Norwegian University of
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Assessment of Service Vessel Operability In Exposed Aquaculture

An exploratory approach combining vessel response and discrete-event simulation

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Preface

This thesis is the final delivery of a master's degree in Marine Technology at the Norwegian University of Science and Technology (NTNU), as part of the study program Marine System Design. The thesis is written during the spring semester of 2017 in cooperation with SFI EXPOSED, a centre for research-based innovation towards exposed aquaculture.

The objective of the thesis is to increase knowledge and insight of service vessel operations in exposed aquaculture, and involves a combination of hydrodynamic analysis and discrete-event simulation. The report is written under the assumption that the reader has some basic knowledge on the aquaculture industry and are familiar with terms and expressions related to hydrodynamics and the maritime industry.

I would like to thank my supervisor Professor Bjørn-Egil Asbjørnslett at the Department of Marine Technology, NTNU, for his guidance and support during the work. I would also like to thank my co-supervisor Dariusz Fathi at SINTEF Ocean for his help and advice on hydrodynamics and vessel response. A special thanks to Møre Maritime AS for providing information and a 3D-model of the Macho 40 service vessel, and to the crew on M/S "Frøy Fighter" for sharing experiences and for having me on board.

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Summary

The aquaculture industry in Norway is gradually moving towards more exposed locations due to lack of production area and improved production environment. However, large parts of the coast are unavailable to production activity due to harsh environmental conditions. Through research, a better interaction between vessel and structure components, operability criteria and tools for decision-making have been identified as key issues to develop safe and reliable production in exposed aquaculture.

The objective of this thesis is to increase knowledge and insight of service vessel operations in exposed aquaculture, with a focus on vessel response and operability during the interaction with facility structures. Through a vessel response analysis and specification of operability criteria for the Macho 40 service vessel, quantitative limits of operation are determined. Along with measured wave data from oceanographic buoys, the operational limits are used as input in a simulation model to analyse the vessel's long-term operability.

The results from the vessel response analysis show that the wave heading is of major importance to the vessel's operating limits. In general, the vessel appears to be more sensitive to lateral wave headings with regard to maximum wave height, than for head and following sea. It is also found that roll is the most critical motion with respect to the vessel's operability. The long-term operability obtained from the simulation shows a tendency to follow the operational limits. It seems clear that the operability increase with the vessel's ability to avoid operating in lateral wave headings. Further, seasonal variations in operability show a reduced ability to perform operations in periods with increasing wave heights, and vice versa.

Efforts have been made to achieve realistic operational limits through specification of criteria modified for the design of the Macho 40. Together with wave data from two exposed aquaculture locations, this contributes to increase the quality and scientific value of the thesis towards the aquaculture industry. However, the validity and reliability from the simulation output are affected by uncertainty regarding frequency and duration of vessel operations and a limited amount of available wave data. The results should therefore not be considered exact values, but rather as indications on the vessel's sensitivity to incident wave headings, as well as estimations of its long-term operability. In accordance with the objective of the thesis, it can be concluded that increased knowledge and insight on service vessel operations in exposed aquaculture have been obtained and that, with further research and longer wave data series, the combination of hydrodynamic analysis and simulation could prove to be a useful approach in assessing and comparing the long-term performance of different vessel designs.

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Sammendrag

Oppdrettsnæringen i Norge beveger seg gradvis mot mer eksponerte lokaliteter på grunn av mangel på areal og bedre produksjonsmiljø. På grunn av tøffe vær- og bølgeforhold er likevel store deler av kysten er utilgjengelig for produksjonsaktivitet. Gjennom forskning har det kommet frem at bedre fartøy-strukturinteraksjon, operabilitetskriterier og støtte for beslutningstaking er sentrale problemstillinger for å kunne utvikle trygg og pålitelig produksjon på eksponerte lokasjoner.

Formålet med denne masteroppgaven er å øke kunnskap og innsikt i servicefartøy-operasjoner i eksponert havbruk, med fokus på fartøybevegelse og operasjonsevne i interaksjonen med havbruksinstallasjoner. Gjennom hydrodynamisk responsanalyse og spesifikasjon av kriterier for fartøydesignet Macho 40, bestemmes kvantitative operasjonsgrenser. Sammen med målte bølgedata fra oseanografiske bøyer, blir operasjonsgrensene brukt som input i en simuleringsmodell for å analysere fartøyets langsiktige operasjonsevne.

Resultatene fra responsanalysen viser at bølgeretningen har stor betydning for fartøyets operasjonelle grenser. Generelt synes fartøyet å være mer følsom for bølger fra sidene med tanke på maksimal operasjonsgrense, enn for bølger forfra og aktenfra. Analysen viser også at rull er den mest kritiske bevegelsen med hensyn til fartøyets operasjonsevne. Resultatene fra simuleringen antyder at den langsiktige operabiliteten har en tendens til å følge de operasjonelle grensene ved at den øker i samsvar med fartøyets evne til å unngå å operere i sidesjø. Videre viser simuleringen sesongvariasjoner i fartøyets operabilitet med en redusert evne til å utføre operasjoner i perioder med økende bølgehøyder.

Det er forsøkt å oppnå realistiske operasjonsgrenser gjennom spesifikasjon av kriterier tilpasset designet til Macho 40. Sammen med bølgedata fra to eksponerte oppdrettsanlegg bidrar dette til å øke kvaliteten og den vitenskapelige verdien av oppgaven inn mot havbruksindustrien. Påliteligheten til resultatene fra simuleringen er imidlertid påvirket av usikkerhet rundt fartøyoperasjonenes varighet og hyppighet, i tillegg til en begrenset mengde tilgjengelig bølgedata. Resultatene bør derfor ikke betraktes som eksakte verdier, men heller som indikasjoner på fartøyets sensitivitet overfor innkommende bølgeretninger samt estimeringer av dets langsiktige operasjonsevne. I samsvar med oppgavens formål kan det konkluderes med at en økt kunnskap om servicefartøyoperasjoner i eksponert havbruk er oppnådd. I tillegg viser resultatene fra oppgaven at med videre forskning og lengre bølgedataserier, kan en slik kombinasjon av hydrodynamiske analyser og simulering vise seg å være en nyttig tilnærming for å vurdere og sammenligne ulike fartøydesign.

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Abbreviations

AHTS	anchor handling tug supply.
AP	aft perpendicular.
bhp	brake horsepower.
CFD	computational fluid dynamics.
EXPOSED	centre for research-based innovation in exposed aquaculture.
GM	metacentric height.
HSE	healt, safety and environment.
JONSWAP	Joint North Sea Wave Project.
LOA	length overall.
MPV	multi-purpose vessel.
MSDV	motion sickness dose value.
MSI	motion sickness incidence.
nmi	nautical miles.
RAO	response amplitude operator.
RMS	root mean square.
RPM	revolutions per minute.
SDGs	sustainable development goals.
UN	United Nations.

Symbols

Greek letters

δ	displacement tonnage.
λ	wavelength.
ω	circular frequency.
ϕ	velocity potential.
ϕ_0	flow potential of incident regular waves.
ϕ_D	flow potential due to flow motion against incident waves to ensure impermeability.
ρ	mass density of sea water.
σ	standard deviation.
ζ	surface elevation.
ζ_a	wave amplitude.

Latin letters

A_{kj}	3D added mass coefficient in mode k due to jth motion.
B	vessel beam.
B_{kj}	3D damping coefficient in mode k due to jth motion.
C_{kj}	restoring coefficient in mode k due to jth motion.
F	freeboard at the considered longitudinal position.
H_S	significant wave height.
K_m	constant varying according to the exposed population.
L_p	length between perpendiculars.
P_s	permissible probability of slamming.
P_{dw}	permissible probability of deck wetness.
T	wave period.

T_0	exposure period.
T_z	mean wave period.
V_{cr}	critical re-entry velocity.
$\overline{GM_L}$	longitudinal metacentric height.
$\overline{GM_T}$	transverse metacentric height.
a_z	vertical acceleration.
d	local draft.
g	acceleration of gravity.
g_r	RMS value of relative vertical motion per meter H_s.
g_{rv}	RMS value of relative vertical velocity per meter H_s.
k	wave number.
m	wave spreading index.
p	pressure.
p_0	constant atmospheric pressure.
p_d	dynamic pressure.
r_{44}	radius of gyration in roll.
r_{55}	radius of gyration in pitch.
r_{66}	radius of gyration in yaw.
v_{max}	wave spreading angle.

Chapter 1

Introduction

Background

In 2015, the United Nations (UN) presented the sustainable development goals (SDGs), an agenda for sustainable development towards 2030. One of the seventeen goals in the agenda aims to end hunger and achieve food security in the world. In order to reach this goal, producing sufficient quantities of food is essential, and fish production is expected to play a major part in this process. The total capture fishery production in the world has been stable at 90-95 million tonnes per year for the last two decades. According to a report presented by the Food and Agriculture Organization of the UN (2016), it will not grow by more than 1 percent by 2025 due to the potential of overfishing and stock extinction. This is on the contrary to the aquaculture production, which according to the same report will grow by 18 percent in the same period. This will make the aquaculture production exceed the capture fishery and reach 52 percent of the total fishery production in the world.

As the second major exporter of fish, and the world's largest producer of salmon, Norway is expected to play a key role in the development of aquaculture production (Hersoug & Revold, 2012). The aquaculture industry in Norway has, since its beginning in the 1970s, become a large industry and a major employer supporting regional communities along the Norwegian coast. In 2014, the total production reached a record high 1.39 million tonnes with an export value of 46.7 billion NOK (Statistics Norway, 2017). The fish farming started in sheltered environments close to the shore, but has gradually moved towards more exposed locations due to lack of production areas and improved production environments (Bjelland, 2015). Several benefits can be obtained from moving the production to more exposed locations. Increased dispersal of waste products, more stable water flow and reduced interaction between wild and cultured fish are features that may increase the capacity of the production environment (Holmer, 2010). For these reasons, there is a large interest from the industry to develop and enable safe and reliable operations in exposed locations.

Despite the potential benefits from utilising exposed locations, large parts of the Norwegian coast is unavailable to aquaculture activity due to harsh wave, current and wind conditions (Bjelland, 2015). A report by Sandberg et al. (2012) on experience and operation of exposed aquaculture facilities shows that operators in the industry experience considerable challenges in maintaining safe and reliable production. Vessel operations and regular work out on the cages is identified as particularly challenging and risk-related. A contributor to this could be the fact that while the production has moved to more exposed areas, there has been little development in technology, operations and design to accompany this transition (Bjelland et al., 2015). Harsh wind, wave and current conditions in exposed areas pose new requirements for vessels, equipment and structures involved in the operations. Thus, in order to comply with these requirements and to improve production efficiency and reliability, new designs and concepts should be considered.

According to Holmen, Utne, and Haugen (2016), the aquaculture industry in Norway is the second most risk exposed occupation after fishing. Sandberg et al. (2012) concludes that in order to operate safely and efficiently at exposed locations, a better interaction between the system components is needed. The report also identifies a need for operability criteria and tools for decision-making as key issues for further research. This is particularly important during vessel operations, where the forces acting between the elements can be immense and the safety of crew and workers at the facility can be jeopardised. In such situations the vessel performance, i.e. its ability to withstand the environmental conditions and carry out its intended mission, is essential. The potential consequences of damage to vessels or structures at farms are considerable, involving both economic losses and unacceptable environmental pollution through fish escapes.

State of the Art

Very few studies and research projects on operability and tools for decision-making aimed for the aquaculture industry has been found in the literature. A project on service vessels in the Norwegian aquaculture was done by Heide, Moe, Lien, and Sunde (2013). The project was extensive, but focused on the service operations in the industry as a whole, and not specifically towards exposed locations. It did, however, address the operability of service vessels with the aim of comparing different vessel designs. A great deal of research exist from the offshore, fishing and shipping industry. A major part of the challenges arising in exposed aquaculture is related to harsh environmental conditions, vessel operability and safety of crew and workers. These are challenges that are eminently present in the offshore, fishing and shipping industry as well. The existing knowledge and research from these industries should therefore, wherever relevant, be considered for exposed aquaculture.

A discrete-event simulation model for evaluation of cost-optimal fleet size configurations of offshore anchor handling operations was proposed by Shyshou, Gribkovskaia, and Barceló (2009). Due to high hiring costs of vessels, determining an optimal fleet size can provide significant economic benefits. Sensitivity of the expected ship availability to different seakeeping criteria was studied by Fonsenca and Soares (2002), while Hoffman and Petrie (1980) considered computer systems for improved weather bound operations and real time monitoring and simulation of the environment. Tello, Silva, and Soares (2010) and Rusu and Soares (2013) studied fishing vessels off the coast of Portugal, with the aim of forecasting vessel responses. The results are presented as operational index maps for different areas which may help to plan operations and increase operability. A common factor in all these projects, which can also be relevant for operations in the aquaculture industry, is the importance of quantitative limits of operation and how this affects the availability of vessels.

Key issues and challenges of exposed aquaculture has been identified and analysed through projects by Sandberg et al. (2012), Senneset (2017b) and Bjelland et al. (2015). EXPOSED is a centre for research-based innovation in exposed aquaculture with the aim of developing knowledge and technology to enable robust, safe and efficient fish farming at exposed locations (Bjelland, 2015). The centre has defined eight projects, each addressing different segments and research areas to be investigated. One of the projects focus on the vessel-structure interaction with the aim of investigating new design solutions for improved vessel operations (Bjelland, n.d.). In order to achieve this, analyses and knowledge on the current operations are essential. Monitoring and operational decision support is the focus in another research area. As part of this project, on-board measurements on a 25.5 meter long service catamaran is currently being performed. The aim is to use the obtained data to quantitatively assess the limiting sea states during different operations. The results may prove useful in the process of developing standardised criteria and procedures for service vessel operations.

Challenges of exposed aquaculture have been identified and analysed through studies and projects in recent years, but specific research on operability criteria, tools for decision-making and other characteristic challenges of the industry should be done in order to continue the development and expansion of the industry. The ability to transfer knowledge and experience from other industries can also prove to be a key factor in this development.

Objective
The objective of this thesis is to increase the knowledge and insight of service vessel operations in exposed aquaculture, with a focus on vessel behaviour and performance during vessel-structure interaction. Through a vessel response analysis and specification of operability criteria, quantitative limits of operation will be determined. Operational limits may improve the ability to plan operations ahead based on weather forecasts, and thereupon increase the overall utilisation and operability of the vessel. Further, a simulation model to analyse the long-term operability of a service vessel, will be developed. The model will use operational limits obtained from the vessel response analysis and wave data series from oceanographic buoys as input. By testing and comparing different vessel designs, a simulation model can also provide valuable information on vessel performance for decision-making in the early phase of a design process, which in turn could contribute to develop new and improved designs with increased operability.

Report Structure
The remainder of this report is organised as follows: Chapter 2 elaborates on the problem description and the system to be considered in the thesis work; a literature review discussing previous work relevant to the scope of this thesis is then presented in Chapter 3; Chapter 4 presents basic theory related to hydrodynamics and vessel motions in a sea environment; Chapter 5 address the principles of assessing vessel performance and the concept of operability criteria, and acts as an introductory part to the vessel response and performance analyses of Chapter 6 and 7; the results from the analyses are presented in Chapter 8 followed by a discussion in Chapter 9; Conclusive remarks are presented in Chapter 10; and Chapter 11 considers recommendations for further work.

Chapter 2

Problem Description and System Considerations

This chapter will elaborate on the motivation and purpose of the thesis, followed by a discussion on vessel performance in a system context where the overall architecture of the thesis work is explained. The operational scenario to be analysed is then introduced, including geographic location and sailing routes, followed by a presentation of typical operations performed by service vessels. The final part of the chapter discusses service vessel design and introduce the vessel to be analysed.

2.1 Motivation and Purpose

This thesis is written in cooperation with SFI EXPOSED, who's main objective is to develop knowledge and technologies for exposed aquaculture operations, enabling a sustainable expansion of the fish farming industry (Bjelland, 2015). This objective is also of great interest to operators in the aquaculture industry, as it will enable safe and efficient production at exposed sites and ensure Norway's global leading position in aquaculture.

EXPOSED has recently initiated on-board measurements of accelerations on a service vessel. The initiative is a part of their goal of developing knowledge and solutions for safe and reliable production in exposed areas. The measurements will provide information on vessel motions and limiting sea states during operations. In time, this information could prove valuable in the process of defining operational criteria on vessel operations in aquaculture. Such criteria can be used to assess current weather conditions with respect to operational limits, but it can also be used in a bigger context like operation planning or a simulation model where it can be used to assess the long-term performance of an aquaculture system.

