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Defining and Evaluating Long-term Operability of Service Vessels in Exposed Aquaculture

Master's thesis in
January

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NTNU
Norwegian University of
Science and Technology

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Supervisor: Bjørn Egil Asbjørnslett
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Norwegian University of Science and Technology
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Preface

This master thesis provides the final delivery for a master's degree in Marine Technology with a specialization in Marine Systems Design, at the Norwegian University of Science and Technology (NTNU), in Trondheim. The thesis is written during the fall semester of 2018 in cooperation with SFI EXPOSED project, a center of research-based innovation for exposed aquaculture. The thesis covers 30 ECTS, which corresponds to a full-time semester.

The purpose of the thesis is to provide PhD candidate, Hans Tobias Slette, with further insight and understanding of what defines a service vessel's operability in the aquaculture industry, and how it can be measurements. The result from the thesis will hopefully provide useful knowledge for Hans Tobias's doctoral study on operability within exposed fish farming.

I want to thank my co-supervisor Hans Tobias Slette for his help and advice during this process. His guidance has been vital for the completion of this master thesis. I would also like to thank my supervisor Professor Bjørn-Egil Asbjørnslett at the Department of Marine Technology, NTNU, for his guidance during the work.

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Trondheim, 14.02.2019
Elise Lossius Nørgaard
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Summary

Norwegian fish farming facilities are traditionally located in sheltered areas along the coast but has gradually started to move towards more exposed locations due to increasing demand, lack of production area and better production environment. This has led to new challenges within the industry, and as a result, the EXPOSED Aquaculture Operations center has been initialized. One of the issues addressed in the project is the future of fish farming vessels. When moving to more exposed waters, it follows that vessel requirements, to perform operations successfully, are sharpened. It also follows that the vessels are more exposed to waiting time due to more harsh and hostile waters. Because of this, the operability of ships is an essential factor, and crucial for further understanding and growth of the industry. In the literature, there is no universal agreement on what defines the operability of a service vessel, and different studies evaluate the operability with varying definitions. In order to compare different designs on equal terms with reliable results, it is important to develop standardized evaluation methods and clearly defined operability.

The objective of this study is to increase insight and knowledge about what factors define the operability of service vessels in exposed aquaculture. This is done by evaluating different definitions of operability found in the literature. Through a vessel response analysis of the service vessel Macho 40, quantitative operational limits are determined for each operation the vessel can perform. Two different approaches are then used to obtain the different definitions of operability; a numerical approach and a simulation-based approach. Together with measured wave data from an oceanographic buoy and weather forecast data from ECMWF, the operational limits are used as input in the analysis.

The results from the numerical approach show that the operability decreases when including weather forecast. This indicates that defining operability without considering weather forecast excludes essential aspects of uncertainty from the real-life scenario of using weather forecast as a decision-making tool. Further, the study shows that transit time and operation duration also have a significant impact on the operability measurement, and should be considered when assessing the operability of a service vessel.

Based on the results from the simulation-based approach it is recommended to define operability as the ratio between operations performed and operations performed during perfect weather, based on an operation demand. The comparison of the results obtained from the two approaches also strongly indicate that a sim-

ulation model is necessary to capture the operability of a service vessel. This is highly due to the complex nature of a service vessel's operational profile, which is difficult to implement in a numerical programming approach.

Efforts have been made in this thesis to define the operability of a service vessel in the aquaculture industry. Several definitions have been assessed and evaluated. To obtain the statistics needed to calculate the performance indicators, a numerical and a simulation-based approach have been used. The consideration of weather forecast has been implemented in the assessment, which has not been done before. Based on the evaluation and discussion of the results, a recommendation for defining operability have been proposed. However, the reliability of the results are affected by uncertainty regarding the weather data and operational profile. Also, because the simulation model is not validated, it is impossible to determine whether or not the results are "better" compared to each other. The results are therefore considered as indicators on how the operability respond to changes in definition, rather than exact values. Nevertheless, the objective of increasing insight and knowledge about what defines the operability of service vessels in exposed aquaculture have been obtained, and the simulation model presented in this thesis form a good basis for further study on operability. Improving the reliability of the weather data and operational profile of service vessels used as input in the analysis, is recommended for further work on defining operability.

Sammendrag

Den norske oppdrettsnæringen er tradisjonelt gjennomført i skjermede sjø langs kysten, men har gradvis begynt å bevege seg mot mer utsatte områder på grunn av økende etterspørsel, mangel på produksjonsområde og bedre produksjonsmiljø. Dette har ført til nye utfordringer i bransjen, og som et resultat har et prosjekt som tar for seg utfordingene ved eksponert fiskeoppdrett, "EXPOSED", blitt initialisert. En av utfordringe prosjektet har lagt vekt på er fremtiden for oppdrettsfartøy. Når man flytter til mer utsatte farvann, følger det at fartøyets krav, for å utføre operasjoner med hell, er skjerpet. Det følger også at fartøyene er mer utsatt for ventetid på grunn av hardere værforhold. På grunn av dette er operabiliteten til et skip en viktig faktor, og avgjørende for videre forståelse og vekst i bransjen. I litteraturen er det ingen universell enighet om hva som definerer operabiliteten til et fartøy, og ulike studier vurderer operabiliteten med varierende definisjoner. For å kunne sammenligne ulike design på like vilkår med pålitelige resultater, er det viktig å utvikle standardiserte evalueringsmetoder og klare defiisjoner på hva begrepet operabilitet innebærer.

Målet med denne studien er å øke innsikt og kunnskap om hva som definerer et service fartøy sin operabilitet i eksponert oppdrett. Dette gjøres ved å vurdere ulike definisjoner av operabilitet funnet i litteraturen. Gjennom en fartøyresponsanalyse av et service fartøy (Macho 40) defineres kvantitative operasjonsspesifike grenser for utføring av operasjonene. To forskjellige tilnærminger brukes til å oppnå de forskjellige definisjonene av operabilitet; en numerisk tilnærming og en simuleringsbasert tilnærming. Sammen med målte bølgedata fra en oceanografisk bøye og værmeldingsdata fra ECMWF, brukes operasjonsgrensene som input til analysen.

Resultatene fra den numeriske tilnærmingen viser at vurderingen av værmeldingen har betydelig innvirkning på operabiliteten. Generelt reduseres operabiliteten når det tas hensyn til værvarsel, noe som indikerer at definisjon av operabiliteten uten å vurdere værvarsel utelukker viktige aspekter av usikkerhet fra det virkelige scenariet om bruk av værvarsel som et beslutningsverktøy. Videre viser studien at reisetid og operasjontid også har en betydelig innvirkning på operabilitetsmålingene, og bør vurderes når man vurderer operabiliteten av et servicefartøy.

Basert på resultatene fra den simuleringsbaserte tilnærmingen anbefales det å definere operabilitet som forholdet mellom operasjoner utført og operasjoner utført under perfekt vær, basert på en etterspørsel av operasjoner, for et servicefartøy i akvakultursektoren. Sammenligningen av resultatene som er oppnådd fra de to tilnærmingene, indikerer også sterkt at en simuleringsmodell er nødvendig for å fange operabiliteten av et servicefartøy. Dette skyldes en høy grad av kompleksitet

til et servicefartøy's operasjonelle profil, noe som er vanskelig å implementere i en numerisk programmeringsmetode.

I denne masteren er det utført et arbeid for å definere operabiliteten av et service skip i akvakulturindustrien. Flere definisjoner er vurdert og evaluert. For å oppnå statistikken som trengs for å beregne operabiliteten, en numerisk og en simuleringsbasert tilnærming har vært brukt. Betraktningen av værprognoser er implementert i vurderingen, som ikke har blitt vurdert før. Basert på evaluering og diskusjon av resultatene, er det foreslått en anbefaling for å definere operabiliteten. Resultatene er imidlertid påvirket av usikkerhet grunnet usikkerhet i værdata og driftsprofil. Også fordi simuleringsmodellen ikke er validert, er det umulig å avgjøre hvorvidt resultatene er "bedre" i forhold til hverandre. Resultatene er derfor betraktet som indikatorer på hvordan operabiliteten respondere til endringer i definisjon, i stedet for som eksakte verdier. Uansett, er målet om å øke innsikt og kunnskap om hva som definerer operabiliteten av service fartøy i eksponert akvakultur, oppnådd.

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Abbreviations

DES	=	Discrete-Event Simulation
IOF	=	Integrated Operability Factor
%OP	=	Percentage Operability
RRO	=	Relative Rate of Operability
RROT	=	Relative Rate of Operational Time
RRNDO	=	Relative Rate of Non-Delayed Operations
RMS	=	Root Mean Square
PI	=	Performance Indicator
EXPOSED	=	Centre for research-based innovation in exposed aquaculture
JONSWAP	=	Joint North Sea Wave Project
ECMWF	=	The European Centre for Medium-Range Weather Forecasts

Chapter 1

Introduction

1.1 Background and Motivation

The world's population is constantly increasing and is expected to reach 9 billion people in 2050. According to the Food and Agricultural Organization of the United Nations (FAO), this implies that world food production must rise by 70%, and food production in the developing world have to double (Institute (2018 (accessed November 7, 2018)). In addition, this must be done with lower resource usage and with the least possible environmental impact. The seas cover over two-thirds of the earth's surface, but only 2% of the food we eat comes from the ocean, measured in energy (Institute (2018 (accessed November 7, 2018)). Producing animal protein through aquaculture requires fewer resources and is more climate-friendly than farming on land. Since the traditional fishing industry is fully exploited, growth in aquaculture is crucial for raising food for future generations (Salmar (2018 (accessed December 7, 2018)).

Norwegian fish farming facilities are traditionally located in sheltered areas along the coast and the fjords. However, the last couple of years this has gradually started to change, and the industry is moving toward more exposed locations. Examples of this are OceanFarm 1 from Salmar AS, Havfarm from Nordlaks AS and Ocean Framing Concepts from Aker Solutions ASA. Exposed fish farming poses many benefits for the fish farming industry, such as more space to expand, less environmental impact and a better environment for the fish to grow. However, there are some challenges connected to exposed fish farming. When moving to more exposed waters, it follows that vessel requirements, to perform operations successfully, are sharpened. It also follows that the vessels are more exposed to waiting

time due to more harsh and hostile waters. Because of this, the operability of ships is an essential factor, and crucial for further understanding and growth of the industry.

Service vessels in the fish farming industry are especially complex due to a high variation of operations and uncertainty of the frequency of occurrence of missions. This is mainly because the aquaculture handles living fish, which causes more stochastic processes. Therefore, it is difficult to predict a service vessel's operational scenario, which again makes it difficult to measure the operability. However, some studies have tried to do precisely that. Stemland (Stemland (2017)) proposed a combination of hydrodynamic analysis and simulation to assessed the operability of the Macho 40 service vessel in his master thesis. In this study, the operability was defined as the ratio between performed operations and requested operations from the simulation, based on an operational profile. Sjøberg and Lund (Sjøberg and Lund (2018)) used the same methodology in their master thesis, to compare the performance of three different service vessels. However, in this study, the operability was defined as the ratio between delayed operations and performed operations, and as the ratio between delayed time and total operational time. There is thus no universal agreement on what defines the operability of a service vessel. The motivation for this study is, therefore, to define and evaluate long-term operability of a service vessel in the aquaculture industry.

EXPOSED

Norway has become a leading actor when it comes to technology and competence within fish farming, and the aquaculture is designated to be one of the industries that will maintain Norway's position as one of the world's leading maritime nations (Nærings- og fiskeridepartementet and Olje- og energidepartementet (2017))). Consequently, there is a strong innovation drive in the Norwegian aquaculture industry, and extensive investments are made (SITEF ocean Ocean (2017)). A new report from SINTEF Ocean on safety management in the aquaculture industry shows that development is moving in the right direction, but that there is still room for improvement in several areas (SINTEF Kongsvik et al. (2018)). As a result of the expansion of the fish farming industry a new research center called the EXPOSED Aquaculture Operations center, has been initialized to develop competence and technology to address the challenges. EXPOSED is a Centre of Research-based Innovation (SFI), founded by the Norwegian Research Council's Division for Innovation (SINTEF ocean Ocean (2017)). The project brings together global salmon farmers, vital services and technology providers, and leading research groups to develop knowledge and technology for robust, safe and efficient

fish farming at exposed locations.

Hans Tobias Slette is a Ph.D. candidate involved in the EXPOSED project and is currently working on a doctoral thesis on the operability of working vessels in the aquaculture industry. This master thesis is initiated with the goal of supporting him with his doctoral dissertation.

1.2 Objective

The objective of this thesis is to increase the knowledge and insight of what defines operability of a service vessel in exposed aquaculture. A literature study aims to provide insight to how an operability study is assessed, as well as document how the term "operability" is defined in previous studies. Based on the findings, an operability assessment will be conducted on a fish farming service vessel.

Through a vessel response analysis and specification of seakeeping criteria, quantitative operational limits for each operation will be established. The operational limits are then used to assess the vessel's long-term operability, using different methods of evaluation, both simulation and non-simulation based. For the simulation-based operability study, a simulation model will be developed. The model will use the operational limits obtained from the vessel response analysis, wave data (forecast and hindcast) from oceanographic buoys and European Centre for Medium-Range Weather Forecasts (ECMWF), and the service vessel's operation profile as inputs. By evaluating different operability definitions found in the literature study, as well as analyze how parameters and operational scenarios (specific for a fish farming service vessels) affect the operability, this report will provide insight and knowledge about how operability should be defined for a service vessel in the aquaculture.

Background Information

As this thesis does not focus on studying the operability of one specific vessel, but rather on the operability assessment in general, it was decided to use the same vessel that was used in Stemland's master thesis, as a basis for the study. Because exposed aquaculture is a relatively new industry, finding information about vessel specifics and operational profile can be time-consuming. Basing my study on the same vessel used in Stemland, therefore, enables me to focus more on other aspects of the operability assessment.

A high-level outline of the system architecture of the case study of this thesis is presented in Figure 1.1. The purpose of this illustration is to give the reader an overview of the main elements involved in the work and to illustrate which parts of the methodology is based on the work from Stemland's master thesis. The red outlined steps represent elements that are based on Stemland's work. This includes the vessel geometry and the operation profile of the vessel.
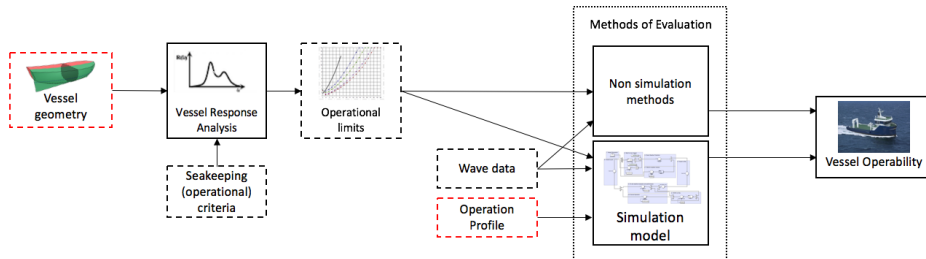
Figure 1.1: Outline of system architecture which illustrates the main elements involved in this thesis

Tasks

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

- Document definitions on operability from existing literature on the topic, as well as provide insight to the methodology of an operability study.

- Develop numerical programming scripts and a simulation model of a service vessel, to calculate the operability.

- Perform a long-term operability assessment based on the definitions obtained from the literature.

- Evaluate the result from different definitions of operability, and how they react to changing parameters and operational scenarios.

1.3 Structure of Thesis

The master thesis is divided into ten chapters:

- **Chapter 2** presents a literature study of the topic *Operability*. The chapter will present different studies on operability and provide an overview of the different elements that are involved in an operability study, as well as how operability is defined.

- **Chapter 3** presents the system description of the scenario that will be studied in the operability study.

- **Chapter 4 and 5** will provide a detailed description of the short- and long-term operability analysis, the definition of the different performance indicators used in the study, as well as a detailed description of the data inputs.

- **Chapter 6 and 7** Presents the results from the shrot- and long-term operability assessments.

- **Chapter 8** will discuss the results obtained from the operability assessment, as well as discuss potential sources of deviation and errors.

- **Chapter 9** provides a conclusion of the study.

- **Chapter 10** presents suggestions for further work on the work done in this thesis.

Chapter 2

Literature Review

A literature study is essential to get familiar with previous work that is conducted within the same topic, and to provide new insight. This chapter will present existing literature and publications on operability of vessels, with focus on how operability is defined. The chapter will also provide an introduction to the overall methodology used to assess the operability of a ship. The findings from this chapter will be used as a basis for the operability assessment performed later in this study.

2.1   Vessel Performance

A vessel's performance can be studied in many different ways, and what defines the performance of a vessel does not have a final answer, but are dependent on situation, context and the purpose of the study. A ship can, for example, be assessed in terms of operational performance, seakeeping performance, structural performance, economic performance, etc. Taking into account all aspects of a ship's performance to determine the "total performance," can quickly become very interconnected and complex. In the literature, it is therefore common to specify the definition to limit the scope of the study. Consequently, the performance of a vessel does not have a final definition but should be defined for each study. When doing a literature study on vessel performance, it is important to be aware of how the study defines performance, in order to understand the results.

The definition of vessel performance also depends on the perspective from which it is viewed. A vessels performance may be defined differently from a designer, an operator or an owner's point of view. From a designer's perspective, it is of interest

to design a ship that maximizes the utility, for the least possible cost. An operator, on the other hand, may not care that much about the initial cost, but rather the ship's capability, capacity and how well the vessel operates in seas.

A ship's operability can be seen as *one* aspect of the performance, but can be as challenging to define as the performance itself. The rest of this thesis and literature study will focus only on the operability aspect of the total performance of a vessel.

2.2   Vessel Operability

There exists a lot of research on operability in the literature, not only for marine applications but within other sectors as well. However, there is no single definition of what defines operability, and throughout the literature, there are a variety of interpretations on operability depending on system and context. Also, the word *operability* is not an established term, and many publications use other terms like performance assessment, availability studies and seakeeping performance to describe the same or similar studies. Searching the literature for papers on operability has therefore not been as straightforward as initially thought.

According to Fonseca and Soares (2002) operability can be defined as a ship's ability to carry out her mission safely, while according to Hoffman and Petrie (Petrie and Hoffman (1980)) the operability is estimated based on the probability that vessel motions remain within acceptable limits for a sufficient amount of time to complete the mission. Defining the operability is one thing, but choosing the method in which to evaluate the operability is another. For example, "estimating a ship's ability to carry out her mission safely" poses different assessment methodologies for a cruise ship that only perform one operation, than for a service vessel that performs multiple different operations and has a much more complex operational scenario.

In the offshore industry, vessel performance is commonly assessed by estimating the limiting sea state curve for a single operational criteria, and calculating the percentage of operable sea states based on a scatter diagram generated using historical weather data from the area of interest (2018). This method has had many different terms, but in this paper it is referred to as percentage operability (%OP). The %OP approach is quite established in the offshore industry and have been used to investigate the seakeeping behavior of ships for a long time. Examples of this is the study on seakeeping behavior of naval ships by Johnson (1979), Bales (1981) and McCreight and Stahl (1985). This index was also used in the Nordic co-operative research project on the seakeeping performance of ships (1987), and in the study

by Guedes Soares et al. (2002) on fishing vessels.

However, for more complex ships that can perform multiple different operations, the %OP definition lack consideration of aspects that are important for sufficient definition of operability. Therefore, later studies have proposed other methods to establish the operability of ships that are more complex. Virtual testing, also referred to as simulation, has become a widely used tool to analyze a ship's performance. The VISTA (Virtual sea trial by simulating complex marine operations) presented in 2015 a simulation framework that enables to accurately and rapidly benchmark the performance of complex ship system over its operational lifecycle (2015). In 2018, Sandvik proposed a simulation-based ship design methodology for evaluating susceptibility to weather-induced delays during marine operations, using discrete-event simulation (2018).

Even though the literature proposes many different methodologies for evaluating the operability, there seems to be an agreement of the general methodology used for the overall process, especially for the short-term operability assessment needed to provide input in long-term analysis. This is presented in more detail in the next section.

2.3 Methodology of Vessel Operability Study

This section presents the general elements of performing a short-term operability assessment for vessels, found in the literature. The results from the short-term study are used as input in the long-term operability study, and is therefore an important part of the overall assessment. The methodology is illustrated in Figure 2.1. The publications that are presented in this section, all follow the general steps of this methodology.
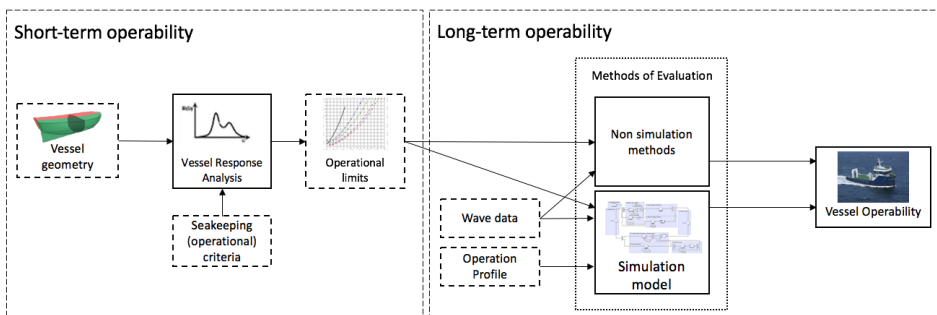
Figure 2.1: Methodology of Operability Study

As seen in the illustration, the methodology is divided into to main groupings; short-term and long-term operability. Vessel performance is in the industry often assessed only using the short term study. However, it is becoming more common to evaluate the vessel's long term operability, as this gives a better estimate of how a vessel performs over time. The elements from the short-term operability will be presented in this section, as this is the part that is similar for both the simple and more advanced long-term operability assessments. It is under the long-term operability assessment that new methods, like simulation, are introduced. However, to understand the full process, the short-term study is presented first.

2.3.1   Vessel Response Analyze

The first step of the operability study, namely the Vessel Response Analyze, is an essential part of the hydrodynamic analysis in all vessel design processes and can contribute to improving designs and ensure better vessel performance. For the operability study, this part of the process is essential for establishing the limiting sea state curve, which defines the acceptable weather conditions for the vessel to be able to perform it's intended operations.

Due to highly complex computer systems, the approach is quite straightforward, and the analysis is relatively standardized. Because of this, recent publications on operability focus more on studying alternative methodologies for the long-term operability. Nevertheless, as this is an essential part of the operability study, the methodology will be briefly explained. One example of a software used to perform vessel response analysis, is VERES, which will be used as a basis for explaining the process here. See appendix D for a more detailed description of the program.
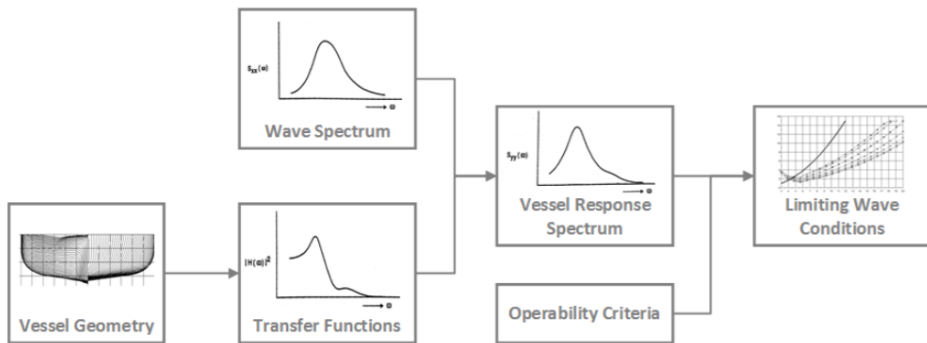
Figure 2.2: Schematic overview of the calculations performed in VERES to obtain the operational limits, collected from Stemland (Stemland (2017))

Firstly, vessel data of the studied vessel are implemented into the software. Based on the specified hull shape and loading conditions, the transfer function is determined in six degrees of freedom. The transfer function represents how the specific vessel will respond to different sea states and are often presented as RAO (Response Amplitude Operators) in heave relative to the wave period. Secondly, in combination with a wave spectrum suited for the studied geographical area, the vessel response spectrum in the irregular sea is calculated based on the transfer function. Finally, the limiting wave conditions are calculated based on predetermined seakeeping criteria of the specified vessel and operation. The seakeeping criteria study is presented in more detailed later.

The limiting weather conditions are often given as significant wave heights as a function of wave period, but can also be wind, current or other factors. Berg's paper on defining operational (seakeeping) criteria for offshore vessels, states that MARINTEK's considers that significant wave height alone is not a suitable way of defining operational limits. They argue that for any offshore operation, safety depends on three factors; the actual metocean situation, including wind, waves and current, the vessel's dynamic characteristics and the tools involved in the operation. For example for ships with launch and recovery systems (LARS), the relative motion between the sea surface and the object to be launched or retrieved and forces when it enters the splash zone might better define safe operational limits (2014). Also, the operational limits are dependent on the heading of the vessel relative to incoming weather. The limiting weather state curve is therefore presented for each heading with a chosen step size. A more detailed review of the VERES

program is found in Fathi (2012).

2.3.2 Seakeeping Criteria

Due to highly complex software tools, calculating the Vessel response spectrum has become relatively standardized and straightforward. However, establishing the quantitative seakeeping criteria input, to permit critical effects of ship motions is not as straightforward. Reliable operation specific seakeeping criteria require detailed knowledge about the operation and its critical phases, the environmental conditions, the dynamic characteristics of the vessel and the type of equipment to be used. Among all of the criteria proposed in the literature, there are no studies explicitly conducted for seakeeping criteria in the aquaculture. When the industry is moving to more exposed locations, this will, however, become important to establish to provide safe and reliable operations. In that process, it is beneficial to learn from the methodologies and results already used and obtained in the offshore industry.

Even though there is a lack of standardized operational specific seakeeping criteria also in the offshore industry, most of the studies follow a general methodology of obtaining the criteria. This is presented in Figure 2.3.
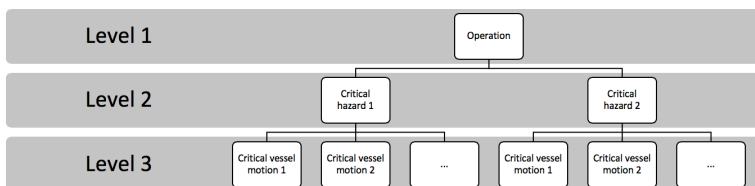
Figure 2.3: Hierarchy of Seakeeping Criteria Assessment

First of all, as discussed before, each set of operational criteria from VERES, does not represent the limit for a vessel, but the limit for a specific operation. This is because depending on the operation, different vessel motions can be more critical than others. The first step (level 2) of determining the seakeeping criteria is to identify which hazards that can lead to limiting situations for the operations of consideration. Examples of this can be, falling on deck, collision of object during lifting, etc. Vessel motion can also cause seasickness and discomfort among the crew, which can consequently create an adverse effect on their effectiveness and performance.

According to the NATO Standardization Agreement (STANAG) 4154

(2000), seakeeping criteria can be divided into two categories; *motion response criteria* and *derived response criteria*. *Motion response criteria* are based on ship motions, and can include Root Mean Square (RMS) values of pitch, roll and yaw angles, as well as vertical and lateral displacement, etc. Examples of *derived response criteria* measures include Motion Sickness Incidence (MSI) parameter (1974) which reports the percentage number of people who will become motion sick at a given acceleration level, frequency, and duration of exposure, and Motion Induced Interruptions (MII) (1990) which represent the number of loss-of-balance events which occur during an arbitrary deck operation (2005), in addition to propeller emergence, slamming etc (Berg et al. (2014)). For marine operations, most hydrodynamic limiting criteria fall under the first category, while for passenger ships, fishing vessels, or other ships where human comfort is important, the second category is most relevant (2018).

