°	99.58	99.87	97.84
300°	99.71	99.93	99.24
330°	99.76	99.99	100

Table F.2: Mean Operability T for all three vessels at fixed wave headings, from 0°to 330°for Site 2

Wave direction	**Vessel 1**	**Vessel 2**	**Vessel 3**
0°	99.18	99.98	100
30°	99.89	100	99.99
60°	99.33	99.36	95.53
90°	97.67	97.74	91.83
120°	99.34	99.33	95.53
150°	99.88	100	99.99
180°	99.07	99.97	100
210°	97.67	99.10	99.88
240°	96.92	98.10	95.53
270°	96.99	97.51	91.82
300°	98.11	99.27	95.53
330°	98.63	99.88	99.99

Appendix G

Simulink Model Terminology

G.1 Simulink Model Terminology

Entities are the discrete items that travel to and interact with the blocks of a model. Entities are given various attributes that help in the interaction with the blocks.

Attributes are the specific traits given to an entity. When moving between blocks, these traits can be modified, and can therefore keep track of which operation is being performed, what vessel is being used, etc.

Global Variables can be accessed from all areas of the model. This means that these variables can be accessed and changed from different blocks, which gives them the ability to communicate with one another. This includes the Data Store Memory blocks.

Blocks hold and interact with the entities as they move through the model. There are a large variety of different block in the Simulink library, each with a different function for interacting with the entities. The blocks most frequently used in this thesis are presented below.

- **Entity Queues** are blocks that withhold entities until the subsequent block is available for access. While different types of ques can be used, first in first out(FIFO) has been used in this model.

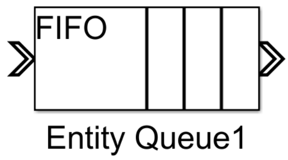


Figure G.1: Entity Que

- **Entity Servers** are the blocks where the entities are served as they arrive and are held for a given time. These blocks are often used to imitate the processes completed by the entity as it moves through the model.

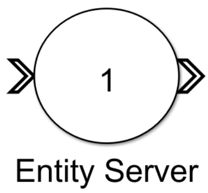


Figure G.2: Entity Server

- **Scopes** are blocks that display the output from the block that it is connected to, with the output changing depending on the block in question. This can for example be the total number of entities departed, or average queue length.

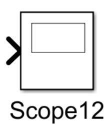


Figure G.3: Scope

- **Simulink Functions** are subsystem blocks used to graphically define a function with Simulink blocks. You can call a Simulink function block from another block and thereby make the Simulink function give a desired output.

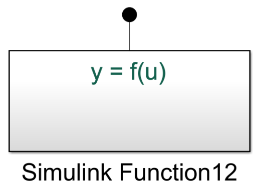


Figure G.4: Simulink Function

- **Entity Gates** are used to allow or block an entities' access to a path. This can be useful when a certain path should be chosen based on a certain event. For example which operation is required to be completed.

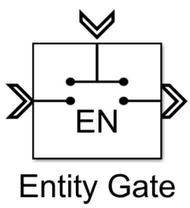


Figure G.5: Entity Gate

- **Data Store Memory** blocks define a shared data storage which can be accessed by data store read and data store write blocks. Since this shared data storage can be accessed form other blocks it gives them the ability to "communicate" data and values.

Figure G.6: Data Store Memory

- **Input and Output Switches** are blocks that decrease or expand the available paths an entity can take. They can also determine which path the entity is allowed to travel based on the values of entities attributes.

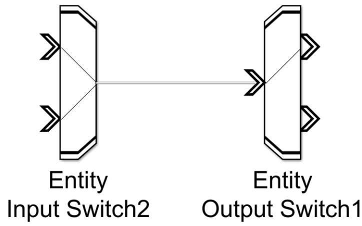


Figure G.7: Input and Output Switches

- **Digital Clocks** output the simulation time at a specified interval. When not at this interval, the block holds the output at the preceding value.

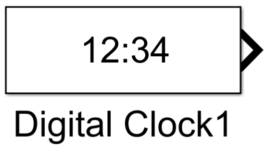


Figure G.8: Digital Clock

Appendix H

Matlab Scripts

The first script presented in H.1 is used to initiate and run the simulation model with fixed wave directions, as well as processing the output.