Including hydrodynamic analyses combined with operability criteria will add possibilities in simulation of aquaculture systems, and open up for long-term evaluations of vessel performance. The work of this thesis will seek to explore this combination and in that way increase the knowledge on the subject and facilitate further research and development.

2.2 Vessel Performance In a System Context

When comparing different vessels or planning new designs, evaluations of their operational performance are essential. In this thesis, a vessel's operational performance is related to its ability to perform the intended tasks and missions. In order to evaluate and compare the performance of vessels, attention must be given to the definition of operational criteria and standardised methods for evaluation. The way in which such evaluations are done may be separated into two categories. One of which makes an isolated evaluation of a single vessel and another which evaluates the vessel performance as part of a system. The latter can be useful in for instance aquaculture, where vessel operations are just one part of a long chain of processes and operations. The ability to assess the vessel in a system context can then be used to facilitate design modifications that also benefits the performance of the entire system.

Aquaculture production with all its involving actors is a highly stochastic process, characterised by complex logistics and a wide range of operations. It involves production, transportation and processing both on land and at sea, and includes an element of biology which is strictly regulated by the authorities. To limit the extent and complexity of the work, the scope of this thesis is only concentrated on the part involving service vessels and their performance from a hydrodynamic point of view. The work will involve both individual vessel evaluation and vessel performance as part of an aquaculture system. The description of the aquaculture system itself and the scenario to be simulated will be further covered in Section 2.3.

A high level outline of the system architecture of this thesis is presented in Figure 2.1. The purpose of the illustration is to give the reader an overview of the main elements involved in the work, and to introduce the overall architecture before going into details. The vessel responses are evaluated through a hydrodynamic analysis in VERES, a vessel response program for calculation of ship motions and loads. The results provide information on the limiting sea states of which the vessel can operate according to the specified criteria. In combination with wave data, this information will be used as basis for decision-making in a simulation model. The operational scenario, presented in the next section, is modelled as a discrete-event system in the software Simulink. The output of the simulation model is the vessel performance in terms of operability.

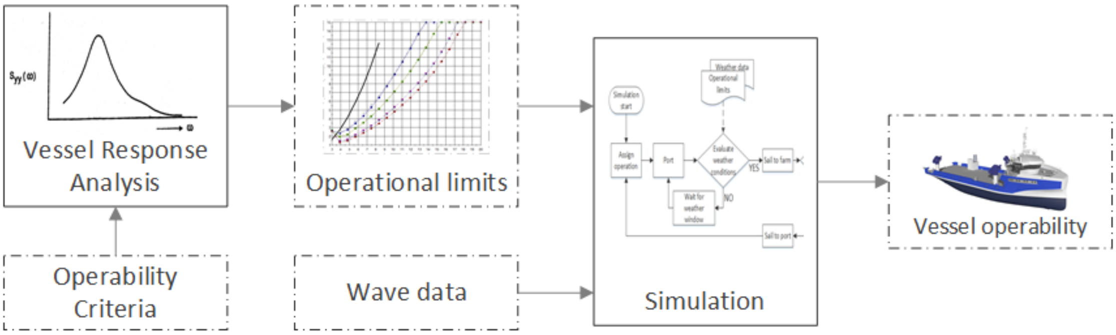


Figure 2.1: The main elements involved in the thesis work. A vessel response analysis provides operational limits, which are used as input in a simulation model to assess the vessel performance.

2.3 Operational Scenario

The operational scenario is to be understood as the real-world process to be modelled through the simulation model. The purpose of this section is to give a brief introduction to the content of the simulation model, as it will give the reader a better understanding of the development and architecture of the simulation model and the performance analysis as a whole.

Throughout the industry, different types of vessels are used to facilitate and support the operation at farming facilities. Small support vessels are often located at each farming facility to assist in daily tasks. Service vessels are typically larger and operate on multiple facilities in a more widespread area. They can perform a wide range of operations, some related to the day-to-day operation while others are more occasionally performed during e.g. launch of a new facility or tensioning of mooring systems.

Including too many variables and components at an early stage in a model is a common pitfall of simulation modelling, which can cause confusion and misleading results (Law, 2007). Thus, to limit the extent and complexity of the model, only two farming facilities

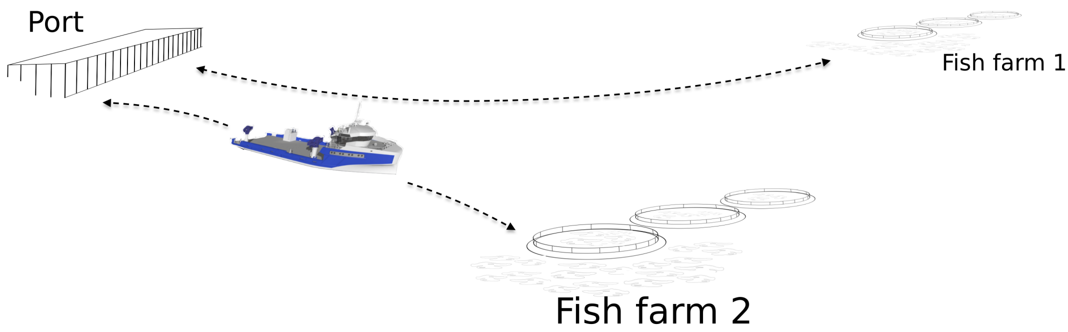


Figure 2.2: The scenario modelled in the simulation model involves a port, two fish farm locations and one service vessel.

and one service vessel are considered in the scenario. A visual representation of the scenario is shown in Figure 2.2. The vessel is requested to perform operations at the facilities and makes a decision of whether to initiate the operation based on the current wave conditions. In order to make this decision, operational limits for the vessel are required as input. This information is obtained from the hydrodynamic analysis as shown in Figure 2.1. When simulating over time, the long-term performance of the vessel can be analysed. The development of the simulation model and a presentation of its structure are covered in Chapter 7.

2.3.1 Geographic Location and Routes

Field experiments are expected to be an important part of the EXPOSED project (Bjelland, 2017). To facilitate such experiments, technical instruments and sensors will be established at three sites specifically chosen due to their rough wave and current conditions. Oceanographic buoys measuring waves, currents and wind data have already been deployed at two of these sites, namely Valøyan and Salatskjæra outside the island of Frøya in Sør-Trønderlag (see Figure 2.3). The buoys are not located exactly at the locations, but at some distance away where the conditions are assumed somewhat more exposed (Senneset, 2017a).

Data from the measurements at the two sites have been made available for use in this thesis, and it was therefore decided to select the geographical area outside Frøya as location for the simulation model. In reality, service vessels operate at different aquaculture sites

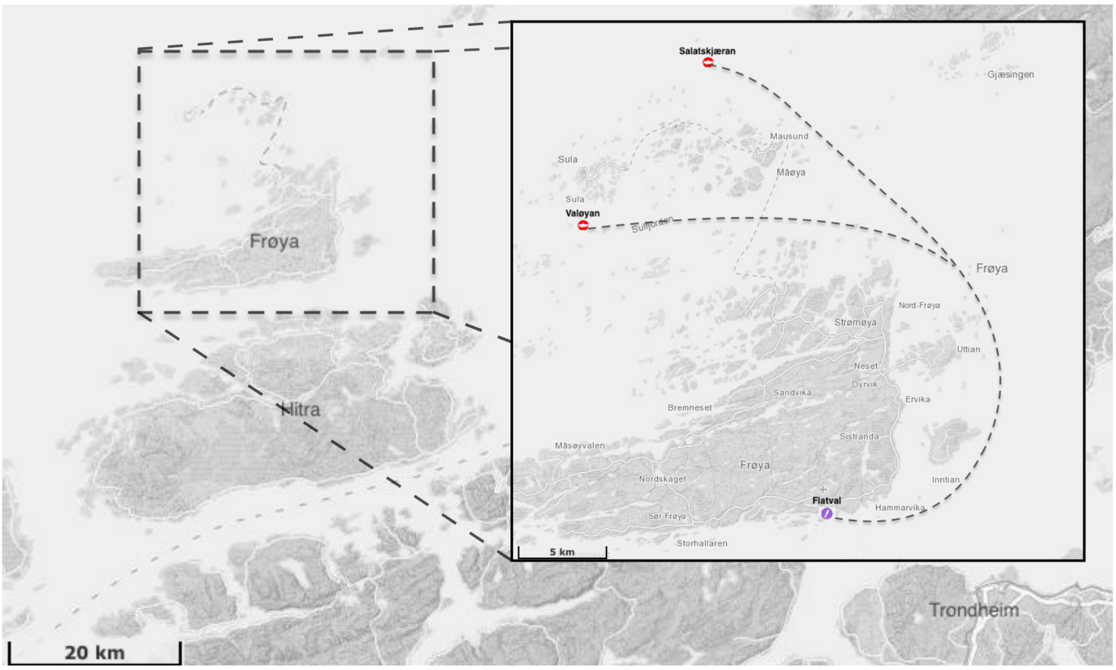


Figure 2.3: A map showing the geographic location considered. The enlarged section shows the port, the two farm locations and the sailing routes (Directorate of Fisheries, 2017).

spread over a relatively large geographical area and multiple vessels operate at the same facilities. Hence, the routes and operations performed can be unpredictable and hard to model in a simulation environment. In order to overcome this challenge, a few simplifications has been made to the system. Firstly, only the two sites where the oceanographic measurements are performed, will be considered. This means that the service vessel will operate only at these sites. Secondly, it is assumed that the vessel always return to the same port in Flatval, which is a frequently used port for aquaculture vessels in the Hitra/Frøya area. Finally, the routes to be sailed are limited to the two shown in Figure 2.3. The approximated distance of the routes are presented in Table 2.1.

Table 2.1: The approximated distance in nmi of the routes considered in the scenario.

Route	**Distance [nmi]**
Flatval - Valøyan	24.5
Flatval - Salatskjæra	22.0

2.4 Operations Performed By Service Vessels

Vessel operations in exposed areas are typically characterised by rough sea and difficult working conditions. The operations are often complex, involving multiple vessels, cranes and human workers both on the vessels and the floating collar. Consequently, there are potentially many factors affecting the safety and reliability of the operations. This thesis will focus on operations from a hydrodynamical point of view and will not go into details on other aspects of the operations such as structural integrity of facility structures and healt, safety and environment (HSE). However, it should be pointed out that safety of crew is considered to some extent through the operability criteria, specified in Section 6.4.3.

Service vessels in the aquaculture industry perform a wide range of operations. Depending on the vessel's capabilities and equipment, it can perform different types of missions. Some operations can be done by small support vessels stationed at the facilities, while others require the combined capacity of several vessels. For simplicity, the operations to be considered in the simulation model has been divided into five main categories. The breakdown is based on conversations with Hansen (2017) and Oppland (2017), master and first officer on M/S "Frøy Fighter", and consultation with Lien (2017). The categories are presented in Table C.1 in Appendix C and includes operations and critical tasks typically associated with each operation.

Operations involving vessel forward speed, typically towing and moving of plants, supply and transport and deployment of anchors, are not considered in this thesis. The exclusion of forward speed means that all hydrodynamic analyses in VERES are done for zero forward speed. The effect of forward speed is, however, a factor that should be considered if power consumption, fuel efficiency and other performance factors related to the actual sailing are of interest. The rest of this section will describe the operation categories and which activities that are considered critical for each of them.

Anchor Handling and Mooring

This category covers operations involving anchors and tensioning of mooring lines. Hence, it has been further split into two main tasks; anchor handling and tensioning of mooring system. As previously mentioned, anchor handling will not be further considered due to the involvement of forward speed. Tensioning of mooring system is done during installation and launch of a new site, but are also performed regularly to reduce slack in anchor and mooring lines. Such operations are typically performed by a service vessel that connects to a mooring plate at one end of the mooring frame by use of a crane. A capstan winch is then used to tension the lines (Lien, 2017). The procedure is easier understood by looking at Figure 2.4, which illustrates the main elements of a typical mooring system. Anchor handling and mooring operations require the presence of crew on deck and also involves high loads and tension. It is therefore characterised as one of the most risk exposed operations at exposed sites (Bjelland, 2015).

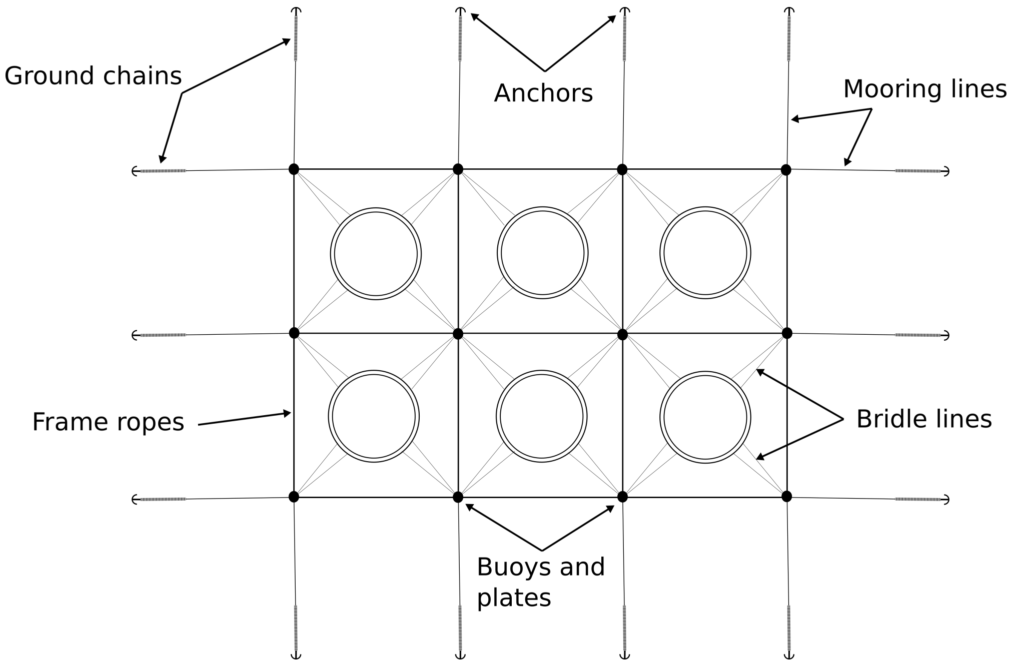


Figure 2.4: Simplified illustration of a mooring system.

Net Handling

When changing or removing the net structure in fish cages, service vessels are used to assist in the operations. Since the net is connected to both the floating collar and the bottom ring, the latter needs to be lifted up with a crane before the net is disconnected and lifted on board the vessel. The operation usually involves one or two vessels with cranes and crew operating both on deck and on the floating collar. The lifting and lowering of the bottom ring is done gradually while the vessel moves around the cage, making the operation relatively time consuming and exposed to the environmental conditions at the site (Oppland, 2017).

When installing a new net, the procedure is similar but performed in the opposite sequence. After the net is installed, divers or ROVs are often used to inspect the net and to ensure that it is connected properly.

Delousing

Salmon lice is a significant problem in the aquaculture industry which has hampered the production growth in recent years. Consequently, a large part of the vessel operations today is related to delousing. It is beyond the scope of this thesis to go into detail on each delousing procedure used in the industry. Common procedures for delousing are mechanical removal, chemical treatment and fresh water bathing. Regulations require that between each generation of fish grown at a facility, there must be a period of fallowing where there are no fish in the farm (Hansen, 2017).

M/S "Frøy Fighter" is currently modified with thermolicer equipment. This is a method for delousing which utilise the fact that the lice has a low tolerance for temperature changes in the water. By bathing the fish in lukewarm water for about 30 seconds, most of the lice will die and fall of the fish. The procedure is fairly sensitive to harsh weather conditions due to the involvement of multiple pumps and cranes, and the containers on deck act as large wind breakers.

Inspection and Maintenance

Inspection and maintenance includes a wide range of operations and tasks. It can involve inspection of subsea components such as the mooring system and the net, or other components like the cage structure, feeding and monitoring systems. Some of these operations can be performed by the on-site working boats and crew, but service vessels are often used to assist and perform heavier, more risk-related operations.

Inspection of the mooring system is important to identify defects or damage to components. This can be done by use of divers, ROVs or by lifting components on board for visual inspection and maintenance. Regular cleaning and disinfection of net and cage structures is performed to avoid extensive fouling, spread of diseases and wear of components (Hansen, 2017). This is normally performed by a dedicated washing system operated by a service vessel. Inspection of the net structure to locate possible tears and holes which can lead to fish escapes is usually done simultaneously with the cleaning. During fallowing periods, when the nets have been removed from the cages, bottom rings and floating collars are normally cleaned and inspected. Specialised systems are used to handle and wash the components, in addition to cranes and crew.