STANAG further divide the criteria into three groups; global, local and other criteria. Global criteria affect the overall ship and limit the global motion of the vessel in six degrees of freedom. Local criteria limits combined movement of heave, surge, and sway of a specific part of the ship, for example, the crane tip or on the bridge. In early ship design, when there is limited information about the vessel, global criteria are often preferred.

The uncertainty in deciding the right seakeeping criteria for an operation is a well-known problem in the literature, and many of the studies on long-term operability lack solid documentation for the choice of different criteria. There are no distinct universal set of criteria for different operations, especially for the aquaculture industry, and the criteria can vary vastly from study to study making it hard to compare. A sensitivity analysis conducted by Fonseca and Soares (2002) in 2002, was motivated by this large uncertainty related to the definition of the limiting seakeeping criteria. The analysis showed that the estimated performance greatly depends on the limiting value selected as the seakeeping criteria and that the sensitivity is depended on the level of operability. Low operability levels have higher sensitivity to different values of limiting criteria, while the sensitivity of high values, in general, is relatively small. This is illustrated in Figure 2.4. This result indicates that a thorough study on defining accurate and precise seakeeping criteria for different operations is vital for further study on vessels long-term operability.
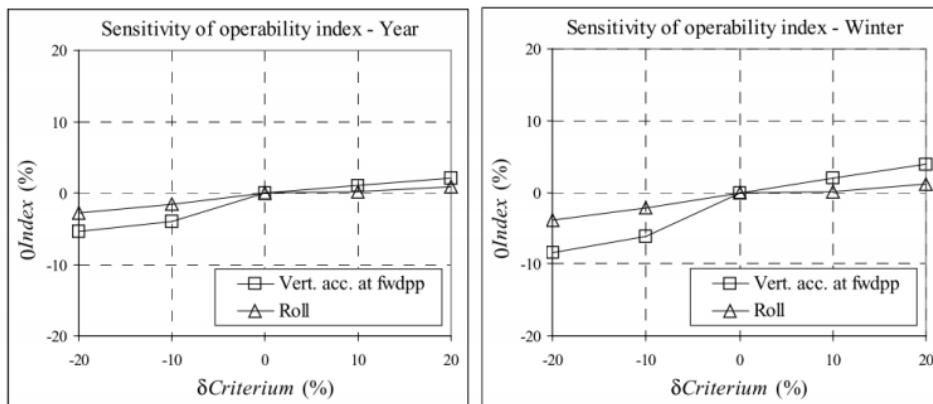
Figure 2.4: Operability sensitivity to limiting criteria (Fonseca and Soares (2002))

In the literature, several seakeeping criteria related to different subsystems and potential hazards have been proposed, and some general rules are frequently used in the literature.

The effect of vertical accelerations on humans is well understood and has been incorporated into International Standard ISO (1985, 1997). The standard provides severe discomfort boundaries for motion sickness as a function of acceleration level, the frequency of acceleration, and the duration of exposure to the acceleration (2005).

In 1987 the *NORDFORSK (1987) - Seakeeping Criteria* (1987) Project aimed at developing a Nordic standard for seakeeping criteria and standard methods of evaluating the motion characteristics to be proposed. The intention was to enable different ship designs to be compared on equal terms (2014). As a part of this project, they developed criteria for acceptable levels of ship motions related to specific subsystems and operations. The subsystems considered were:

- Ship hull

- Propulsion machinery

- Ship equipment

- Cargo

- Personnel efficiency

- Passenger comfort

- Special operations involving helicopter, soar or crane

Further, the criteria were specified these potential motions or incidents:

- Slamming

- Deck wetness

- Vertical acceleration

- Horizontal acceleration

- Roll angle

- Pitch angle

- Vertical motion

- Vertical velocity

- Relative motion

The result from the project provides a set of standardized limiting criteria for ships, both general criteria, and criteria for human effectiveness, as seen in Figure 2.5.

General Operability Limiting Criteria for Ships (NORDFORSK, 1987)			
Description	Merchant Ships	Navy Vessels	Fast Small Craft
RMS of vertical acceleration at FP	0.275 g ($L \leq$ 100 m) 0.050 g ($L \geq$ 330 m)	0.275 g	0.65 g
RMS of vertical acceleration at Bridge	0.15 g	0.20 g	0.275 g
RMS of lateral acceleration at Bridge	0.12 g	0.10 g	0.10 g
RMS of Roll	6.0 deg	4.0 deg	4.0 deg
Probability of Slamming	0.03 ($L \leq$ 100 m) 0.01 ($L \geq$ 300 m)	0.03	0.03
Probability of Deck Wetness	0.05	0.05	0.05

(a) General Operability Limiting Criteria for Ships

Criteria for Accelerations and Roll (NORDFORSK, 1987)			
Description	RMS Vertical Acceleration	RMS Lateral Acceleration	RMS Roll Motion
Light Manual Work	0.20 g	0.10 g	6.0°
Heavy Manual Work	0.15 g	0.07 g	4.0°
Intellectual Work	0.10 g	0.05 g	3.0°
Transit Passengers	0.05 g	0.04 g	2.5°
Cruise Liner	0.02 g	0.03 g	2.0°

(b) Seakeeping Performance Criteria for Human Effectiveness

Figure 2.5: Standardized Seakeeping Criteria from NORDFORSK (1987) 1987

In 2011, DNV GL also published a document on limitations for marine operations. This publication specifies that a limiting environmental criterion (OP_{lim}) must be established and described in the marine operation manual. The design criterion OP_{lim} is the limiting weather condition and must not be chosen greater than the limiting criteria for all equipment and activities in the planned operation, and not higher than the environmental design criteria (2011).

Berg's et al. (2014) study on defining operational (seakeeping) criteria for offshore vessels recommends close cooperation between personnel, ship designers, equipment manufacturers, and researcher to develop an overall operational criterion to be applied when comparing different ship designs for location-specific missions. Even though there lacks a universal agreement on a set of operational specific seakeeping criteria, especially for service vessels, and especially in the aquaculture, the EXPOSED research project is, however, currently studying the issue of seakeeping criteria by measuring the onboard movement of a service vessel catamaran. In time, this data can contribute to establishing standards and precise operational criteria for that specific vessel type, to easier compare vessel designs and performance.

2.4   Discrete-Event Simulation-based Study

Simulation has become an essential step in development and design of systems and technologies for a wide range of applications. For the maritime industry, the ability to test ship designs and concepts in an operational context, exposed to realistic weather conditions and operation demands, represents a leap forward in terms of predicting and understanding design performance (2018). Simulation-based operability methods enables the designer to obtain more information about the vessel's long-term performance than with traditional non simulation-based methods.

Discrete-event simulation (DES) is commonly used to analyze and study relative deterministic processes, like applications within production processes, logistics and supply chain. In the marine industry this typically involves seaport logistics and fleet performance and optimization (2017). In the vast majority of papers reviewed, discrete-event simulation is traditionally used as a tool for decision-making and support, rather than research and development of new system designs. However, there are a few publications using discrete-event simulation to capture the complex nature of a service vessel's long-term performance.

In 2017, Stemland introduced the methodology of combining vessel response analysis with simulation to assess the operability of a service vessel in the aquaculture

industry. The simulation model is developed to represent the real life operational scenario of a service vessel in the aquaculture industry. Including different operations and frequency of operations, several sites and limiting sea state curves dependent on heading. The study presents the operability as the ratio between total operations performed and total operations requested during a simulation.

Sjøberg & Lund's master thesis (2018) follows the same methodology proposed by Stemland (2017), and evaluates and compare the operability and operational limits of three fish farming service vessels; two catamarans and one monohull. The method used to determine the operability factor is however a bit different than in Stemland's, and is presented in two ways. In the first approach the operability was 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, see equation 2.1. The second approach calculated 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, see equation 2.2. The study demonstrated how the different vessels performed at different exposure and which criteria that dictated their operability.

$$\text{Operability N} = \frac{\text{Total delay operations}}{\text{Total operations performed}} \tag{2.1}$$

$$\text{Operability T} = \frac{\text{Total delay time}}{\text{Total operational time}} \tag{2.2}$$

Sandvik, Gutsch and Asbjørnslett (2018) presented a simulation based ship design methodology for evaluating susceptibility to weather-induced delays during marine operations. This methodology proposed an alternative to the percentage operability (%OP) and integrated operability factor (IOF), and looked at the impact of considering weather windows as an operational criterion in terms of ship design performance evaluation (operability) of a offshore construction vessel. In addition, they compared the proposed simulation-based methodology to %OP and IOF. The introduced measure of performance is called relative rate of operation (RRO) and is similar to the method used by Stemland (2017). The measure considers the ratio between the number of performed operations and number of feasible operations. The RRO differs from the %OP and IOF by being simulation-based which includes transit and duration of operation as parameters. This method also differs from Stemland by including only feasible operations, hence all the operations the vessel could perform if there were no weather limits, and not just the total of performed and canceled operations from one simulation. However, this study does

not consider more than one operation in the simulation, or the operation profile of the vessel.

2.5 Discussion

Vessel Performance

This section aimed to provide the reader with an understanding of how operability not necessarily defines a vessel's total performance but is only one aspect of a much more complex assessment. To limit the scope of this thesis, it is decided only to consider the operability aspect of a ships performance based on the hydrodynamic capabilities.

Vessel Operability

The most obvious benefit of being able to measure a vessel's long-term operability is the ability to compare vessel performance under given circumstances. This is of course with the assumption that the operability is a reasonable estimate for the performance of a vessel, which is further dependent on the method of evaluation. From a designer's perspective, it is beneficial to include as much information about the performance when comparing different designs, to end up with the best ship. However, because ships are so complex and intricately connected, more analytic approaches, such as simulation-based methods, may not improve the performance of the design compared to old ways, like percentage operability. In addition, the benefits of improved outcome must overcome the cost of spending extra time and resources on a model. It could, therefore, be interesting to analyze the difference between results obtained from more simple numerical programming approaches and simulation-based approaches. Thus, the methodology of combining hydrodynamic analysis with a simulation approach, introduced by Stemland, will together with a more classical and "simpler" methodology of a numerical programming approach, be used to obtain the operability in this thesis.

As presented in this chapter, the operability of a vessel can be defined in many ways. For a service vessel it might not be accurate to define the operability as "the vessel's ability to sail during harsh weather" and calculate the percentage of operable sea states based on a single criteria. A definition like this could be sufficient for a shipping vessel or a cruise vessel, but for a service vessel that has an entirely different operational profile, it is not a good definition. Other definitions like "the probability of vessel motions remaining within acceptable limits for a

sufficient amount of time to complete the mission", might capture the nature of a service vessel better. Because a service vessel's lifetime scenario is dependent on so many different factors, it is hard to determine the best definition of operability. As presented in this literature review, multiple definitions have been proposed and used to determine the operability of service vessels, both in the offshore and aquaculture industry. However, besides the study by Sjøberg & Lund that compare two different methods of evaluating the operability, there are no studies comparing multiple methods with the same basecase. This thesis will, therefore, assess the operability of a service vessel, using numerous definitions based on the methods used in the studies from Stemberg, Sjøberg & Lund and Sandvik.

In the aquaculture, there is a lack of specified seakeeping criteria for the industry. In general, the studies on the operability of fish farming vessels are based on criteria obtained for other sectors, like the offshore, shipping and cruise industry. Also, there is a lack of operational specified seakeeping criteria, meaning that the criteria are specified for one type of operation. With more specified criteria it is possible to obtain a much more accurate result about the vessel's true operability. This aspect is especially important for service vessels, that perform multiple operations, that can vary significantly. Having the same criteria for all the operations is therefore not a very accurate estimation. With this in mind, the operability study in this thesis will consider the implementation of operation specified seakeeping criteria when performing the analysis. Even though these criteria does not exist yet, it will probably be important in future long-term operability studies. This study is not performed to analyze the operability for a specific vessel, but rather to explore different methods of evaluation. Therefore it is decided to "create" such operational criteria based on existing criteria.

As a summary, based on the literature on the existing study on this topic, this thesis will analyze the operability using two approaches; numerical programming and simulation. A vessel response analysis combined with seakeeping criteria will be used to obtain the operational limits, but will not be the focus of this study. Several operability measurement methods will be compared and analyzed as to how they react to changes of different parameters and operational scenarios, that are considered essential for the operability.

Chapter 3

System Description

The aquaculture industry, with its highly stochastic processes, are characterized by complex logistics and a wide range of operations. The supply chain involves production, transportation, growth, and processing, and includes living animals which is strictly regulated by the authorities. To limit the magnitude and complexity of this thesis, the scope of the thesis only consider a service vessel and its operational scenario.

In this report, the vessel performance his studied as the vessel operability. As discussed in Chapter 2 operability can be defined in many ways, and include multiple aspects of a ship's performance. To simplify the definition, the operability in this thesis is only considered from a hydrodynamic point of view. Factors like the economy, fuel efficiency, and personnel competence are not included in the definition of vessel operability. Also, only wave height is considered as the limiting criteria for vessel performance, meaning that other factors like wind, current, and sight are not considered.

A high-level outline of the system architecture of the operability study is presented in Figure 1.1. The purpose of this illustration is to give the reader an overview of the main elements involved in the work and to provide an understanding of the connections between the different analysis and data inputs. The vessel response is determined through a hydrodynamic analysis in VERES. VERES is a vessel response program in ShipX for calculation of ship motions and loads. A more detailed description of the program can be found in Appendix D. The results from this software provide a set of limiting sea states, in the form of a limiting specific wave height curve relative to wave period, in which the vessel can operate according to specified seakeeping criteria. Further, there are two categories of methods

in which the vessel's long-term operability will be assessed. The first alternative does not involve a simulation model and is only based on the operational limits and weather data. The second alternative is simulation based, where the operational limits together with weather data and operation profile are used as a basis for making decisions in a simulation model. The focus of this thesis will be to evaluate different methods of evaluation, both non-simulation based and simulation-based, and not so much on the vessel response analysis, which is relatively standardized as explained in Chapter 2. Both simulation-based and non-simulation based approaches, as well as specific analyzing tools, are presented in detail later in the report. A visual representation of the scenario is given in Figure 3.1.
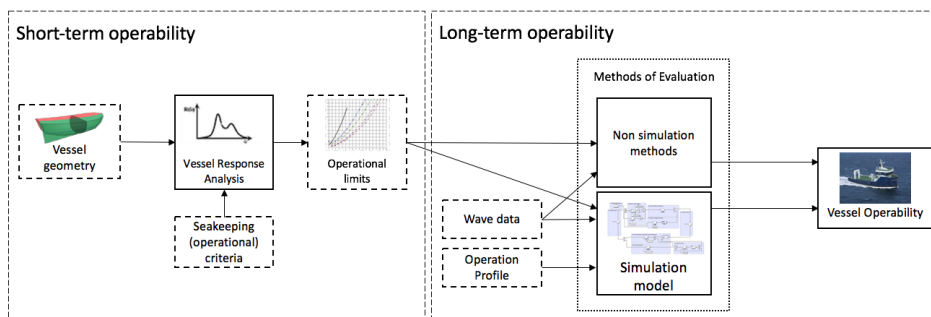
Figure 3.1: Outline of system architecture which illustrates the main elements involved in this thesis

3.1 Operational Scenario

In this section, the operational scenario of the system to be studied is presented. The operational scenario can be understood as the real-life process of the vessel. The goal of the simulation model is to model the operational scenario as accurate as possible, to capture the vessel's operability in the real world. The purpose of this section is to describe, in details, the studied system, to provide the reader with an understanding of the development and content of the simulation model and the operability analysis as a whole. Even though this scenario forms the basis for both the simulation and non-simulation based approaches, most of the information presented here is only necessary to build the simulation model.

A common mistake in simulation modeling is to include too many variables and components that can cause confusion and misleading results (Law (2009)). So to limit the perplexity of the model, only one fish farm, one port, and one service

vessel are included in the operational scenario — the vessel sails back and forth from port to site depending on requested site missions. Only if predicted weather conditions lies within limits for the specific operation, the vessel can initiate and complete the operation. In order to determine this, operational limits for each operation is implemented as inputs to the model. This is illustrated in Figure 3.1. When simulating or calculating the operation scenario over time, the long-term operability can be calculated. The model and the methods used to calculate the operability will be described in more detail in chapter 5.
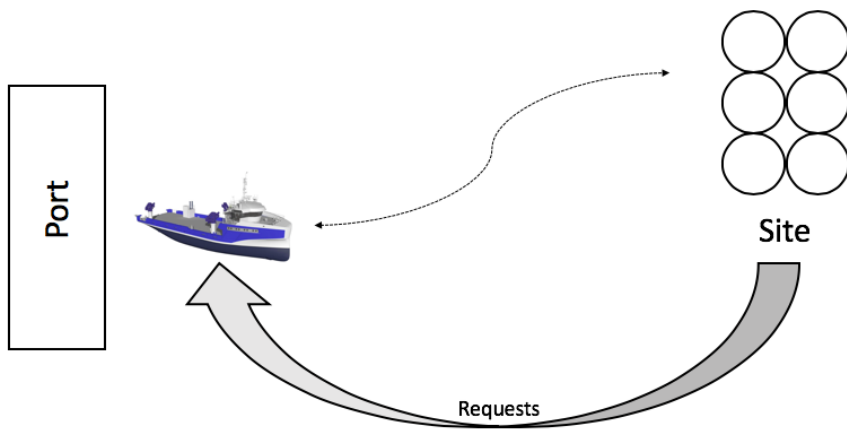
Figure 3.2: Illustration of the scenario modelled in the simulation model

3.1.1 Site Details

According to the EXPOSED project, field testing on an industrial scale will be an important basis for the development of new knowledge and technology for the exposed fish farming. To facilitate such testing for EXPOSED, Marine Harvest and Salmar Farming have bought two oceanographic buoys outside the coast of Trøndelag, namely Saltskjæra and Valøyan (Ocean (2018 (accessed November 17, 2018)). The buoys measure wave, current and wind data, and can provide valuable data for the weather conditions on site. This data have been made available for use, and due to this, it was decided to select Saltskjæra as the geographical location for the operability analysis. The only reason for choosing Saltkjære over Valøyan, was because only one site is included in the simulation model.
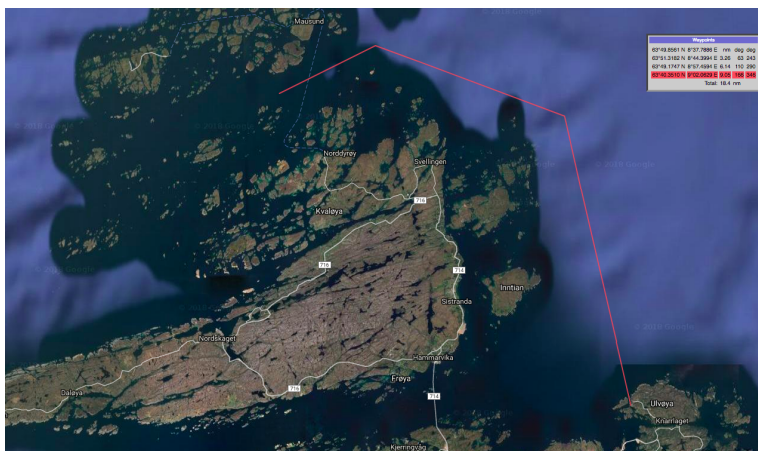
Figure 3.3: Route from port to site generated from searouts.com

Figure 3.3 illustrates the route considered in the simulation model and the approximated distance is presented in Table 3.1. The route is from the location of the buoy and the corresponding port; Marine Harvest Ulvan at Ulvøya. In reality, service vessels will operate at a variety of different aquaculture sites which are often spread over a much larger geographical area. This means that the vessels will often travel long distances to operate on another site. Also, there are often several vessels working simultaneously on the same facilities, being both the assisting vessel and the vessel executing the operation. This makes the routs and operations performed for a service vessel unpredictable and complex, making it hard to model. To overcome some of these challenges, simplifications have to be done. First, only one site next to the oceanographic buoy will be considered in the simulation model. This simplification is also due to the lack of available weather data from other exposed sites. Because the site considered is quite close to the port, the results from the model will be less influenced by the sailing part of the operations than in real life. Secondly, it is assumed that the service vessel will return to port after completing or canceling an operation. In reality, this is not always the case, as a service vessel can do multiple operations without sailing back to port.

Table 3.1: The approximated distance from port to site

Route	Distance [nm]
Port - Valøyan	19

3.2 Service Vessel

In the aquaculture industry, several different types of vessels are used to obtain the operation at a fish farming site, like well boats, feeding carriers, and service vessels. However, as already stated, this thesis will only consider the service vessel. Typically, a service vessel in the aquaculture industry will perform a variety of different operations. Depending on the vessel's specific capabilities and equipment, each vessel can perform its individual set of missions. Small support vessels are often located at each facility to assist in daily tasks, while a service vessel is typically larger and operate on multiple locations in a widespread area (Stemland (2017)). Nekstad splits service vessels into two different types of vessels; Specialized service vessels (SSV) and multi-purpose service vessels (MPV), based on their flexibility regarding the types of operations they can perform (Nekstad (2017)). Specialized vessels are designed and optimized to perform one kind of mission or a set of similar types of missions, with a high mission specific efficiency. A multi-purpose vessel on the other hand, is flexible and designed to perform a wide range of operations. The flexibility allows the vessel to adapt to changing demands and needs in the market, and operation requirements. However, such flexibility comes with a cost of reduced efficiency and performance in general, as the vessel is not optimized for any specific task. Also, the MVPs are often larger than the specialized vessels, as they have to accommodate more types of equipment and mission-related systems.

The development of service vessels in the Norwegian aquaculture has been towards larger and more advanced ships, and this sector today has the fastest growing membership of the coastal shipping companies (Kystrederiet) (Kystverket (2018 (accessed October 20, 2018))). This is mainly because the industry has experienced a significant expansion in the last years, and thus becoming more industrialized. This expansion includes not only larger sites but also moving to more exposed locations, where the weather is harsher. In turn, this has lead to an increased focus on developing vessels that can handle such environments, and the EXPOSED project has mentioned vessel design for exposed operations as one of its six core research areas that will be crucial with exposed fish farming (Bjelland et al. (2015)). Because this thesis is part of the EXPOSED project and the simulation model is developed to look at more exposed locations, the seakeeping criteria for the vessel considered in this thesis is based on the Macho 40 from Stemland.

The Macho 40

The Macho 40 is designed by Møre Maritime AS and has an LOA of 40 m, which makes it the largest service vessel for the aquaculture industry in the world. As of today, M/S "Frøy Fighter" is the only vessel built of this type (Stemland (2017)). The ship is a monohull MPV design and is specially adapted for work in exposed waters. According to Stemland, who have talked to the master on board the vessel, the vessel shows excellent stability and performance during rough weather. Waagbø (Waagbø (2014)) argues that robust multi-purpose vessels with large deck area, cargo space, and high maneuvering capabilities, is the future of service vessel. These are properties that the Macho 40 holds, and therefore makes it a reasonable basis for this study.

Figure 3.4: The Macho 40 Service vessel, used to obtain the seakeeping criteria for the vessel response analysis

3.2.1 Vessel Operations

As the fish farms move towards more exposed locations, the environmental conditions for service vessel operations bear a closer resemblance to the offshore industry, which is characterized by rough sea and difficult working conditions. Many of

the operational challenges seen at present sheltered sites are also likely to be amplified when moving production to more exposed locations Bjelland et al. (2015). The operations are usually complex and involve multiple elements, like several vessel, equipment, and human workers. Consequently, many potential factors can affect the reliability and safety of the operations.

In today's aquaculture industry, there is little operational planning concerning weather windows and weather forecasts as seen in the offshore sector (DNV GL (2011). A vessel will wait for a good weather window to ensure for the safe completion of an operation, either on site, moored to the feed barge or at the nearest port (Sjøberg and Lund (2018)). The operations are not required to comply with DNV GL's regulations for Marine Operations as it is in the offshore industry. According to Sjøberg &, Lund 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 or travel to the nearest harbor to wait for the conditions to improve (Sjøberg and Lund (2018)).

Service vessels in the aquaculture industry can perform a wide range of operations, depending on the vessel's capabilities and equipment. What kind of missions the vessel can perform, is therefore highly dependent on the specific vessel. In his master thesis, Stemland investigated the operations performed by the Macho 40. The vessel operations presented here is therefore based on Stemland's work. In his study, the operations performed by service vessel in the aquaculture were identified and categorized into five main categories;

- Anchor Handling and Mooring

- Net Handling

- Delousing

- Inspection and Maintenance

- General support

The breakdown was based on conversations with people from the industry, including master and first officer of M/S "Frøy Fighter." Operations involving vessel forward speed, typically towing and moving of plants, supply and transport and deployment of anchors, were not considered in the thesis and will therefore not be considered in this thesis as well. The exclusion of forward speed means that all hydrodynamic analyses in VERES are done for zero forward speed. A more detailed description of the operation categories and which activities that are considered critical, can be found in Section 2.4 in Stemland's master thesis (Stemland (2017)) and in Appendix B.1.

Chapter 4

Short-term Operability Study in VERES

As presented in Chapter 2, a response analysis of the vessel is essential for determining it's long-term operability. The outputs from this analysis will be used as the operational criteria inputs in the long-term operability assessment.

A software program in ShipX, called VERES is used to perform the vessel response analysis and calculate the limiting sea state curves (operational limits). VERES is a software that enables evaluation of hydrodynamic motions and loads on vessels. In this thesis, VERES is used to establish the response motions of the Macho 40, and to obtain a set of limiting wave conditions for each operation to be used as input in the simulation model. This Chapter will present an overview of the methodology used in VERES, the data inputs used for the analysis, and the post-processing calculations are done to obtain the operational limits.

4.1   Method Overview

A full methodology of obtaining operational limits in VERES can be found in Fathi (Fathi (2012)), so only a short description will be presented here. Figure 4.1 shows a schematic overview of the methodology and the main elements of the process.
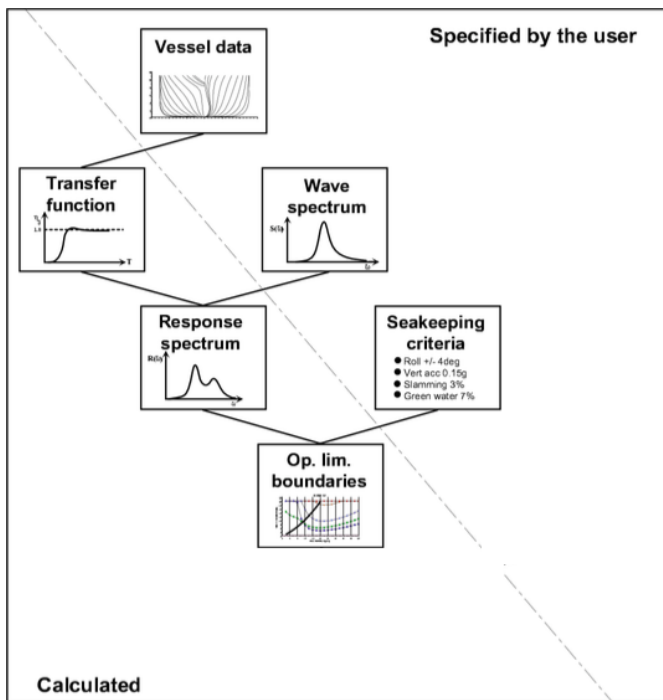
Figure 4.1: The principal calculations performed by VERES to obtain operational limits, gathered from Fathi (Fathi (2012))

First, the vessel data for a specific vessel is implemented in the program. This includes vessel geometry, characteristics and loading conditions. Based on this a transfer function in six degrees of freedom is determined. In combination with a wave spectrum, the vessel response function in irregular seas is calculated. Once this is established, the operational limits are determined based on specified seakeeping criteria for each operation. The operational limits are presented as significant wave height as a function of wave period, for each heading and operation. With a heading step size of 30 degrees, this results in 12 different operational limit curves for each operation. With eight operations, 96 individual operational limit curves are calculated in VERES.

4.2 Data Inputs

Prior to the response analysis, the software runs a data check to verify the model. This is done by manually implementing vessel dimensions, loading conditions, and

environmental conditions. This following section will present a short step-by-step description of the consideration done regarding the inputs.