H.2 is the script used to evaluate the operational limits during the model with fixed wave directions.

H.3 presents the script used to initiate and run the simulation model with operation specific headings and variable wave directions. Although there is one version for each site the only difference is in regard to some variable names, so only one of them is presented.

In H.4 the scripts show how the operational limits are evaluated under different operations. Only ”Anchor and mooring frame deployment”, ”Delousing support” and ”ROV inspections” are presented. This is due to large similarities between the operations: ”Anchor and mooring frame deployment” and ”Tension of mooring lines”, and ”Delousing support” and ”Net pen handling”.

H.1 Run-Fixed Wave Directions

```
clear all;
clc;
% Load systems and prealocate arrays
Nr = 1; % nr of iterations with different seeds
Site = 1;%Sal = 1 Val = 2 %NB! manually change name of sim for site 1 and 2
Ship_Type = 3;  %1 = Vessel 1, 2 = Vessel 2, 3 = Vessel 3
Values_ship = [ 10;Ship_Type];%First row:service speed, second row: ship_type.
xlswrite('ReadValuesShip.xlsx',Values_ship);%write ship values to excel
if Site == 1
    Stop_Time = 12864;%stop time for simulation
    Wait_time_Sal = zeros(Nr,24);
    Number_Wait_times_Sal = zeros(Nr,24);
else
    Stop_Time = 18556;%stop time for simulation
    Number_Wait_times_Val = zeros(Nr,24);
    Wait_time_Val = zeros(Nr,24);
end
if Ship_Type == 1
    load_system('Final_OpLim_Site2_fixed_dir');% Final_OpLim_Site1_fixed_dir or Final_OpLim_Site2_fixed_dir
Limits = xlsread('V1OPLIM.xlsx',1,'A1:AV30');%limits for all 24 sectors
elseif Ship_Type == 2
    load_system('Final_OpLim_Site2_fixed_dir');% Final_OpLim_Site1_fixed_dir or Final_OpLim_Site2_fixed_dir
Limits = xlsread('V2OPLIM.xlsx',1,'A1:AV30');%limits for all 24 sectors
else
     load_system('Final_OpLim_Site2_fixed_dir');% Final_OpLim_Site1_fixed_dir or Final_OpLim_Site2_fixed_dir
Limits = xlsread('V3OPLIM.xlsx',1,'A1:AV30');%limits for all 24 sectors
end
%prealocating
Sector_limits = zeros(30,2);
Calculated_operability_Time = zeros(Nr,24);
Calculated_operability_N = zeros(Nr,24);
Number_of_Operations = zeros(Nr,24);


Random_Seeds = xlsread('RandomIntSeed.xlsx',1,'A1:GR8');%read random seeds for op generation
R_S = zeros(8,1);
```

```
tic

% For loop adding correct sector limits and Random seeds
for i = 1:4:size(Limits,2)%number of itereations because of different sectors
Sector_limits(:,1) = Limits(:,i);
Sector_limits(:,2) = Limits(:,i+1);
xlswrite('LimitsOneSector.xlsx',Sector_limits);%write Sector limits values to excel

for k = 1:Nr%Number of different runs with diffrent Seeds
R_S(:,1) = Random_Seeds(:,k);
xlswrite('R_S.xlsx',R_S);%write random seeds values to excel
%Final_OpLim_Site1_fixed_dir or Final_OpLim_Site2_fixed_dir
set_param('Final_OpLim_Site2_fixed_dir', 'StopTime', '12864')%choosing simulation stop time Site 2 = 18556,Site 1 = 12864
sim('Final_OpLim_Site1_fixed_dir');%start sim

% Total waiting time to perform operations on chosen site in hours

if Site == 1
Tot_WT_Sal = 0;
N_WT_Sal = 0;
for j = 2:length(Waittime_Sal)
   if Waittime_Sal(j) == 0 && Waittime_Sal(j-1) ~= 0
    Tot_WT_Sal = Tot_WT_Sal + Waittime_Sal(j-1);
    N_WT_Sal = N_WT_Sal + 1;
   end
end
Total_WT = Tot_WT_Sal;
else
Tot_WT_Val = 0;
N_WT_Val = 0;
for j = 2:length(Waittime_Val)
   if Waittime_Val(j) == 0 && Waittime_Val(j-1) ~= 0
    Tot_WT_Val = Tot_WT_Val + Waittime_Val(j-1);
    N_WT_Val = N_WT_Val + 1;
   end
end
Total_WT = Tot_WT_Val;
end

% Total time used to perform operations in hours and number of operations
```

```
Total_OPT = 0;
N_Operations = 0;
for j = 2:length(OPtime)
   if OPtime(j) == 0 && OPtime(j-1) ~= 0
    Total_OPT = Total_OPT + OPtime(j-1);
    N_Operations = N_Operations +1;
   end
end

 % Exporting wait and operation times, as well as total number of both
 if Site == 1
Wait_time_Sal(k,ceil(i/2))= Tot_WT_Sal;
Number_Wait_times_Sal(k,ceil(i/2))= N_WT_Sal;
Tot_N_Wait_times = N_WT_Sal;
 else
Wait_time_Val(k,ceil(i/2))= Tot_WT_Val;
Number_Wait_times_Val(k,ceil(i/2))= N_WT_Val;
Tot_N_Wait_times = N_WT_Val;
 end
Number_of_Operations(k,ceil(i/2))= N_Operations;

%percentage of total waiting time vs total time used on operations
Op_T = 100 - (Total_WT/(Total_OPT+Total_WT))*100;
Calculated_operability_Time(k,ceil(i/2))= Op_T;

%percentage of total number of operations with waiting vs total time
    number of operations
Op_N = 100 - (Tot_N_Wait_times/N_Operations)*100;
Calculated_operability_N(k,ceil(i/2)) = Op_N;

end
end
toc
```