Regulations require periodic inspections of the facilities to ensure safe and reliable operation (Hansen, 2017). After three and six months, inspection on things like buoys and mooring plates are performed. These inspections are not very time consuming and are normally completed within one or two days per facility. After 12 months a more thorough inspection is performed. This inspection takes about two or three days, and includes an inspection of the entire facility with ROVs (Hansen, 2017).

General Support
In addition to the operations discussed above, service vessels can be requested to support the daily operation at a farm. This can for instance be if the capacities of the working boat at a site is not adequate, or it can be to assist during well-boat operations. Well-boats are used to transport fish to and from the facilities and also in certain delousing operations. Such operations often require extensive crane capacities and multiple service vessels are sometimes needed to assist the well-boat. The cranes are used to lift the bottom ring and to handle sweep nets which is used to huddle the fish towards the pumps.

2.5 Service Vessel Design

The development of service vessels in the Norwegian aquaculture industry has in general been towards larger and more advanced vessels. One of the main drivers for this development is the fact that the industry has experienced a significant expansion and thus becoming more industrialised (Waagbø, 2014). In turn, this has led to an increased focus on safe and efficient operations, and thus introduced new demands for vessel capabilities. Service vessels can be specialised for certain types of operations, or they can be so-called multi-purpose vessels (MPVs). Specialised vessels are designed and equipped to perform one or a few types of operations with a high degree of efficiency. Multi-purpose vessels are flexible and can be modified to perform a wide range of operations and adapt to changing market demands and operation requirements. Such flexibility, however, often comes at the expense of reduced efficiency and performance in certain types of operations (Johnsen, 2017).

As the work in this thesis will have a large focus on the hydrodynamic part of the operations, an important aspect to consider is the hull structure. According to Lien (2017), the majority of service vessels in the aquaculture industry is catamarans, i.e. a hull structure featuring two equal and parallel hulls. Catamaran designs are popular as they provide large working decks and initial stability. This allows for increased lifting capacities and reduced draft compared to monohulls with the same length overall (LOA). Due to regulations concerning vessels over 15 m, the vast majority of service vessels have a length less than 15 m. As the industry requirements have increased over the years, this has led to dangerous situations and loss of lives due to a mismatch between vessel dimensions and operational capacities (Bjelland et al., 2015). It seems, however, that the vessels can no longer remain under 15 m of length and at the same time hold the capacities required to perform all operations. Examples of recently built service vessels above this limit are M/S "AQS Loke" (25.5 m) and M/S "Frøy Fighter" (40 m), the former being a catamaran (see Figure 2.5).

Figure 2.5: The catamaran M/S "AQS Loke" (left) (AQS AS, 2017) and M/S "Frøy Fighter", both built in 2015, are examples of service vessels exceeding an LOA of 15 m. Illustration of "Frøy Fighter" provided by Møre Maritime AS.

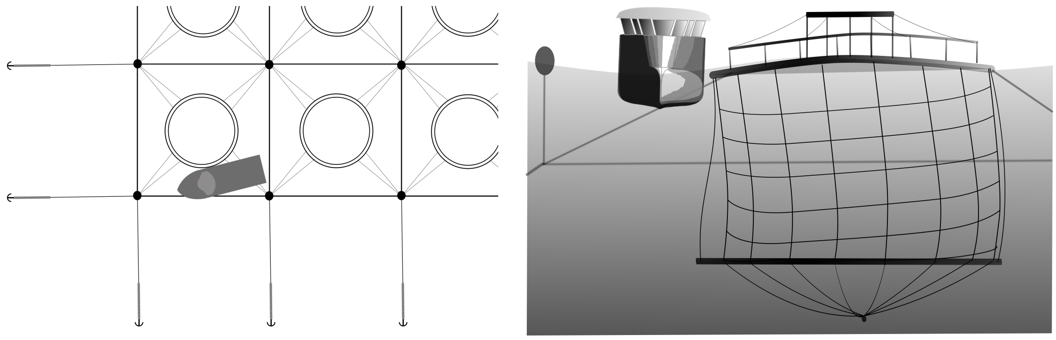
Despite the benefits of large working decks and initial stability of catamarans, they also come with some drawbacks. A high initial stability imply a high metacentric height (GM). A consequence of this is that the vessel motions during sailing may become very "stiff", which can lead to discomfort and damage to crew and equipment (Tupper, 2013). The effects of a high GM become particularly evident during harsh wave conditions, making catamarans potentially less suitable for operations in exposed sea environments. This could make an argument for monohull designs for operation in exposed locations, as they can be designed with lower GM values and thereby reduced motion stiffness and longer roll periods. Even though monohulls in general have less stiff motions in roll, it does not necessarily mean that they are better suited for operation in exposed aquaculture. A study of service vessels by Heide et al. (2013) shows that the operability of the catamaran is significantly less dependent on the incident wave direction than the monohull for a given set of operability criteria. The fact that both monohulls and catamarans are still being built for service operations shows that there are both advantages and limitations of both hull designs, and that the best design may very well depend on the type of operation to be performed and the physical environment in the area of operation.

2.5.1 Interaction with Facility Structures and Installations

During vessel operations at aquaculture facilities there will be vessel-structure interactions. Depending on the type of operation, different types of interactions may occur. Some are related to direct contact between the hull side and the cage structure, while others can be related to the vessel navigation and manoeuvring at the facility. A qualitative assessment of the interaction between vessels and installation structures was done in the project thesis as part of the preparatory work for this thesis. The assessment indicates that the challenges of the vessel-structure interaction are mostly related to the hydrodynamical performance of the vessel, the structural integrity of the facility installations and the relative motions between them. Hence, these are important aspects to consider when assessing operability and performance of service vessels.

On-Site Vessel Approach and Navigation

As a vessel approach a facility, the navigation may become challenging, particularly at exposed locations. Waves, wind and current all contribute to create relative motions between the vessel and components of the facility structure. Increasing vessel dimensions may impose new challenges during the operations both due to increasing loads, but also due to different manoeuvring and hydrodynamic behaviour. Larger vessels are also likely to enquire increased draught, and so the depth of frame ropes and bridles becomes an issue to consider. Increased dimensions can also cause unintentional interaction between the vessel, bridles and buoys. An attempt on illustrating these situations are presented in Figure 2.6.



(a) (b)

Figure 2.6: Vessel dimensions and draft can be a challenge during navigation and approach close to the cage structures, as illustrated in (a) and (b), respectively.

Direct Interaction

When the vessel is moored to the cage, there will be a direct load interaction between a dynamic and a relatively static element, being the vessel and cage structure, respectively. Loads from waves, currents and wind can easily increase the magnitude of the loads, and consequently cause damage to the moorings or the cage structure itself. If the structure is not strong enough or the relative motions become too excessive, it may result in structural damages and possibly escape of fish.

The net structure is essential to prevent fish escapes, as it is the only barrier keeping the fish inside the cage. According to Svåsand et al. (2015), escaped salmon from aquaculture represents a threat to the genetic integrity of the wild salmon populations. The nets are dynamic, and may take damage from external forces like currents, waves or thruster jets from nearby vessels or from foreign materials drifting in the sea. Regular inspections and maintenance of the net structure is therefore essential to reduce the risk of fish escapes.

2.5.2 The Macho 40

The Macho 40 vessel design has been selected for the vessel response analysis in this thesis. The vessel is designed by Møre Maritime AS and is, with an LOA of 40 m, currently the largest service vessel in the world built for aquaculture operations (Frøy Gruppen, 2017). As of today, M/S "Frøy Fighter" is the only vessel built of this type. It is a robust MPV designed with emphasis on improved working conditions during harsh weather conditions. The hull is designed with a blunt bow and nearly vertical ship sides above the main deck to maximise the deck area (Møre Maritime AS, 2014). In addition to large cargo holds, this makes it able to handle a number of service operations.

The vessel is equipped with one main engine and two generator sets. The main engine is a Cummins Marine Diesel QSK38-M1 rated for 1000HP operation at 1800 revolutions per minute (RPM), while each generator set has a rated power of 376 bkW. A ducted CP propeller, one bow and one aft thruster with capacities of 320 and 250 bhp, makes it capable in rough weather conditions, which is essential when performing operations at exposed locations. According to Hansen (2017), the master on M/S "Frøy Fighter", the vessel shows great stability and performance during rough conditions. However, it is particularly exposed to wind, which often is the limiting factor during their operations. A possible reason for this is that the vessel is currently modified for delousing operations with large containers installed on deck. The standard modification of the Macho 40, as seen in Figure 2.7, does not involve delousing containers, and is therefore less exposed to wind and gusts (Oppland, 2017). A more detailed specification of the vessel can be found in Appendix D.

Figure 2.7: The Macho 40, used in the vessel response analysis in this thesis. Illustration provided by Møre Maritime AS.

It could be argued that a catamaran would be more relevant to study since the majority of service vessels in the industry is in fact catamarans. The decision of using the Macho 40 in the analysis is, however, based on the fact that it is specifically designed to operate in exposed locations. This makes the Macho 40 a good match considering the emphasis on exposed aquaculture in this thesis. According to Waagbø (2014), the future of service vessels lies in multi-purpose robust vessels with large deck area, cargo space and high manoeuvrability. These are all features that the Macho 40 holds, and due to regulations concerning vessels larger than 500 GT, it is unlikely that service vessels exceed the 499 GT of the Macho 40 within the next few years.

Chapter 3

Literature Review

The literature review is important to become aware of, and get familiar with previous work on the topic to be investigated in the thesis. The focus is on topics related to vessel operability, metocean conditions and the application of simulation to marine systems, as these are central topics of the thesis work.

3.1 Vessel Operability and Performance

The definition of vessel operability is not explicitly defined in literature, and can vary depending on situation and context. Fonsenca and Soares (2002) defines operability of a vessel as its ability to carry out the mission safely. Hoffman and Petrie (1980) claims that the vessel operability can be estimated based on the probability that vessel motions remains within the acceptable limits for a sufficient amount of time to complete the operation. Even though there is no exact definition of the term, it seems that the literature is more or less in agreement of its meaning. In general, it can be defined as the vessel's ability to perform its intended tasks in a safe and reliable manner. In order to measure the operability, a set of key parameters must be defined. The parameters are often related to the vessel's ability to withstand metocean conditions at sea, known as *seakeeping* or *seaworthiness*.

An assessment of ship performance in a seaway was done by Nielsen (1987). The aim of the project was to increase the knowledge of the seakeeping capability of a ship by defining operational criteria and methods for verification of the performance. The criteria was related to ship motions, human performance, ship propulsion and manoeuvring, and specific criteria was assigned to individual ship types. The project was motivated by the lack of precisely defined criteria and evaluations methods to measure and judge the performance of ships and hence decide on the best ship designs.

A study on the seakeeping performance of fishing vessels was done by Tello et al. (2010). Their objective was to identify the criteria and sea states that would limit the operability of the vessels. Vessel responses were calculated using transfer functions of the hull geometries. The motivation for the study was mainly the high number of working accidents on fishing vessels occurring in harsh sea conditions. A statistical study of fishing vessels accidents in the UK by Wang, Pillar, Kwon, Wall, and Rodríguez (2005), showed that most accidents are related to vessels of about 24 m of LOA. Antão and Soares (2004) studied maritime accidents in Portugal, and found that small fishing vessels represent 89% of the total accidents over a period of 20 years. Based on the results from these studies, it is obvious that seakeeping performance of small vessels is an important field of study. Holmen et al. (2016) claims through a report that fishing vessels is the most risk exposed occupation in Norway, followed by sea-based aquaculture. Hence, it would be reasonable to regard service vessel operations in exposed aquaculture as risk exposed operations, in a similar manner as fishing vessels. On the study on seakeeping performance of fishing vessels, Tello et al. (2010) found that roll and pitch criteria were most critical, and the location of the reference design points had a significant influence on the seakeeping performance. The study concluded that a U shaped cross section on the hull enhanced the performance in roll, while a V shaped cross section enhanced the performance in pitch. The importance of the GM was also pointed out, as an increase of GM will decrease the resonant period of roll, which in turn can coincide with the wave period and cause resonance motions.

A project ranging over four years with the aim of developing a new design concept for service vessels was done by Heide et al. (2013). The focus was on vessel design, but also on procedures and methods for safe and efficient service operations. The project work resulted in several design concepts, from which one ended up as basis for the development of the Macho 40 vessel used in this thesis. One of the reports in the project presents an operability analysis of four different service vessels during crane operations. The limiting criteria applied in the analyses were based on experience from crane operations, and the point of observation of the response was kept constant for all vessels. The study was, however, limited to identifying operational limits and did not consider metocean data and operability in the time domain.

The sensitivity of the expected vessel operability to different seakeeping criteria was studied by Fonsenca and Soares (2002). The relation between the operability and the mission is established through these criteria, and is measured through an operability index. The index is calculated based on the mission profile, hydrodynamic characteristics of the vessel and the ocean climate in the area of operation. The sensitivity analysis was motivated by the uncertainty in the seakeeping criteria, which was mostly based on the experience on board vessels. The analysis showed that for vessels operating in coastal areas, the accuracy of wave climate statistics are important. The study concluded that the sensitivity of operability to different values of the criteria in general was relatively small, but for low operability values the sensitivity was higher.

Hoffman and Petrie (1980) presented a computer modelling system for control of weather bound vessel operations which provides capabilities and information for operational planning, routing and management, by combining vessel response, wave forecasting and different measurement methods. The system consists of three sub-systems, each serving a specific purpose in the operations. One system is a pre-analysis which assess the vessel performance to be anticipated during the operation. Another system provides the operator with real-time quantitative measurements of the vessel response, so that necessary means can be taken to optimise the operations. The third system, developed for the shore-based operation management, provides much of the same information as the on-board system, but in conjunction with a better access to weather forecasts and information of an entire fleet. This enables the management to efficiently control and guide the vessel operations, and thus reduce operational costs and operation durations. The systems were successfully installed on a numerous of offshore vessels in the 1980's and substantial benefits from utilisation of the system were reported.

The ability to estimate and measure a vessel's operability can be useful in several contexts. The most obvious is probably the benefit of being able to measure and compare vessel performances under given circumstances. Other applications that has been discussed in this section is the importance of seakeeping performance in terms of risk exposure and optimisation of operations through real-time analyses and feedback. An alternative approach was proposed by Rusu and Soares (2013). Through a system for forecasting the operability of vessels, they were able to produce operability "heat" maps for various geographical areas of the coast. The information could then be used by vessel operators to plan routes and operations ahead, and to avoid areas that could degrade the operability due to weather conditions.

3.2 Metocean Conditions and Weather Forecasting

An important aspect of vessel operability is the weather conditions at sea, often referred to as metocean conditions. As a vessel performs an operation, it is affected by the physical environment through forces from waves, currents and wind. In the Norwegian aquaculture industry, there is a lack of regulations regarding operational limits, and it is often up to the vessel crew to determine when the conditions are too harsh to conduct an operation. The decisions are often based on experience and gut feelings, meaning the operational limits varies throughout the industry. In the offshore industry there has been systems to quantify vessel motions and provide the operators with real-time information for evaluating the conditions and make strategic changes if necessary (Hoffman & Petrie, 1980). In combination with weather forecasts, such analyses can be effective tools for decision making and planning of vessel operations.

According to DNV (2011), vessel operations can be either weather *restricted*, or weather *unrestricted*. Weather restricted operations can be defined as "operations with defined restrictions to the characteristic environmental conditions, planned performed within the period for reliable weather forecasts", and is normally limited to 72 hours. They account for uncertainty in weather forecasts by including a factor, α. It assures that the operational limit is less than the limit obtained in design. Values for the α-factor is obtained from designated tables in DNV-OS-H101, Section B 700. The operational limit for significant wave height can thus be expressed as

$$H_{s,oper} = \alpha H_{s,design} \tag{3.1}$$

where α is less than one. A study of the uncertainty in weather forecasts for marine operations was done by Natskår, Moan, and Alvær (2015). They found that the uncertainty in the forecasts decrease with decreasing lead time. It was also pointed out that there is a lower correlation between forecasted and experienced data for wave periods than for significant wave heights. Even though the correlation between forecasts and experienced data seems to be fairly good, not accounting for the uncertainty will in most cases give overestimated operability.

"Weather window" is a common term related to marine operations. It refers to the period of time of which the metocean conditions are below the critical limits to undertake a specific operation. To account for uncertainties in weather forecasts, weather windows for anchor handling operations must be at least 1.5 times longer than the expected time of the operation (Shyshou et al., 2009). O'Connor, Lewis, and Dalton (2012) performed a weather window analysis of wave data to quantify the level of access for operation and maintenance of marine renewables. They claim that quantifying the accessibility will assist designers in developing improved solutions and procedures, and at the same time lead to more reliable estimations of costs.