4.2.1 Vessel Data and Loading Conditions

As already stated in Chapter 1, the vessel geometry implemented in the vessel response analysis is obtained from Stemland. Further discussion on this will therefore not be included in this report.

When the vessel geometry is imported into VERES, main particulars of the vessel must be defined, and the loading condition must be specified. Ships can operate in many different loading conditions, depending on the type of operation performed. However, to simplify this study, only one loading condition is considered. Based on Stemland's study, who had conversations with people from the industry, it was decided that a fully loaded ballast tank is a suitable loading condition to be considered for most operations. The specifics of the vessels in this loading condition can be found in Appendix B.

How the vessel is equipped and modified, define the values for the radius of gyration. Heavy components outside the centerline of the vessel, will typically affect these values. However, in this study, it is assumed a normal ballast condition. Typical values found from Fathi (Fathi (2012)) is therefore considered sufficient, and presented in Table 4.1.

Table 4.1: Applied values for radius of gyration in roll, pitch and yaw (Fathi (2012))

Parameter	Typical values	Applied Value [m]
r44	0.3B - 0.45B	4.20
r55	0.20Lp - 0.30Lp	10.0
r66	0.25Lp - 0.30Lp	10.0

4.2.2 Environmental Condition

The last step was to decide the environmental condition. This includes describing in which vessel velocity, wave headings and wave periods the response analysis will be analyzed. The more values are chosen, the more analysis has to be run. The range of wave periods selected must be broad enough to cover the entire wave spectrum for the short-term statistics. For this, a wave period from 3-20, with a

small step size of 0,5 was chosen to capture all aspect of the spectra. This will be discussed more in Section 4.3.1.

According to Fathi (Fathi (2012)), a resolution of at most $30°$ heading between each heading and minimum of seven headings within the wave spreading interval should be applied for a cosine squared distribution. Therefore, it was applied wave headings from $0°$ - $330°$ with $15°$ intervals.

4.3   Post-Processing

After the response calculations are completed, the post-processing part of the analysis can begin. In this part the transfer functions are combined with a sea state, which is characterized by a standard wave spectrum appropriate for the ocean area selected, to calculate the short term statistics. This combination is done as in equation 4.1. Short term statistics come in the form of a response spectrum and expresses the behavior of the vessel in terms of statistical properties, in this case, the response amplitude operator (RAO) of roll motion. Figure 4.2 shows the transition from a transfer function and a wave spectrum to a response function.

$$S_R(\omega) = |H(\omega)^2 S_\zeta(\omega) \qquad (4.1)$$
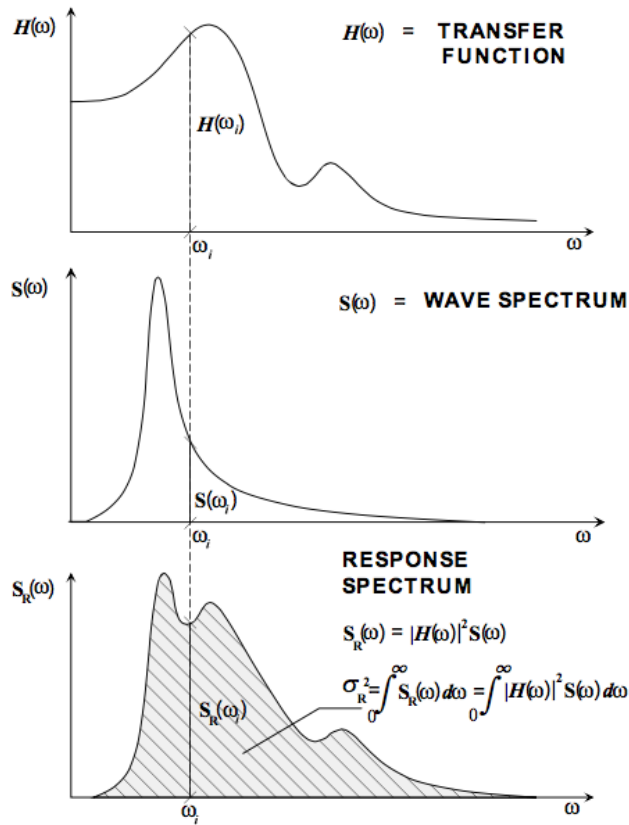
Figure 4.2: Principle procedure to obtain the Short term statistics of the response $S_R(\omega)$ obtained from Fathi (Fathi (2012))

4.3.1 Transfer Function

The transfer function is known as the response amplitude per amplitude of excitation as a function of the wave frequency and describes the vessel response in regular waves. Physically, this means that the transfer function describes the vessel motion, in response to a wave property, in this case, the wave period. Figure 4.3 shows the transfer function in roll for the Macho 40 for 90 different heading. The response of the vessel is made dimensionless by dividing it by the amplitude. This makes it easier to understand the motion of the vessel relative to the size of the waves. It is seen that short and long waves give little response, while waves with wave period between 5-6 seconds give a high vessel motion response. Transfer functions in roll, for every heading is found in Appendix E.

DISPLACEMENTS
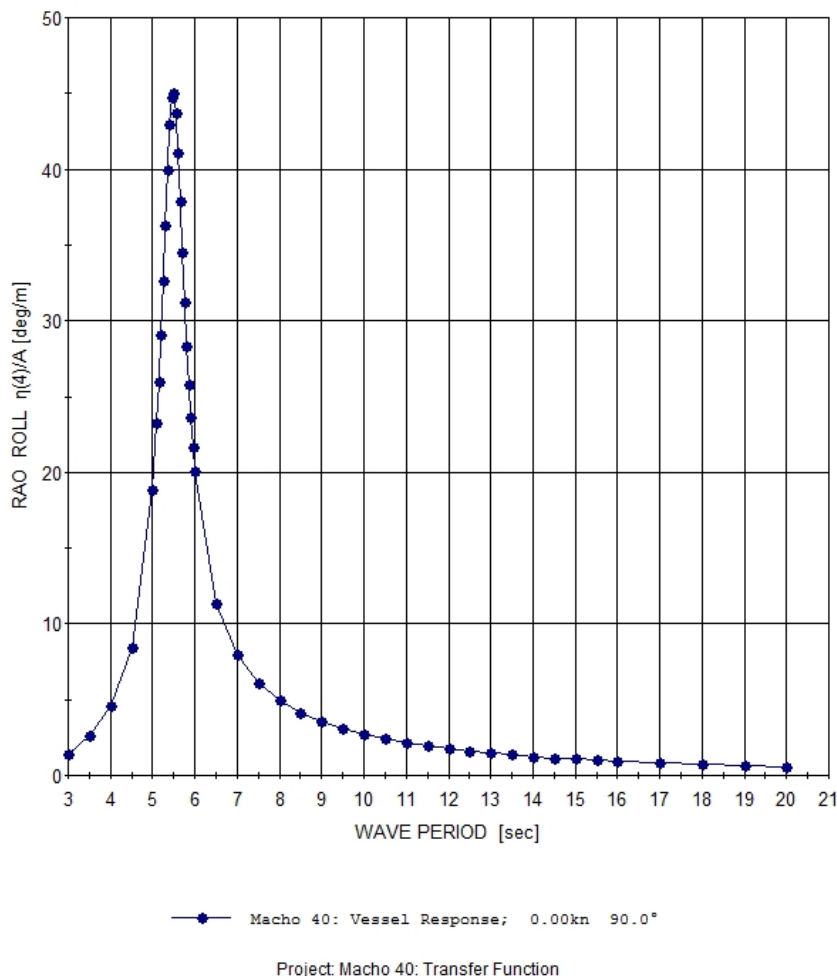
Figure 4.3: Transfer function in roll for 90 degree heading for the Macho 40.

The peak of the transfer function corresponding to the natural period of the vessel, and as seen in equation 4.1 and Figure 4.2 it is important to consider the natural frequencies when designing a vessel for specific sea areas. The resolution of the data points close to the resonance frequency is critical when establishing the natural period of the vessel. A low resolution can cause important motion effects to be ignored if a high RAO motions lie between two data points. Figure 4.3 and

4.4 illustrates the consequence of low resolution around the resonance frequency. As seen, accurate resonance values are not properly captured with low-resolution calculations.

DISPLACEMENTS
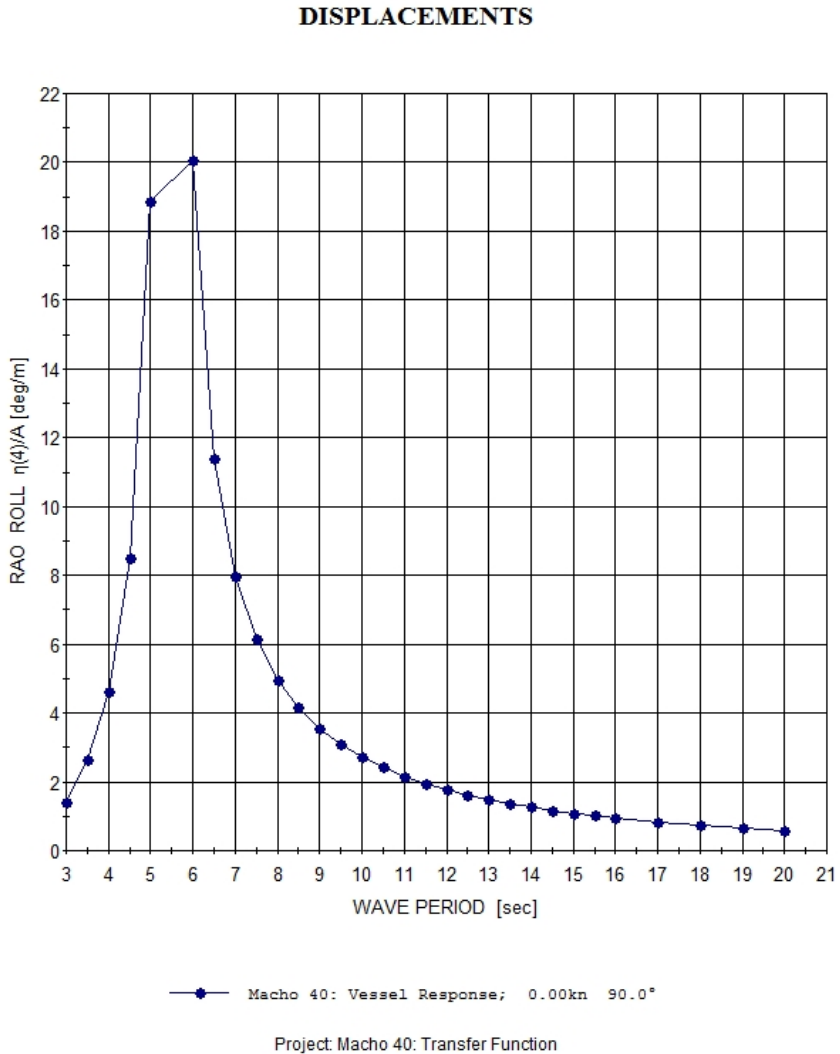
Figure 4.4: Transfer function in roll for 90 degree heading for the Macho 40.

4.3.2 Representation of sea states using Wave Spectrum

The transfer functions are based on motions in regular waves; however, this does not capture the real-world sea. At sea, the wave amplitude and period vary over time, which is referred to as irregular waves. By combining several vessel responses in regular weaves, the vessel response in irregular waves can be captured. An irregular sea state may be characterized by a standard wave spectrum. A wave spectrum is mathematical representations of a particular sea state and expresses the distributing of wave energy for different wave frequencies. Each spectrum is suited for different types of irregular seas, the choice of wave spectrum is, therefore, crucial for the result of the analysis.

There is a limited amount of available wave spectra, and one is therefore often left with the choice of selecting among the existing theoretical wave spectrum models. The commonly used wave spectra on the Norwegian continental shelf are the Pierson-Moskowitz spectrum, the JONSWAP spectrum, and the Torsethaugen spectrum. These are also the three spectra to choose from in VERES. The analysis is carried out for a site located in coastal areas, where the fish farm is somewhat sheltered from open sea and affected by shallow and varying water depths. However, this study intends to understand how a service vessel performs at an exposed location. The basis for choosing wave spectrum is therefore based on waves experienced in open sea.

Waves are usually generated from wind blowing uninterrupted over an open area of ocean for a period of time. This is referred to as wind-generated waves and typically range from 1-10 seconds. When the wind dies, the energy transferred to the ocean continues to move, but with a decreasing frequency until very long waves are left (10-100 seconds). These type of waves are called swell. When deciding the wave spectrum, it is important to consider how much wind-generated waves and how much swell that will affect the operations.

According to Orimolade (Orimolade and Gudmestad (2016)) the occurrence of swells is a concern to marine operations. Experience has shown that even when the sea is relatively calm, long swells can limit the operational capability of an installation or a maintenance vessel in the offshore industry. However, for the fish-farming industry that operates with smaller vessels and structures, it is limited, in terms of vessel motion, how much influence the swell has on the operations. This is because small structures, like small boats and cages, will generally follow the swell motion, which will limit the relative motion as well. Nevertheless, as the service vessels and fish farm structures are becoming larger, the effect of swell on operations will also become greater, and should, therefore, be included in this analysis.

A double peak spectrum is better suited to describing a sea state comprising of both wind sea and swell, and according to Haver (Haver (2004)) the Torsethaugen double peak spectral model has frequently been used for the Norwegian Continental Shelf. The model represents wave conditions in open ocean areas where the waves are dominated by local wind sea, but also exposed to swell. For this analysis, the Torsethaugen spectrum with short-crested seas is therefore selected.

After the transfer function and the weave spectrum is established, they can be combined to obtain the response spectrum as a function of wave frequency, as showed in Figure 4.2.

4.3.3 Seakeeping Criteria

After establishing the vessel's short term statistic of the response, criteria of acceptable levels of ship motions are necessary to obtain the limiting sea-state curve to be used for long-term operability measures later in the study. As previously mentioned, many factors can affect the safety of different operations performed by the Macho 40. This thesis will only look at potential hazards from a hydrodynamic point of view and does not consider other aspects such as health, safety, and environment (HSE) or structural integrity of facility structures.

Previous studies on operability in the aquaculture industry (Stemland (2017), Sjøberg and Lund (2018)) have only generated one set of limiting criteria for the vessel as a whole and not for each operation. Stemland (Stemland (2017)) argue that the reason for this is because to achieve reasonable accuracy of operation specified seakeeping criteria, significant amounts of vessel motion measurements from real-world operations would be required. Because such data is not available today, this aspect of the operability study is neglected. However, as I want to adjust my calculations and model for future scenarios of fish farming, such operation specified criteria are generated for the sake of the study.

According to Stemland (Stemland (2017)) the roll motion is by far the most critical vessel motion for the Macho 40, except at head and following seas where deck wetness is the limiting criteria. This indicates that even though the analysis includes many criteria, the roll motion or the deck wetness will be the limiting ones. Based on this, global roll motion and deck wetness are the only criteria considered in this study.

Roll is a motion that affects the ability of the workers on deck to keep their balance. According to St. Denis (St. Denis (1976)), the critical angle for a safe grip is about 14 degrees. Further, Nielsen (Nielsen (1987) found that the limiting RMS value

for roll cannot exceed 6 degrees if the criteria of safe grip are to be met. The same report, states that a roll motion criteria of 4° RMS are often used to ensure safety and effectiveness of crew performance.

Deck wetness is highly dependent on relative motions between the hull and the waves. In VERES the relative motion is calculated with the assumption that the waves are not disturbed by the presence of the vessel (Fathi (2012)). This assumption is only valid for the forward part of the ship, as the waves will become more affected by the vessel at the back end relative to the wave direction. Deck wetness is a relative term and can be everything from a little spray to green water. In VERES, green water criteria are the only criteria available for deck wetness, o only this will be considered. Green water occurs when the amplitude of relative motion exceeds the freeboard of the vessel. In Fathi (Fathi (2012)) the criteria are defined as the limiting significant wave height due to the probability of green water on deck. This can be seen in Equation 4.2, where P_{dw} is the permissible probability of deck wetness and F is the freeboard at the considered longitudinal position.

$$H_s^{lim}(T_p) = \frac{F}{g_r\sqrt{-2lnP_{dw}}} \tag{4.2}$$

To determine the criteria, the "Nordic standard of seakeeping criteria" from the NORDFORSK (NORDFORSK (1987)) project have been used (seen Figure 2.5a and 2.5b). The criteria are presented as the root mean square (RMS) and as the probability of deck wetness in Table 4.2. According to Stemland (Stemland (2017)), only cleaning of net and inspection of the mooring system do not include significant manual work on deck. For the most part, the work performed on deck is heavy manual work involving heavy components and large tensioning during crane lifting. The basis for the assigned values in Table 4.2 is, therefore, the assumption of light manual work on deck for cleaning of net and inspection of the mooring system, and heavy manual work on deck for the rest of the operations. The NORDFORSK project recommends a criterion of maximum 4° of roll motion for heavy manual work, maximum 6 degrees of roll motion for light manual work and less than 5 % probability of deck wetness. The criteria presented in Table 4.2 are based on these recommendations but changed a bit for each operation in order to generate different criteria and consequently different operational limits for each operation. Ideally, a more thorough study of operation specified seakeeping criteria would give this study a much better basis for the operability study. But as such criteria are not yet available, it is decided not to specify the criteria any further.

Table 4.2: Seakeeping Criteria for each operation, including global roll motion and probability of deck wetness

Operation	Roll [degree]	Deck Wetness [%]
Tensioning of mooring line	4	4
Install/remove net	3.5	3
Delousing	3	5
Clean/inspect net	6	4.5
Clean/inspect collar/bottom ring	4.5	4.5
Inspect anchoring/mooring	6	5
General support	5.5	-
Regular inspections	5	-

4.3.4 Operational Limiting Boundaries

The operability limiting boundary is defined as the limiting sea-state the operations can perform in, as a function of the wave period. The limits are obtained in VERES by combining the seakeeping criteria defined above, and the results from the short term statistics of the vessel response calculated in VERES. The data is presented as limiting significant wave height as a function of mean zero-crossing period, as shown in Figure 4.5. The plots provide the input for the long-term operability study in the next Chapter 5, and describes the vessel's operative and non-operative state for each operation, and in each heading. The black line in the plot describes the theoretical limit of wave breaking. This result will be described and discussed in more detail in Chapter 6.
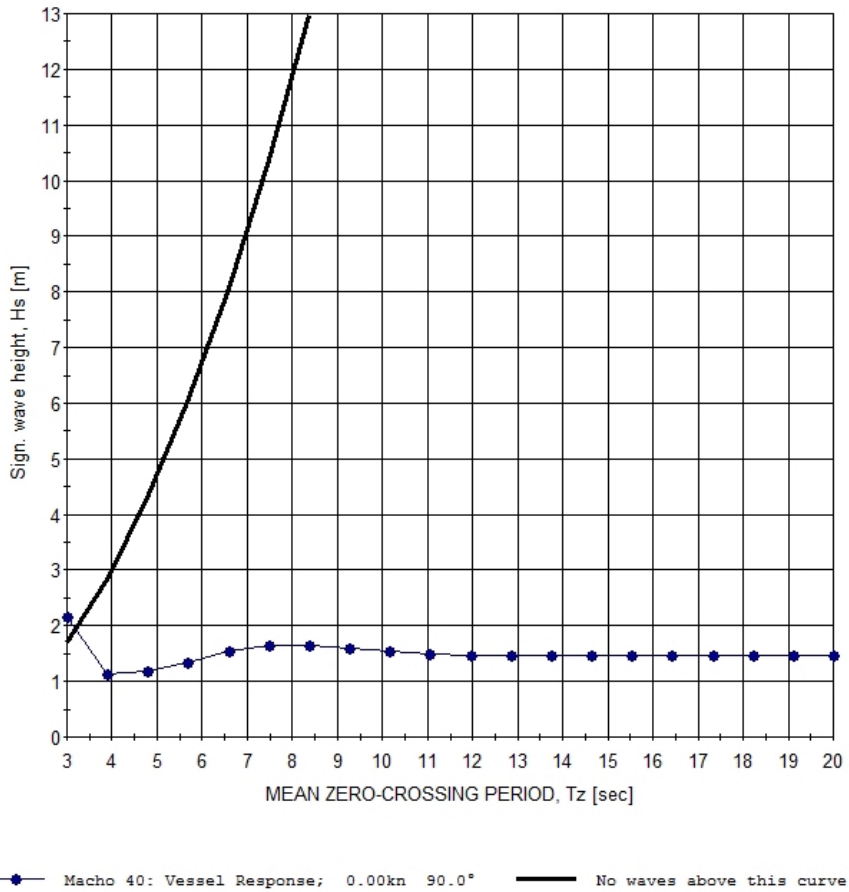
Figure 4.5: Operational criteria for "Tensioning of mooring line" in 90 degree heading

Chapter 5

Long-Term Operability Study

This chapter covers the long-term operability study of this thesis. Long-term operability, unlike short-term operability, takes into account how the vessel performs over a period of time. In this thesis, two evaluation approaches will be used to obtain the operability of the vessel considered. The first approach is a numerical programming approach, and the second approach is a discrete-event simulation approach.

Dependent on the method, the operability is assessed with respect to the operational limits obtained from VERES, wave data from oceanographic buoys and "European Centre for Medium-Range Weather Forecasts", and the operational profile of the vessel. As mentioned previously, the analysis only considers the operability based on a hydrodynamic aspect. Other factors like wind, current, sight, etc. are not considered.

First, the data inputs used in both methods are presented in Section 5.1. Secondly, the different methods used to calculate the operability, called performance indicators, are shown in Section 5.2 Next, the numerical programming approach is presented in Section 5.3, followed by the DES approach in Section 5.4. Finally, a step-by-step review of the complete model used in the DES approach will be presented in Section 5.4.3.

5.1   Data Input

This section will present the data inputs used in both the percentage operability method and the simulation-based method. First, the operational limits from

VERES are presented, followed by the weather data, both hindcast, and forecast. Lastly, the operational profile is presented.

5.1.1   Operational Limits

The operational limits are obtained from the hydrodynamic analysis in VERES, based on the seakeeping criteria for each operation, specified in Section 4.3.4. They are presented as curves showing the limiting significant wave height, H_s, as a function of mean wave period, T_z. The operational limits also change with the heading, meaning that there exists one curve for each heading, as well as with each operation listed in the operational profile. This means that, for each operation, wave heading and mean wave period, there exists a maximum significant wave height above which the vessel is not allowed to operate. One example of a curve like this for "Tensioning of mooring lines" with $90°$ wave heading is illustrated in Figure 5.1. Wave heights above the limiting curve are categorized as the non-operative zone, while the wave heights under the limiting curve are classified as the operating zone.
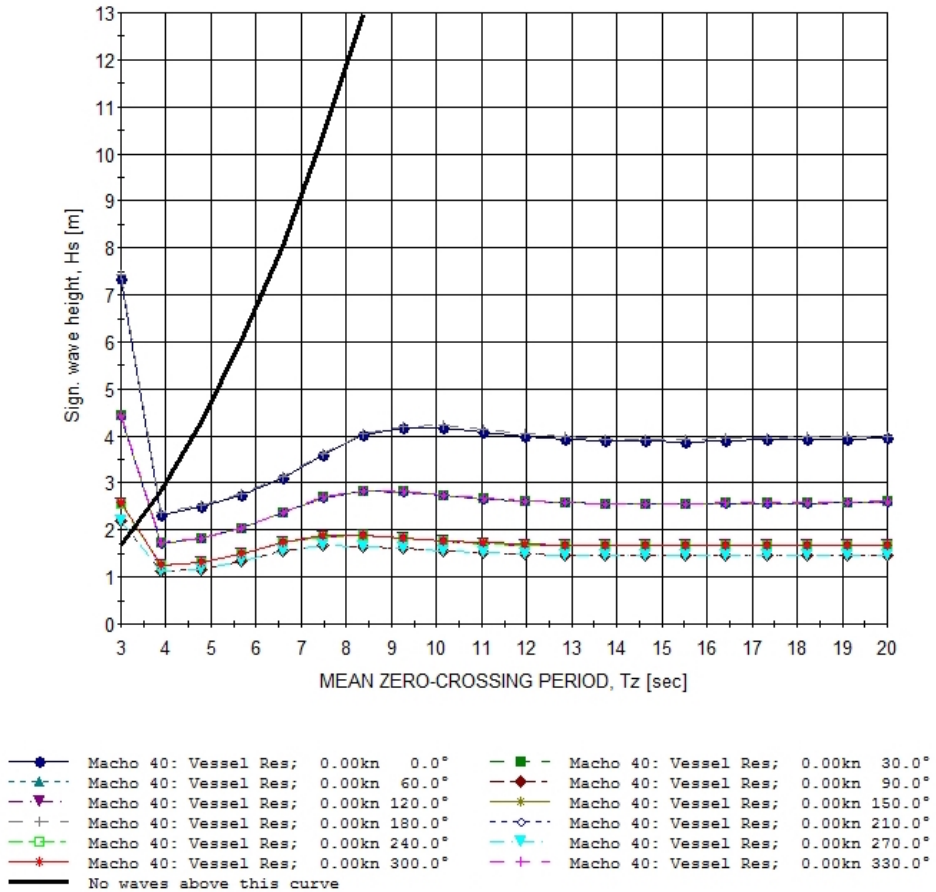
Figure 5.1: Operational criteria for "Tensioning of mooring line" in 90 degree heading

The data from VERES is exported as XML-files and imported into MATLAB. As described in Chapter 4, one limiting curve is generated for each operation and each heading, resulting in 96 different limiting curves in total. Each limit is imported as a set of two vectors, one representing the significant wave height and one representing the corresponding wave period. This enables the simulation model to extract the right limiting wave height based on operation, heading and wave period.

5.1.2 Weather Data

The percentage operability method only considers weather data from the on-site measurement by the oceanographic buoy when evaluating the operability. For a simulation model that aims to imitate the decision-making process in real life, weather forecast data is vital.

The weather data implemented in the simulation model is gathered from the on-site measurements from the oceanographic buoy by Valøyan site, and The European Centre for Medium-Range Weather Forecasts (ECMWF). The oceanographic buoy provides the real-time measured weather conditions on site, while ECMWF provides the weather forecast for the simulation model. Both sources will be described in turn below.

Forecast from European Centre for Medium-Range Weather Forecasts

The weather forecast is obtained from The European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF is an independent intergovernmental organization supported by 34 states, including Norway.

The organization is both a research institute and a 24/7 operational service, producing and disseminating numerical weather predictions. The data is fully available to the national meteorological services in the Member States. The supercomputer facility (and associated data archive) at ECMWF is one of the largest of its type in Europe, and Member States can use 25% of its capacity for their purposes. The organization was established in 1975, and today it employs around 350 staff from more than 30 countries. ECMWF is one of the six members of the Co-ordinated Organisations, which also include the North Atlantic Treaty Organisation (NATO), the Council of Europe (CoE), the European Space Agency (ESA), the Organisation for Economic Co-operation and Development (OECD), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

ECMWF's operational forecasts aim to show how the weather is most likely to evolve. To do this, the Centre produces an ensemble of predictions. Individually they are full descriptions of the evolution of the weather, but collectively they indicate the likelihood of a range of future weather scenarios. ECMWF uses a model called the Integrated Forecasting System, which provides forecasts for multiple time ranges. These time ranges are divided between medium, extended and long-range forecasts. Medium range is predictions up to 15 days, extended range is up to 32 days while long range is up to 13 months. Because the operations in the

simulation model are requested no more than three weeks before they have to be performed, the medium range forecasts are used in the simulation model.

For the medium-range forecasts, an ensemble of 52 individual ensemble members is created twice a day, hence at 06.00 and 18.00. One member is at a higher spatial resolution than the other members (called the HRES), and its initial state is the most accurate estimate of the current conditions, and it uses the currently best description of the model physics.