H.2 Matlab Script Evaluating Operational Limits during Fixed Wave Headings

```
persistent Limits Hs_lim OP_duration %choose persistent variables
coder.extrinsic('xlsread');

if isempty(Limits)
    Limits = zeros(30,2);%prealocation
    Limits = xlsread('LimitsOneSector.xlsx',1,'A1:B30'); %import
        operational limits
    OP_duration = 0;
    Hs_lim = 0;
end

%Determine the duration of the given operation in hours
if entity.Opstart == 1

    if entity.Operation_Type == 1
        OP_duration = 96;
    elseif entity.Operation_Type == 2
        OP_duration = 64;
    elseif entity.Operation_Type == 3
        OP_duration = 54;
    elseif entity.Operation_Type == 4
        OP_duration = 16;
    else
        OP_duration = 48;
    end
end


%Check the weather data at sites compared to operational limits of the
    vessel
    %Data for Site.
    Hs = ReadSeaStateSal();
    Tz = ReadSeaStateTZSal();

    %interpolate to find correct Hs
    for j = 1:30
        if Tz >= Limits(j,1) && Tz <= Limits(j+1,1)

            Hs_lim = interp1(Limits(j:j+1,1),Limits(j:j+1,2),Tz);
            break;
```

```
        end
    end


%Check if the operation must be postponed
if (Hs) >= Hs_lim
    entity.waitOp = 2;%go to WaitOp entity server

else
    entity.waitOp = 1;%go to Opstep entity server

end
%check to see if the operation is completed
if ReadOPtime() >= OP_duration
    entity.FinishOp = 2;
else
    entity.FinishOp = 1;
end
```