3.3 Simulation of Marine Systems

Simulation is commonly used to study and analyse operational processes within applications like logistics, production processes and supply chains. In the marine industry this typically concerns seaport logistics and fleet performance and optimisation. Based on the literature review, it seems that simulation is mostly used as a tool for decision-making and support, rather than research and development of new system designs.

A discrete-event simulation model for evaluation of cost-optimal fleet size configurations of offshore anchor handling operations was proposed by Shyshou et al. (2009). The modelling of weather conditions and the link between operability and weather was given a significant effort through this study. Due to the high hiring costs of anchor handling tug supply (AHTS) vessels, determining the optimal fleet size may provide significant economic benefits for the offshore operators. The planning of anchor handling operations can be challenging due to the uncertainty related to weather conditions and the volatility in spot market rates. In combination with an uncertainty in duration of operations and operational costs, this makes the problem highly stochastic. The efficiency measure used to determine the optimal number of vessels on long-term contracts is the annual vessel hiring costs. Vessel operability is considered through threshold values on significant wave height (H_S). Even though the study address the economical aspect of vessel operations, similarities regarding weather windows and duration of operations could be drawn towards the aquaculture industry.

Longo, Huerta, and Nicoletti (2013) conducted a performance analysis of a southern Mediterranean seaport via discrete-event simulation. The aim of the study was to propose a simulation-based tool that could be used by the port administration to support process management and decision-making. The methodology related the seaport performance to the model input, and revealed crucial factors for the seaport performance in terms of turnaround time. Another study related to ferry traffic was done by Darzentas and Spyrou (1996). They addressed the problem of controlling and managing a complex ferry transportation system, by developing a simulation model with the aim of aiding decision makers to effectively plan, design and intervene in the transportation system. Due to the complexity of the problem, the results obtained from the study are suggested as indications of the model's potential as an effective tool for decision-making.

Since simulation models are widely used for support and decision making, verification and validation is a very important aspect to consider when developing such models. Sargent (1998) discuss this issue and presents different procedures to deciding model validity. It is emphasised that the validity of a simulation model developed for a specific purpose should be determined with respect to that purpose. The statement is obvious, but nevertheless important to bear in mind, since a model considered valid for one purpose may be invalid for any other purposes. The degree to which a model may be validated depends on the available resources. Sargent (1998) presents a relation between model confidence and cost of model validation, where the costs increase exponentially towards 100% model confidence. The study concludes that each simulation project represents a unique challenge regarding model validation and verification, and that no specific tests or algorithms exists to determine what approach or techniques to use in each case.

Chapter 4

Vessel Motions In a Sea Environment

Evaluation of a vessel's operational performance is an essential part of the planning and development of new vessel designs. To a wide extent, the operational performance of a vessel depends on its seakeeping ability, which can be defined as all the features influencing the vessel's ability to withstand the wave environment and carry out its intended operation or mission (Tupper, 2013). This includes factors like strength, manoeuvrability, stability and vessel motions. This chapter will consider those aspects of the operational performance attributable to the vessel motions due to the wave environment, as this is one of the most important factors to evaluate when assessing vessel performance (Nielsen, 1987).

To properly understand a vessel's wave-induced motions, a basic knowledge of the sea environment and hydrodynamics is necessary. Section 4.1 will therefore cover the basics of wave theory, followed by a discussion on vessel response in regular and irregular sea states in Section 4.2 and 4.3, respectively.

4.1 Sea Environment

Vessel motions can be calculated through approximating methods such as strip theory, but more advanced methods like computational fluid dynamics (CFD) are also available. The software VERES, which is used in this thesis, is based on strip theory using potential theory. This section will therefore present linear wave theory of regular waves in deep water and discuss the basic assumptions of potential theory.

4.1.1 Basic Assumptions of Potential Theory

In potential theory, the fluid is assumed inviscid and incompressible. The flow is irrotational and its velocity vector can be described by a velocity potential, ϕ. The velocity potential itself has no physical meaning, but acts as a convenient mathematical term given the assumption of irrotational fluid flow (Faltinsen, 1999). The velocity vector is used to describe the fluid motion at a time t at a point (x,y,z) in a Cartesian coordinate system fixed in space, and can be written as

$$\mathbf{V} = \nabla\phi = \mathbf{i}\frac{\partial\phi}{\partial x} + \mathbf{j}\frac{\partial\phi}{\partial y} + \mathbf{k}\frac{\partial\phi}{\partial z} \tag{4.1}$$

where **i**, **j** and **k** are unit vectors along the x-, y- and z-axes, respectively. The assumption of incompressible fluid implies that the velocity potential has to satisfy the equation below, which in principle is conservation of mass, also known as the Laplace equation. Also, due to the assumption of irrotational fluid motion, the vorticity vector ω given in Equation 4.3, must be zero everywhere in the fluid.

$$\nabla \cdot \mathbf{V} = \nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{4.2}$$

$$\omega = \nabla \times \mathbf{V} \tag{4.3}$$

The velocity potential of a fluid is, given a set of boundary conditions, found from the solution of the Laplace equation. For a body moving with velocity **U** in a fluid, Equation 4.4 expresses impermeability, i.e. no fluid can flow through the body surface. The vector **n** is the unit normal vector on the body surface, pointing into the fluid domain as shown in Figure 4.1. At the fixed sea bottom, the condition is: no fluid flow through the surface of the bottom, and is given by Equation 4.5.

$$\frac{\partial\phi}{\partial n} = \mathbf{U} \cdot \mathbf{n} \tag{4.4}$$

$$\frac{\partial\phi}{\partial z} = 0 \tag{4.5}$$

It is further assumed that a fluid particle at the free surface remains on the free surface. This assumption requires two conditions to be applied: a kinematic boundary condition related to the motion at the free surface and a dynamic condition dealing with the force balance in the interface. The pressure p at the free surface follows from the Bernoulli's equation given in Equation 4.6, where ρ is the mass density of the fluid, g is the acceleration of gravity and z is the vertical position of the fluid particle on the free surface.

$$p + \rho g z + \rho \frac{\partial \phi}{\partial t} + \frac{\rho}{2} \mathbf{V} \cdot \mathbf{V} = C \tag{4.6}$$

Assuming a linear relation between the velocity potential and the wave elevation, in addition to zero current and no forward speed of the body, it can be shown that the kinematic and dynamic free surface conditions on the mean free surface ($z = 0$) is expressed as in Equation 4.7 and 4.8, where ζ is the surface elevation.

$$\frac{\partial \zeta}{\partial t} = \frac{\partial \phi}{\partial z} \qquad \text{(kinematic condition)} \tag{4.7}$$

$$g\zeta + \frac{\partial \phi}{\partial t} = 0 \qquad \text{(dynamic condition)} \tag{4.8}$$

In physical terms, the dynamic condition states that the water pressure must be equal to the constant atmospheric pressure p_0 on the mean free surface (Faltinsen, 1999). Equation 4.7 and 4.8 can be combined to give what is referred to as the combined free surface condition

$$\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \qquad \text{on z} = 0 \tag{4.9}$$

Figure 4.1 shows the application of the boundary conditions in a fluid domain with a freely floating vessel.

4.1.2 Regular Waves

Regular waves are assumed to be long-crested and sinusoidal, which means they can be described by sine or cosine functions. A regular wave is defined by its wave amplitude, ζ_a, wavelength, λ and period, T. In addition, the wave propagation direction and phase angle are needed to fully specify the wave. According to Faltinsen (1999), the velocity potential for infinite water depth ($z \rightarrow -\infty$) can be expressed as shown in Equation 4.10, where ω is the wave frequency and k is the wave number, respectively.

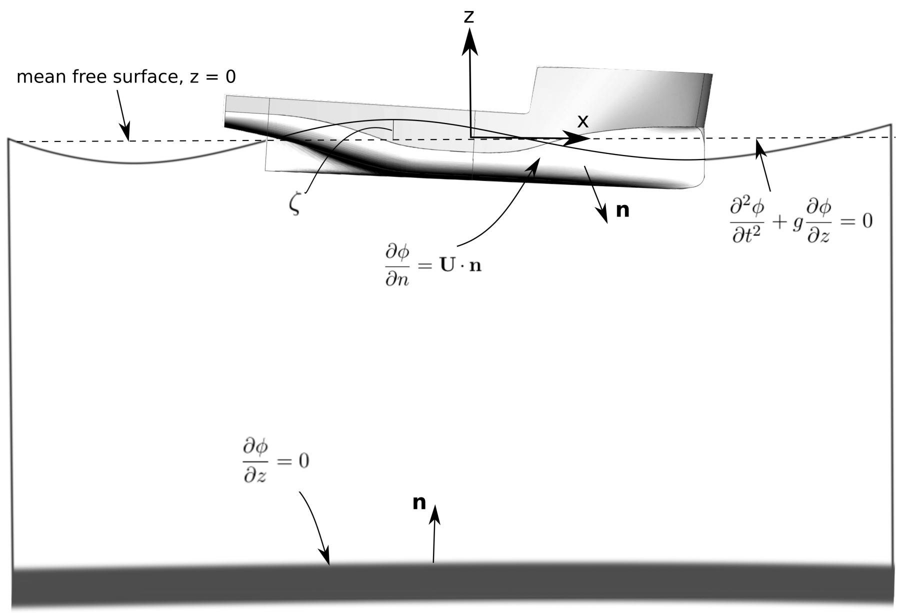


Figure 4.1: Kinematic and dynamic free surface conditions of potential theory. The coordinate system is defined with positive z-direction upwards, and the mean free surface at z = 0.

$$\phi = \frac{g\zeta_a}{\omega} e^{kz} cos(\omega t - kx) \tag{4.10}$$

The pressure distribution under a wave is illustrated in Figure 4.2. At the free surface, the hydrostatic pressure $-\rho g \zeta_a$ should cancel the dynamic pressure $-\rho\partial\phi/\partial t$, to fulfil the assumption of atmospheric pressure. It can be seen from the figure that this condition is satisfied at the wave crest, where the total pressure goes to zero at the free surface. At the wave trough there will be an error approximately proportional to O(ζ_a^2) (Faltinsen, 1999). Hence, the theory is valid as a first-order approximation to satisfy the free-surface conditions. It should also be noted that the linear dynamic pressure diminish quickly with increasing depth.

Since the dynamic pressure, p_d, is assumed constant above the mean free surface ($z > 0$), we can write the total pressure as shown below.

$$p = \begin{cases} \rho \text{ g}(\zeta \text{ - z}) & \text{for z} \geq 0 \\ \rho \text{ gz} + p_d & \text{for z} < 0 \end{cases} \tag{4.11}$$

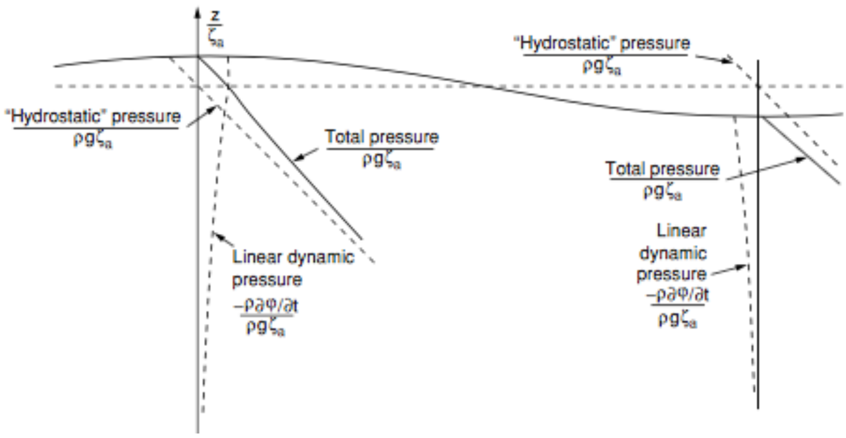


Figure 4.2: Pressure distribution according to linear wave theory (Faltinsen, 2005).

4.2 Response in Regular Waves

Wave-induced motions of a vessel can, to a large extent, be described by linear theory. However, in rough sea non-linear effects becomes more significant (Faltinsen, 2005). For a vessel in incident regular waves, linear theory implies that the motion amplitudes are linearly proportional to the wave amplitude, ζ_a. It is common to divide the hydrodynamic problem in regular waves into two parts, often referred to as the *radiation* problem and the *diffraction* problem.

$$\text{Wave-body interaction} = \text{Radiation loads} + \text{Diffraction loads} \tag{4.12}$$

The wave-body interaction is basically the wave-induced motions, accelerations and loads of which the vessel will experience when exposed to incident regular waves. The radiation problem deals with the forces on the body when it is forced to oscillate with the wave excitation frequency in calm water, i.e. no incident waves. The forces on the body when it is restrained from oscillating in incident regular waves is considered in the diffraction problem (Faltinsen, 1999). Due to linearity, the loads obtained from the two sub-problems can be superposed to give the total hydrodynamic loads.

4.2.1 Radiation Loads

The radiation problem deals with the forces and moments on the body when it is forced to oscillate with the wave excitation frequency in calm water. The hydrodynamic loads involved in this problem are identified as added mass, damping and restoring loads. This section will provide a brief introduction to the terms, and how they affect the vessel motions. A more detailed presentation on this subject can be found in Salvesen and Faltinsen (1970).

To be able to describe these terms, it is necessary to define a coordinate system and the rigid-body motions. Faltinsen (1999) base the motions of floating structures upon three principle axes (x,y,z), each with two degrees of freedom: translation and rotation. The coordinate system, which is presented in Figure 4.3, is fixed to the mean position of the vessel, with the origin in the plane of undisturbed free surface. The oscillatory motions of translation are referred to as surge, sway and heave, and are referred to as η_1, η_2 and η_3, respectively. The oscillatory motions of rotation are referred to as roll, pitch and yaw, and are referred to as η_4, η_5 and η_6, respectively.

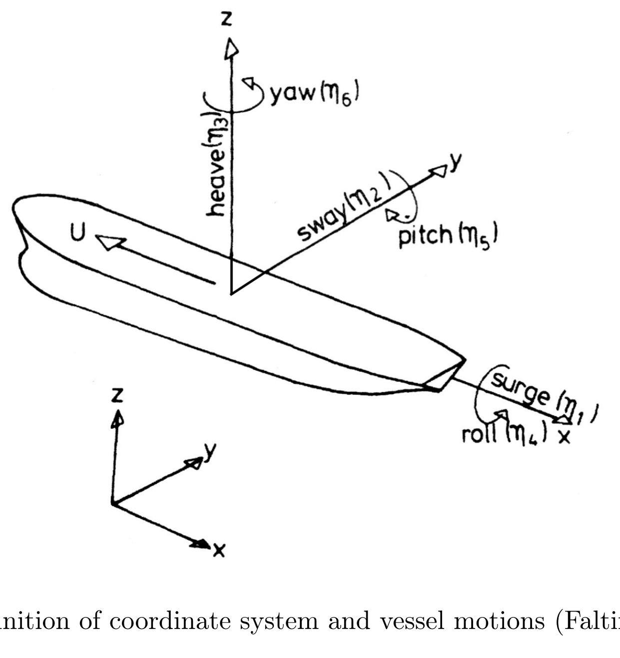


Figure 4.3: Definition of coordinate system and vessel motions (Faltinsen, 1999).

Added Mass and Damping Coefficients

Added mass and damping loads occur due to forced harmonic body motions. The forced motions of the body will generate waves, resulting in oscillating pressure fields on the body surface. Integrating these pressure fields over the mean position of the body surface, gives the resulting added mass and damping loads (Faltinsen, 2005). The loads can be written as in Equation 4.13, where A_{kj} and B_{kj} are the three-dimensional added mass and damping coefficients, respectively.

$$F_k = -A_{kj}\frac{\partial^2 \eta_j}{\partial t^2} - B_{kj}\frac{\partial \eta_j}{\partial t} \tag{4.13}$$

An approximation of the three-dimensional coefficients on a vessel can be found by combining the two-dimensional coefficients with strip theory. The hull will then be divided into a number of strips, and for each strip the two-dimensional coefficient are calculated. Integrating over the length of the hull will give the three-dimensional coefficients. This approach is questionable for vessel geometries with a low length to beam ratio, due to the assumption of a small change of flow along the longitudinal direction in strip theory (Faltinsen, 1999).

The term added mass can often be misleading, as it should not be confused with a finite mass of fluid, but rather a hydrodynamic load. The added mass and damping coefficients depend on the motion mode, and shows a strong frequency dependence. They can also be strongly influenced by the body shape. Hence, the coefficients may have different values in different motion modes. Another parameter dependence worth to note is the fact that for very long wave periods, i.e. $\omega \to 0$, the damping coefficient in heave goes to zero while the added mass coefficient goes to infinity.