Unlike the hourly measurement from the oceanographic buoy, the weather forecast data is only sampled every 6th hour. This causes problems for the operability methods, which are based on checking weather conditions on an hourly basis. To match the predicted data up against the real-time data, the data were modified to predict the same value for the 5-hour gap before between the observations. This is illustrated in Figure 5.2 where each measure is a straight line for a time series of six hours. This, of course, is not in compliance with reality and will be a source of deviation in the model.
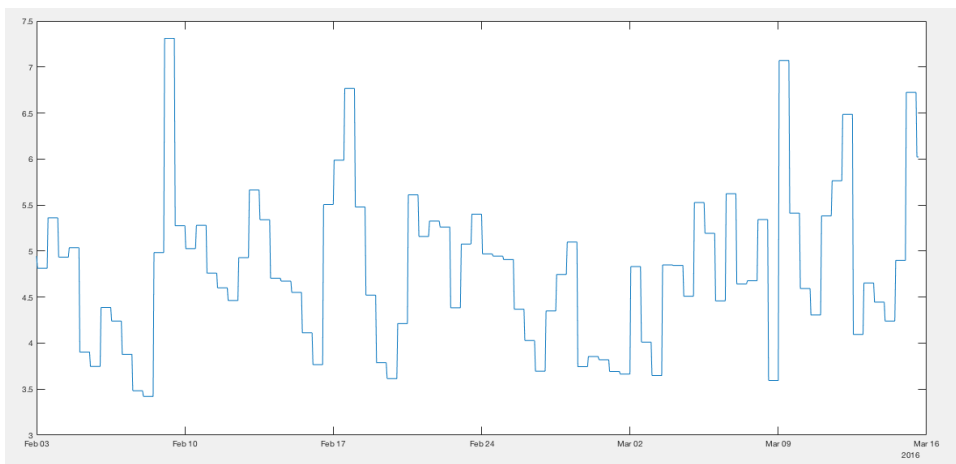
Figure 5.2: Weather forcast

Weather Data from Oceanographic buoy

The Oceanographic buoy is a small buoy as illustrated in Figure 5.3. The buoy is not located precisely at the Valøyan site location but some distance away from where the conditions are assumed to be somewhat more exposed to weather (Stemland (2017)). The data is measured every hour and is the mean values of the last 15 minutes of each hour. The buoy measures the mean value of wave height, period

and directions of waves, as well as current and wind, but only the wave height H_s and the wave period T_z are used in the analysis. The data from the oceanographic buoy is used as the real-time data in the simulation model, to check whether or not the predicted weather is correct.

The measurements began in 2016 and are still active today. The data set used in the model stretches from 3th of February 2016 to 31th of August 2018 and contains more than 22500 hours of measured data. However, during the period from 2 May 2017 to 4th September 2017, the data showed a constant value of zero for the wave height. The reason for this is not apparent, but most likely it is because of failure or maintenance on the buyer. This would lead to higher operability than in reality, because the real-time weather in this period would lie below the forecast and hence the limit, no matter what. So to avoid simulating with damaged data, this whole period was removed from the data set. The final data is therefore 19970 hours long, and because the model is run based on weather data, this is also the duration of the simulation model.

Figure 5.3: Oceanographic buoy, picture from Haver (2015)

5.1.3   Operational Profile

A service vessel's operational profile is a highly stochastic process, and are characterized by complex logistics and a wide range of operations. This makes it difficult to predict precisely when and how often each operation will be requested at a site. However, to model the day to day operation of a service vessel, it is necessary to provide the model with an operational profile. This includes in what frequency

each operation is requested, how long it will take and the deadline before an operation is canceled.

As described in Section 1.2, the operation profile considered in the simulation model are obtained from Stemland's master thesis (Stemland (2017)). From this study, the operations are divided into five main categories and eight operations, see Appendix B.1. Because of variations in environmental conditions, site structure, and other factors, each farming facility is unique regarding maintenance and support. The operation profile presented here is therefore customized for this particular case and site. The frequency of occurrence and duration of the different operations are based on the questionnaire in Appendix B.2 which was given to the master and chief officer of M/S "Frøy Fighter" by Stemland (Stemland (2017)).

In collaboration with Ph.D. student Hans Tobias Slette (Slette (2019)), and based on his conversations with the industry, it was also decided to implement a deadline for each mission in which the operation had to be performed before it was canceled. This was applied as a factor in the model to provide a more realistic scenario for the service vessel operation profile. If a mission is not performed right away, it is stored away in the *Request* list until it is either completed later or canceled due to an exceeded deadline. This is more accurate to the real-life operation than having to cancel an operation before the vessel can receive a new mission. The different operations with the corresponding duration, frequency, and deadline are listed below in Table 5.1.

Table 5.1: Operation Profile, including frequency of occurrence, duration and deadline, measured in hours

Operation	Frequency of occurrence		Duration	Deadline
	Mean	St. dev.		
Tensioning of mooring line	288	48	48	168
Install/remove net	8760	360	4	168
Delousing	288	48	5	168
Clean/inspect net	168	24	5	336
Clean/inspect collar/bottom ring	8760	360	4	336
Inspect anchoring/mooring	8760	360	2	168
General support	750	100	4	24
Regular inspections	-	-	40	336

The frequency of occurrence is presented as hours between each time the farming facility requests the specified operation. The frequency is modeled with a nor-

mal distribution, with a mean value corresponding to the frequency of occurrence and standard deviation. To simplify the study, it is assumed that the three vessels considered, all have the same operational profile.

5.2 Performance Indicators

In this Section, the method of evaluating the operability is presented, namely the performance indicators (PI). Based on the litterateur review in Chapter 2, it is decided to use the performance indicators presented in Table 5.2.

Table 5.2: Performance indicators

Name	Obtained from
Relative Rate of Operations (requested) (RRO_1)	Stemland (2017)
Relative Rate of Operations (feasible) (RRO_2)	Sandvik et al. (2018)
Relative Rate of Non-Delayed Operations (RRNDO)	Sjøberg and Lund (2018)
Relative Rate of Operative Time (RROT)	Sjøberg and Lund (2018)

Two different approaches are used to achieve the data needed to calculate the performance indicators, namely the numerical programming approach and the discrete-event simulation (DES) approach. Figure 5.4 shows an overview of the methodology and inputs used to obtain the different methods. The different PIs are presented in turn in the next sections.
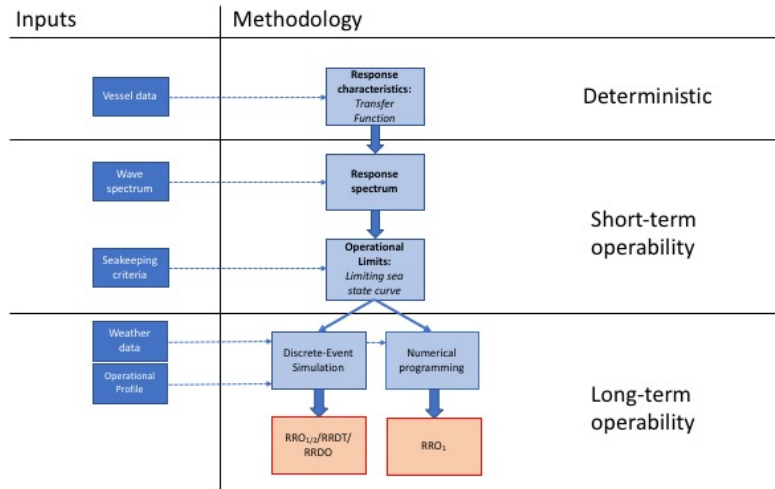
Figure 5.4: Overview of Methodology and Inputs for evaluating the long-term Performance

5.2.1 Relative Rate of Operations

The relative rate of operations (RRO), is defined as the ratio between the number of performed operations and number of feasible operations that can be performed or the number of requested operations, during a time duration, as discussed in Chapter 2. This is illustrated in equation 5.1 and 5.2. The important difference here is that the requested operations are not always equal to the feasible operations performed in perfect weather.

$$RRO_1 = \frac{OP_{performed}}{OP_{feasible}} \tag{5.1}$$

$$RRO_2 = \frac{OP_{performed}}{OP_{requested}} \tag{5.2}$$

5.2.2 Relative Rate of Non-Delayed Operations

The relative rate of Non-delayed operations (RRNDO) is defined as the relationship between the number of operations completed and the number of operations where there was no need to wait for the conditions to improve. This is illustrated

in equation 5.3. The method is as used in Sjøland & Lund's master thesis, as previously presented in Chapter 2.

$$\text{RRNDO} = \frac{\text{Total non-delayed operations}}{\text{Total operations performed}} \tag{5.3}$$

5.2.3 Relative Rate of Operational Time

The relative rate of Operative time (RROT) is defined as the relationship between the total operational time and the time spent operative (perform operation or sailing to the site) during a simulation. This is illustrated in equation 5.4. The method is inspired by the similar method used in Sjøland & Lund's master thesis, as previously presented in Chapter 2.

$$\text{RROT} = \frac{\text{Total Operative Time}}{\text{Total Operational time}} \tag{5.4}$$

5.3 Numerical Programming

Numerical programming is a simple and quick tool to process data. Compared to a simulation model, it is easy to modify and does not have "hidden" code that can make it hard to locate bugs in the programming.

Operability measurements based on a numerical programming approach are in this thesis conducted in MATLAB. This approach uses numerical programming to determine the number of performed operations and the number of possible operations, based on a set of operational limits and weather data. The statistics needed to calculate the RRDO, RRTO and the RRO_2 is not possible to obtain with the numerical method presented in this thesis. Therefore, the RRO_1 performance indicator will be used to determine the operability using this approach.

One aspect of the objective of this thesis is to analyze the effect of including parameters and operational scenarios to the operability calculations. With the numerical programming approach, the impact of including weather forecast to the operability calculations are analyzed. The benchmark and weather forecast scenarios are presented below. The first scenarios, namely the Benchmark method, is included to have a benchmark in which the scenario including weather forecast will be compared towards. By doing this, it is possible to analyze the effect of considering the weather forecast. A more detailed description of the scenarios is presented next.

Benchmark

The benchmark scenarios only consider the measured weather data when calculating the operability. Transit time and operation duration are not considered, meaning that operations can be performed with bad weather in between and without any transit time in between operations. This is of course not possible in real life, where the vessel has to perform an operation in a constant weather window and often has to travel back to port between missions. Because the weather is considered on an hourly basis, another way of defining this method is with a constant operation duration of one hour, and zero transit time. Using this definition, the method can be compared to the percentage operability (%OP) method, which is often referred to as the "commonly" applied operability assessment approach. The %OP method is a measure of how many percents of historical weather data, in a particular area, that lies below limiting operational criteria. As the weather is measured at an hourly basis, the Benchmark scenarios are identical to the %OP method scenarios when the transit time is assumed constant at 1 hour.

Weather forecast

The weather forecast scenario includes the consideration of weather forecast. In this scenario, the vessel will consider the forecast to see if it is possible to perform the operation. If so, the measured weather will be checked to see if the forecast was "right", and that the vessel was able to perform the operation. This enables the vessel to plan when it should begin it's travel to the site, to be there when the weather window starts. This scenario differs from the Benchmark scenario by including the uncertainty of relying on forecasts. Transit time and operation duration are assumed to be deterministic.

Weighting of Operations

The problem with the numerical programming methods described above is that it is limited to the analysis of single sea states, meaning that the operational limit applies to the vessel and not a specific operation. For shipping vessels, cruise ships or other ships that mainly do one type of operation, this method are sufficient to determine the overall operability. However, for offshore vessels or other special vessels that will perform multiple different operations, this simplification is not sufficient. To account for this, a weighting of operations are proposed, as presented in Table 5.3. The weighting is based on the operation frequency presented in Table

5.1, and reflects the percentage demand for operation, assuming a constant demand for operations.

Table 5.3: Weighting of operations for calculation of operability from numerical programming

Operation	Weighting [%]
Tensioning of mooring line	22.76
Install/remove net	0.75
Delousing	22.76
Clean/inspect net	39.01
Clean/inspect collar/bottom ring	0.75
Inspect anchoring/mooring	0.75
General support	8.74
Regular inspections	4.49

5.4 Discrete-Event Simulation

According to the literature review, the overall definition of operability can be defined as the vessel's ability to perform its intended tasks safely and reliably (Chapter 2). The numerical programming approach does not really include the aspect of "intended tasks", because the operability is calculated for each operation separately, assuming a constant demand. Creating a demand, which might not be constant, is difficult to implement using a numerical programming approach. This is where a discrete-event simulation can be useful. Using a DES model enables the operability assessment to include an operational profile, by creating a set of operation demands that the vessel is requested to perform. A more detailed description of how this is implemented, is presented in the review of the model in Section 5.4.3.

This section will first present the modifications implemented compared to other simulations models in the literature, in Section 5.4.1. Next, an overview of the model will be presented in Section 5.4.2, followed by a detailed review of the simulation model in Section 5.4.3.

5.4.1 Model Modifications

Compared to the simulation model used in previous studies on fish farming service vessels, the model built in this thesis takes in to account additional operational

scenarios. The most important modifications is the *Request* list and the implementation of deadlines for operations, and also the ability for the vessel to wait on site for up to six hours. This will be explained in more detail next.

In reality, a vessel might have several operation requests simultaneously, and the choice of which operation to perform might depend on the weather or how urgent the mission is. Also, if it is not possible to perform the operation due to bad weather when arriving at the site, the mission is not necessarily canceled, but only postponed. To account for this, the operation requests generated in the Operation Generator, are implemented in a global list, as explained in Section 5.4.3. The model then optimizes the choice of mission by choosing the most favorable operation to perform from this list. This is done with the elimination method, based on two criteria. First, all the operations with operational limits under the predicted weather are eliminated, then the remaining operation with the shortest deadline is chosen. Also, if an operation is not performed due to bad weather, the vessel aborts the mission and travels home, but keeps the mission in the list. In that way, the operation can be performed at a later time, if it doesn't exceed its deadline.

If the weather turns out to be outside acceptable limits when the vessel arrives at the site, it will rarely travel back to port immediately after arriving. Instead, it will wait on site, so it will be ready to start the mission right away if the weather were to be acceptable. To account for this behavior, the vessel will, in the model, wait at the site for up to six hours before postponing the mission and travel back to port.

5.4.2   Model Overview

A simulation model aims to imitate the real-life scenario of a system, to analyze its performance. In this case, the system is the long-term operational scenario of the aquaculture service vessel Macho 50, as introduced in Chapter 3. The system further consists of one port and one fish farming site. Limiting wave heights, measured wave data from the buoy and weather forecast data from ECMWF are used as input. The output is the number of operations the vessel can perform under the given circumstances and the number of requested operations. Together this provides the values needed to evaluate the performance indicators, as presented in 5.2, and hence the operability. The model is relative complex, therefore a flowchart in Figure 5.5 is presented to give the reader an understanding of the of the decisions and actions that take place in the simulation model.
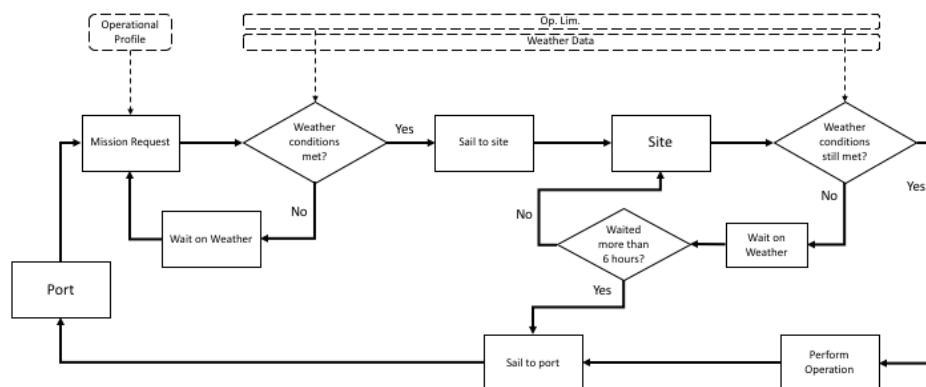
Figure 5.5: Flowchart of the decision and actions performed in the model

Once a mission is requested, the vessel checks if the predicted weather conditions meet the operational limits of that particular operation. If not, the vessel will wait on weather for one hour before checking again. If the weather conditions are met, the vessel will travel to the site. There the vessel will check if the "real" weather still fulfills the operational requirements. If not, the vessel will wait on site for up to six hours to see if the weather improves, before sailing back to port. If the weather is sufficient, however, the vessel will perform the operation and travel back to port. There the vessel will wait on the next operation request.

5.4.3   Detailed Review of Simulation Model

This section will provide a detailed presentation and explanation of each part included in the simulation model. The simulation model is built in a software called Simevents, which is a program for discrete-event simulation in MATLAB. See Appendix G for a more detailed description of the program. The model is built by me, but is inspired and bears a resemblance to the simulation models in the master thesis of Stemland and Sjøberg & Lund (Stemland (2017), Sjøberg and Lund (2018)). The operation generator in the model, as seen in Figure 5.7, is quite similar to the one in Stemland. However, there is one crucial difference. Instead of opening a gate in the vessel round-trip for each operation that is generated, the operations generated is placed in a global *Request* list. When the vessel is ready to perform a new mission, it will choose a mission from the list that fulfills the weather conditions and that has the shortest deadline. This allows the vessel in the model to perform operations in a more realistic scenario, rather than always having to either

complete or cancel one operation before receiving a new mission.

Global Variables

If more than one function needs access to the same value, it can be advantages to place it in a global variable. This makes it possible for multiple functions to implement and influence the same variable from any server at any time. In many ways, this is an easy solution for enabling different servers to communicate with each other. In this model, four such global variables are defined as seen in figure 5.6. The most obvious global variable is the time, which is important for accessing the right weather conditions. The time variable is being updated for each step in the simulation, and not in real time. Another important global variable is the *Request* variable. This data store memory is a 3x100 matrix and contains a list of requested operations, together with its duration and deadline. For each operation generated, it is added to this list, and when the vessel is ready to start a mission, the vessel looks through this list to decide which operation to do next. When an operation is completed or has exceeded the deadline, it is removed from the list. *WOWcount* counts how many hours the vessel has waited for weather on site. If it exceeds 6 hours, the operation is postponed.
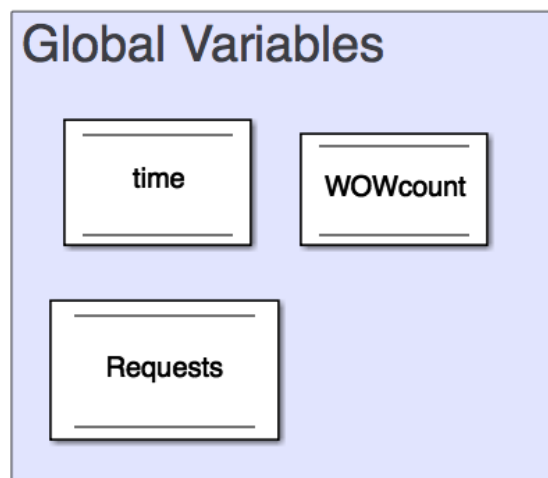
Figure 5.6: Global Variables used in the simulation model

Operation Generator

The operation generator is modeled as a separate section in the model and is not directly attached to the vessel round-trip block, see Figure 5.7. The block's mission is to generate a sequence of operation requests based on the probability distribution presented in Section 5.1. Each operation is generated by an entity generator block, as seen to the left in Figure 5.7. Once an operation is generated, in the form as an entity, it continues through to the "Operation Request" server. This server will then write the operation and its attributes (operation duration and deadline) into the first available spot in the global list "Requests" before it is terminated. Each operation has a deadline in which the operation must be performed, and this can be everything from one day to several weeks. The deadline value added to the list is therefore calculated as the current simulation time plus the deadline.
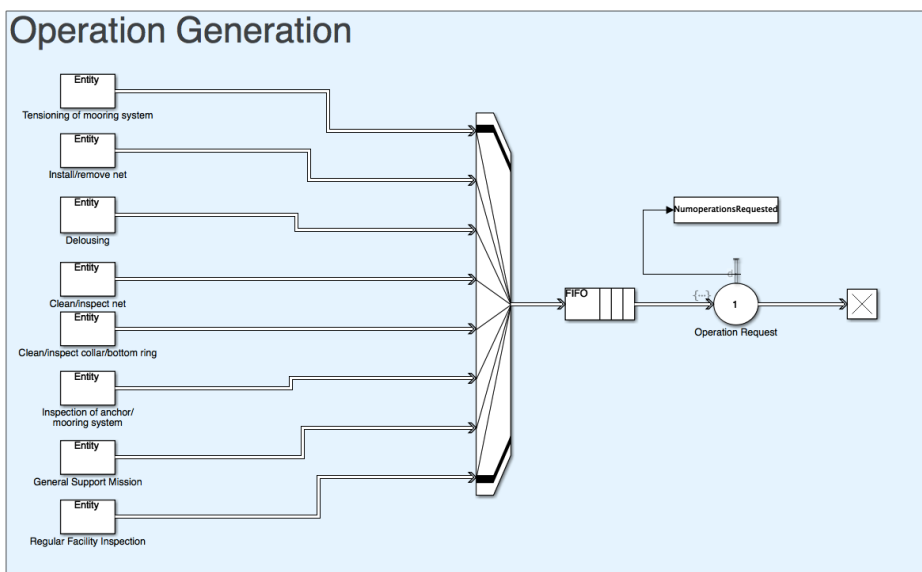
Figure 5.7: Operation Generation section of the complete simulation model

Vessel round-trip section

The rest of the sections presented are all a part of the central part of the model, namely the vessel round-trip, as seen in Figure 5.8. Each section is assigned a number that represents the sequence in which the vessel will operate in the simulation. Sections that serve as alternative actions if particular criteria are not fulfilled

are numbered on step down in the numbering hierarchy. One important note of the model is that not every activity in the model represents a physical movement, in fact only the "sail to site" and "sail to port" are actions that represent an actual movement. Another note is that not every action in the model is time-consuming in real life. Consequently, some servers will not add value to the time variable. For example, the "Operation Canceled" server does not generate any time.
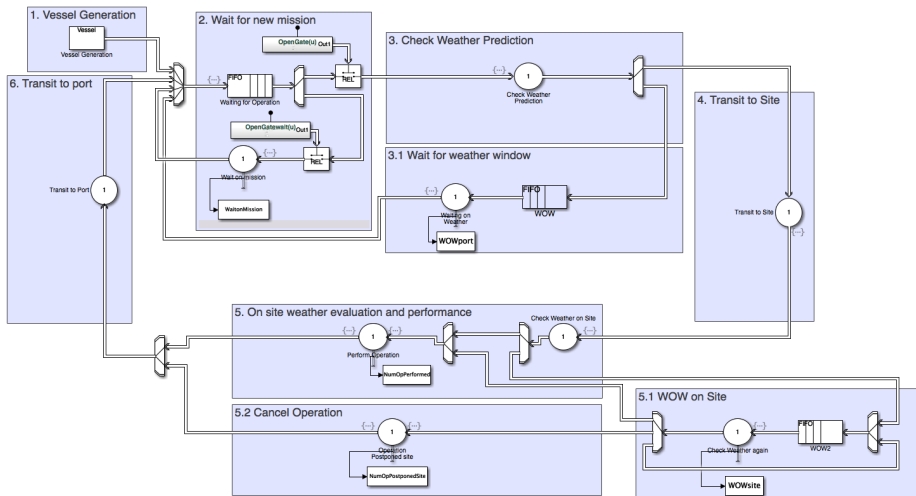
Figure 5.8: Overview of the vessel round-trip section of the model

1. Vessel Generation

The vessel generation section is the first step of the simulation and contains an entity generator block that generates only one entity at the beginning of the simulation. The entity represents the service vessel, and once the vessel is generated this section is no longer active in the simulation. The vessel is assigned two attributes, whose values will determine the behavior of the vessel at several points in the model. The application of this attribute will be discussed further in these specific points.

2. Wait for new mission

Step number two in the model is to wait for a mission from the *operation generation* to be added to the global *Request* list. Once the list contains one operation

request or more, it will open the "OpenGate" gate enabling the vessel to move on to section 3 (*Check for weather conditions*).

3. Check weather prediction

Step three is to evaluate whether or not the required weather window to complete the mission is fulfilled, and based on that decide if it is possible to start the mission. This is done in the "Check Weather Prediction" server block by importing weather data and comparing it to the operation's specific operational limits. This block contains the most comprehensive code in the simulation and considers not only the current weather, but also predicted the weather. To decide which operation to perform, the server first checks which operations from the *Request* list that is possible to perform based on weather. This is done by comparing the operational limits for each operation with the predicted weather for the duration of that specific operation. If the predicted weather lies below the operational limits, the operation is further considered. If none of the operations in the *Request* list fulfills the weather requirements, the vessel will move to section *3.1 Wait for weather window* and wait for the weather to improve or a new mission to be requested. After eliminating the operations that did not fulfill the weather requirements, the mission with the shortest deadline is chosen to be executed. For the full Simulink script for this entity block, see appendix G.3.4. Once a mission is selected, the mission number is assigned to one of the vessel attributes called "id", and the vessel will move to step 4 (*Sail to site*), to complete the mission.

3.1 Wait for weather window

If the required weather window in step 3 (*Check for weather window*) is not fulfilled for any requests in the list, the vessel will move to this section. Here the vessel will wait for one hour before returning to step 2 where it will check for missions, before moving to section 3 where the weather will be checked again. It is important to check the *Request* list again before checking the weather, because the deadline for the mission might be exceeded, causing there to be no missions in the list.

4. Sail to Site

If the weather conditions are accepted the vessel moves to step 4 and sails towards the site. The travel time is assumed to be deterministic, at 1 hour.

5. On-site weather evaluation and performance

Once the vessel arrives at the server in step 5, the vessel will check if the conditions at site are still met. Ideally, this should include checking new updated predicted weather, but because only one set of predicted weather is available, checking the same prediction will not have any impact. Due to this, only the current "real" weather is checked against the operational limits. If the "real" condition is still acceptable, the vessel will stay in this section and move to the next server where the operation is performed. Once the mission is performed, the operation request is removed from the global *Request* list. However, if the predicted weather from the port does not comply with the "real" weather, and falls outside acceptable limits, the vessel will move to step 5.1, Here the vessel will wait for one hour before checking the weather again. If the operation is delayed more than six times, hence the vessel has been waiting for weather for more than six hours on site, the vessel will move to step 5.2 (*Postpone operation*) and postpone the operation.

6. Return to port

Once the operation is completed or postponed, the vessel will move to step 6 and return to port. The rout duration is identical to the duration in step 4, 1 hour. Once the vessel returns to section 2, the simulation loop is completed, and the vessel will look for new mission requests in the list.

Chapter 6

Results - Operational Limits from VERES

This chapter presents the obtained operational limits from the vessel response calculations in VERES. The results are later used as input for the long-term operability analysis. The calculations are done for each operation and heading, with eight operations and 12 headings, this resulted in 96 limiting sea state curves. To keep the report short and organized, only the curves for two operations are included in the text. As the plots follow the same pattern and are based on the same methodology, two plots are decided to be sufficient for presenting and understanding the results from this part of the study. The operational limits for the rest of the operations are presented in Appendix F. The limits are presented as maximum significant wave height, H_S as a function of mean wave period, T_z, as seen in Figure 6.2 and Figure 6.3.

After running the calculations, it was discovered that the deck wetness criteria did not really affect the operational limits. As seen in Figure 6.1, the limiting criteria from the deck wetness is much higher than the limiting criteria from roll, in all headings. Due to this, the operational limits from deck wetness are not considered further in this thesis.