H.3 Run-Operation Specific Headings and Variable Wave Directions

```
clear all;
clc;
% Load systems and prealocate arrays
Nr = 100; % nr of iterations with different seeds
load_system('Final_OpLim_Site2_W_ST');%load correct simulation
Stop_Time = 18556;%steps in simulation: Site 2 = 18556

%prealocating
Calculated_operability_Time = zeros(Nr,1);
Calculated_operability_N = zeros(Nr,1);
Number_of_Operations = zeros(Nr,1);
Wait_time_Val = zeros(Nr,1);
Number_Wait_times_Val = zeros(Nr,1);
Random_Seeds = xlsread('RandomIntSeed.xlsx',1,'A1:GR8');%read random seeds
R_S = zeros(8,1);

Values_ship = [ 10;2];%First row:service speed, second row:ship_type. 1 = Vessel 1, 2 = Vessel 2, 3 = Vessel 3
xlswrite('ReadValuesShip.xlsx',Values_ship);%write ship values to excel

tic

for k = 1:Nr%Number of runs with different seeds
R_S(:,1) = Random_Seeds(:,k);
xlswrite('R_S.xlsx',R_S);%write random seeds values to excel

set_param('Final_OpLim_Site2_W_ST', 'StopTime', '18556')%choosing simulation stop time
sim('Final_OpLim_Site2_W_ST');%start sim

% Total waiting time to perform operations on site in hours

Tot_WT_Val = 0;
N_WT_Val = 0;
for j = 2:length(Waittime_Val)
   if Waittime_Val(j) == 0 && Waittime_Val(j-1) ~= 0 %find intervals with waiting
      Tot_WT_Val = Tot_WT_Val + Waittime_Val(j-1);%total wait time
      N_WT_Val = N_WT_Val + 1;%nr of wait times
```

```
    end
end
Total_WT = Tot_WT_Val;

% Total time used to perform operations in hours and number of
    operations
Total_OPT = 0;
N_Operations = 0;
for j = 2:length(OPtime)
    if OPtime(j) == 0 && OPtime(j-1) ~= 0
     Total_OPT = Total_OPT + OPtime(j-1);%total operation time
     N_Operations = N_Operations +1;%total operations
    end
end

% Exporting wait and operation times, and operability percenteges
Wait_time_Val(k)= Tot_WT_Val;

Number_Wait_times_Val(k)= N_WT_Val;

Tot_N_Wait_times = N_WT_Val;
Number_of_Operations(k)= N_Operations;

%percentage of total waiting time vs total time used on operations
Op_T = 100 - (Total_WT/(Total_OPT+Total_WT))*100;
Calculated_operability_Time(k)= Op_T;
%percentage of total waiting time vs total time used on operations
Op_N = 100 - (Tot_N_Wait_times/(N_Operations))*100;
Calculated_operability_N(k) = Op_N;

end
toc
```