The damping level for a vessel with zero forward speed depends on wave generation, viscous effects and active damping components. As discussed in Section 4.1.1, viscous effects are neglected in potential theory. Thus, the only factor affecting the damping in potential theory is the wave generation from the body motions.

Viscous Roll Damping

In general, the assumption of neglecting viscosity has little effect on the damping. However, a comparison of theory versus experiments done by Vugts (1968) shows that the *roll* damping is strongly affected by viscosity. The report concludes that for the case of calculating roll motions near resonance, a reasonable accuracy can be obtained only if a correction for viscous damping is included.

Viscous damping can be divided into several components. Skin friction damping is caused by friction between the body surface and the fluid. It depends on the density of the fluid and level of roughness on the surface, and will be non-linear. The forward speed of a vessel will create linear lift effects from the hull in roll motion, often referred to as lift damping. The roll motion also cause a non-linear damping effect caused by flow separation at the bilge of the hull cross section, known as eddy damping (Fathi & Hoff, 2014). The roll motion of a vessel can be significantly reduced by implementing bilge keels on the hull sides. Due to its shape it increases the hydrodynamic resistance to roll, and induce eddy damping through vortex shedding along the edges.

Restoring Coefficients

The restoring forces and moments are independent of frequency and forward speed, and follow from hydrostatic considerations (Fathi & Hoff, 2014). They are hydrostatic forces, meaning they are proportional to rotation and displacement in the vertical direction. Hence, restoring coefficients are non-zero for heave, roll and pitch motions only. Whereas the added mass and damping loads are obtained from linear dynamic pressure, the restoring loads are found by integrating the instantaneous hydrostatic pressure field on the body surface. It is defined by Equation 4.14, where C_{kj} is the restoring coefficient.

$$F_k = -C_{kj}\eta_j \tag{4.14}$$

4.2.2 Diffraction Loads

The second part of the wave-body interaction as presented in Equation 4.12 is the diffraction problem. When considering the diffraction loads, the vessel is assumed restrained from oscillating and there are incident regular waves. The forces acting on the body from the incident waves are called wave exciting forces, and are split into Froude-Kriloff force and diffraction force. The Froude-Kriloff force represents the force due to the undisturbed pressure field, i.e. as if the body was not there. In reality, the presence of the body will change this pressure field and there will be no flow through the body. The force related to this is called the diffraction force.

The velocity potential solving this problem can be written as in Equation 4.15, where ϕ_0 and ϕ_D are the velocity potential of the incident wave and the flow motion against the incident wave to ensure impermeability, respectively.

$$\phi(x,y,z,t) = \underbrace{\phi_0(x,y,z,t)}_{\text{incident wave}} + \underbrace{\phi_D(x,y,z,t)}_{\text{diffraction}} \tag{4.15}$$

The velocity potential satisfies the condition of impermeability given in Equation 4.16, where n is the unit vector normal to the body surface.

$$\frac{\partial \phi_D}{\partial n} = -\frac{\partial \phi_0}{\partial n} \tag{4.16}$$

The flow due to ϕ_0 penetrates the body surface with the normal velocity $\partial\phi_0/\partial n$, causing the hydrodynamic loads referred to as Froude-Kriloff forces (Faltinsen, 1999). The body impermeability is recovered through the diffraction forces, caused by the flow associated with ϕ_D. The sum of the two gives the total wave excitation force on the body, and are obtained by integrating the wave dynamic pressure and the diffraction pressure along the body surface:

$$F_{exc,k}(t) = \underbrace{-\int_S \rho \frac{\partial \phi_0}{\partial t} n_k dS}_{\text{Froude-Kriloff}} - \underbrace{\int_S \rho \frac{\partial \phi_D}{\partial t} n_k dS}_{\text{diffraction}} \qquad k = 1...6 \tag{4.17}$$

where S is the mean wetted hull surface.

4.2.3 Equations of Motion

In order to fully understand a vessel response analysis, it is essential to have some knowledge about vessel motions and how they are affected by the wave environment. When the hydrodynamic forces acting on the vessel are found, the equations of motion can be set up. Assuming linear and harmonic responses, the six equations of motion can be written on the form

$$\sum_{k=1}^{6} [(M_{jk} + A_{jk})\ddot{\eta}_k + B_{jk}\dot{\eta}_k + C_{jk}\eta_k] = F_j e^{i\omega t}; \quad j = 1...6 \tag{4.18}$$

where M_{jk} are the components of the vessel's mass matrix. A_{jk}, B_{jk} and C_{jk} are the added-mass, damping and hydrostatic restoring coefficients, respectively. Exciting forces and moments are given by the real part of $F_j e^{i\omega t}$, where ω is the frequency of encounter. The dots express time derivatives, so that $\dot{\eta}_k$ and $\ddot{\eta}_k$ represents the velocity and acceleration of the displacement η_k.

In general, a vessel is symmetric about the longitudinal-vertical plane (xz-plane). This makes it possible to distinguish between symmetric and non-symmetric motion components. Surge, heave and pitch are all symmetric about this plane, while sway, roll and yaw are not. Symmetric and non-symmetric motions are uncoupled, i.e. they do not affect each other. Hence, if it is assumed that the vessel has lateral symmetry, surge, heave and pitch are uncoupled with sway, roll and yaw. This follows from the six equations of motions in Equation 4.18 which reduce to two sets of equations: One set of three coupled equations for surge, heave and pitch, and the other for three coupled equations for sway, roll and yaw.

If, in addition, a long, slender hull is assumed, it can be shown that the forces in surge mode is negligible compared to the remaining five modes (Salvesen & Faltinsen, 1970). For a freely floating vessel, the resonance frequencies in roll will be more significant than that of sway and jaw motions (Faltinsen, 2005). Taking this into account, the equations of motion for heave, pitch and roll are reduced as shown in Equation 4.19, 4.20 and 4.21, respectively.

$$(M + A_{33})\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + C_{33}\eta_3 + A_{35}\ddot{\eta}_5 + B_{35}\dot{\eta}_5 + C_{35}\eta_5 = F_3 e^{i\omega t} \tag{4.19}$$

$$A_{53}\ddot{\eta}_3 + B_{53}\dot{\eta}_3 + C_{53}\eta_3 + (I_5 + A_{55})\ddot{\eta}_5 + B_{55}\dot{\eta}_5 + C_{55}\eta_5 = F_5 e^{i\omega t} \tag{4.20}$$

$$(A_{42} - Mz_c)\ddot{\eta}_2 + B_{42}\dot{\eta}_2 + (A_{44} + I_4)\ddot{\eta}_4 + B_{44}\dot{\eta}_4 + C_{44}\eta_4 + (A_{46} - I_{46})\ddot{\eta}_6 + B_{46}\dot{\eta}_6 = F_4 e^{i\omega t} \tag{4.21}$$

In the equations above, z_c is the vertical coordinate of the centre of gravity, I_j is the moment of inertia in mode j and I_{kj} is the product of inertia. A more detailed derivation of the equations of motion is presented by Salvesen and Faltinsen (1970).

4.2.4 Natural Periods

In assessing amplitudes of motion for a vessel, the natural periods are important parameters. If a vessel is excited with oscillation periods close to its natural periods, large motions known as resonance are likely to occur. Damping or cancellation effects may, however, make it difficult to distinguish the motions at resonance periods from any other motions (Faltinsen, 1999). The uncoupled natural periods in heave, roll and pitch for a vessel, or any other freely floating body is by Faltinsen (1999) defined as in Equation 4.22, 4.23 and 4.24.

$$T_{n3} = 2\pi \left(\frac{M + A_{33}}{\rho g A_w} \right)^{0.5} \tag{4.22}$$

$$T_{n4} = 2\pi \left(\frac{M r_{44}^2 + A_{44}}{\rho g V \overline{GM_T}} \right)^{0.5} \tag{4.23}$$

$$T_{n5} = 2\pi \left(\frac{M r_{55}^2 + A_{55}}{\rho g V \overline{GM_L}} \right)^{0.5} \tag{4.24}$$

M and V is the mass and displaced volume of the vessel, respectively. A_w is the waterplane area and $\overline{GM_T}$ and $\overline{GM_L}$ are the transverse and longitudinal metacentric height. A_{33} is the added mass in heave, while A_{44} and A_{55} are added moments in roll and pitch. r_{44} and r_{55} are the radius of gyration in roll and pitch about an axis parallel to the x-axis and y-axis, respectively. In a vessel context, radius of gyration can be explained as a measure of the vessel's mass distribution about the axis of consideration. For a vessel with no forward speed, the resonance oscillations in heave will occur when excited by waves with wavelength in the order of magnitude of the vessel length.

For a vessel, resonance motions may lead to dangerous situations. Excessive motions may lead to damage to the hull and equipment, as well as threaten the safety of the crew. The most critical is often the roll motion, which can become so large that capsizing may occur. For this reason, measures to reduce roll motions are commonly used. This is typically stabilising fins, anti-roll tanks and bilge keels. Such measures provide damping effects which influence the vessel motions and, as previously mentioned, this can make it difficult to identify the exact range of resonance motions.

4.3 Response in Irregular Waves

Regular wave spectra do not exist in a real sea environment. In reality, the wave amplitudes and periods will vary over time, causing irregular sea states. For a vessel in irregular sea, there will be many excitation frequencies and transient effects. Added mass and damping are frequency dependent, and thus the equations given by Equation 4.18 cannot be directly used in the time domain (Faltinsen, 2005). However, if transient effects are neglected this problem can be circumvented. The application of linear theory means that we can represent irregular sea states as a sum of regular wave components with different phase angles (see Figure 4.4). This also means that vessel response in irregular seas can be obtained from the same principle. Hence, it is sufficient to analyse vessel responses in incident regular sinusoidal waves to find the results in irregular waves.

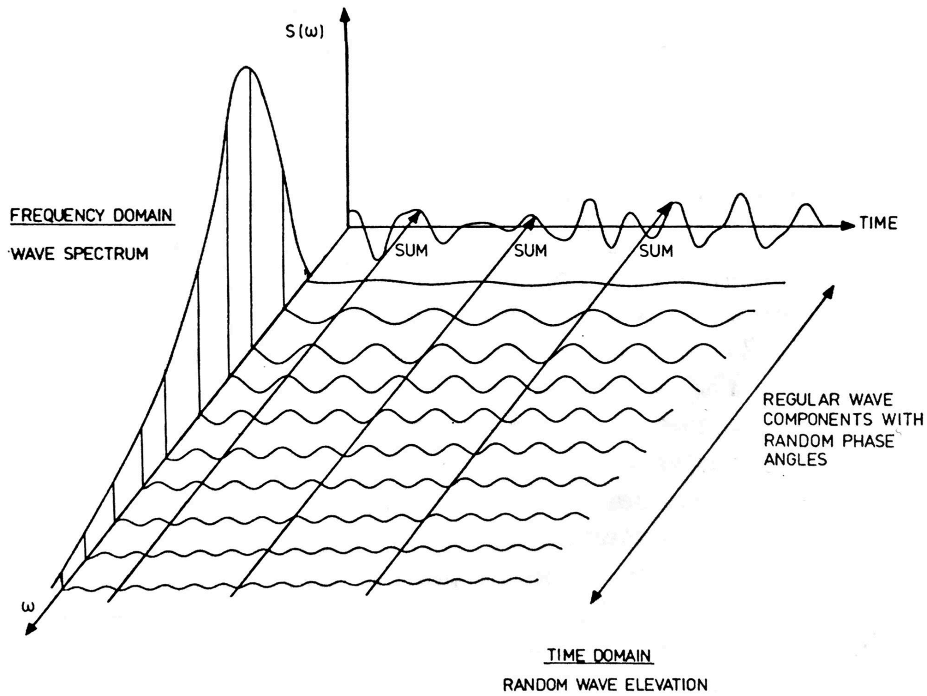


Figure 4.4: Illustration of how the sum of regular wave components in the frequency domain relates to an irregular wave in a short-term sea state in the time domain.

The response spectrum of the vessel is found by combining the response transfer functions with a selected wave spectrum representing the sea state in the area of interest. The resulting response spectrum is a function of wave frequency, as shown in Equation 4.25,

$$S_{yy}(\omega) = |H(\omega)|^2 S_{xx}(\omega) \tag{4.25}$$

where $S_{yy}(\omega)$ is the response spectrum, $|H(\omega)|$ is the transfer function and $S_{xx}(\omega)$ is the input wave spectrum. A transfer function, also known as an response amplitude operator (RAO), is defined as the ratio between the vessel response amplitude and the amplitude of the incoming wave. In other words, the amplitude of the vessel motion in response to an incident wave. RAOs are normally obtained through linear response analysis of regular waves (Steen, 2014). The principles of the relation of Equation 4.25 is shown in Figure 4.5.

Short-term sea conditions are defined by a constant significant wave height (H_S), mean wave period (T_z), wave heading, wave energy spreading and duration. The representation of short-term sea states is made under the assumption that the sea is a stationary random process (Faltinsen, 1999). It is obvious that in a real sea environment, this will not be true over time. Hence, typical durations of short-term description of the sea ranges from 0.5 to about 10 hours. For periods ranging longer than this, a long-term statistics should be applied.

Long-term statistics takes into account the variation of sea states over time. The joint frequency of the significant wave height and the mean wave period is required to describe the long-term sea state, and can be used to show the long-term probability of occurrence for different sea states. It can also be used to estimate the operability of a vessel given a set of operability criteria, which is further discussed in Chapter 5.

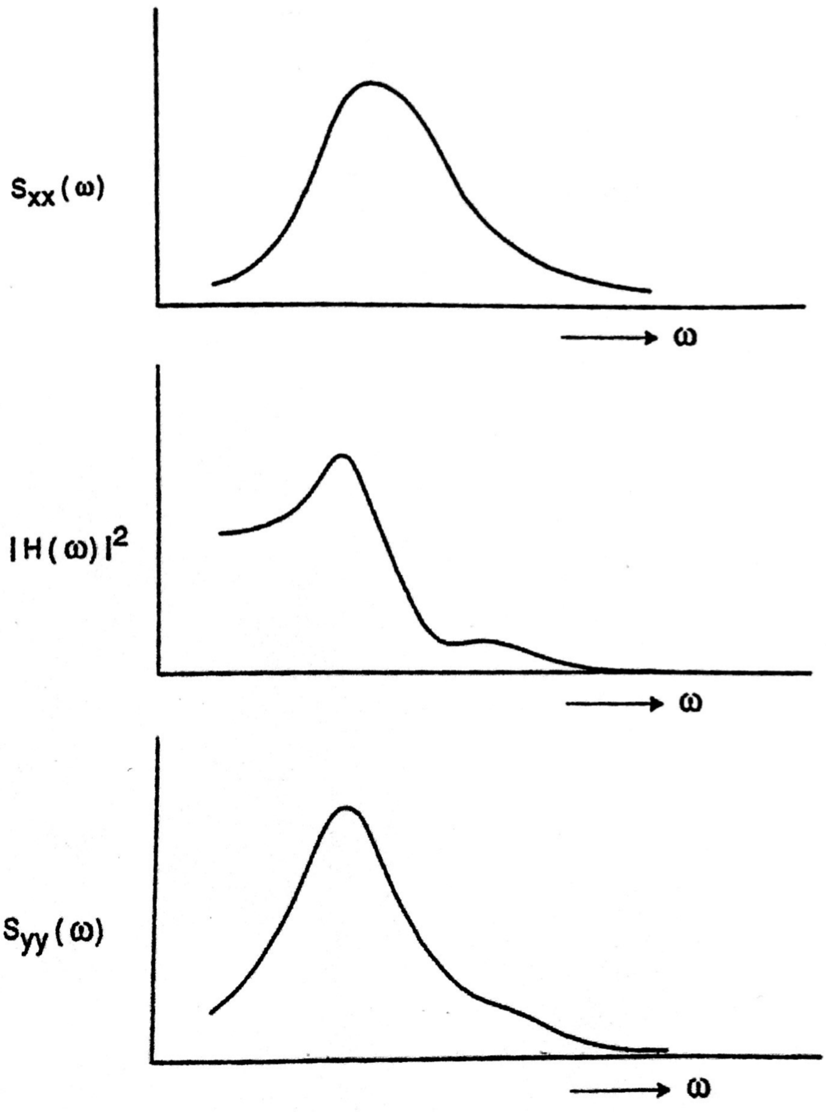


Figure 4.5: The input wave spectrum ($S_{xx}(\omega)$) is combined with the transfer function ($H(\omega)$) to provide the measured response spectrum ($S_{yy}(\omega)$) (Steen, 2014).