Figure 6.2 and Figure 6.3 show that the vessel's operational limits are much higher in head and in following seas (0° and 180°), meaning that the operations should ideally be performed in these positions. The curve also shows that the headings close to beam sea (90° and 180°) are the most critical ones when it comes to operational limits in wave heights. The maximum H_S limit is around 2.6 meter, while the most critical limit is around 1.3 meter. This pattern occurs for all the
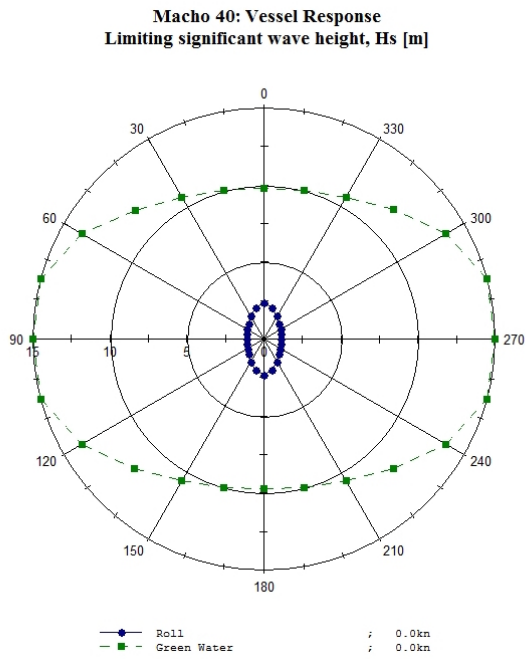
Figure 6.1: Polar plot of limiting wave conditions for operation "Tensioning of mooring line", with both roll and deck wetness criteria included
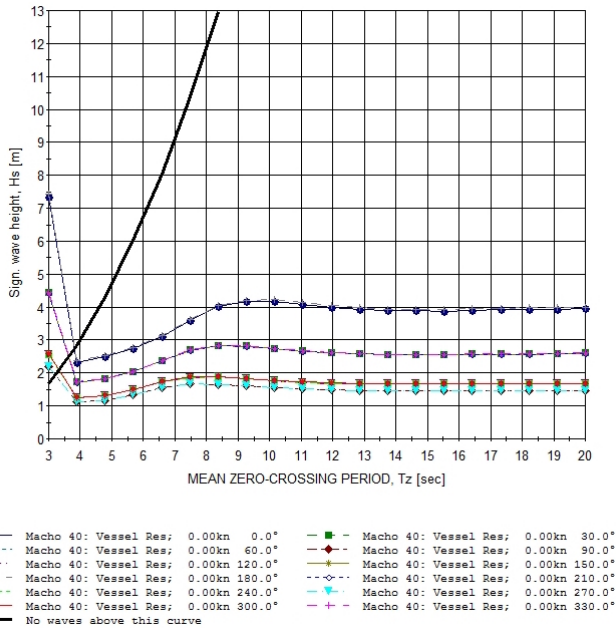
Figure 6.2: Limiting wave conditions for operation "Tensioning of mooring line" with all headings included.

operations, but with different limits. These results are as expected, as it is well known that a vessel response in head and following seas are generally lower than in beam seas. Further, it is seen that the operation "tension of mooring lines" has much lower operational limits than the operation "Clean/inspect net", which is due to the difference in seakeeping criteria (Table 4.2).

Polar curves are used in many previous studies and are a good way to visualize the operational limits and get a more intuitive impression of the results. It can be seen that the plot is symmetric. This is because only global motions are considered. If motions on specific locations on the vessel were included, that did not lie in the centerline, like for example a crane tip, the graph would not be symmetrical. But, because only one criterion and only global motions are considered, the limits are equal in head and follow seas, as well as in beam sea.
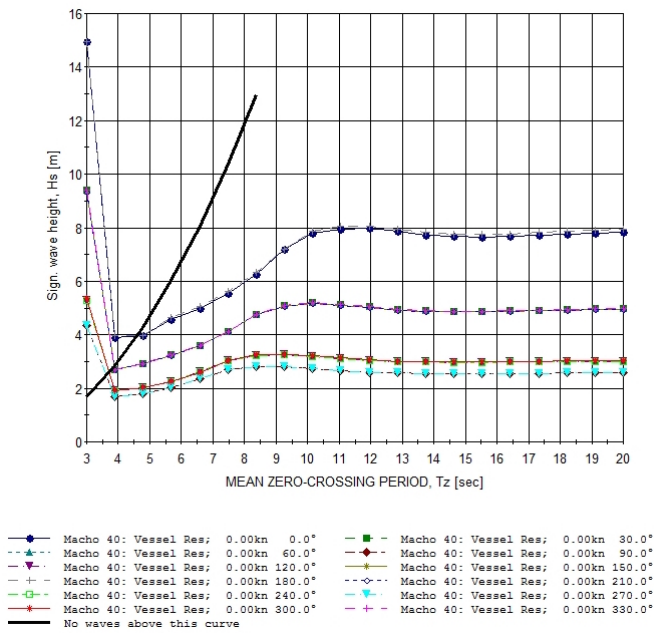
Figure 6.3: Limiting wave conditions for operation "Clean/inspect net", with all headings included.
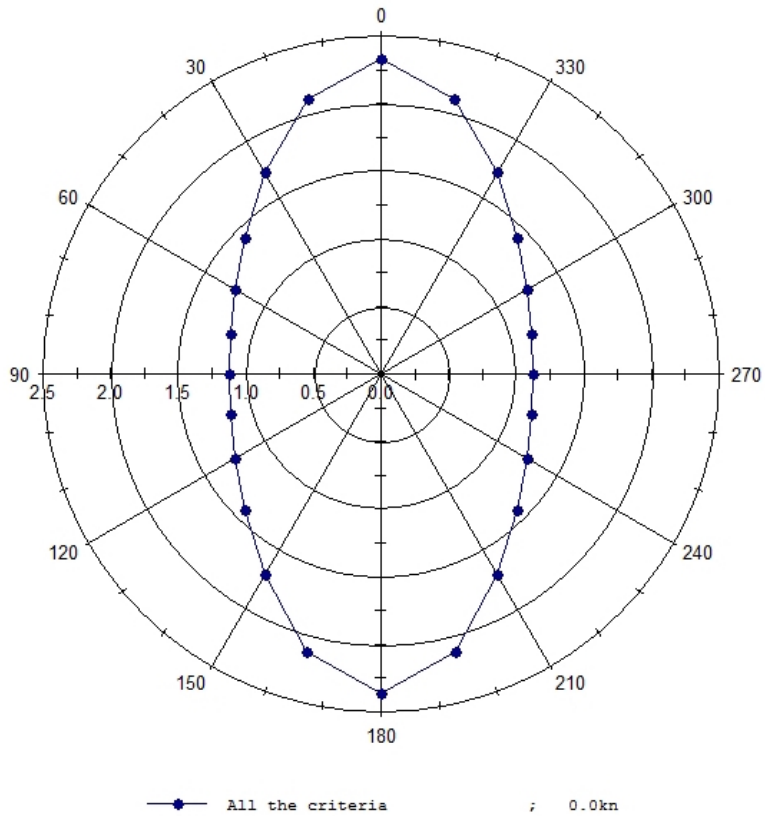
Figure 6.4: Polar curve of limiting wave conditions for operation "Tensioning of mooring line" with all headings included. 0° heading correspond to head sea.

Chapter 7

Results - Long-term Operability

This chapter presents the long-term operability results from the different methods described in Chapter 5. First, the results from the numerical programming approach are presented in Section 7.1, before the results from the simulation-based approach, are presented in Section 7.2. Finally, the different methods are compared in Section 7.3.

7.1 Numerical Programming

This section will present the operability of the vessel, obtained from the numerical programming approach. For this approach, the operability is calculated as the relative rate of operations between operations performed and feasible operations, RRO_2, as discussed in Section 5.2.

7.1.1 Impact of weather forecast

The following results are obtained from the two numerical programming scripts configured in MATLAB (Appendix G).

Figure 7.1 show that the operability, when including weather forecast, decreases for every seakeeping criteria of roll. However, Figure 7.2 further show that the difference between the operability measurements decreases with increasing criteria. Hence, the higher waves the vessel can handle, the less will including weather forecast affect the operability. The percentage decrease for each seakeeping criteria are presented in Table 7.1, with the highest being 11,35% for 3° roll criteria.
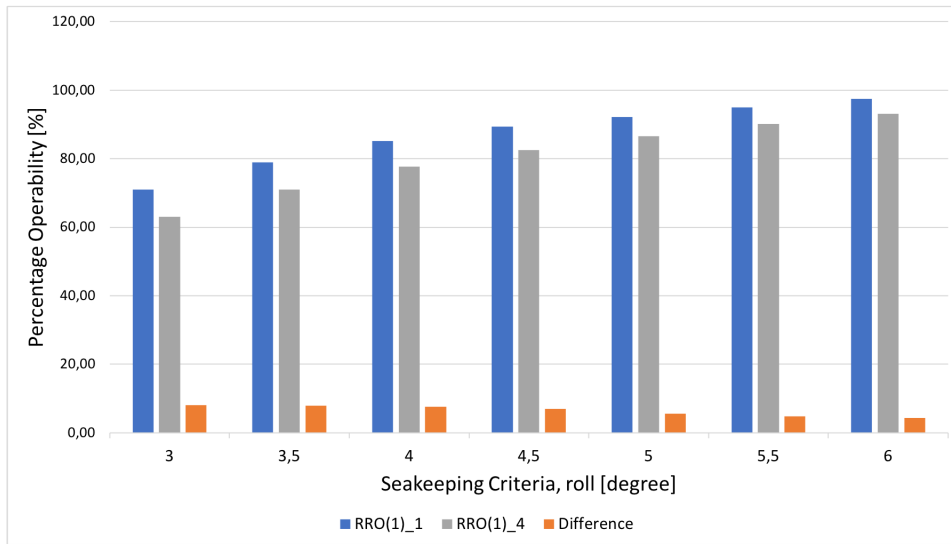
Figure 7.1: RRO_1 with and without weather forecast, for increasing seakeeping criteria of roll, in 90° heading.
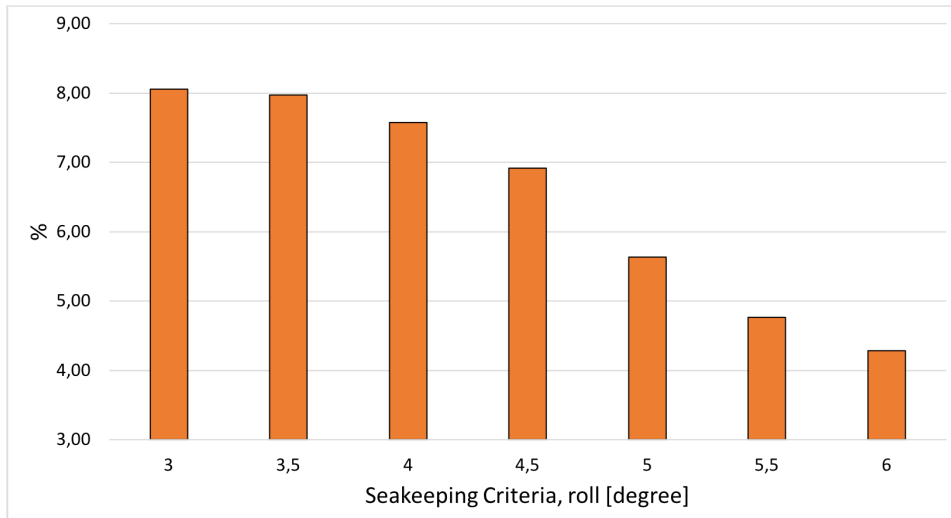
Figure 7.2: Close-up of the difference between operability with and without weather forecast, for increasing seakeeping criteria of roll.

Table 7.1: Percentage decrease in operability when including weather forecast in the numerical programming approach

Seakeeping criteria	Decrease in Operability [%]
3	11,35
3,5	10,09
4	8,9
4,5	7,74
5	6,11
5,5	5,02
6	4,40

7.1.2 Impact of Operation duration and Transit Time

This section presents how the operability reacts to changing parameters. These results are presented to see how the operability to the method that includes weather forecasts, react to changing parameters, relative to the benchmark method. The parameters that vary are the operation duration and transit time. The basecase is set to zero transit time, 3 hours operation duration and a constant seakeeping criteria of 3° roll. When one parameter is varying, the other ones are kept constant at these values. The benchmark method differs from the other method by not considering transit time, operation duration and weather forecast.

Impact of Operation Duration

Figure 7.3 show that the operability from the weather forecast method decreases with increasing duration of the operation. The benchmark method that does not consider operation duration, is kept constant.
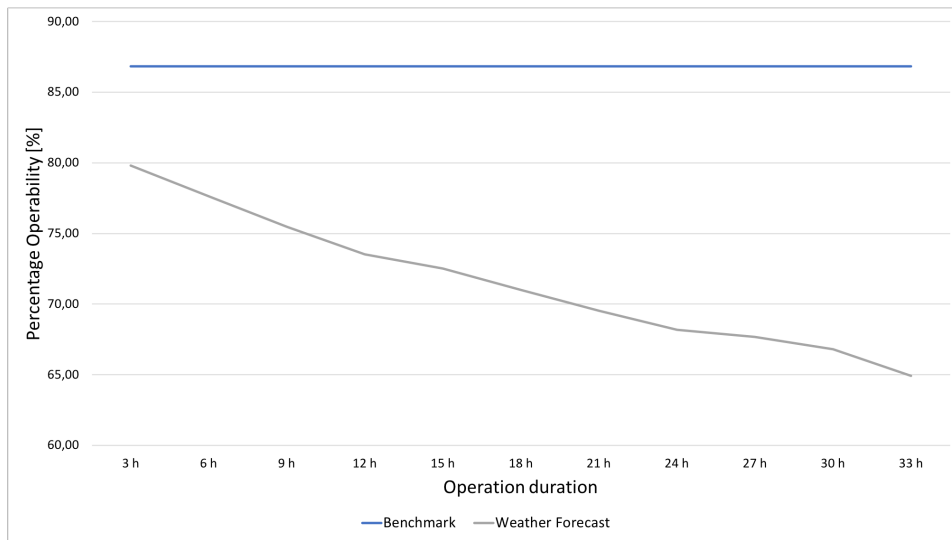
Figure 7.3: RRO_1 with and without forecast in constant $90°$ heading, zero transit time and roll criteria of $3°$, but with increasing operation duration.

Impact of transit time

Figure 7.4 show the operability for both scenarios, with increasing transit time. Transit time differs from operation duration because the transit does not have a limiting sea state criteria. This is because the vessel is assumed to be able to sail to site in any weather. The impact of increased transit time between 0 and 10 hours is presented Figure 7.4. It is seen that the operability increases for the methods that include weather forecast. Further, the weather forecast scenario is equal to the benchmark at 8,7 hours of transit time.
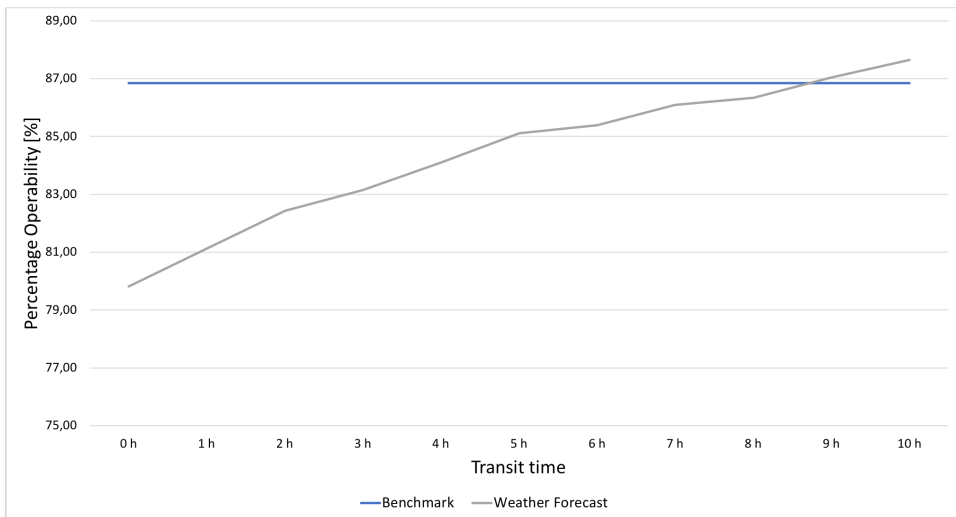
Figure 7.4: RRO_1 with and without forecast in constant $90°$ heading, three hours operation duration and roll criteria of $3°$, but with increasing transit time.

7.2 Discrete-event Simulation

The purpose of the simulation model is to recreate the real-life scenario of a service vessel as best as possible, in order to obtain the most accurate operability measure. Using a simulation model makes it possible to implement more aspects of the life-cycle, than by numerical programming. Depending on the objective of the study and area of interest, several statistics can be obtained with a simulation model. This also makes it possible to discover interesting statistic about the vessel's performance, without having to explicitly program it.

Due to the normal distribution of requested operations in the operation generator, the simulation is exposed to a degree of randomness. Due to this randomness, the results from the simulation model is said to be the mean value of the results from several runs. The number of iterations was set to 20, as the mean operability started to convert towards one value around this point. See Appendix H for graph.

Until now, the RRO_1 method has been used to calculate the operability of the vessel. However, the statistics obtained from the simulation runs makes it possible to calculate the other methods presented in Section 5.2, namely the RRO_1, RROT and RRNDO.

Service vessels are used for the day-to-day operation at site, and are in constant operation according to Utne's paper on Exposed fish farming in Norway (Bjelland et al. (2015)). From the simulation runs, it is, however, seen that the time the vessel is waiting on a mission is very high. This is not a scenario that suits well with the real-life operational scenario and can result in unrealistic values of operability. So to see how the PIs react to higher demand, the frequency of operations is increased. The next section will present the results for fixed wave headings, while Section 7.2.2 addresses the impact of increased frequency of operations.

7.2.1 Fixed Wave Heading

In this section, the operability for fixed wave heading from 0°-90° is presented. This means that the operations are assumed to be performed with a fixed incoming wave direction during all operations throughout the simulation. This may not be a realistic case, but for the purpose of analyzing and comparing the behavior of the different operability PIs, the results can help gain insight into the methods. Because the operational limits from VERES are symmetrical around the vessel (see Figure 6.1), only headings from 0° - 90° with a step size of 30°, will be presented.

Table 7.2: Key values from simulation, presented for constant 90°, 120°, 150° heading.

	Heading			
Mean Values	0°	30°	60°	90°
Completed Operations	288	284	269	258
Requested Operations	291	291	291	291
Feasible Operations	289	289	289	289
Canceled Operations	3	7	23	33
Delayed Operations	2	25	92	158
WOW Port	462	1285	2857	3459
WOW Site	12	149	550	943
Wait on Mission	14433	13632	12201	11467

The mean operability is calculated using the four different performance indicators, namely RRO_1, RRO_2, RRNDO, RROT, and presented in Table 7.3.

Table 7.3: Mean operability from simulation for all performance indicators, presented for constant heading from 0° - 180°.

Heading	Operability			
	RRO_1	RRO_2	RROT	RRNDO
0°	99	99,7	97,6	99,3
30°	97,6	98,3	92,8	91,2
60°	92,4	93,1	82,9	65,8
90°	88,7	89,3	78	38,8

The operability PIs are calculated from the key values as follows:

$$RRO_1 = \frac{\text{Completed Operations}}{\text{Requested Operations}} \tag{7.1}$$

$$RRO_2 = \frac{\text{Completed Operations}}{\text{Fesible Operations}} \tag{7.2}$$

$$RROT = 1 - \frac{\text{WOW Port + WOW Site}}{\text{Total Simulation Time}} \tag{7.3}$$

$$RRNDO = 1 - \frac{\text{Delayed Operations}}{\text{Performed Operations}} \tag{7.4}$$

The results show that the RRO_1, RRO_2, RROT and RRNDO differ, as expected, and that they in general decrease with heading moving from 0° to 90°. The degree of decrease is, however, a bit different. RRO_1, RRO_2, RROT and RRNDO decrease with 10,3 , 10,4 , 19,6 and 60,5 percentage points respectively. This indicates that the RROT and RRNDO are more sensitive to stricter operational limits than the RROs.

Feasible operations are determent from how many operations the vessel was able to perform when the simulation was run with weather data, both current and forecast, constant at zero value, hence perfect weather. From Table 7.3 it can be seen that the RROs are very similar for every heading, but however not equal. It would be expected that the operations requested and the operations performed during perfect weather are equal, but as seen in Table 7.2 this is not the case as they differ with three operations. The reason for this is assumed to be because some operations have high operation duration, and some have low deadline duration. This enables operations with a short deadline that are being requested when another operation

is being executed, to be canceled before the vessel has gotten a chance to perform it.

7.2.2   Increased Frequency of Operations

From the simulation runs it is clear that the vessel is waiting on mission requests on site, a large part of the simulation time. From Table 7.2 it can be determined that the percentage of time the vessel is waiting on a mission range from 72,3% - 57,42%, with heading from 0° - 90°, respectively. This is a relatively high waiting percentage compared to real life. So to reduce the amount of time waiting for missions, the frequency of operations was increased. This was done by increasing the value n in equation 7.5. The x-axis in Figure 7.5 corresponds to this n value, and varies with a value from 1-20, which is equivalent to increasing the frequency with 1-20 times the current frequency, or with 100-2000% of the current frequency.

$$\text{Frequency} = \frac{\text{Mean hours between operations}}{n} \qquad (7.5)$$

Table 7.4 and Figure 7.5 show that the operability seem to converge towards a constant value, except for the RRO_1, which decreases significantly with increasing operation frequency. This is an important effect to note. When the frequency reaches a point where the simulation is saturated with requests, the requested operations will continue to increase, while the performed operations do not increase as much. This is a consequence of using the global request list, because the simulation continues to generate requests and put them in the list, instead of the vessel having to perform or cancel an operation before a new request is generated. However, this aspect of the model is important, as it allows for the demand to be independent of the vessel's performance.

Further, as also illustrated in Figure 7.5, it can be seen that the RROT index decreases, before it increases again. This is because the sum of the WOW from port and site, first increases before it increases. The reason for this is because the WOW port increases until the n value reaches 3 before it continuously drops.

Another interesting note is that the RRO_2 and RROT seem to converge towards a relative similar operability value, only differing with a mean 0,3 percentage points. And that the RRNDO converges towards a value around 7,3 percentage points above RRO_2 and RROT.

Table 7.4: Mean operability from simulation for all performance indicators, with increasing frequency of operations. Constant heading of 120°.

n	RRO$_1$	RRO$_2$	RRNDO	RROT
1	92,1	92,7	65,7	82,7
2	89,8	91,7	68,7	70,0
3	87,5	90,5	72,1	68,7
4	82,9	88,6	74,8	72,1
5	78,5	89,0	77,9	75,8
6	74,6	88,3	81,4	78,8
7	71,5	88,1	81,8	80,8
8	68,8	87,4	84,8	82,5
9	66,8	85,8	86,1	83,2
10	65,1	85,6	87,9	83,9
11	63,3	84,1	88,4	83,8
12	61,8	83,7	89,8	84,3
13	59,7	83,6	90,7	84,4
14	57,2	83,8	90,5	84,5
15	54,4	84,2	91,3	84,7
16	51,8	84,6	91,7	84,9
17	49,5	84,9	92,1	85,2
18	47,2	85,0	92,6	85,4
19	45,0	85,5	92,6	85,5
20	43,2	86,4	93,7	86,1
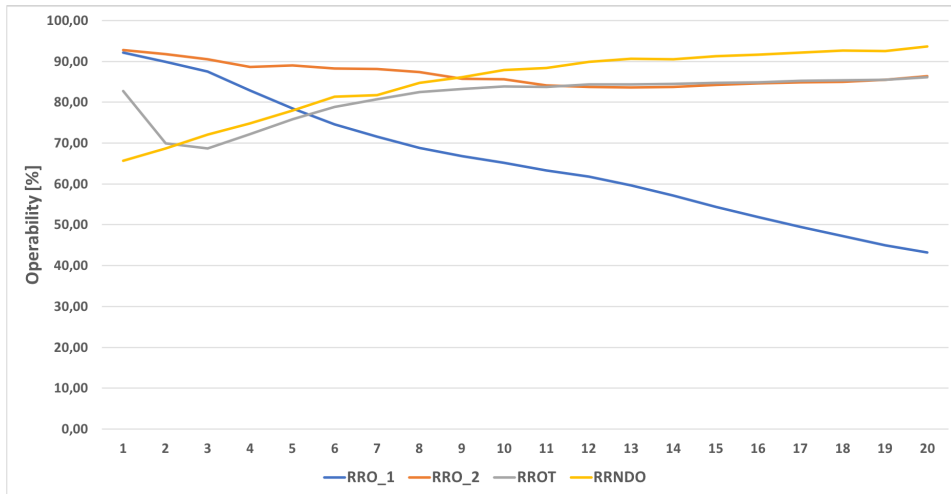
Figure 7.5: Mean operability from simulation for all performance indicators, with increasing frequency of operations. Constant heading of 120°.
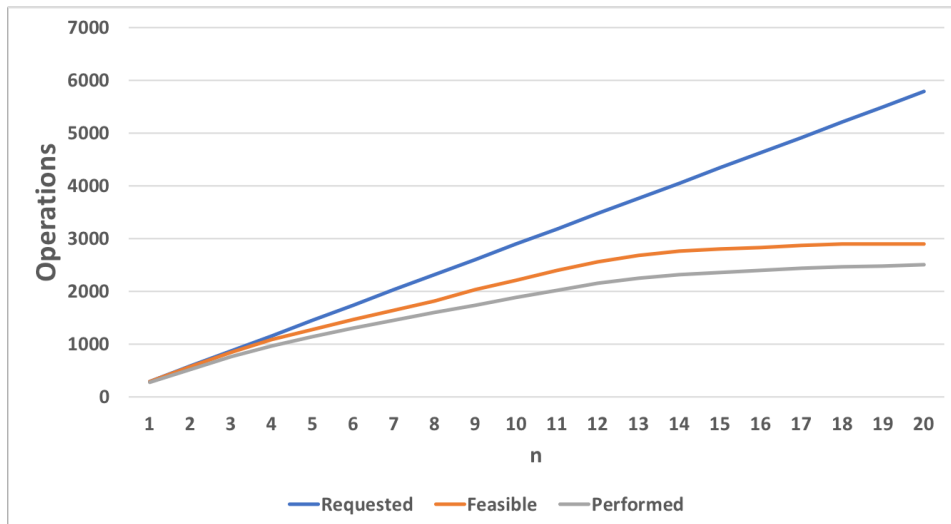
Figure 7.6: Operations Requested and Performed with and without weather restrictions. Constant heading of 120°.
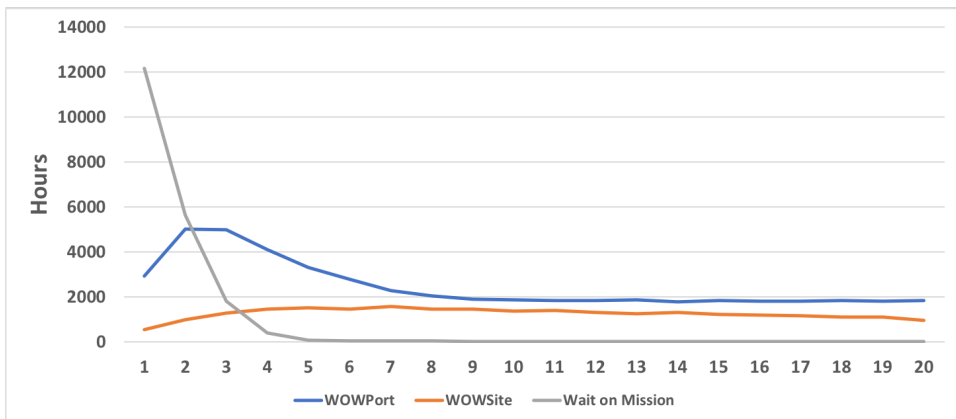
Figure 7.7: Operations Requested and Performed with and without weather restrictions. Constant heading of 120°.