H.4 Operation specific evaluation of operational limits

H.4.1 Anchor and mooring frame deployment

```
persistent Limits OP_lim Hs_lim OP_duration Init_pos %set persistant
    variables
coder.extrinsic('xlsread');

if isempty(Limits)

    Limits = zeros(30,48);
    if entity.Ship_type == 1 %Vessel 1
        Limits = xlsread('V1OPLIM.xlsx',1,'A1:AV30');%limits for all 24
            sectors
    elseif entity.Ship_type == 2 %Vessel 2
        Limits = xlsread('V2OPLIM.xlsx',1,'A1:AV30');%limits for all 24
            sectors
    else %Vessel 3
       Limits = xlsread('V3OPLIM.xlsx',1,'A1:AV30');%limits for all 24
           sectors
    end
    Op_lim = zeros(30,2);%limits for one sector
    OP_duration = 0;
    Hs_lim = 0;
    Init_pos = 0; %initial position when vessel starts operation
end
%Determine the duration of the given operation
if entity.Opstart == 1;

OP_duration = 54;

end


%Deciding position based on which mooring lines are being deployd
if ReadAM_OP() <= 6 %main lines on east side
    Init_pos = 270;
elseif ReadAM_OP() > 6 && ReadAM_OP() <=12 %main lines on west side
    Init_pos = 90;
elseif ReadAM_OP() > 12 && ReadAM_OP() <=18  %deployment of frame
    Init_pos = 180;
elseif ReadAM_OP() > 18 && ReadAM_OP() <= 27 %lines on east side
    Init_pos = 270;
elseif ReadAM_OP() > 27 && ReadAM_OP() <= 36 %lines on west side
```

```
    Init_pos = 90;
elseif ReadAM_OP() > 36 && ReadAM_OP() <= 48 %lines on south side
    Init_pos = 0;
else Init_pos = 180; %lines on north side
end

%Check the weather data at sites compared to operational limits of the
    vessel
    %Data for Site.
    Hs = ReadSeaState();
    Tz = ReadSeaStateTZ();
    Dir = ReadWavedirMH();


%Compare the weather data at sites to operational limits of the vessel
    with regard to heading and wave direction
if Dir < Init_pos
    delta_wavedir = abs(Dir - Init_pos) ;
else
    delta_wavedir = Dir - Init_pos ;
end

%Decide sector based on the initial heading of the vessel and the
    incomming wave direction
 if delta_wavedir > 352.5 || delta_wavedir <= 7.5
        Op_lim = Limits(:,1:2); %sector 1
    elseif delta_wavedir > 7.5 && delta_wavedir <= 22.5
        Op_lim = Limits(:,3:4); %sector 2
    elseif delta_wavedir > 22.5 && delta_wavedir <= 37.5
        Op_lim = Limits(:,5:6); %sector 3
    elseif delta_wavedir > 37.5 && delta_wavedir <= 52.5
        Op_lim = Limits(:,7:8); %sector 4
    elseif delta_wavedir > 52.5 && delta_wavedir <= 67.5
        Op_lim = Limits(:,9:10); %sector 5
    elseif delta_wavedir > 67.5 && delta_wavedir <= 82.5
        Op_lim = Limits(:,11:12); %sector 6
    elseif delta_wavedir > 82.5 && delta_wavedir <= 97.5
        Op_lim = Limits(:,13:14); %sector 7
    elseif delta_wavedir > 97.5 && delta_wavedir <= 112.5
        Op_lim = Limits(:,15:16); %sector 8
    elseif delta_wavedir > 112.5 && delta_wavedir <= 127.5
        Op_lim = Limits(:,17:18); %sector 9
    elseif delta_wavedir > 127.5 && delta_wavedir <= 142.5
        Op_lim = Limits(:,19:20); %sector 10
```

```
    elseif delta_wavedir > 142.5 && delta_wavedir <= 157.5
        Op_lim = Limits(:,21:22); %sector 11
    elseif delta_wavedir > 157.5 && delta_wavedir <= 172.5
        Op_lim = Limits(:,23:24); %sector 12
    elseif delta_wavedir > 172.5 && delta_wavedir <= 187.5
        Op_lim = Limits(:,25:26); %sector 13
    elseif delta_wavedir > 187.5 && delta_wavedir <= 202.5
        Op_lim = Limits(:,27:28); %sector 14
    elseif delta_wavedir > 202.5 && delta_wavedir <= 217.5
        Op_lim = Limits(:,29:30); %sector 15
    elseif delta_wavedir > 217.5 && delta_wavedir <= 232.5
        Op_lim = Limits(:,31:32); %sector 16
    elseif delta_wavedir > 232.5 && delta_wavedir <= 247.5
        Op_lim = Limits(:,33:34); %sector 17
    elseif delta_wavedir > 247.5 && delta_wavedir <= 262.5
        Op_lim = Limits(:,35:36); %sector 18
    elseif delta_wavedir > 262.5 && delta_wavedir <= 277.5
        Op_lim = Limits(:,37:38); %sector 19
    elseif delta_wavedir > 277.5 && delta_wavedir <= 292.5
        Op_lim = Limits(:,39:40); %sector 20
    elseif delta_wavedir > 292.5 && delta_wavedir <= 307.5
        Op_lim = Limits(:,41:42); %sector 21
    elseif delta_wavedir > 307.5 && delta_wavedir <= 322.5
        Op_lim = Limits(:,43:44); %sector 22
    elseif delta_wavedir > 322.5 && delta_wavedir <= 337.5
        Op_lim = Limits(:,45:46); %sector 23
    elseif delta_wavedir > 337.5 && delta_wavedir <= 352.5
        Op_lim = Limits(:,47:48); %sector 24
 %if direction does not correlate to a sector,
%set to head sea and export wave dir
else
    Op_lim = Limits(:,1:2)
    delta_wavedir
end

    %interpolating to find correct Hs limit
    for j = 1:30
        if Tz >= Op_lim(j,1) && Tz <= Op_lim(j+1,1)

        Hs_lim = interp1(Op_lim(j:j+1,1),Op_lim(j:j+1,2),Tz);
        break;
        end
    end