Chapter 5

Principles of Assessing Vessel Performance

An important part of developing new vessel designs is to evaluate and compare alternative designs and concepts (Nielsen, 1987). Depending on the situation and the type of vessel, different factors may be emphasised. The operational performance of a vessel as well as fuel efficiency are very often emphasised, since these are factors directly affecting the operational costs in the long term. An important factor in the vessel performance is its ability to withstand the physical environment at sea, also known as seakeeping capability. In order to assess a vessel's seakeeping capability, there must be some criteria and methods by which to measure and verify its performance. This chapter therefore addresses methods for evaluation, as well as the importance of operability criteria in such processes. Further, a discussion on criteria related to vessel motions and human performance will be discussed in the context of the Macho 40. The specification of criteria to be used in the vessel response analysis is covered in Section 6.4.3.

Ships are designed to perform different types of operations in variable sea conditions. For tankers and bulk ships, wave resistance and fuel efficiency may be the most important factors of the performance, while for service vessels in the aquaculture industry, vessel motions and their influence on the operations is likely to be of more significance. Another factor which can influence the performance is the decision-making and general skills and experience of the master and crew on board the vessels. Developing criteria and establish limits of operation could improve their ability to make the right decisions during the operations.

5.1 Method For Evaluation

The purpose of operability criteria is to obtain precise, quantified limits of operation. It is important to develop standardised evaluation methods so that comparison and benchmarking of different designs can be done on equal terms and provide reliable results. Clearly defined operability criteria will also assist operators and decision makers to make the right decisions based on quantitative measures and limits, rather than just experience and intuition which is very much the case today (Hansen, 2017).

Despite the growth of the Norwegian aquaculture industry over the last decades, there is still a lack of standardised methods, procedures and criteria related to vessel operations. As the industry expands and becomes more industrialised, the need for standard procedures and regulations increase accordingly. The research project EXPOSED is currently studying the issue of operability criteria through on-board measurements on a service catamaran. In time, data obtained from such projects can be used to establish standards and precise criteria for specific vessel types and in that way make it easier to evaluate and compare vessel designs and performances.

In this thesis the affection of vessel motions on the personnel and equipment during service operations at the aquaculture site is emphasised when specifying the criteria. Factors like economy, fuel efficiency and vessel speed in a seaway will not be considered.

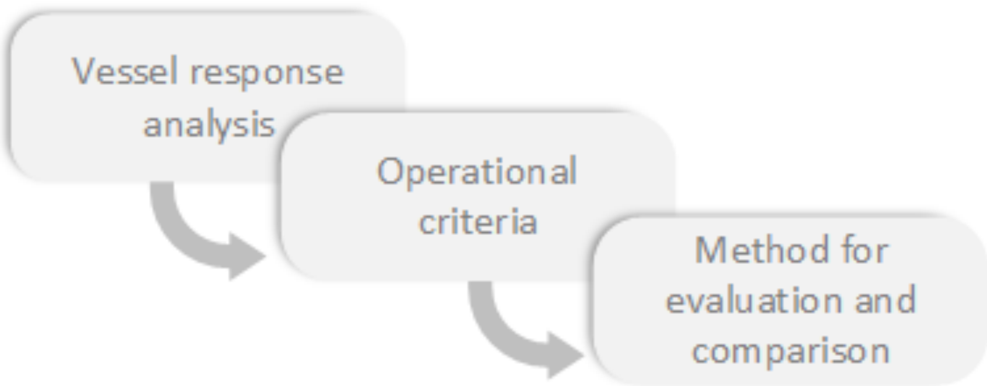


Figure 5.1: The main elements of the vessel performance assessment system.

Figure 5.1 shows the three main elements involved in the process of evaluating the vessel performance in this thesis. The first element is the vessel response analysis, which predicts the vessel motions in an irregular sea environment. The second element is the specification of operability criteria, which is combined with the motion predictions to obtain a set of limiting wave conditions. The final element, the evaluation method, may be done in different ways. Nielsen (1987) developed a "seakeeping performance index" as a measure of the ship's ability to fulfil its function. The method, however, requires extensive amounts of wave statistics in order to provide reliable results. Hence, in this thesis the simulation model will be used for evaluation of the vessel performance. How the vessel response analysis and simulation model is combined will be clarified through Chapter 6 and 7.

5.2 Criteria Related To Vessel Motions and Human Performance

Vessel motions and accelerations are important to consider as they determine loads on cargo and equipment, and are also an important reason for malaise and seasickness amongst passengers and crews (Faltinsen, 1999). The physiological response of a person to the vessel motions is primarily affected by the linear accelerations induced by waves (St. Denis, 1976). However, their effect on a person can not be simply apportioned into the different degrees of freedom, as it is a joint interaction with coupled effects from the different motions. This makes it somewhat hard to derive exact levels of critical motion, but fairly good estimates can be obtained with the help of empirical data and previous studies.

In this thesis, critical levels of motion have been determined based on the findings of a co-operative project on seakeeping performance of ships (Nielsen, 1987). In addition, conversations with Oppland (2017), Hansen (2017) and Lien (2017) have provided useful input to modify certain criteria to suit the specific case of the Macho 40. Depending on the type of operation, different vessel motions can be more critical than others. According to Oppland (2017) the roll motion is by far the most critical to the operations with the Macho 40. In general, operations are ceased if the conditions becomes critical with respect to safety of the personnel or vessel, or if the efficiency of the personnel drops. The latter can be the case during operations which demands a high degree of human involvement and seasickness becomes an issue.

Nielsen (1987) evaluated which responses that matters from the point of view of different operations and ship types. Table 5.1 shows a selection of their findings. It can be seen that roll and pitch are important in most cases, while for instance slamming only has a significant effect on the structural integrity of the hull. In the prediction of criteria, pitch has not been considered since, according to Hansen (2017), pitch motions in themselves are rarely critical during the operations performed by the Macho 40. Some effects of pitch are, however, accounted for in the criteria for vertical acceleration, slamming and deck wetness. Heave and vertical motion should be considered when analysing crane operations, but has been neglected in this case since it would require extensive and detailed analysis of crane operations.

Table 5.1: Important vessel motions for different ship subsystems (Nielsen, 1987).

Ship subsystem	**Slam**	**Deck wetn.**	**Vert. acc.**	**Lat. acc.**	**Roll**	**Pitch**	**Heave**	**Vert. vel.**
Ship hull	•	•	•					
Ship equipment		•	•	•	•	•		
Cargo			•	•	•	•		
Personnel effective-ness		•	•	•	•	•		
Passenger comfort			•	•	•	•		
Lifting (cranes)			•		•	•	•	•

The level of manual work performed by the crew vary depending on the type of operation. Of the operations considered in this analysis (see Section 2.4), only cleaning of net and inspection of the mooring system do not include significant manual work on deck (Oppland, 2017). For the most part, the work performed on deck is heavy manual work involving heavy components and large tensions during crane lifting. The involvement from the bridge during operations often involve a different type of work, and is by Nielsen (1987) defined as "intellectual work". They define it as "work of more demanding nature, performed by people not so well adapted to ship motions". This can for instance be researchers or scientists working on board for a limited period. For the masters and the crew working on the bridge, this is not an accurate definition as they are for the most part well adapted to the motions experienced during operations. Their work is typically cognitive (e.g. supervision, coordination and decision-making), and can be demanding in terms of concentration and endurance. The criteria related to work at the bridge is therefore modified to suit the working crew on the Macho 40 rather than people not so well adapted to vessel motions.

Different types of work on board the vessel enquires different limiting criteria. In order to separate the different types of work and obtain more specific criteria, three working stations has been established on the vessel. Table 5.2 shows the working stations and the typical work at each respective station. The locations are illustrated in Figure 5.2.

Table 5.2: Definition of working stations on board the Macho 40, and the typical work performed at each station.

Working station	**Typical Work**
1. Bridge	Cognitive work
2. Midship ($L_p/2$)	Heavy manual work
3. Aft perpendicular (AP)	Heavy manual work

Vessel motions can cause seasickness and discomfort among the crew, and consequently have adverse effects on their effectiveness and performance. The effect of motions vary for each individual and depends on external factors like ergonomics and type of activity (ISO 2631-1, 1997). The exact range of this issue and its influence on human performance, however, have not been established (Haward, Lewis, & Griffin, 2009). The accuracy of predicting degraded human performance as a result of vessel motions is therefore somewhat limited. Nevertheless, there exist current standards for evaluating vessel motions with respect to human comfort and motion sickness (ISO 2631-1:1997, BS 6841:1987, ABS Guide For Passenger Comfort On Ships).

Laboratory experiments was conducted by McCauley, Royal, Wylie, O'Hanlon, and Mackie (1976) to determine the effect of vessel motions and habituation on motion sickness incidence (MSI). Habituation, or adaptation to vessel motions, describes the declination of motion sickness due to repeated and continuous exposure. The experiments

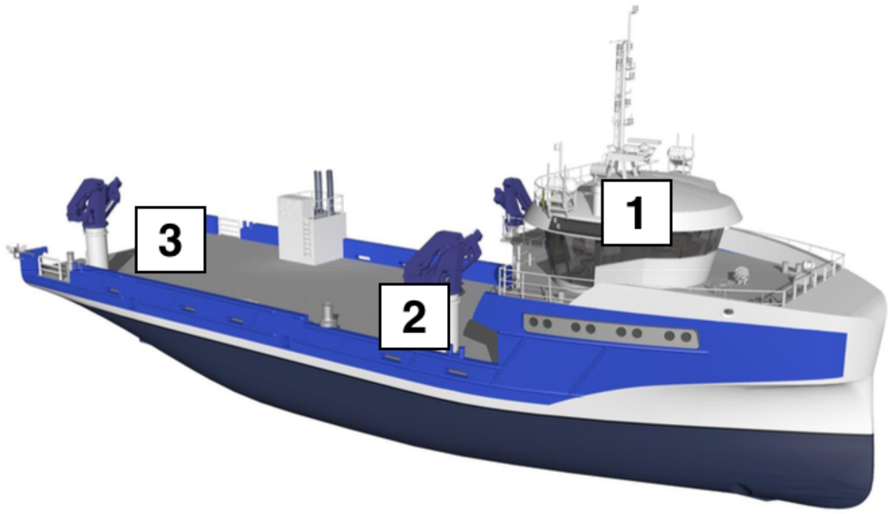


Figure 5.2: Working stations at the bridge (1), midship (2) and aft perpendicular (3) as defined in the analysis. Illustration provided by Møre Maritime AS.

done by McCauley et al. (1976) show a decrease in MSI from 75% to 30% in just five daily 2-hours exposures of 0.22 g vertical oscillation. Even though the experiment had some weaknesses in terms of limited data and sinusoidal wave motions, it can be taken as an indication of the effect of habituation. Haward et al. (2009) studied the effect of motion sickness in terms of task performance difficulties. They found that physical tasks (e.g. lifting, keeping balance, use of tools and equipment) seemed to be more affected by the magnitudes of motion than cognitive tasks like decision-making and coordinating tasks on the bridge.

Ideally, a specific set of operability criteria should be specified for each type of vessel operation performed by the Macho 40. This would provide a more accurate evaluation of the operational conditions and make the basis upon which the decisions are made, more reliable. In order to achieve a reasonable accuracy of such criteria, significant amounts of vessel motion measurements from real-world operations would be required. As this data is not yet available, it is decided to not specify criteria for each type of operation, but for the vessel as a whole. A fair amount of research has been done on criteria for vessel motions related to human performance and seasickness. Since service vessel operations involve a large degree of manual work and general human performance, this forms the basis upon which the criteria are defined.

Chapter 6

Vessel Response Analysis

Analysing wave induced vessel responses is essential when developing new vessel designs. The operability of a vessel can be related to its motions in a seaway and the loads acting on the hull. VERES is a software that can be used to evaluate hydrodynamic motions and loads on existing vessels or in an early design phase of new vessel designs. Hydrodynamic analyses are essential in all vessel design processes and can contribute to improve designs and ensure better vessel performances. In this thesis, the software is used to evaluate the response motions of the Macho 40 and to obtain a set of limiting wave conditions to be used as input in the simulation model. In the following sections, an overview of the method is presented, followed by a description of basic assumptions of the calculations in VERES. Further, the data input used in the analysis and the post-processing of the calculations are discussed, including the specification of operability criteria.

6.1 Method Overview

The methodology for obtaining limiting operational conditions is explained in detail by Fathi (2012). The approach is, however, quite straightforward and will now be briefly explained. Figure 6.1 shows a schematic overview of the applied methodology and its main elements. The vessel geometry of the Macho 40 is imported into VERES where transfer functions are determined in six degrees of freedom based on a specified vessel description and loading condition. In combination with a wave spectrum (see Equation 4.25) the vessel response in irregular sea is then calculated, before the operability criteria are applied. The combination of criteria and vessel response provides the limiting wave conditions, given as significant wave heights as a function of wave period.

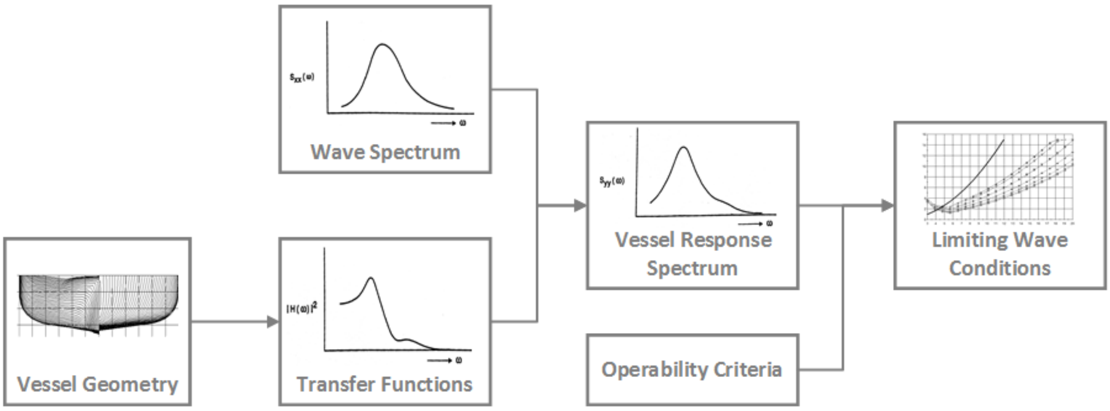


Figure 6.1: Schematic overview of the sequence of calculations performed in VERES to obtain operational limits.

The vessel response analysis itself is in fact completed once the transfer functions are obtained, i.e. at the second element of the figure. The application of wave spectrum and operability criteria are not affecting the response calculations, and are only part of the post-processing.

6.2 Basic Assumptions of VERES Calculations

The theoretical background for response calculations in VERES are based on several assumptions and theories. This section presents a brief summary of the main assumptions of the program. A more detailed survey on the theory was reviewed in Chapter 4. In short, the basic assumptions in VERES are:

- Traditional strip theory, implying that the three-dimensional hull is divided into two-dimensional "strips". The total forces are found by integrating the forces on each two-dimensional cross-section.
- High speed theory, implying that the interaction from upstream strips is accounted for.
- Slender body is assumed, meaning the hull length is much larger than the beam and draught.
- Linear relation between vessel response and wave amplitude. This is not valid for

large wave heights.

- The vessel oscillates harmonically equal to the encounter frequency.
- Potential theory, i.e. homogeneous, incompressible, irrotational and inviscid. However, viscous damping effects can be taken into account by empirical formulas.
- Loads and motions are derived according to the superposition principle.
- The vessel is assumed symmetric about the centreline

As can be seen from the list above, VERES uses strip theory and assumes a slender hull. This simplification is used to reduced the calculation time, as the three-dimensional problem can be reduced to many two-dimensional problems along the length of the hull. This method is good for hull designs where three dimensional effects are not dominating, i.e. tankers. For smaller vessels and complex hull shapes, the accuracy may not be as good. Despite the fact that the simplifications may neglect some important effects, the approach has been found to give good results compared to empirical tests (Fathi, 2012).

6.3 Data Input

Prior to the response calculations, it is important to give the correct input and to run a *data check* to verify the model. This is done by manually providing values to describe the vessel dimensions, loading condition, environmental conditions and roll damping effects. The following sections will present a step-by-step description of the considerations regarding the input used in the analysis.