7.3 Weighted Numerical Programming-based RRO VS. Simulation-based RRO

This section will present the relation between the results from the numerical programming approach and the simulation-based approach. The different approaches are not directly comparable, because they use different methods to obtain the operability. However, it is interesting to see how numerical programming results that are weighted for operations, differ from simulation-based results that include operation requests. Both the weighting and the operation requests are based on the operational profile presented in Table 5.1.

Because RRO_2 was used to determine the operability for the numerical programming approach, the compared simulation based operability will also use the same PI.

The results from the numerical programming approach with weather forecast, calculated with PI RRO_2, are presented in Table 7.5 for each operation, as well as the weighted total operability. The results show that the weighted operability is 78,3%.

Table 7.5: RRO_2 from numerical programming approach with real forecast, weighted for operations. Constant 90° heading.

Operation	Weighting [%]	RRO_2 Real forecast
Tensioning of mooring line	22,76	61,1
Install/remove net	0,75	73,2
Delousing	22,76	64,3
Clean/inspect net	39,01	93,7
Clean/inspect collar/bottom ring	0,75	83,9
Inspect anchoring/mooring	0,75	94,7
General support	8,74	90,9
Regular inspections	4,49	75,3
Weighted Operability		**78,3**

The results from the weighted RRO_2 is further presented in 7.8 together with the RRO_2 result from the simulation. The figure shows that the operability increases with **11** percentage points by using a simulation model, relative to a weighted numerical programming method. This corresponds to a 14% increase in operability. One of the reasons for this difference is because the vessel in the simulation does not always have a demand. The frequency of operation requests is so low that the vessel will have periods without any requests, which can be seen in Table 7.2. This is an important difference from the numerical programming approach where it is assumed a constant demand for the calculation of the operability of each operation. What would happen if the frequency of operation generation were increased in the simulation model, such that the vessel would have a constant demand? Would the operability from the simulation-based method get closer to the operability from the numerical programming method? This is analyzed in the next section.
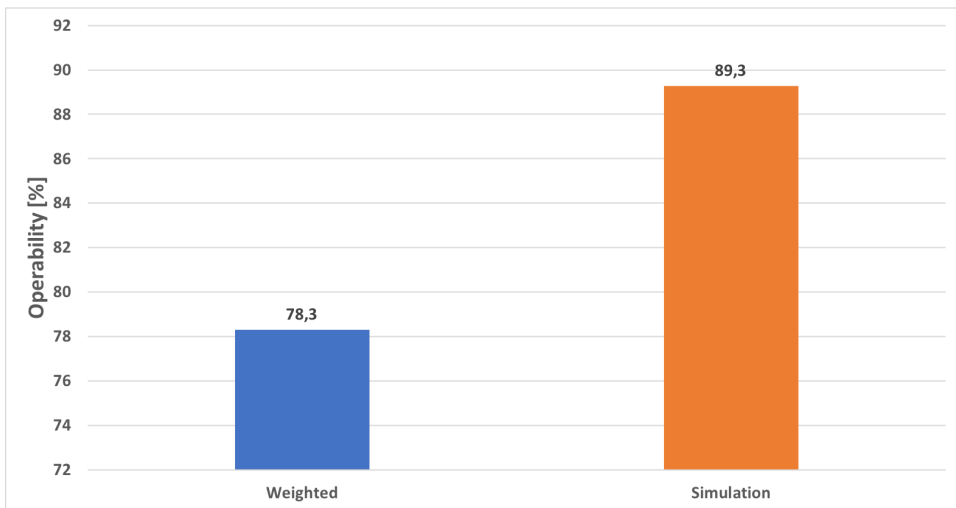
Figure 7.8: Comparison of Weighted operability (Real forecast) from numerical programming, and from simulation. Constant heading of 90°.

7.3.1 Increased Frequency of Operations

Figure 7.9 show the mean operability from the simulation, RRO_2, with increasing frequency of operations. It can be seen that the operability converges towards a value very similar to the one obtained from a weighting of the numeric approach.
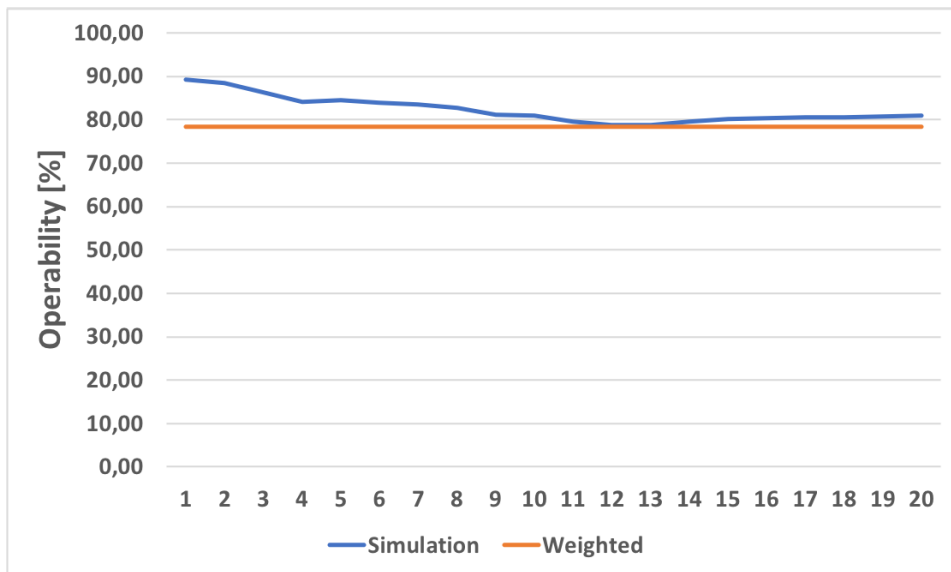
Figure 7.9: Operability from numeric approach with real forecast and from the simulation approach, with increasing n. Operability calculated as RRO_2

Chapter 8

Discussion

This chapter will first discuss the results from the long-term operability assessment, before the model fidelity and sources of uncertainty and errors are discussed.

The operational limits obtained from the short-term operability assessment in VERES, are only used as input to the long-term operability assessment in this report, and not as an assessment of vessel performance itself. Further evaluation of the results, then presented in Chapter 6, is therefore not considered as part of the scope of this thesis, and will not be discussed here.

The objective of this thesis is to increase knowledge and insight about how to measure the operability of service vessels in the aquaculture, as this will be important for further development of exposed fish farming. The work done to achieve this objective have included several aspects regarding hydrodynamics and long-term operability analysis. Using vessel response analysis to determine the operability of a vessel during design phase have been used by ship designer for a long time. Simulation of marine systems are becoming more common in the industry, and several studies show that it has an promising effect. Newer studies have also demonstrated the advantages of combining hydrodynamic vessel response analysis with DES modeling to assess a vessel's long-term operability. In the literature, multiple methods of evaluations have been used to calculate the operability of a vessel, hence there is no universal agreement on the definition of operability of service vessels. The work of this thesis, therefore, aims to compare different operability measurement methods, both simulation-based and non-simulation based, and analyze how they react to different operational scenarios of the vessel, in order to increase knowledge and insight into how the operability of a service vessel should be measured. As a consequence of the work done in this thesis, a simulation

model is also presented.

8.1 Evaluation and Reliability of Results

8.1.1 Numerical Method

Part of the objective of this thesis has been to evaluate the effect of considering additional operational scenarios, as well as the impact of changing parameters on the operability. The numerical programming has been used as a tool to obtain this objective, by providing the needed statistics for calculating the operability. The additional operational scenario considered is weather forecast, and the changing parameters are the duration of operation and transit time.

The numerical programming results presented for each heading clearly show that the long-term operability depends on wave heading. This trend is expected, considering the operational limits from the vessel response analysis in VERES, that shows lower limits in beam seas. The operability results from this analysis are however under the assumption that the vessel will operate in a fixed heading, which is not the case in real life. To combine the operability in each heading to an overall operability for all headings, more information about the statistical probability of wave heading in which the vessel will operate, need to be provided. Such information is not available for the site considered, and therefore it was decided only to consider fixed headings for further analysis.

Further operability assessments were conducted to analyze the impact of considering weather forecasts. Both methods were analyzed with increasing seakeeping criteria in roll from 3° - 6°. The results show that the operability is lower for the method that considers forecasts, for all the criteria. This was as expected, as the benchmark method can be said to assume perfect weather forecasts. However, it is also seen that the difference decreases with increasing seakeeping criteria. This is reasonable because, if the forecast is wrong, there is less chance for the "real" weather to be over the limit if the limit is higher. Overall it can be concluded that weather forecasts come with a degree of uncertainty that will cause a decrease in operability, that should be considered. For low seakeeping criteria, the weather forecast has higher importance.

The impact of operation duration and transit time on the operability, are further assessed. The results show that the increase in operation duration, hence increasing weather window criteria, has a negative effect on the operability. Most likely, this is due to fewer weather windows in the data sets that fulfill the increasing weather

window requirement. However, the impact of transit time has a different effect than the impact of operation duration. This is because it is assumed that the vessel can sail in any weather, meaning that there are no sea state criteria requirements for the transit time. Consequently, the results from the weather forecast scenario increase with increasing transit duration. More ideally, the transit operation should itself have its own limiting sea state criteria. Depending on the strictness of the criteria, and the weather experienced in the area, the impact of increasing transit time would be different. Nevertheless, it is seen that both transit time and operation duration has a significant effect on the operability measurement and should be considered when assessing the operability of a service vessel.

The reliability of the numerical programming results is high because there is no degree of randomness in the results, and errors in MATLAB scripts are easy to discover because the functions are not "hidden" and debugging in MATLAB is very well defined. A numerical approach also makes it easy to modify for other operational limits from other types of vessels with a similar operational scenario. The technical competence needed to develop a numerical script is also not as high as to develop a simulation model. A numerical script can, therefore, be built using less time and resources. Whether or not the results from a numerical approach are a good estimation of operability for a service vessel, is however another question. One important aspect of a service vessel is the highly complex operational profile. A service vessel will perform many different operations, with a varying frequency. This particular presentation of operability is therefore insufficient as it is assumed that the vessel will perform only one operation with that particular operational limit. An overall weighted representation of the operability, based on the operational profile, is presented as a solution for this problem. This will be discussed in the section 8.1.3. However, to analyze the effects of implementing weather forecast with changing operation duration and transit time, this representation of the results are useful.

8.1.2 Simulation-based Method

Part of the objective of this thesis has been to evaluate and compare different methods of operability calculations, hence performance indicators. The simulation model has been used as a tool to obtain this objective, by providing the needed statistics for calculating the operability PIs presented in Chapter 5.

The results from the fixed wave direction simulation show that the long-term operability measurement methods, in general, are dependent on the direction of incoming waves. The operability is highest when the vessel is in head and following

seas, and lowest when the vessel is in beam seas. Compared to other similar studies, like Stemland and Sjøberg & Lund, this was as expected, because the limiting sea state curve is lowest at beam seas and gradually higher to the highest limits at following and head seas, as seen in Figure 6.1. However, the increase in operability is much higher for the RRNDT method, which increases from 38,8% - 99,3% operability, hence the operability increases with 255,9%. This indicates that the number of delayed operations decreases significantly with increased limiting wave height. Consequently, it can be concluded that heading during operation is very important, and that head seas are favorable for all PIs.

The results in Table 7.2 show that there is a difference between operations *requested* and operations that are *feasible* to perform during perfect weather. In Stemland's study, the operability is calculated as RRO_1, e.i. as the ratio between performed and requested operations. As seen from the results here, this might not be the best estimation, as the number of requested might not be the same as number feasible during perfect weather. To calculate the operability based on something that is not possible for the vessel to perform initially, might not be the best way of defining the operability. In Stemland's model, the number of requested operations are also affected by the performance of the vessel, as requests are only generated if an operation is completed or canceled. If the previous operation has waited a long time on weather, this consequently affects when the next operation is requested, and in time the number of operations requested in total. In Sandvik's paper, the relative rate of operations is defined as the ratio between performed and feasible operations during perfect weather, i.e. how many operations the vessel performs, based on what is possible for the vessel to perform. By running the simulation model with weather data equal to zero, the number of feasible operations is obtained. The results show that the RRO_1 is in general 0,675 percentage points lower than the RRO_2. This is not very much, but might be more important if the frequency of operations requested were higher.

As discussed in Chapter 7, the amount of waiting time for the vessel in the simulation is unrealistic compared to real-life experience. Due to this, the frequency of operation requests was increased, to create a more realistic scenario. The results show that the PIs have a different response to the increase in demand. First of all, the RR_1 decreases significantly with increasing demand. As illustrated in Figure 7.6, this is because the number of requested operations will at one point continue to increase while the performed operations and feasible operations begin to converge. Consequently, the RRO_1 will decrease drastically.

Further, from figure 7.5, it is seen that the RRO_2, RROT and RRNDO begin to stabilize around a n value of 11-12. However, it is seen from Figure 7.7 that the hours spent waiting on a mission, is basically nothing when the n parameter reaches a

value of 5, meaning that the simulation is saturated with requests at this point. The reason for why it takes an even higher demand to stabilize the performance indicators is uncertain, but it is seen from Figure 7.6 that the difference between the completed and feasible operations begin to stabilize around the same n value of 11-12.

From Table 7.4 and Figure 7.5 it is also seen that the RRO_2 and the RROT converge around the same value. This indicates that with a saturated simulation, e.i. the vessel has a constant demand, the time spent waiting on a mission is so low that it doesn't affect the RROT.

As an overall evaluation of the statistics obtained from the simulation, the operability defined as the number of performed operations and number of performed operations in perfect weather is the best definition of the operability of a service vessel. This definition includes the fact that the number of requested operations might not even be possible for the vessel to perform under perfect weather conditions. And compared to the RROT, the RRO takes into account that the vessel can have times without any missions, without it impacting the operability. As the demand of the vessel is not a part of the vessel itself, it should not be included as a criterion for obtaining high operability. The RRNDO seems to be too focused on performing operations without any delays, than actually being able to perform it's intended operations, resulting in very varying results relative to seakeeping criteria.

The simulation model presented here, also provide a different approach to modeling the demand of operations, compared to the methods used in the simulation models from Stemland and Sjøberg & Lund (Stemland (2017), Sjøberg and Lund (2018)), which are the most advanced methods provided for service vessels in the fish farming industry today. The model itself is, therefore, provide a solid basis for further work on the operability of service vessels.

The reliability of the simulation results are uncertain, which is first of all a consequence of the nature of simulation. The model is also affected by simplifications and assumptions that may affect the confidence of the results. The most significant sources of uncertainty is the weather forecast and the operational profile. This will be discussed further in Section 8.2.

8.1.3   Weighted numerical-based RRO VS. Simulation-based RRO

A weighted analysis of the numerical programming approach is done in order to compare this approach with the simulation-based approach. By weighting the op-

erability for each operation, it is possible to obtain one accumulated RRO value for the whole operational scenario system (in 90° heading), and not just for one operation. The two RROs are not directly comparable because they are not obtained using the same approach or assumptions. This is important to be aware of when evaluating them together.

The result shows that the two RROs differ from each other with 11 percentage points from the weighted numerical approach to the simulation approach. However, as discussed in the Result chapter, it was suggested that one of the reasons for this difference was because the vessel in the simulation model has periods without any requests, in contrast with the weighted numerical method that assumes a constant request when calculating the RRO for each operation. Therefore, the vessel in the simulation model has more time to find a weather window to perform all the operations that are "feasible" to perform. So in order to create a scenario that is more comparable, the simulation-based RRO were analyzed for an increasing n. The mean operability from the simulation seems to converge towards the RRO_2 value from the weighted method, with a small offset of 3 percentage points. It is not possible to conclude from these results that a weighted numerical approach provides similar results as a simulation approach saturated with requests. First, the analysis is only conducted for a fixed wave heading, so it should be analyzed for all the other headings as well to see if the same response is observed. Secondly, the vessel needs to have a constant demand in order for the two approaches to providing a similar result.

Having the ability to consider the vessels demand is a big advantage when assessing the operability of a service vessel. For other non-special vessels, such as shipping vessels, this is not as important because the vessel is only doing one operation (sailing), hence calculating the percentage of how long the vessel can sail is considered sufficient as a definition of operability. For more advanced vessels, a simulation model provides a solution to the complex nature of the operational scenario, which is an important factor to consider when defining the operability. If the vessel does not have a demand, it should not have lower operability because it could not do a particular operation at that point.

The downside of simulating the operation profile of a service vessel is the complexity of the operational scenario and the high degree of stochastic processes. Due to this, it is very difficult or simply impossible to fully recreate the scenario in a model. This raises the question, if the operability measurements become "better" by defining them based on operations performed from a modeled demand, instead of a weighted calculation of a numerical approach with constant demand. However, based on the significant difference between the two RROs presented in Figure 7.8, it seems like the demand for operations for the vessel should be considered.

Overall, the results from the long-term operability assessment show that implementing multiple aspects to the operability calculations, has a significant impact on the operability. It is difficult to conclude anything for certain without sufficient validation of the model, but the results strongly indicate that a simulation model is necessary to capture the operability of a service vessel. This is highly due to the operational profile, which is difficult to implement in a numerical programming approach.

8.2   Model Fidelity and Source of Uncertainty and Errors

In this section, the model fidelity will be discussed, followed by a discussion on the uncertainty from the seasonal variance, weather data and operational profile.

8.2.1   Model Fidelity

The level of model fidelity has a significant impact on the results and should be carefully considered when interpreting the results. It is important to ensure that all relevant behavior of the vessel and the overall system is included, but it is also important to be aware of the shortcomings of the model.

It is assumed that the vessel has a deterministic transit time of 1 hour. In reality, this should be modeled with a certain degree of uncertainty, concerning the harshness of the weather. Another, simplification on the transit route is that the weather forecast for the transit time is not considered. This implies an assumption that the vessel can sail in any weather. Again, because the transit time is relatively small, this is considered sufficient for the particular case in this study. However, when offshore aquaculture sites move to even more exposed locations, the transit time will have an increasing impact on the overall operability. A more comprehensive model that includes seakeeping criteria and corresponding weather limitations for the transit operation, as well as weather impact on transit duration, will be important to achieve better operability measures, especially for operations where transit time is longer. An example of this is Berg's (Berg et al. (2014)) paper on defining operational/seakeeping criteria for offshore vessels, which include seakeeping criteria for the transit. In this paper the critical parameters for operability during transit to/from the work site are defined as; after-ship slamming, vertical acceleration, horizontal acceleration, and roll motion.

The vessel is modeled to wait for weather on site no more than six hours. This means if the current and forecasted weather does not lie within the criteria for

more than six hours, the vessel will return to port no matter what. In real life, this would not necessarily be the case every time. Firstly, dependent on how long or important the operation is the vessel would maybe wait longer or shorter. The value of six hours was only decided based on Stemland's thesis and are not necessarily a good estimate. Also, in real life, the vessel would probably evaluate each situation to decide whether or not it should wait or stay. If the weather forecast showed that the weather was likely to ease after seven hours, the vessel would maybe wait on site for seven hours and not leave after six. Or if the weather forecast showed that the weather would probably not ease after x amount of hours, the vessel would maybe decide to go back to port and not wait six hours before probably having to leave then anyway.

8.2.2 Seasons

The results of this thesis are not divided into seasons. Figure 8.1 show that the weather has a clear seasonal trend, with much lower significant wave height during the summer months. Dividing the results into seasons, are a common way to present results, and could prove more accurate results in this thesis as well. However, as the goal for this study was to analyze effects and compare different methods, and not obtain the operability for a specific vessel, it was decided not to divide the results into seasons.
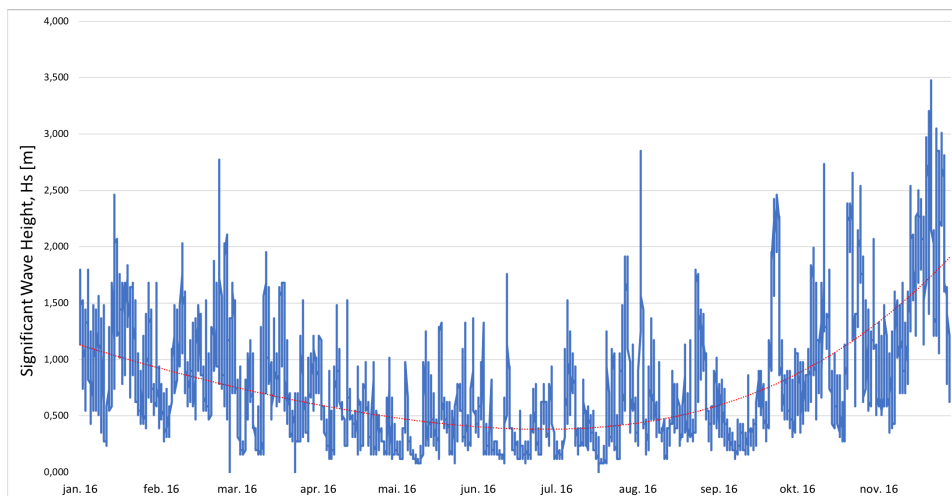
Figure 8.1: Significant wave height from measured data on site, relative to months

8.2.3 Operational Profile

The operational profile is a significant source of uncertainty in the operability assessment. The values to describe the operational profile are obtained from Stemlands thesis, and there it is stated that there is a large degree of uncertainty of the frequency and duration of the operations. In reality, service vessels operate between a large number of fish farms spread over a large area. The results from the simulation show that the vessel spend a significant amount of hours just waiting on a mission. Based on experience from toady's sites, this scenarios is highly unlikely. The operability profile is a major part of the complexity of the operability assessment of a service vessel, and therefore have a significant impact on the reliability of the results. Without sufficient trust to this input it is difficult to conclude anything for certain.

To be able to include the operational profile in the operability definition is one of the main reasons for using a simulation model. If the values provided for the operational profile is exposed to such a degree of uncertainty, it should be considered if a simulation model will provide a more accurate estimation of the operability. However, in the future when large service vessels like the Macho 40 have been operating for a while, more knowledge about the operational pattern of the vessel will be able to increase the reliability of the operational profile provided to the simulation model.

8.2.4 Weather Data

One of the biggest factors that affect the confidence of the results, besides the operational profile, is the weather data. In this section, several reasons will be discussed.

Due to a limited amount of available weather data from the oceanographic buoys, the operability analysis is limited to 19970 hours, which are approximately 2,5 years. According to Faltinsen (Faltinsen (2005)), 100,000 observations are needed to to obtain reliable results. With an hourly measurement, this corresponds to at least 10 years of weather data needed to account for extreme values and long-term variations in the data.

The degree of accuracy in the weather forecast is maybe the most significant source of diminishing confidence to the results on operability. First of all, as discussed in Section 5.1.2, this is because the weather forecast is only sampled every 6th hour. To compensate for the missing data, it was assumed a constant value for the 5-hour gap, corresponding to the predicted value at the beginning of the time gap.

Naturally, this is not a very reliable assumption and causes less confidence in the results.

In the operability measurement methods, the weather forecasts are matched up against the real-time measurements, to check if the conditions are still met when the vessel arrived at site. It is not expected that the data will match all the time, but the data sets only match 4.31% of the time with an allowed deviation of 5%. This is considerably low and should be taken into consideration when interpreting the results. Also, 74.5905% of the measured wave heights lies below the forecast. This indicates that the weather forecast might be too "strict" for the location of the site, and can cause the operability to be lower than in real life. A combination of several factors probably causes the reason for this weather mismatch.

Firstly, the data is obtained from different sources that use different measuring techniques and methods. Secondly, because the data sets are of considerable size, it is possible that a deviation in the data can cause the matching of time to be inaccurate. This means that a weather forecast for a certain time can be checked up against a real-time measure of a different time. However, from Figure 8.2, the forecast, and hindcast measurements seem to generally follow the same pattern.

Lastly, and probably the most important reason, is that the oceanographic buoy is located inshore, while the forecasts are predicted offshore. Consequently, this causes the wave height measurement obtained from the buoy to be more sheltered and hence lower than the forecast. This can be seen in Figure 8.2, where the forecast (green) generally lies underneath the hindcast (red).
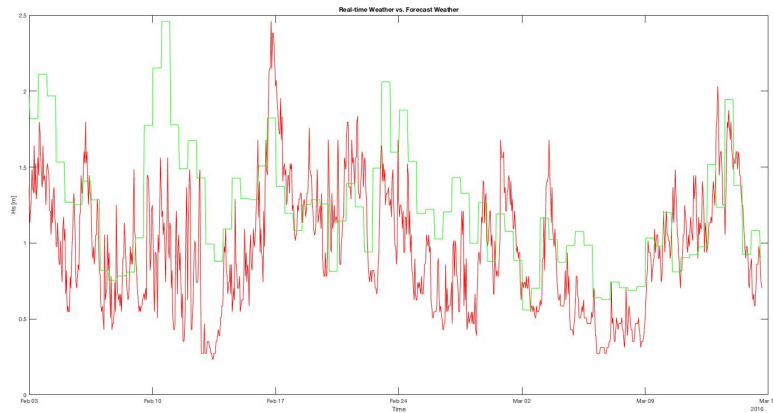
Figure 8.2: Plotted real-time measurement and forecast measurement of specific wave height. Green line represents the forecast and the red line represents the real-time measurement

Overall, due to these factors discussed above, the degree of uncertainty in the weather forecast is most likely much higher than in real life. DNV GL (GL (2011)) accounts for the uncertainty in the weather forecast for the execution of marine operations, by including the alpha factor, α. This assures that the operational limit is a bit less than the obtained limits in design. This uncertainty is not accounted for in the simulation model and is, therefore, an important source of uncertainty of the results. If an α factor were to be included, fewer operations would probably be performed during the simulation, but less initiated operations would have experienced delays at site. Dependent on how the operability is measured, this will affect the results. The RRNDO, would probably increase, due to its consideration of delayed operations. However, the operability measures that only consider performed operations would probably have a decrease in operability.

The wave data from the oceanographic buoys are also a source of uncertainty as the measurements instruments can be faulted. However, this is not considered as a significant source of uncertainty.

Chapter 9

Conclusion

In this paper, a numerical approach and a DES approach are used to assess the operability of a service vessel using different performance indicators, to obtain insight and knowledge about how to define operability of a fish farming service vessel. The RRO_1, the RRO_2, the RROT and the RRNDO are considered as possible definitions of operability and analyzed with different approaches, operational scenarios, and parameters.

From the numerical approach, the RRO_2 method is benchmarked towards the "commonly" used percentage operability method for its ability to include weather forecast, transit time, and operation duration. The result from this study shows that considering weather forecasts has a significant impact on the operability and that the "commonly" used benchmark method excludes essential aspects of uncertainty that comes with using weather forecast as a decision-making tool. Further, the study shows that transit time and operation duration also have a significant impact on the operability measurement, and should be considered when assessing the operability of a service vessel.

Based on the results from the simulation-based approach it is recommended to define operability as the ratio between operations performed and operations performed during perfect weather (RRO_2) corresponding to an operation demand. By comparing a weighted numerical calculation and a simulation-based calculation on operability, the result strongly indicate that a simulation model is necessary to capture the operability of a service vessel. This is due to the complex nature of a service vessel's operational profile, which is difficult to implement in a numerical programming approach.

The lack of relevant weather forecast data resulting in high variability in the match

between predicted and measured data, as well as uncertainty related to the operational profile, strongly affect the reliability of the results in this thesis. Further work to increase the reliability of these inputs in the operability assessment, is therefore, needed in order to obtain reliable results. However, despite uncertainties related to the methods and inputs, the results provide valuable insight regarding different performance indicators of the operability of a service vessel, and what factors the definition should be based on. The simulation model built in this thesis, also forms a good basis for further study on operability of service vessels. In accordance with this thesis's objective, it can be concluded that increasing knowledge and insight about how to measure the operability of service vessels in the aquaculture, is obtained.

Chapter 10

Further Work

As discussed in Chapter 8 the operability measurements are subject to simplifications and lack of verification, that in the end will affect the reliability and authenticity of the results. This chapter will present suggestions for further work that can help improve the quality of the operability study.