```

```
%Check if the operation must be postponed
if (Hs) >= Hs_lim
    entity.waitOp = 2;

else
    entity.waitOp = 1;

end
%check to see if the operation is completed
if ReadOPtime() >= OP_duration
    entity.FinishOp = 2;
else
    entity.FinishOp = 1;
end
```

H.4.2 Delousing support

```
persistent Limits OP_lim Hs_lim OP_duration Init_pos %set persistant variables
coder.extrinsic('xlsread');

if isempty(Limits)

    Limits = zeros(30,48);
    if entity.Ship_type == 1 %Vessel 1
        Limits = xlsread('V1OPLIM.xlsx',1,'A1:AV30');%limits for all 24 sectors
    elseif entity.Ship_type == 2 %Vessel 2
        Limits = xlsread('V2OPLIM.xlsx',1,'A1:AV30');%limits for all 24 sectors
    else % Vessel 3
       Limits = xlsread('V3OPLIM.xlsx',1,'A1:AV30');%limits for all 24 sectors
    end
    Op_lim = zeros(30,2);%prealocating limits for one sector
    OP_duration = 0;
    Hs_lim = 0;
    Init_pos = 0; %initial position when vessel starts operation
end
%Determine the duration of the given operation
if entity.Opstart == 1

OP_duration = 96; %(8*12);

end



%Set the initial position to head sea when starting a new operation or new
%net pen
if entity.Opstart == 1 || entity.Next_step == 1
    Init_pos = ReadWavedirMH();
end

%Check the weather data at sites compared to operational limits of the vessel
    %Data for Site.
    Hs = ReadSeaState();
```

```
    Tz = ReadSeaStateTZ();
    Dir = ReadWavedirMH();


%Compare the weather data at sites to operational limits of the vessel
    with regard to heading and wave direction
if Dir < Init_pos
    delta_wavedir = abs(Dir - Init_pos) ;
else
    delta_wavedir = Dir - Init_pos ;
end

%Decide sector based on the initial heading of the vessel and the
    incomming wave direction
 if delta_wavedir > 352.5 || delta_wavedir <= 7.5
        Op_lim = Limits(:,1:2); %sector 1
    elseif delta_wavedir > 7.5 && delta_wavedir <= 22.5
        Op_lim = Limits(:,3:4); %sector 2
    elseif delta_wavedir > 22.5 && delta_wavedir <= 37.5
        Op_lim = Limits(:,5:6); %sector 3
    elseif delta_wavedir > 37.5 && delta_wavedir <= 52.5
        Op_lim = Limits(:,7:8); %sector 4
    elseif delta_wavedir > 52.5 && delta_wavedir <= 67.5
        Op_lim = Limits(:,9:10); %sector 5
    elseif delta_wavedir > 67.5 && delta_wavedir <= 82.5
        Op_lim = Limits(:,11:12); %sector 6
    elseif delta_wavedir > 82.5 && delta_wavedir <= 97.5
        Op_lim = Limits(:,13:14); %sector 7
    elseif delta_wavedir > 97.5 && delta_wavedir <= 112.5
        Op_lim = Limits(:,15:16); %sector 8
    elseif delta_wavedir > 112.5 && delta_wavedir <= 127.5
        Op_lim = Limits(:,17:18); %sector 9
    elseif delta_wavedir > 127.5 && delta_wavedir <= 142.5
        Op_lim = Limits(:,19:20); %sector 10
    elseif delta_wavedir > 142.5 && delta_wavedir <= 157.5
        Op_lim = Limits(:,21:22); %sector 11
    elseif delta_wavedir > 157.5 && delta_wavedir <= 172.5
        Op_lim = Limits(:,23:24); %sector 12
    elseif delta_wavedir > 172.5 && delta_wavedir <= 187.5
        Op_lim = Limits(:,25:26); %sector 13
    elseif delta_wavedir > 187.5 && delta_wavedir <= 202.5
        Op_lim = Limits(:,27:28); %sector 14
    elseif delta_wavedir > 202.5 && delta_wavedir <= 217.5
        Op_lim = Limits(:,29:30); %sector 15
```

```
    elseif delta_wavedir > 217.5 && delta_wavedir <= 232.5
        Op_lim = Limits(:,31:32); %sector 16
    elseif delta_wavedir > 232.5 && delta_wavedir <= 247.5
        Op_lim = Limits(:,33:34); %sector 17
    elseif delta_wavedir > 247.5 && delta_wavedir <= 262.5
        Op_lim = Limits(:,35:36); %sector 18
    elseif delta_wavedir > 262.5 && delta_wavedir <= 277.5
        Op_lim = Limits(:,37:38); %sector 19
    elseif delta_wavedir > 277.5 && delta_wavedir <= 292.5
        Op_lim = Limits(:,39:40); %sector 20
    elseif delta_wavedir > 292.5 && delta_wavedir <= 307.5
        Op_lim = Limits(:,41:42); %sector 21
    elseif delta_wavedir > 307.5 && delta_wavedir <= 322.5
        Op_lim = Limits(:,43:44); %sector 22
    elseif delta_wavedir > 322.5 && delta_wavedir <= 337.5
        Op_lim = Limits(:,45:46); %sector 23
    elseif delta_wavedir > 337.5 && delta_wavedir <= 352.5
        Op_lim = Limits(:,47:48); %sector 24
 %if direction does not correlate to a sector,
 %set to head sea and export wave dir
 else
     Op_lim = Limits(:,1:2)
     delta_wavedir
 end

  %interpolating to find correct Hs limit
    for j = 1:30
        if Tz >= Op_lim(j,1) && Tz <= Op_lim(j+1,1)

        Hs_lim = interp1(Op_lim(j:j+1,1),Op_lim(j:j+1,2),Tz);
        break;
        end
    end
%make sure Next_step is not innitiated too soon
entity.Next_step = 0;

%Check if the operation must be postponed
if (Hs) >= Hs_lim
    entity.waitOp = 2;

else
    entity.waitOp = 1;

end
```

```
%check to see if the operation is completed
if ReadOPtime() >= OP_duration
    entity.FinishOp = 2;
else
    entity.FinishOp = 1;
end
```