6.3.1 Vessel Description and Loading Condition

When the vessel geometry is imported into VERES, main particulars of the vessel must be defined and the wanted loading condition must be specified. The Macho 40 can operate in a number of loading conditions depending on the type of mission to be performed. In their stability report, Møre Maritime AS have performed stability calculations for 17 different loading conditions. However, for the case of this analysis only one loading condition has been selected. Based on conversations with Hansen (2017), Oppland (2017) and Johnsen (2017) it was decided that fully loaded ballast tanks, ready for departure would be a relevant loading condition suitable for most operations. An excerpt from the stability report describing this particular loading condition can be found in Appendix E.

Based on the data in the stability report, the design draft is defined in VERES. For the case of the ballast condition, this is taken as the mean draft given as d = 3.335 m. In Figure 6.2 this corresponds to the vertical distance between the red and blue line. The vessel's displacement tonnage, δ, at the given draft is estimated to 929.16 t. The hydrostatic data report obtained in VERES gives approximately the same results, and is presented in its entirety Appendix F.

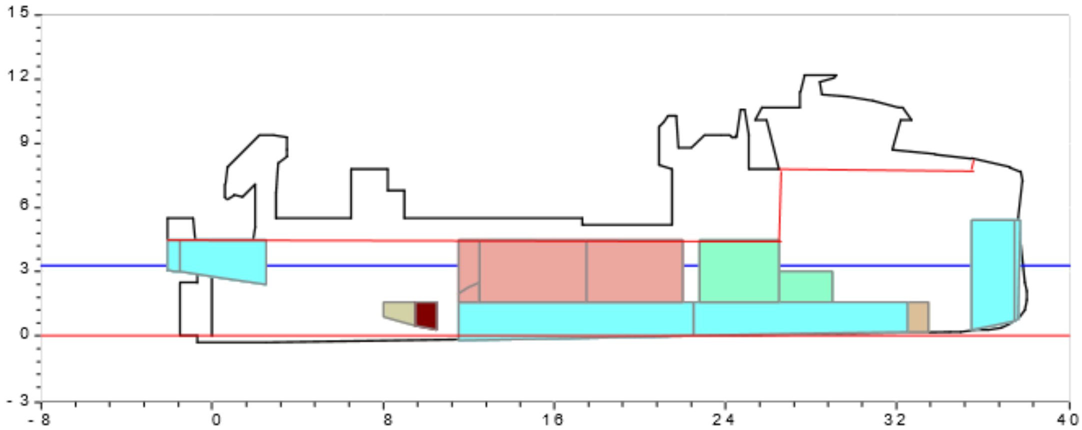


Figure 6.2: Lateral plane, view from starboard. The illustration shows the loading condition selected for the analysis, where the mean draft is indicated by the distance between the blue and red line. Illustration provided by Møre Maritime AS.

Mass moment of intertia are specified by r_{44}, r_{55} and r_{66}, the radius of gyration in roll, pitch and yaw, respectively. The coupled radius of gyration in roll-yaw is often neglected (Fathi, 2012). The radius of gyration refers to the mass distribution of the components about the centre of gravity. According to Fathi (2012), typical values for a monohull are as given in Table 6.1. The rightmost column shows the values applied in the analysis.

The values of the radius of gyration depends on how the vessel is equipped and modified. Heavy components is likely to affect these values, particularly if they are placed a distance from the centre of gravity. However, since this analysis assumes a normal ballast condition without any special equipment or other components, the typical values given in the table has been considered applicable.

Table 6.1: Typical and applied values for radius of gyration in roll, pitch and yaw (Fathi, 2012).

Parameter	**Typical values**	**Applied values**
r_{44}	$0.30B$ - $0.45B$	4.20 m
r_{55}	$0.20L_p$ - $0.30L_p$	10.0 m
r_{66}	$0.25L_p$ - $0.30L_p$	10.0 m

6.3.2 Roll Damping

As discussed in Section 4.2.1, a reasonable accuracy for calculating roll motions can be obtained only if a correction for viscous damping is included. Due to the shape of a conventional hull, its ability to generate waves in roll is low, and so the level of roll damping is limited. Other means like bilge keels and roll stabilizing fins and tanks are often implemented to increase the damping effects and reduce the roll. Near resonance, the motions are highly dependent on the damping, hence it is very important to include viscous damping in the calculations. If it is neglected, the calculations will provide unrealistic response motions (Fathi, 2012). The bilge keels on the Macho 40 are included in the analysis by manual implementation. In addition, frictional damping by skin friction stresses on the hull and eddy damping from pressure variations are included in the calculations.

Some viscous effects have a non-linear relation to the wave amplitude. To account for this, the non-linear effects are linearised through an input wave amplitude corresponding to the mean value of the operating wave heights. A wave amplitude of 2 metres is therefore chosen, corresponding to a maximum operating wave height of 4.0 meters. In this case, the selected value is chosen with respect to an approximated maximum operating wave height, to assure that non-linear effects are accounted for in the entire operating range of wave heights.

6.3.3 Environmental Condition

The final step before running the analysis is to describe the wave environment. This is where vessel velocities, wave headings and wave periods to be used in the analysis are specified. The range of wave periods to be chosen must be large enough to cover the entire wave spectrum for later short-term statistics. For this analysis a waver period range from 3 to 20 seconds is chosen.

In order to get reasonable results from VERES when calculating the response in short-crested sea, the resolution of wave headings are essential. Short-crested sea is generated by local wind fields, and are often both irregular and directional. It may therefore be difficult to distinguish wave fronts and observe the actual wave direction. This is as opposed to long-crested sea, or swell, which tend to be both regular and unidirectional. According to Fathi (2012), a resolution of at most 30°between each heading and minimum seven headings within the wave spreading interval, should be applied for a cosine squared distribution. Cosine squared distribution will be further explained in Section 6.4.2. After consulting with Fathi (2017), it was decided to apply wave headings with 15°intervals from 0°to 345°.

6.4 Post-Processing

When the response calculations are completed, the analysis goes on to the post-processing part. This is where the wave spectrum is chosen, operational criteria specified and results obtained and plotted in the form of transfer functions and limiting wave conditions. This section will elaborate on the relevant parts of the post-processing for this analysis.

6.4.1 Transfer Functions

As discussed in Chapter 4.3, the vessel response in irregular sea can be calculated by combining a number of regular waves. The motion response in regular waves are presented as transfer functions, or response amplitude operators (RAOs). Figure 6.3 shows the transfer function in heave for the Macho 40 for four different wave headings. The response is divided by the wave amplitude, making it dimensionless. It can be seen that for short waves the response is small, while for long waves the response converge towards a unit wave amplitude and are dominated by hydrostatic effects (Fathi, 2012). For wave periods between three and five seconds, a small drop can be observed for some wave headings. This is a result of cancellation effects occurring for wave lengths close to the vessel length. Transfer functions for roll and pitch are presented in Appendix K.

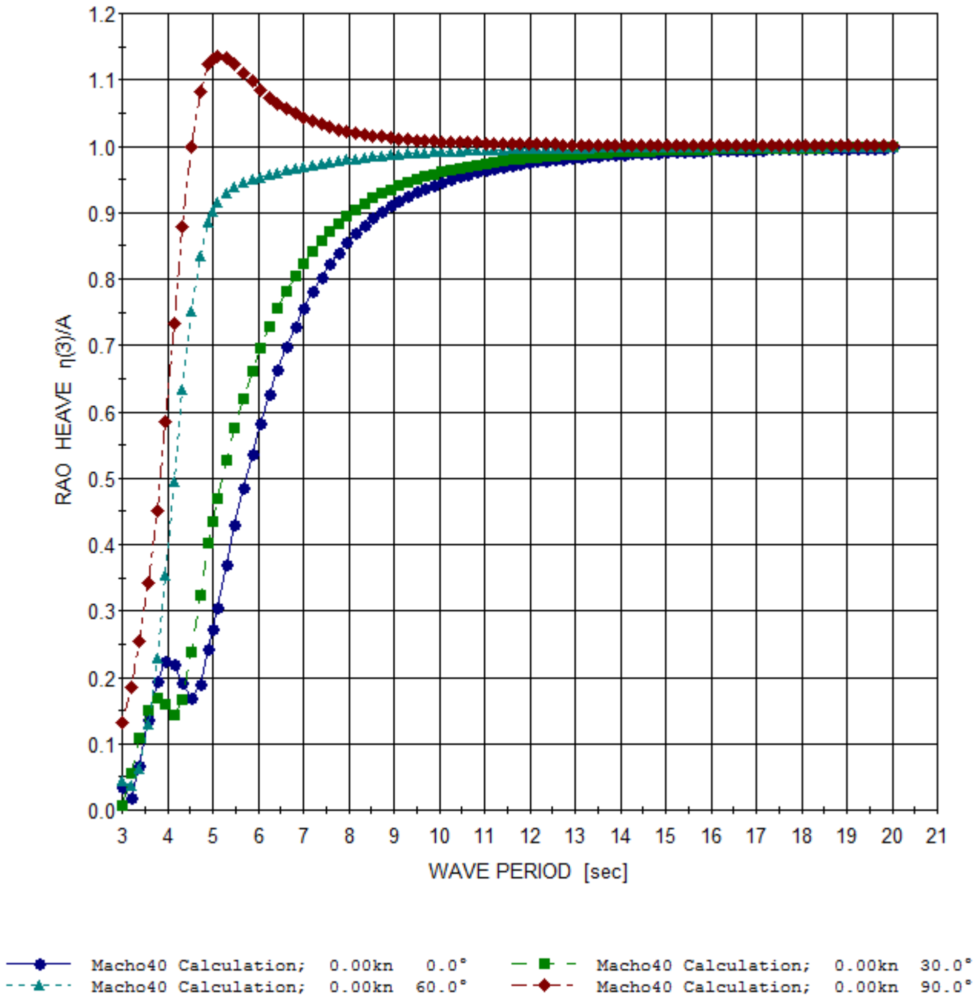


Figure 6.3: Transfer function in heave for the Macho 40. The cancellation and resonance effects can be observed for wave periods in the range of 3-6 s.

The resolution, or the number of data points close to the resonance frequency, is extremely important to obtain reliable results. Too low resolution means that peak values and consequently important motion effects can be ignored. This is illustrated in Figure 6.4, where the number of periods close to resonance is reduced. Compared to Figure 6.3, it can be seen that neither cancellation effects nor the resonance peak are properly captured. A sufficient resolution is equally important for all transfer functions. Since the resonance and cancellation effects in heave, roll and pitch all occur within the interval of $4 < \mathrm{Ts} < 8$, a higher resolution has been applied in this region.

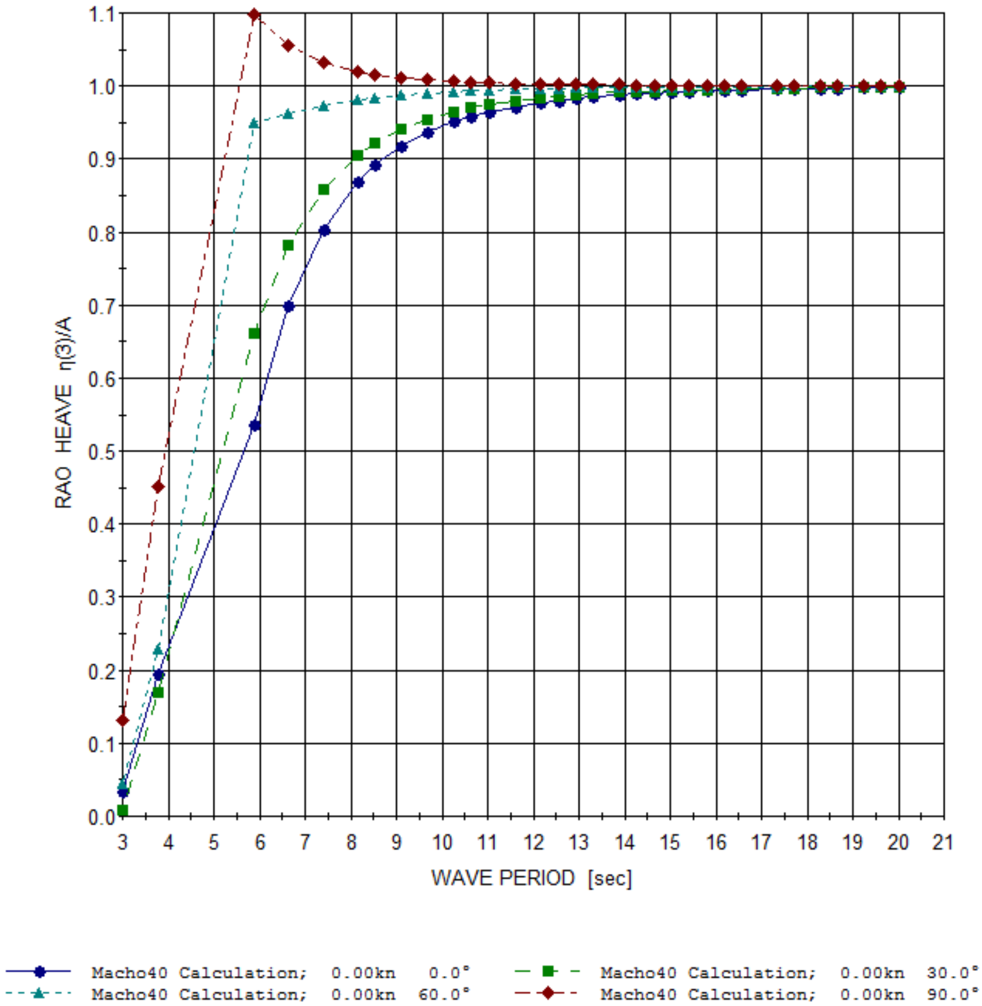


Figure 6.4: Too low resolution of wave periods means that cancellation effects and resonance peaks are not properly captured compared to the transfer functions in Figure 6.3.

6.4.2 Wave Spectrum

The results from the analysis is highly dependent on the choice of wave spectrum. A wave spectrum is mathematical representations of a certain sea state, and can be understood as the harmonic content of the wave height over the frequency range (Nielsen, 1987). By choosing the right wave representation for the area of interest, a more realistic result will be obtained. The regular wave spectra, upon which the RAOs are defined, do not exist in a real sea environment. In reality, the wave amplitudes and periods vary over time, causing an irregular sea state. Three standard irregular wave spectra are available in VERES; Pierson-Moskowitz, Joint North Sea Wave Project (JONSWAP) and Torsethaugen.

- *JONSWAP*
  Wave spectrum based on measured data from the North Sea. It does not represent a fully developed sea state, i.e. the wind has not been blowing long enough over a large stretch of open water. A peakedness factor, γ, is used to specify the concentration of waves about the peak period.

- *Pierson-Moskowitz*
  Fully developed sea state, which means that high frequency waves due to wind has reached equilibrium (Fathi, 2012). It is equivalent to the JONSWAP spectrum with $\gamma = 1.0$, and waves are on the verge of breaking. It is based on data from the North Atlantic ocean.

- *Torsethaugen*
  Two-peak spectrum, meaning it includes both low-frequent swell and high-frequent wind-generated waves. Typically used in analysis of some offshore installations where the sea is a combination of both swell and wind generated waves.

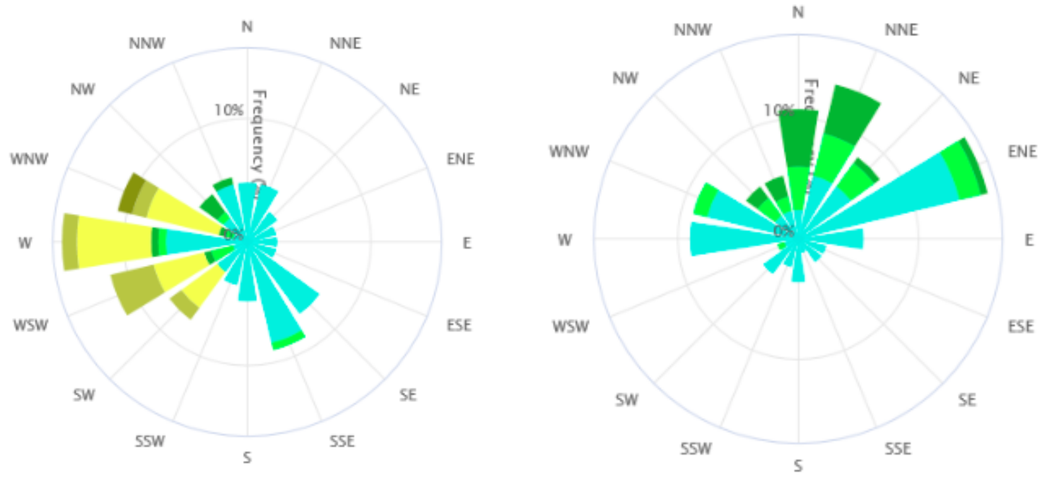
Specifying a correct wave spectrum for the two aquaculture locations at Salatskjæra and Valøyan is challenging due to the high density of islets and varying water depth in the area. Based on the available wave data, it seems there are both swell and wind-generated waves at both locations. In principle this should mean that the fully developed two-peak spectrum of Torsethaugen should be applied. However, even though swell is present at the locations, it does not necessarily mean it is fully developed due to disturbances from nearby islets, skerries and shallow water.