10.1   Operability

The simulation-based operability assessment approach, provide a wide range of statistics for the operational life-cycle of the vessel. For further work, it could be interesting to investigate how other aspects of the life-cycle can affect the overall performance of the vessel, with focus on profit. For example, as part of an overall assessment of a service vessel's lifetime profit, it could be interesting to use the statistics on WOW and canceled operations, to evaluate the cost. Lower operability might be more desirable when it comes to a vessel's profit, if the cost from other aspects, like canceled operations or WOW, is high.

10.2   Seakeeping Criteria

In this thesis, the research project by Nielsen, NORDFORSK (NORDFORSK (1987)), are used as the basis for choosing the seakeeping criteria. The criteria considered were roll and deck wetness, which was based on the results from Stemland's study (Stemland (2017)). These criteria, are however not specified for operations conducted in the fish farming industry, but rather as overall seakeeping

criteria for manual work and general motions. Consequently, the criteria used in this thesis are not a particularly good estimation for several of the operations considered. Especially operations that require the use of a crane or other type of equipment.

The operability of a vessel is highly dependent on the seakeeping criteria used to establish the operational limits. It is therefore recommended for further work, to establish operation specified criteria, that clearly define the limiting movement of that particular operation. It is, however, difficult to obtain this from simulations, as there are no real-life measurements to verify the results. However, the EXPOSED project has initiated onboard measurements of accelerations on service vessels. Hopefully, these measurements will provide information needed to establish more customized criteria for operations performed in the aquaculture industry. A set of standardized criteria will also provide a basis for vessel designs to be compared on equal terms, making it easier to use operability measurements as a tool during the design phase.

In addition to the significant wave height, other weather states should be considered as limiting operational criteria as well. This can, for example, be current, wind, sight or rain, as recommended by Berg (Berg et al. (2014)).

10.3   Operational Profile

The operational profile is, as also stated in Stemland's thesis, a significant source of uncertainty in the operability assessment. The results from the simulation show that the vessel spend a significant amount of hours just waiting on a mission. Based on experience from toady's sites, this scenarios is highly unlikely. Further work on assessing a service vessel's operational profile is therefore recommended to obtain more reliable results on operability.

In this thesis, the aspect of operation deadline was added to the operational profile. Through a study on this, it should be considered that other aspects of an operational profile, that are not mentioned in the literature today, can be established to better simulate the true scenario of a service vessel. Also, in time when large service vessels like the Macho 50 have been in operation longer, more information about the operational profile and its patterns will be possible to establish.

10.4 Weather Data

Dividing the operability measurements into seasons was discussed in Section 8.2, to obtain even more insight into the different PIs behavior. However, as also discussed, weather data from at least ten years are needed to estimate long-term statistics on seasonal variance accurately. An alternative solution for this is to build a forecasting model based on already existing data from the site. In simulations, typically a Markov chain is used for this. A Marcho chain is a stochastic process that describes a sequence of possible outcomes. The probability of the next outcome is only based on the state of the previous outcome; hence the model is memory-less. However, there are some issues with using this method, as it is a product of already existing data.

As discussed in Section 8.2.4, the weather forecast data provides a high degree of uncertainty to the results. Further work on improving the data could, therefore, have a significant impact on the confidence of the results. One suggestion for improving the forecast data could be to use a March chain to fill in the unknown wave data in the six-hour gap between two measurements, instead of assuming constant value.

Another weakness of the operability study, as pointed out in Chapter 8.2.4, is that the operability assessment in this thesis only considers wave height as a limiting factor. Hence, involving wind, current, and sight should be considered as it would add additional authenticity to the analysis and results.

10.5 Model Improvements

The use of a simulation model is a surrogate for experimentation with an actual system. Thus, if the model is not a "close" approximation to the actual system, any conclusions derived from the model are likely to be erroneous and may result in costly decisions being made. According to Law (Law (2009)), validation should be done for all models, regardless of whether the corresponding system exists in some. This is however not done in this thesis but is a recommendation for further work. When more experience and data are obtained from larger service vessels in the future, more information will also be available for validation of models.

Further, multiple small modifications can be done to the model in order to obtain an even more realistic operational scenario:

- Implement operational limits for transit operation. As fish farms move to-

wards more exposed locations, the transit time will have a larger impact on the operability.

- Include several sites.

- Include more vessels, which will make it possible to perform a fleet assessment and possible optimize a fleet configuration.

- Include weather-induced delays in transit time.

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Appendix A

Problem Statement

Master Thesis, Autumn 2018
for
Stud. Techn. Elise Lossius Nørgaard

Defining and Evaluating Long-term Operability of Service Vessels in Exposed Aquaculture

Introduction

The Norwegian fish farming industry is traditionally conducted in sheltered areas along the coast but have gradually started to move towards more exposed locations due to increasing demand, lack of production area and better production environment. This has led to new challenges within the industry, and as a result the EXPOSED Aquaculture Operations center has been initialized to develop competence and technology to address these challenges. One of the issues addressed in the project is the future of fish farming vessels. When moving to more exposed waters, it follows that vessel requirements, to perform operations successfully, are sharpened. It also follows that the vessels are more exposed to waiting time due to more harsh and hostile waters. Because of this, the operability of ships is an essential factor, and crucial for further understanding and growth of the industry.

In the literature there is no universal agreement on what defines the operability of a service vessel, and different studies evaluate the operability with varying definitions. To use operability as a way of comparing different vessel designs, a common approach needs to be followed.

The motivation for this study is, therefore, to obtain more insight and knowledge about service vessels operability, by evaluating different definitions of operability found in the literature, and analyze how they respond to important parameters and operational scenarios specified for a fish farming service vessel.

Objective

The objective of this thesis is to increase the knowledge and insight of what defines operability of a service vessel in exposed aquaculture. A literature study aims to provide insight to how an operability study is assessed, as well as document how the term "operability" is defined in previous studies. Based on the findings, an operability assessment will be conducted on a fish farming service vessel.

Through a vessel response analysis and specification of seakeeping criteria, quantitative operational limits for each operation will be established. The operational limits are then used to assess the vessel's long-term operability, using different methods of evaluation, both simulation and non-simulation based. For the simulation-based operability study, a simulation model will be developed. The model will use the operational limits obtained from the vessel response analysis, wave data (forecast and hindcast) from oceanographic buoys and

(European Centre for Medium-Range Weather Forecasts) ECMWF, and the service vessel's operation profile as inputs. By evaluating different operability definitions found in the literature study, as well as analyze how parameters and operational scenarios (specific for a fish farming service vessels) affect the operability, this report will provide insight and knowledge about how operability should be defined for a service vessel in the aquaculture.

Tasks

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

- Document definitions on operability from existing literature on the topic, as well as provide insight to how an operability study is assessed.
- Perform a long-term operability assessment based on the definitions obtained from the literature.
- Develop numerical programming scripts and a simulation model of a service vessel, to calculate the operability.
- Evaluate the result from different definitions of operability, and how they react to changing parameters and operational scenario implementations.

In the thesis the candidate shall present his personal contribution to the resolution of problems within the scope of the thesis work. Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

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

The thesis should be organised in a rational manner to give a clear exposition of 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, references and (optional) appendices. All figures, tables and equations shall be numbered.

The supervisor may require that the candidate, in an early stage of the work, presents 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.

Supervisor: Bjørn Egil Asbjørnslett

Co-supervisor: Hans Tobias Slette

Start-up: August 15th, 2018

Deadline: February 14th, 2019

Signature (supervisor):

Appendix B

Background Information

This appendix chapter presents a more detailed description of the background information obtained from Stemland. The purpose of the chapter is to provide the reader with easy access to information about how Stemland obtained the results. Mark that all of the work presented in this chapter is directly implemented from Stemland, and is not a part of the scope of this thesis.

B.1 Service Vessel Operations

The vessel operations are divided into categories, operations and critical tasks as presented in Table C.1. It should be noted that this categorisation is just a suggestion based on conversations with the crew on the Macho 40, and that other ways may be more relevant for other projects or studies.

Table C.1: Categorisation of the service operations considered in the analysis and typical critical activities related to each operation.

Category	Operation	Critical activities
Anchor handling and mooring	Tensioning of mooring system	Capstan winch
		Lifting of mooring plates/lines/buoys
		Crew on deck
Net handling	Installation/removal of net	Net lifting
		Bottom ring lifting
		Deploy/lift ROV
		Diving
		Crew on deck
Delousing	Delousing	Crew on deck
		Sweep net handling
		Pump handling
Inspection/maintenance	Clean and inspect net	Deploy/lift ROV
		Deploy/lift washing component
		Diving
	Inspect anchoring and mooring system	Deploy/lift ROV
		Diving
		Lifting of mooring plates/lines/buoys
	Clean and inspect floating collar and bottom ring	Floating collar lifting
		Bottom ring lifting
		Crew on deck
	Regular inspections according to regulations	Deploy/lift ROV
		Lifting of mooring plates/lines/buoys
		Crew on deck
General support	General support	Bottom ring lifting
		Crew on deck
		Sweep net handling

Figure B.1: Background information about vessel operations for the Macho 40, from Stemland (Stemland (2017))

B.2 Operational Profile

The frequency of operation occurrence and the duration of operation, hence the operational profile, are in Stemland obtained from a questionnaire that was given to Hansen (2017) and Oppland (2017), the master and chief officer at M/S "Frøy Fighter". The questionnaire is shown in Figure B.2 below.

	Frequency of operation (per location)								Duration				Most critical vessel motion			Crew present on deck?	
	Daily	Weekly	2-3/ mnth	Monthly	4-6/y	2-3/y	Yearly	Other	1-3 h	3-5 h	5-7 h	Other	Heave	Roll	Pitch	Yes	No
Tensioning of mooring system			x									1-3 days		x		x	
Install/remove net								x		x				x		x	
Delousing			x							x	x			x		x	
Clean/inspect net	x									x	x			x			x
Clean/inspect floating collar/bottom ring								x		x				x		x	
Inspect anchoring/mooring system								x	x					x			x
General support				x						x				x		x	

Notes:
Regular inspections every 3, 6 and 12 months
Disinfection of hull between operations at different locations

Answered by:
Bent Hansen, Master of Frøy Fighter
Glen Oppland, Chief Officer of Frøy Fighter

Figure B.2: The questionnaire that was given to Hansen (2017) and Oppland (2017), the master and chief officer at M/S "Frøy Fighter", and used as basis to determine the frequency of occurrence as well as the duration of the service operations in Stemland (Stemland (2017)).

Appendix C

Vessel Specification

C.1 Macho 40

Main dimensions

LOA	40.00 m
Breadth	12.00 m
Depth	4.50 m
Draft (design)	3.60 m
GT	< 500

Speed

Service speed	10 knots

Machinery

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

Deck equipment

Windlasses	2 x hydraulic, 2 x chain stoppers
Warping	1 x 60 tons, 1 x 20 tons
Towing hook	1 x 200 kN
Capstan	2 x 10 tons
Aux. winch	2 x 5 tons
Anchors	2 x 900 kg
Deck crane	1 x 23 tm, 2 x 104 tm

Lifesaving equipment

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

Accomodation

Berths	8
Galley	1
Ventilation system	Central/electrical

Capacity

Fuel oil	80.0 m3
Fresh water	60.0 m3
Cargo hold	320.0 m3, incl. 100.0 m3 fish hold
Water ballast	250.0 m3
Sludge tank	3.0 m3

Navigation/communication

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

Registration details

Built	2015
Builder	Sletta Verft
Class	---
Flag	Norway

Appendix D

Description of Software

This appendix provides a short but description of the software and how they are used in this thesis.

VERES

VERES is a ShipX plug-in software that evaluate VEssel REsponse in seas. The program implements a vessel geometry and calculates ship motions in different loads, short- and long-term statistics and operability. In this thesis, VERES is used to calculate the long-term operational limits based on specified criteria for ship motion (roll).

MATLAB

MATLAB is a programming language for numerical computing. In this thesis, the program is used to calculate the operability of the vessel.

Simulink

Simulink is an add-on program to MATLAB. This program is a graphical discrete-event simulation (DSE) program, that enables simulation and analysis of dynamic systems. In this thesis, the Simulink is used to calculate the simulation-based operability factor RRO.

Appendix E

Transfer Function
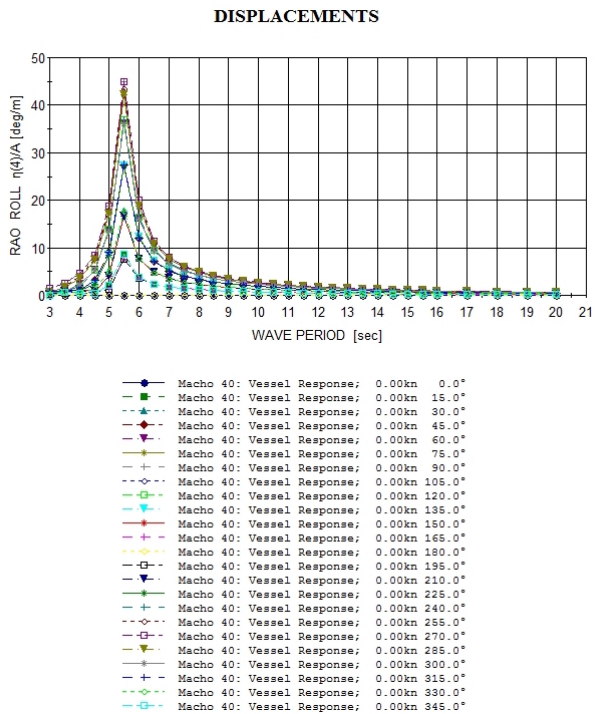
DISPLACEMENTS

Figure E.1: Response amplitude operator in roll.

Appendix F

Operational Limit

In addition to the results presented in the report (Chapter 6), this appendix presents the remaining results. This includes the operational limits for each operation and each heading. All the calculations are done with the short-crested Torsethaugen spectrum with a cosine squared distribution and a wave spreading of 90°. The plots show the resulting limiting wave height of both the roll and deck wetness criteria. However, because the limiting wave height from the deck wetness criteria are higher than the roll criteria for every heading, the resulting criteria corresponds to the limiting wave height from the roll criteria.
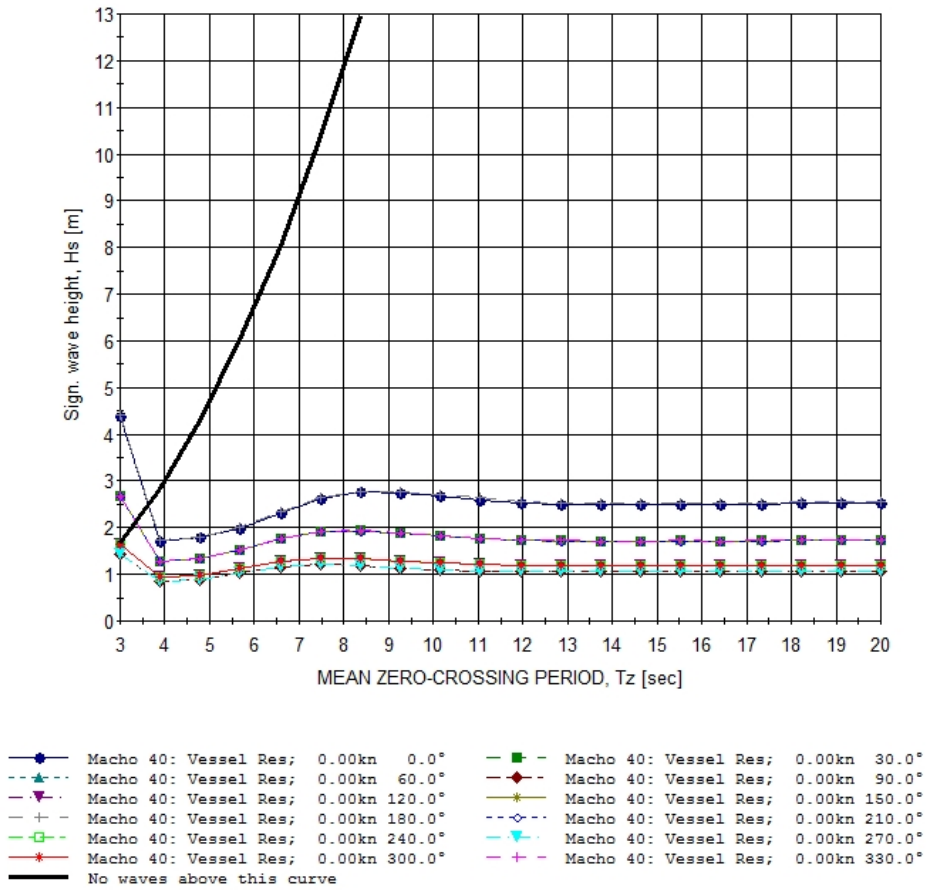
All the criteria
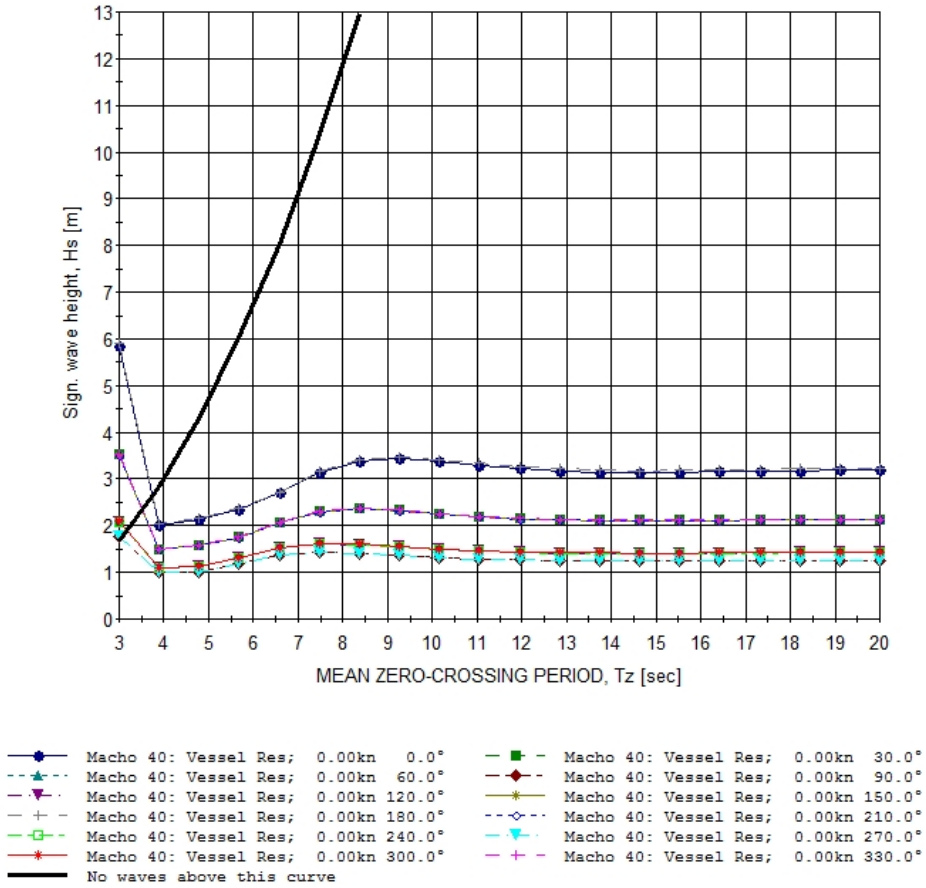
Project: Macho 40: Transfer Function
Wave spectrum Torsethaugen (two peaked)
Short-crested seas (Cosine squared distribution, wave spreading angle = ±90.0°)

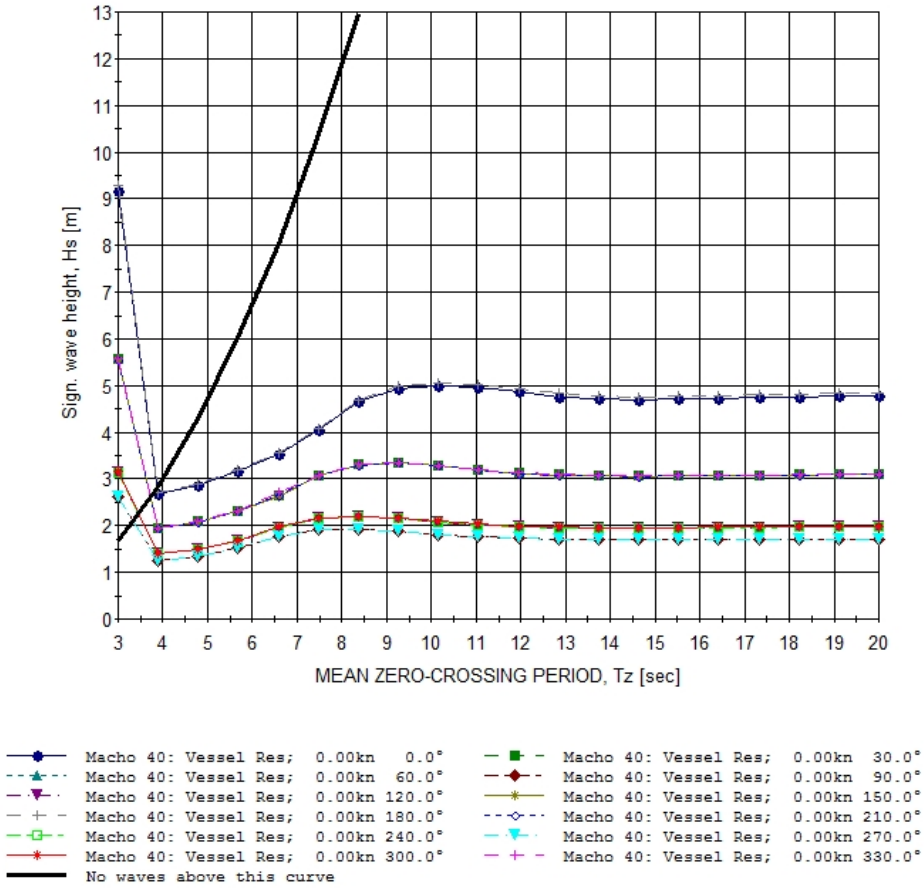Figure F.1: Limiting wave height for operation "Install/remove net"

All the criteria

Figure F.2: Limiting wave height for operation "Delousing"

All the criteria

Figure F.3: Limiting wave height for operation "Clean/inspect collar/bottom ring"

All the criteria

Figure F.4: Limiting wave height for operation "Inspect anchoring/mooring"

Figure F.5: Limiting wave height for operation "General support"

All the criteria

Figure F.6: Limiting wave height for operation "Regular inspections"

Appendix G

MATLAB Script

This Appendix presents all the MATLAB scripts created to calculate the RRO. First the the scripts from the numerical methods are presented, followed by the script for the simulation-based operability method.

G.1 Numerical Programming: Benchmark

This script calculates the RRO Benchmark, or also referred to as the %OP. It is calculated with a constant transit time of zero and operation duration of 1 hour, only considering heading, operational limits from one operation and current weather.

```matlab
%% Procent Operability for Perfect Weather Forecast

function Operability=RROBenchmark(opLim_all, Weather,
    heading, operation)
tic

%% Calculate percent operability for one operation,
    heading and transit

countBelow = 0;
countBelow_hour = 0;
a=0;
k = 0;

while k < length(Weather)
```

```matlab
14
15      if a == 1
16          k = k +1;
17          a=0;
18      else
19          k = k + 1;
20      end
21
22      %% Check if k exceeds length of Weather vector
23
24      if k > length(Weather)
25          break
26      end
27
28      %% Chekc weather limit
29      Hs_lim = interp1(opLim_all(:,1, heading, operation
            ),opLim_all(:,2, heading, operation),Weather(k
            ,5),'linear','extrap');
30
31      if Weather(k,4) < Hs_lim
32
33          countBelow_hour = countBelow_hour+1;
34
35      else
36          countBelow_hour = 0;
37      end
38
39      if countBelow_hour == 1
40          countBelow = countBelow + 1;
41          k = k;
42          a=1;
43          countBelow_hour = 0;
44      end
45  end
46
47
48      %% Calculate Operability
49      %Operability = (countBelow*(duration + 2*
            transit))/(size(Weather,1))*100;
50
```

```matlab
51            Possible_Op = size(Weather,1);
52
53            Operability= (countBelow/Possible_Op)*100;
54 toc
```

G.2 Numerical Programming: Real Weather Forecast

These scripts calculates the RRO including weather forecast. First the overall
script to calculate the weighted operability is presented, followed by the actual
function that calculates the RRO based on heading, operation, duration of opera-
tion, transit time and weather.

```
1   tic
2   clc;
3   clear;
4   %% Percentage Operability with real forecast
5
6   Durations = [ 48 4 5 5 4 2 4 40];
7
8   Weighting_operations = [ 8760/288 1 8760/288 8760/168
        1 1 8760/750 6 ];
9
10  Weighting_operations = Weighting_operations ./ sum(
        Weighting_operations);
11
12  run( 'ReadWeatherandOpLim ');
13
14  Operability = zeros(1, length(Durations));
15
16  transit = 0;
17
18
19  for i=1:length(Durations)
20
21
22      heading = 4;
23      duration = Durations(i);
24
25      Operability(1, i) = RRO(opLim_all, Weather, heading
            , i, duration, transit);
26
27
28  end
29
```

```
30  Operability_weighted = Operability *
        Weighting_operations ';
31  toc
```

```matlab
%% Procent Operability with real forecast

function Operability = RRO(opLim_all, Weather, heading,
    operation, duration, transit)
tic

%% Calculate percent operability for inout operation
    and heading

countBelow = 0;
countBelow_forecast = 0;
countBelow_current = 0;
countBelow_all = 0;
a = 0;
k = 0;

while k < length(Weather)

            if a == 1
                k = k + transit+1;
                a = 0;
            else
                k = k + 1;
            end

    if k > length(Weather)
        break
    end




    %
        =========================================================

    %Count below limit for weather forecast

        Hs_lim_forecast = interp1(opLim_all(:,1,
            heading, operation), opLim_all(:,2, heading,
             operation), Weather(k,10), 'linear', 'extrap'
            );
```

```matlab
34
35
36         if  Weather(k,4) < Hs_lim_forecast
37
38             countBelow_forecast = countBelow_forecast+1;
39
40         else
41             countBelow_forecast = 0;
42             countBelow_current = 0;
43
44         end
45
46     %
           ========================================================

47     %Count below limit for current weather
48
49             Hs_lim_current = interp1(opLim_all(:,1,
               heading, operation),opLim_all(:,2, heading,
                operation),Weather(k,5),'linear','extrap')
               ;
50
51
52         if  Weather(k,4) < Hs_lim_current &&
           countBelow_forecast ~= 0
53
54             countBelow_current = countBelow_current+1;
55
56         else
57             countBelow_current = 0;
58             countBelow_forecast = 0;
59         end
60
61     %
           ========================================================

62     %Count below limit for both forecast and current
63
64         if  countBelow_current ~= 0 || countBelow_forecast
               ~= 0
```

```
65
66           countBelow_all = countBelow_all + 1;
67
68      else
69           countBelow_all = 0;
70
71      end
72
73      if countBelow_all == duration
74
75           k = k + transit;
76           a=1;
77           countBelow = countBelow + 1;
78           countBelow_all = 0;
79           countBelow_forecast = 0;
80           countBelow_current = 0;
81      end
82
83  end
84
85           Possible_Op = size(Weather,1)/(duration + 2*
                 transit);
86
87
88           Operability= (countBelow/Possible_Op)*100;
89
90
91  toc
92  end
```

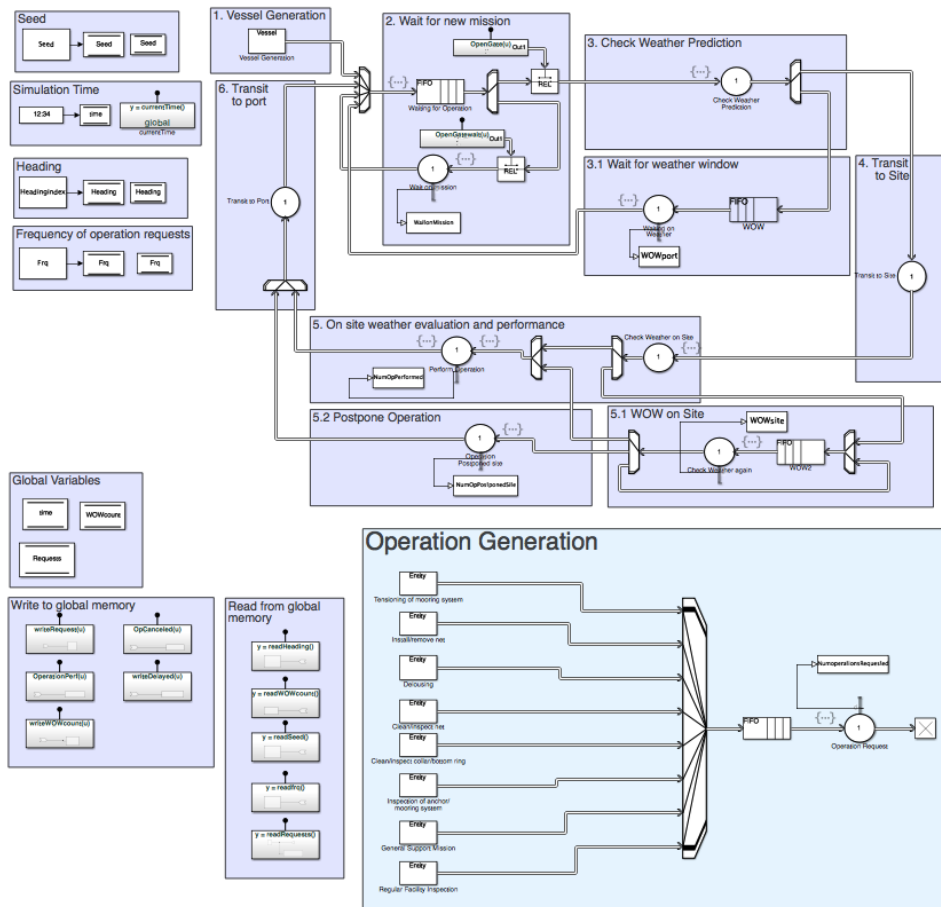# G.3 Simulation

G.3.1 Model Overview

Figure G.1: Complete overview of the simulation model. The lower part is the operation generation. The upper part concerns the vessel sailing cycle. The part to the left is the global variables and inputs.