H.4.3 ROV inspection

```
persistent Limits OP_lim Hs_lim OP_duration Init_pos %set persistant
    variables
coder.extrinsic('xlsread');

if isempty(Limits)

    Limits = zeros(30,48);
    if entity.Ship_type == 1 %Vessel 1
        Limits = xlsread('V1OPLIM.xlsx',1,'A1:AV30');%limits for all 24
             sectors
   elseif entity.Ship_type == 2 %Vessel 2
        Limits = xlsread('V2OPLIM.xlsx',1,'A1:AV30');%limits for all 24
             sectors
    else % Vessel 3
       Limits = xlsread('V3OPLIM.xlsx',1,'A1:AV30');%limits for all 24
           sectors
    end
    %prealocate
    Op_lim = zeros(30,2);%limits for one sector
    OP_duration = 0;
    Hs_lim = 0;
end
%Determine the duration of the given operation
if entity.Opstart == 1;

OP_duration = 48;

end


%Check the weather data at sites compared to operational limits of the
    vessel
    %Data for Site.
    Hs = ReadSeaState();
    Tz = ReadSeaStateTZ();


%Compare the weather data at sites to operational limits of the vessel
Op_lim = Limits(:,1:2); %set to head sea for all of the operation
%interpolate to find correct hs lim
    for j = 1:30
        if Tz >= Op_lim(j,1) && Tz <= Op_lim(j+1,1)
```

```
        Hs_lim = interp1(Op_lim(j:j+1,1),Op_lim(j:j+1,2),Tz);
        break;
        end
    end


%Check if the operation must be postponed
if (Hs) >= Hs_lim
    entity.waitOp = 2;

else
    entity.waitOp = 1;

end
%check to see if the operation is completed
if ReadOPtime() >= OP_duration
    entity.FinishOp = 2;
else
    entity.FinishOp = 1;
end
```