G.3.2 Main Script

This script is the external MATLAB script that runs the simulation in Simulink, and collects the necessary data to calculate the operability. The operability is calculated for each frequency of operation requests, and as the mean value from 20 iterations.

```matlab
1  clc ;
2  clear ;
3  %% Read Weather data and Operationa Limits to
        Workspace
4  tic
5  run ( 'ReadWeatherandOpLim ' ) ;
6  %Weather=zeros (22572 ,11) ;
7  iterations = 40;
8  frekvenser =1;
9
10  %% Define variables
11  OperationsPerf = zeros ( iterations , frekvenser ) ;
12  numCanc_all = zeros ( iterations , frekvenser ) ;
13  TimeWOWport = zeros ( iterations , frekvenser ) ;
14  TimeWOWsite = zeros ( iterations , frekvenser ) ;
15  opRequested = zeros ( iterations , frekvenser ) ;
16  OperabilityAcc = zeros ( iterations , frekvenser ) ;
17  Operability_all = zeros ( iterations , frekvenser ) ;
18  TimeWaitonMission = zeros ( iterations , frekvenser ) ;
19  OperationDelayed = zeros ( iterations , frekvenser ) ;
20  index =0;
21  Headingindex = 4;
22
23  %% Run Simulation
24  for j = 1: frekvenser
25
26      index=index +1;
27      Frq= j ;
28
29      for i = 1: iterations
30
31      Seed = i ;
32
33      sim ( 'Model ' ) ;      % Run simulation
34
```

```matlab
%% Post−Simulation Data Gathering

%Number of operations canceled
    numCanc = length(OperationCanceled.Data);
    numCanc_all(i,index)=numCanc;

% Waiting on Weather
    if  isempty(WOWsite.Data)==0
    TimeWOWsite(i,index) = WOWsite.Data(length(WOWsite
        .Data));
    end

    if  isempty(WOWport.Data)==0
    TimeWOWport(i,index) = WOWport.Data(length(WOWport
        .Data));
    end

% Waiting on Mission
    TimeWaitonMission(i,index) = WaitonMission.Data(
        length(WaitonMission.Data));

% Total number of operations performed
    numOp = NumOpPerformed.Data;
    timeOp = NumOpPerformed.Time;
    opPerformed = numOp(length(numOp));
    OperationsPerf(i,index)=opPerformed;

% Operations Requested
    opRequested(i,index) = NumoperationsRequested.Data
        (length(NumoperationsRequested.Data));

% Operability
    Operability_all(i,index) = OperationsPerf(i,index)
        /opRequested(i,index)*100;

% Delayed Operations
    OperationDelayed(i, index) = length(OpDelayed.Data
        );

% Accumulated Operability
```

```
69      OperabilityAcc(i, index) = sum(Operability_all(:,
            index))/i;
70

71
72      end
73 end
74

75
76 %% Post-Simulation Calculation
77

78
79 OperationsPerf_mean = round(mean(OperationsPerf))';
80 opRequested_mean = round(mean(opRequested))';
81 numCanc_all_mean = round(mean(numCanc_all))';
82 TimeWOWsite_mean = round(mean(TimeWOWsite))';
83 TimeWOWport_mean = round(mean(TimeWOWport))';
84 TimeWaitonMission_mean = round(mean(TimeWaitonMission)
        )';
85 OpDelayed_mean = round(mean(OperationDelayed))';
86
87 RRO = OperationsPerf_mean/opRequested_mean*100';
88
89      A = zeros(frekvenser,1)+100;
90

91
92 RROT =A - (TimeWOWsite_mean + TimeWOWport_mean)
        /19970*100;
93
94 RRNDO =A - (OpDelayed_mean/OperationsPerf_mean);
95
96 toc
```

G.3.3 Read Weather and Operational Limits

```matlab
1  clear;
2  Headingindex =1;
3
4  cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
       Modell/Operational Limits from VERES/Operation1')
5  run('import_oplim0');
6  run('import_oplim30');
7  run('import_oplim60');
8  run('import_oplim90');
9  run('import_oplim120');
10 run('import_oplim150');
11 run('import_oplim180');
12 run('import_oplim210');
13 run('import_oplim240');
14 run('import_oplim270');
15 run('import_oplim300');
16 run('import_oplim330');
17
18 cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
       Modell/Operational Limits from VERES/Operation2')
19 run('import_oplim0');
20 run('import_oplim30');
21 run('import_oplim60');
22 run('import_oplim90');
23 run('import_oplim120');
24 run('import_oplim150');
25 run('import_oplim180');
26 run('import_oplim210');
27 run('import_oplim240');
28 run('import_oplim270');
29 run('import_oplim300');
30 run('import_oplim330');
31
32 cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
       Modell/Operational Limits from VERES/Operation3')
33 run('import_oplim0');
34 run('import_oplim30');
35 run('import_oplim60');
```

```
36  run('import_oplim90');
37  run('import_oplim120');
38  run('import_oplim150');
39  run('import_oplim180');
40  run('import_oplim210');
41  run('import_oplim240');
42  run('import_oplim270');
43  run('import_oplim300');
44  run('import_oplim330');
45
46  cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
        Modell/Operational Limits from VERES/Operation4')
47  run('import_oplim0');
48  run('import_oplim30');
49  run('import_oplim60');
50  run('import_oplim90');
51  run('import_oplim120');
52  run('import_oplim150');
53  run('import_oplim180');
54  run('import_oplim210');
55  run('import_oplim240');
56  run('import_oplim270');
57  run('import_oplim300');
58  run('import_oplim330');
59
60  cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
        Modell/Operational Limits from VERES/Operation5')
61  run('import_oplim0');
62  run('import_oplim30');
63  run('import_oplim60');
64  run('import_oplim90');
65  run('import_oplim120');
66  run('import_oplim150');
67  run('import_oplim180');
68  run('import_oplim210');
69  run('import_oplim240');
70  run('import_oplim270');
71  run('import_oplim300');
72  run('import_oplim330');
73
```

```matlab
74   cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
         Modell/Operational Limits from VERES/Operation6')
75   run('import_oplim0');
76   run('import_oplim30');
77   run('import_oplim60');
78   run('import_oplim90');
79   run('import_oplim120');
80   run('import_oplim150');
81   run('import_oplim180');
82   run('import_oplim210');
83   run('import_oplim240');
84   run('import_oplim270');
85   run('import_oplim300');
86   run('import_oplim330');
87
88   cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
         Modell/Operational Limits from VERES/Operation7')
89   run('import_oplim0');
90   run('import_oplim30');
91   run('import_oplim60');
92   run('import_oplim90');
93   run('import_oplim120');
94   run('import_oplim150');
95   run('import_oplim180');
96   run('import_oplim210');
97   run('import_oplim240');
98   run('import_oplim270');
99   run('import_oplim300');
100  run('import_oplim330');
101
102  cd ('/Users/elisenorgaard/Documents/NTNU/Master/MATLAB
         Modell/Operational Limits from VERES/Operation8')
103  run('import_oplim0');
104  run('import_oplim30');
105  run('import_oplim60');
106  run('import_oplim90');
107  run('import_oplim120');
108  run('import_oplim150');
109  run('import_oplim180');
110  run('import_oplim210');
```

```matlab
111  run ( 'import_oplim240 ' ) ;
112  run ( 'import_oplim270 ' ) ;
113  run ( 'import_oplim300 ' ) ;
114  run ( 'import_oplim330 ' ) ;
115
116
117  cd ( '/ Users / elisenorgaard / Documents /NTNU/ Master /MATLAB
        Modell / Weather ' )
118
119  run ( 'ReadWeatherData ' )
120
121  cd ( '/ Users / elisenorgaard / Documents /NTNU/ Master /MATLAB
        Modell ' )
122  %Number of operations
123  n = 8;
124  %Number of headings
125  h = 12;
126
127  opLim_all = zeros ( 20 , 2 , h , n ) ;
128
129  %Operation 1
130      opLim_all ( : , : , 1 , 1 ) = opLim0_op1 ;
131      opLim_all ( : , : , 2 , 1 ) = opLim30_op1 ;
132      opLim_all ( : , : , 3 , 1 ) = opLim60_op1 ;
133      opLim_all ( : , : , 4 , 1 ) = opLim90_op1 ;
134      opLim_all ( : , : , 5 , 1 ) = opLim120_op1 ;
135      opLim_all ( : , : , 6 , 1 ) = opLim150_op1 ;
136      opLim_all ( : , : , 7 , 1 ) = opLim180_op1 ;
137      opLim_all ( : , : , 8 , 1 ) = opLim210_op1 ;
138      opLim_all ( : , : , 9 , 1 ) = opLim240_op1 ;
139      opLim_all ( : , : , 10 , 1 ) = opLim270_op1 ;
140      opLim_all ( : , : , 11 , 1 ) = opLim300_op1 ;
141      opLim_all ( : , : , 12 , 1 ) = opLim330_op1 ;
142
143   %Operation 2
144      opLim_all ( : , : , 1 , 2 ) = opLim0_op2 ;
145      opLim_all ( : , : , 2 , 2 ) = opLim30_op2 ;
146      opLim_all ( : , : , 3 , 2 ) = opLim60_op2 ;
147      opLim_all ( : , : , 4 , 2 ) = opLim90_op2 ;
148      opLim_all ( : , : , 5 , 2 ) = opLim120_op2 ;
```

```matlab
149     opLim_all(:,:,6,2) = opLim150_op2;
150     opLim_all(:,:,7,2) = opLim180_op2;
151     opLim_all(:,:,8,2) = opLim210_op2;
152     opLim_all(:,:,9,2) = opLim240_op2;
153     opLim_all(:,:,10,2) = opLim270_op2;
154     opLim_all(:,:,11,2) = opLim300_op2;
155     opLim_all(:,:,12,2) = opLim330_op2;
156
157     %Operation 3
158     opLim_all(:,:,1,3) = opLim0_op3;
159     opLim_all(:,:,2,3) = opLim30_op3;
160     opLim_all(:,:,3,3) = opLim60_op3;
161     opLim_all(:,:,4,3) = opLim90_op3;
162     opLim_all(:,:,5,3) = opLim120_op3;
163     opLim_all(:,:,6,3) = opLim150_op3;
164     opLim_all(:,:,7,3) = opLim180_op3;
165     opLim_all(:,:,8,3) = opLim210_op3;
166     opLim_all(:,:,9,3) = opLim240_op3;
167     opLim_all(:,:,10,3) = opLim270_op3;
168     opLim_all(:,:,11,3) = opLim300_op3;
169     opLim_all(:,:,12,3) = opLim330_op3;
170
171
172     %Operation 4
173     opLim_all(:,:,1,4) = opLim0_op4;
174     opLim_all(:,:,2,4) = opLim30_op4;
175     opLim_all(:,:,3,4) = opLim60_op4;
176     opLim_all(:,:,4,4) = opLim90_op4;
177     opLim_all(:,:,5,4) = opLim120_op4;
178     opLim_all(:,:,6,4) = opLim150_op4;
179     opLim_all(:,:,7,4) = opLim180_op4;
180     opLim_all(:,:,8,4) = opLim210_op4;
181     opLim_all(:,:,9,4) = opLim240_op4;
182     opLim_all(:,:,10,4) = opLim270_op4;
183     opLim_all(:,:,11,4) = opLim300_op4;
184     opLim_all(:,:,12,4) = opLim330_op4;
185
186     %Operation 5
187     opLim_all(:,:,1,5) = opLim0_op5;
188     opLim_all(:,:,2,5) = opLim30_op5;
```

```matlab
189    opLim_all(:,:,3,5) = opLim60_op5;
190    opLim_all(:,:,4,5) = opLim90_op5;
191    opLim_all(:,:,5,5) = opLim120_op5;
192    opLim_all(:,:,6,5) = opLim150_op5;
193    opLim_all(:,:,7,5) = opLim180_op5;
194    opLim_all(:,:,8,5) = opLim210_op5;
195    opLim_all(:,:,9,5) = opLim240_op5;
196    opLim_all(:,:,10,5) = opLim270_op5;
197    opLim_all(:,:,11,5) = opLim300_op5;
198    opLim_all(:,:,12,5) = opLim330_op5;
199
200
201    %Operation 6
202    opLim_all(:,:,1,6) = opLim0_op6;
203    opLim_all(:,:,2,6) = opLim30_op6;
204    opLim_all(:,:,3,6) = opLim60_op6;
205    opLim_all(:,:,4,6) = opLim90_op6;
206    opLim_all(:,:,5,6) = opLim120_op6;
207    opLim_all(:,:,6,6) = opLim150_op6;
208    opLim_all(:,:,7,6) = opLim180_op6;
209    opLim_all(:,:,8,6) = opLim210_op6;
210    opLim_all(:,:,9,6) = opLim240_op6;
211    opLim_all(:,:,10,6) = opLim270_op6;
212    opLim_all(:,:,11,6) = opLim300_op6;
213    opLim_all(:,:,12,6) = opLim330_op6;
214
215
216    %Operation 7
217    opLim_all(:,:,1,7) = opLim0_op7;
218    opLim_all(:,:,2,7) = opLim30_op7;
219    opLim_all(:,:,3,7) = opLim60_op7;
220    opLim_all(:,:,4,7) = opLim90_op7;
221    opLim_all(:,:,5,7) = opLim120_op7;
222    opLim_all(:,:,6,7) = opLim150_op7;
223    opLim_all(:,:,7,7) = opLim180_op7;
224    opLim_all(:,:,8,7) = opLim210_op7;
225    opLim_all(:,:,9,7) = opLim240_op7;
226    opLim_all(:,:,10,7) = opLim270_op7;
227    opLim_all(:,:,11,7) = opLim300_op7;
228    opLim_all(:,:,12,7) = opLim330_op7;
```

```matlab
229
230
231     %Operation 8
232     opLim_all(:,:,1,8)  = opLim0_op8;
233     opLim_all(:,:,2,8)  = opLim30_op8;
234     opLim_all(:,:,3,8)  = opLim60_op8;
235     opLim_all(:,:,4,8)  = opLim90_op8;
236     opLim_all(:,:,5,8)  = opLim120_op8;
237     opLim_all(:,:,6,8)  = opLim150_op8;
238     opLim_all(:,:,7,8)  = opLim180_op8;
239     opLim_all(:,:,8,8)  = opLim210_op8;
240     opLim_all(:,:,9,8)  = opLim240_op8;
241     opLim_all(:,:,10,8) = opLim270_op8;
242     opLim_all(:,:,11,8) = opLim300_op8;
243     opLim_all(:,:,12,8) = opLim330_op8;
```

G.3.4 Check Weather at port

This script is located in the entity service element in the "Check weather predic-
tion" block. The necessary data to check the predicted weather conditions at site
are imported and compared with the operational limits for the operation consid-
ered. A decision is then made to weather or not the vessel should initiate the
operation or wait for better weather.

```matlab
1  simTime = currentTime();
2
3  if simTime == 0
4       simTime = simTime +1;
5  end
6
7  TransitTime = 1;
8
9  %% Get the request list
10  requests = readRequests();
11
12  %% Determine Heading
13  heading = readHeading();
14
15  %% Find predicted weather and Hs_lim for each
        potential operation
16
17  [maxDuration, idx]=max(requests(:,2));
18
19  WaveHeight_pred = zeros(size(requests,1),maxDuration);
20
21  Hs_lim=zeros(size(requests,1),maxDuration);
22
23  WaveHeightvector=zeros(size(requests,1),1);
24
25  for row = 1:size(requests,1)
26
27       if requests(row,2)>0
28
29            OpDuration = requests(row,2);
30            Operation = requests(row,1);
31
32            WavePeriod_pred = zeros(1,OpDuration);
```

```matlab
33
34           for j=1:OpDuration
35
36                   WavePeriod_pred(j) = Weather(simTime+
                           TransitTime+j,10);
37                   WaveHeight_pred(row,j) = Weather(simTime+
                           TransitTime+j,9);
38
39
40                   if WaveHeight_pred(row,j)== 0
41                       WaveHeight_pred(row,j) = 0.0001;
42                   end
43           end
44
45           [WaveHeight,idx1]= max(WaveHeight_pred(row
                   ,:));
46           WaveHeightvector(row)=WaveHeight;
47
48           for i=1:OpDuration
49           if WavePeriod_pred(i) <= 3
50                       Hs_lim(row,i) = WaveHeight_pred(
                           row,i);
51           else
52
53                   Hs_lim(row,i) = interp1(opLim_all(:,1,
                           heading,Operation),opLim_all(:,2,
                           heading,Operation),WavePeriod_pred(
                           i),'linear','extrap');
54
55           end
56
57           end
58
59
60
61       end
62 end
63 %% Optimize which Operation to perform
64
```

```matlab
65  %Start whit eliminating the operations that can't
        operate in predicted weather
66
67  OperationsConsidered = zeros(size(requests,1),size(
        requests,2));
68  count=0;
69
70  for row=1:size(Hs_lim,1)
71      if Hs_lim(row,1) ~=0
72          if WaveHeight_pred(row,:) <= Hs_lim(row,:)
73              OperationsConsidered(row,:) = requests(row
                    ,:);
74              count=1;
75          end
76      end
77  end
78
79  %If no operations can be performed due to weather
80
81  if count == 0
82      entity.Weatherok=2; %Wait on weather
83      return
84  else
85
86  % From the remaining operation requests, pick the one
        with the closest deadline
87      timeLeft = OperationsConsidered(:,3)-simTime;
88      mintimeLeft=1000;
89
90      for row=1:size(OperationsConsidered,1)
91          if timeLeft(row) < mintimeLeft && timeLeft(row
              )>0
92              mintimeLeft = timeLeft(row);
93              entity.id=row;
94          end
95      end
96      row=entity.id;
97      entity.Weatherok=1;
98  end
```

G.3.5 Check Weather at site

This script is located in the entity service element in the "5. On site weather evaluation and performance" block. The necessary data to check the current weather conditions at site are imported and compared with the operational limits for the operation considered. A decision is then made to weather or not the vessel should perform the operation or wait for better weather.

```matlab
simTime = currentTime();

if simTime == 0
    simTime = simTime +1;
end

TransitTime = 1;

%% Get the request list
requests = readRequests();

%% Determine Heading
heading = readHeading();

%% Find predicted weather and Hs_lim for each
    potential operation

[maxDuration, idx]=max(requests(:,2));

WaveHeight_pred = zeros(size(requests,1),maxDuration);

Hs_lim=zeros(size(requests,1),maxDuration);

WaveHeightvector=zeros(size(requests,1),1);

for row = 1:size(requests,1)

    if requests(row,2)>0

        OpDuration = requests(row,2);
        Operation = requests(row,1);

        WavePeriod_pred = zeros(1,OpDuration);
```

```matlab
33
34          for j =1: OpDuration
35
36              WavePeriod_pred ( j ) = Weather ( simTime+
                    TransitTime+j ,10 ) ;
37              WaveHeight_pred ( row , j ) = Weather ( simTime+
                    TransitTime+j ,9 ) ;
38
39
40              if WaveHeight_pred ( row , j )== 0
41                  WaveHeight_pred ( row , j ) = 0.0001;
42              end
43          end
44
45          [ WaveHeight , idx1 ]= max ( WaveHeight_pred ( row
                 ,: ) ) ;
46          WaveHeightvector ( row )=WaveHeight ;
47
48          for i =1: OpDuration
49              if WavePeriod_pred ( i ) <= 3
50                  Hs_lim ( row , i ) = WaveHeight_pred (
                        row , i ) ;
51              else
52
53                  Hs_lim ( row , i ) = interp1 ( opLim_all (: ,1 ,
                        heading , Operation ) , opLim_all (: ,2 ,
                        heading , Operation ) , WavePeriod_pred (
                        i ) , 'linear' , 'extrap' ) ;
54
55              end
56
57          end
58
59
60
61      end
62  end
63  %% Optimize which Operation to perform
64
```

```matlab
65  %Start whit eliminating the operations that can't
        operate in predicted weather
66
67  OperationsConsidered = zeros(size(requests,1),size(
        requests,2));
68  count=0;
69
70  for row=1:size(Hs_lim,1)
71      if Hs_lim(row,1) ~=0
72          if WaveHeight_pred(row,:) <= Hs_lim(row,:)
73              OperationsConsidered(row,:) = requests(row
                    ,:);
74              count=1;
75          end
76      end
77  end
78
79  %If no operations can be performed due to weather
80
81  if count == 0
82      entity.Weatherok=2; %Wait on weather
83      return
84  else
85
86  % From the remaining operation requests, pick the one
        with the closest deadline
87      timeLeft = OperationsConsidered(:,3)-simTime;
88      mintimeLeft=1000;
89
90      for row=1:size(OperationsConsidered,1)
91          if timeLeft(row) < mintimeLeft && timeLeft(row
                )>0
92              mintimeLeft = timeLeft(row);
93              entity.id=row;
94          end
95      end
96      row=entity.id;
97      entity.Weatherok=1;
98  end
```

Update "Request" List

This script is located in the entity queue element in the "Wait for new mission" block. The purpose of the script is to check if the deadline for any of the missions in the list has expired, and if so remove them. Further, it checks if there are any requests in the list, to decide weather or not the vessel should go to the "Check weather prediction" block or wait for a mission request.

```matlab
simTime = currentTime();

if simTime == 0
    simTime = simTime +1;
end

TransitTime = 1;

%% Get the request list
requests = readRequests();

%% Determine Heading
heading = readHeading();

%% Find predicted weather and Hs_lim for each
    potential operation

[maxDuration, idx]=max(requests(:,2));

WaveHeight_pred = zeros(size(requests,1),maxDuration);

Hs_lim=zeros(size(requests,1),maxDuration);

WaveHeightvector=zeros(size(requests,1),1);

for row = 1:size(requests,1)

    if requests(row,2)>0

        OpDuration = requests(row,2);
        Operation = requests(row,1);

        WavePeriod_pred = zeros(1,OpDuration);
```

```matlab
33
34          for j=1:OpDuration
35
36              WavePeriod_pred(j) = Weather(simTime+
                    TransitTime+j,10);
37              WaveHeight_pred(row,j) = Weather(simTime+
                    TransitTime+j,9);
38
39
40              if WaveHeight_pred(row,j)== 0
41                  WaveHeight_pred(row,j) = 0.0001;
42              end
43          end
44
45          [WaveHeight,idx1]= max(WaveHeight_pred(row
                ,:));
46          WaveHeightvector(row)=WaveHeight;
47
48          for i=1:OpDuration
49          if WavePeriod_pred(i) <= 3
50                  Hs_lim(row,i) = WaveHeight_pred(
                        row,i);
51          else
52
53                  Hs_lim(row,i) = interp1(opLim_all(:,1,
                        heading,Operation),opLim_all(:,2,
                        heading,Operation),WavePeriod_pred(
                        i),'linear','extrap');
54
55          end
56
57          end
58
59
60
61      end
62  end
63  %% Optimize which Operation to perform
64
```

```matlab
65  %Start whit eliminating the operations that can't
        operate in predicted weather
66
67  OperationsConsidered = zeros(size(requests,1),size(
        requests,2));
68  count=0;
69
70  for row=1:size(Hs_lim,1)
71      if Hs_lim(row,1) ~=0
72          if WaveHeight_pred(row,:) <= Hs_lim(row,:)
73              OperationsConsidered(row,:) = requests(row
                    ,:);
74              count=1;
75          end
76      end
77  end
78
79  %If no operations can be performed due to weather
80
81  if count == 0
82      entity.Weatherok=2; %Wait on weather
83      return
84  else
85
86  % From the remaining operation requests, pick the one
        with the closest deadline
87      timeLeft = OperationsConsidered(:,3)-simTime;
88      mintimeLeft=1000;
89
90      for row=1:size(OperationsConsidered,1)
91          if timeLeft(row) < mintimeLeft && timeLeft(row
                )>0
92              mintimeLeft = timeLeft(row);
93              entity.id=row;
94          end
95      end
96      row=entity.id;
97      entity.Weatherok=1;
98  end
```

L

Appendix H

Number of Iterations

Figure H.1, show the convergence of the RRO operability measurement from the simulation model, relative to number of iterations.
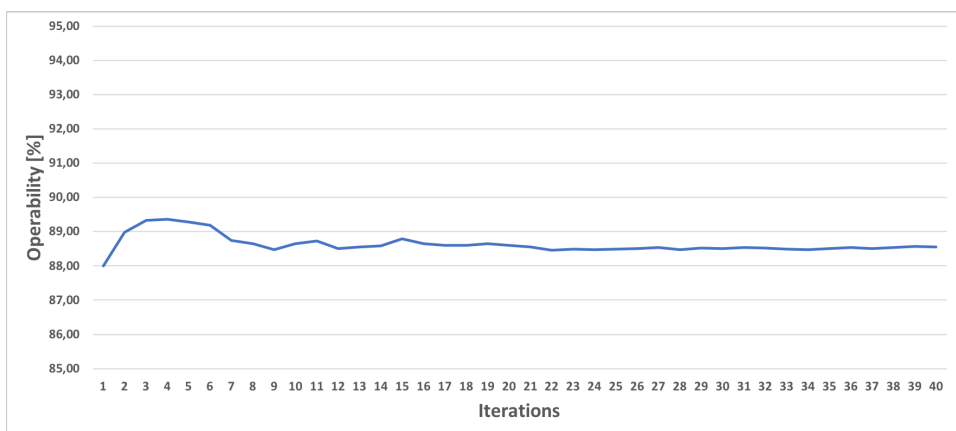

Figure H.1: Operability from simulation model, in 90° heading

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