Another aspect to consider is how much swell actually affects the vessel operations. A swell is waves generated by distant weather systems and is often characterised by long wave periods and small steepness. In terms of vessel motions, this generally means that the vessel will follow the motion of the wave. Since this is also the case for the motion of floating cage structures, the relative motions are likely to be small and not severe to the operations. For some specific operations or combinations of wave period and direction, however, the swell could have an impact on the operations, and should be considered accordingly.

For the purpose of this analysis, a short-crested JONSWAP spectrum is applied, as it is expected to provide the most authentic results. The main reason is the assumption that wind-generated waves have a much larger influence on the operation than low-frequent swell. The fact that the wave system is disturbed by surrounding islets and shallow water also contributes to the decision of not choosing the fully developed spectrum of Torsethaugen in the analysis. A *short-crested* spectrum is applied to ensure the most realistic results from all wave directions. Long-crested waves would in most cases provide more conservative results, since all the energy will be concentrated in one direction. An exception would be in the case of head sea, where long-crested waves will not induce any roll motions (Fathi, 2017). Also, long-crested waves are more common in swells and are rarely encountered in wind-generated waves. The decision of applying a short-crested spectrum is therefore also linked to the assumption of neglecting the influence of low-frequency swell to the operations.

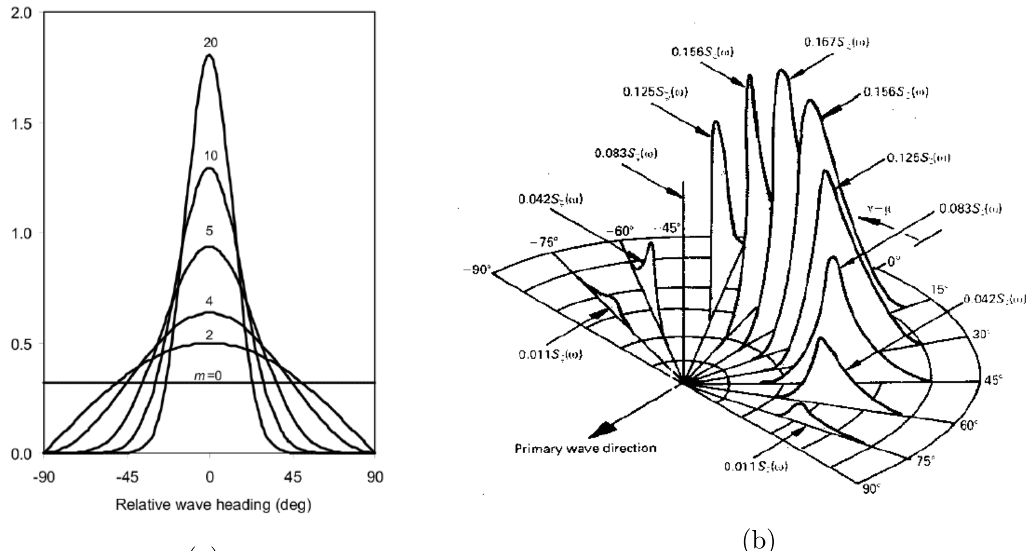
Figure 6.5 shows how the spreading of incoming waves are distributed on the two locations Valøyan and Salatskjæra. It can be seen that some headings are more exposed than others, and that the major part of waves are distributed over approximately 180°on both locations. In other words, the sea state is short-crested and not uniformly distributed over all directions. A common way to describe short-crested sea is with a wave spreading index $m = 2$, commonly referred to as a cosine squared distribution, and a wave spreading angle of $v_{max} = 90°$.

The wave energy distribution for different values of m is shown in Figure 6.6a. For $m = 0$, the wave energy is uniformly distributed for all directions, and is increasingly concentrated with increasing value of m. Figure 6.6b shows the distribution of the wave spectrum applied in the analysis with $m = 2$, $v_{max} = 90°$ and a discrete heading interval of 15°.



(a) (b)

Figure 6.5: Rose diagrams showing the direction of incoming waves for one week of buoy measurements at the locations at Valøyan (a) and Salatskjæra (b) (EXPOSED, 2017).



(a) (b)

Figure 6.6: Wave energy spreading for different values of m (a) and the directional wave spectrum for heading intervals of 15° and a cosine squared distribution over ±90°(b) (Fathi, 2012).

6.4.3 Operability Criteria

To determine the criteria for the Macho 40, the method applied by Nielsen (1987) has been used. Acceleration and roll criteria are presented as root mean square (RMS) values in Table 6.2 while values for slamming and deck wetness are given as permissible probabilities in Table 6.3, where permissible probability is to be understood as the number of events per hundred wave encounters (Nielsen, 1987).

The basis for the assigned values are the assumption of heavy manual work midship and aft, and cognitive work on the bridge. The rest of this section will elaborate on the quantification of each criterion and explain any adjustments made to suit the specific case of the Macho 40. Additional information, tables and figures regarding operability criteria can be found in Appendix G.

Table 6.2: Acceleration and roll criteria as root mean square (RMS) values at the three working stations. g = acc. of gravity = 9.81 m/s^2.

Criterion	**Bridge**	**Midship**	**AP**
Vertical acc.	0.15 g	0.15 g	0.15 g
Lateral acc.	0.1 g	0.07 g	0.07 g
Roll deg	4 deg	4 deg	4 deg

Table 6.3: Limiting criteria for slamming and deck wetness. Probabilities are gives in terms of events per hundred wave encounters.

Criterion	**Probability**
Slamming	0.03
Deck wetness	0.05

Vertical Acceleration
Acceptable limits of vertical acceleration depends on both the type and size of the vessel. For instance, due to the wide spectrum of high frequencies, small fast crafts will have much higher limits than for instance a large merchant ship. In general, humans have a much higher tolerance to motions at high frequencies than at low frequencies (Payne, 1976). The criteria for vertical acceleration given in Table 6.2 are based on the intended work at each working station. According to Nielsen (1987), cognitive work is limited to

0.1 g, g being the acceleration of gravity. However, this value is intended for people not well adapted to vessel motions. Since the crew on the Macho 40 is well adapted to vessel motions, it is decided to increase the limit on the bridge to 0.15 g. Amidships and at the stern working position, the limiting criteria is also set to 0.15 g. This is in accordance with the values for heavy manual work as defined by Nielsen (1987).

Lateral Acceleration

Applebee and Baitis (1984) allow a lateral acceleration on the bridge of 0.1 g based on crew safety and performance in the U.S. Navy, while Nielsen (1987) suggests a limit of 0.05 g for cognitive work. The work at the bridge on a navy vessel and the Macho 40 can be compared in terms of operation management, coordination and navigation. It is therefore decided to apply the same limit for lateral acceleration on the bridge as suggested by Applebee and Baitis (1984). During heavy manual work on deck, large forces are often involved and the probability of falling into the sea is present. The ability to keep balance in such situations is important, and the limit for lateral acceleration is hence set quite low at 0.07 g at working station 2 and 3. This is in compliance with the values presented by Nielsen (1987) for heavy manual work.

Roll

As for the vertical and lateral accelerations, roll is a parameter affecting the ability of keeping balance. According to St. Denis (1976), the critical angle for safe footing appears to be about 14 degrees. Nielsen (1987) found that the limiting RMS value for roll can not be more than 6 degrees, if the criteria of safe footing at 14 degrees is to be met. In the same report it is suggested that a limiting roll criteria of 4 degrees RMS is often used to ensure a maximum level of crew effectiveness on board naval vessels. The same criterion is considered relevant for the Macho 40 and applied on all three working stations.

Relative Motions Between Vessel and Waves

Slamming and deck wetness are largely determined by relative motions between the hull and the waves, and are important when considering the seakeeping performance of a vessel. The relative motions are calculated in VERES under the assumption that the waves are undisturbed by the presence of the vessel (Fathi, 2012). These assumptions are likely to be reliable only in the forward area of the vessel, since further aft the waves will be affected by the presence of the hull.

Slamming occurs when the hull bottom hits the water surface with a high velocity. For this to happen, the location to be considered must come out of the water surface, and the pressure at re-entry must exceed a certain threshold value considered a slam (Fathi, 2012). In VERES, the limiting significant wave height is obtained from Ochi's (1964) definition:

$$H_s^{lim}(T_p) = \sqrt{-\frac{1}{2\ln P_s}\left(\frac{d^2}{g_r^2} + \frac{V_{cr}^2}{g_{rv}^2}\right)} \tag{6.1}$$

where,

P_s = permissible probability of slamming
d = local draft
g_r = RMS value of relative vertical motion per meter H_s
g_{rv} = RMS value of relative vertical velocity per meter H_s
V_{cr} = critical re-entry velocity

In VERES, the critical re-entry velocity can be determined based on Ochi's (1964) definition, a user-specified value or a user-specified critical pressure. In this thesis the former is applied, and the critical re-entry velocity is hence given in Equation 6.2, where g is the acceleration of gravity and L is the vessel length. The permissible probability of slamming applied in the analysis is 3%, which is the value recommended by Nielsen (1987).

$$V_{cr} = 0.093\sqrt{gL} \tag{6.2}$$

Deck wetness is a relative term, and may include different degrees of wetness from spray to green water. The limiting criteria applied in this thesis will only consider green water, which occurs when the amplitude of relative motion exceeds the freeboard of the vessel. Fathi (2012) defines the limiting significant wave height due to the probability of green water on deck as in Equation 6.3, where P_{dw} is the permissible probability of deck wetness and F is the freeboard at the considered longitudinal position. The permissible probability of deck wetness applied in the analysis is 5%, which is the value recommended by Nielsen (1987).

$$H_s^{lim}(T_p) = \frac{F}{g_r\sqrt{-2\ln P_{dw}}} \tag{6.3}$$

Motion Sickness

The MSI according to ISO 2631-1:1997 is used as basis for defining criteria related to motion sickness. The criteria suggested in the regulations are meant for unadapted adults. Hence, some modifications are done to account for the crew's adaptation to vessel motions. The MSI is in practice the percentage of people who may vomit, and is determined using frequency weightings for one-third octaves of the encounter frequencies (Fathi, 2012). It is defined as $K_m \cdot MSDV_z$, where K_m is a constant varying according to the population to be investigated. For a mixed population of unadapted male and female adults, $K_m = 1/3$. The motion sickness dose value (MSDV) is calculated from the frequency-weighted RMS of the vertical accelerations, and is given by:

$$MSDV_z = a_z\sqrt{T_0} \tag{6.4}$$

where a_z is the vertical acceleration and T_0 is the exposure period (Fathi, 2012). A graph showing the boundaries for severe discomfort according to the ISO 2631-3:1985 can be found in Appendix G. These values are based on a K_m value of 1/3, and is thus not intended for an adapted crew. It has therefore been decided to adjust this parameter to better suit the particular case of the Macho 40. As discussed in Section 5.2, the physical tasks seems to be more affected by the magnitudes of motion than the typical work at the bridge. The criteria for work on the bridge is consequently considered somewhat different than for the other two working stations. With a basis in the given values in the regulations, the exposure time has been set to 2 hours and a motion sickness incidence ratio of 16%, corresponding to approximately one out of six crew members vomiting when exposed for two hours. K_m has been set to 0.15 at the bridge and 0.2 on the other two working stations. The values applied are summarised in Table 6.4.

Table 6.4: Applied parameter values for limiting criteria on motion sickness according to ISO 2631:1-1997.

	MSI [%]	**Exposure time [h]**	K_m **[-]**
Bridge	16	2	0.15
Midship	16	2	0.2
AP	16	2	0.2

Chapter 7

Performance Analysis via Discrete-Event Simulation

This chapter covers the performance analysis of the Macho 40 and the development of the simulation model used for this purpose. As discussed in Chapter 5, the vessel performance is here defined as its ability to perform the intended tasks in a safe and reliable manner, also referred to as operability. For the purpose of this analysis, which only considers the hydrodynamic aspect of the operations, the operability is assessed with respect to the operational limits obtained from the vessel response analysis in VERES and wave data from the oceanographic buoys.

Section 7.1 begins with an overview of the model to explain the aim and the extent of the analysis, before the basic theory of simulation is presented in Section 7.2. Further, the data input used in the analysis will be presented followed by a step-by-step review of the entire simulation model. The software used to develop the model and run the analysis is Simulink, a graphic programming platform for simulation of dynamic systems.

7.1 Model Overview

The aim of the simulation model is to imitate and assess the performance of the Macho 40 in day-to-day operation over time. Further, it is desirable to show how such a model can be used to assess the long-term performance of a specific vessel design, and by such provide valuable information on operability, or other aspects such as seasonal variations. The results may then be used to compare other vessel designs implemented in the same model structure, and thereby provide feedback on how design changes affects the long-term performance of the vessel.

The system, which was introduced in Section 2.3, consists of one vessel, one port and two aquaculture sites. Limiting wave conditions and measured wave data from the buoys are used as input, while the output from the model is the vessel's long-term operability. The model itself is fairly complex, and will be described in more detail in Section 7.4.

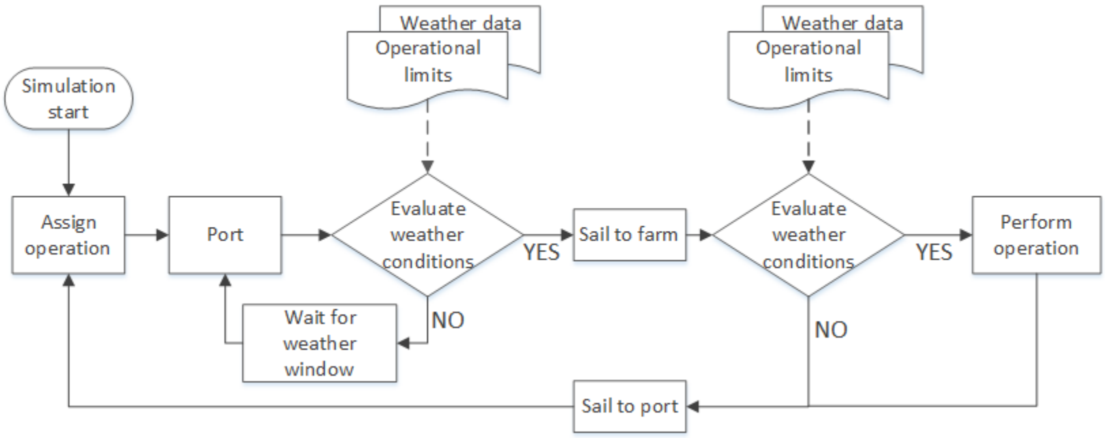


Figure 7.1: Flowchart of the simulation model as organised in Simulink.

A simplified flowchart of the model is presented in Figure 7.1. As the simulation time runs, the vessel is requested to perform operations at the farms. Once a request is made, a decision of whether or not to perform the operation is taken based on the current sea conditions at the current location. If the conditions are within the allowable limits, the vessel sails towards the location. Upon arrival, it performs the requested operation if the conditions are still within the allowable region, before returning to port. If the conditions have changed during the sailing and exceeds the limits upon arrival, the operation is cancelled and the vessel returns to port. Once returned, the vessel waits for the next operation request to be made.

7.2 Basics of Simulation

Simulation can be defined as an imitation of a real-world process or system over time. A definition of a *system* was proposed by Schmidt and Taylor (1970) as a collection of entities that act or interact together toward the accomplishment of some logical end. Entities can be understood as people, machines, or as in the case of this thesis; vessels. Figure 7.2 shows different ways in which systems might be studied. They may be evaluated based on experiments with the actual system or by model experiments, which can be both physical and mathematical. In order to do mathematical studies of such systems, a set of assumptions about how it works is often needed (Law, 2007). Some models may be simple enough for it to be studied by applying analytical methods. However, many systems are too complex to be solved analytically, and must rather be studied numerically through simulation models.

Studying systems can be done to gain knowledge of the interaction between various components in the system itself, or to evaluate and predict performance due to changing conditions and assumptions. Alternative designs or operating conditions can also be compared to see which best meets the pre-set objectives of the study. The state of a system is defined by a set of state variables required to describe the system at a particular point in time. For an aquaculture system, examples of variables are the number of vessels in operation, the number of aquaculture locations waiting to be served by a vessel and so on.

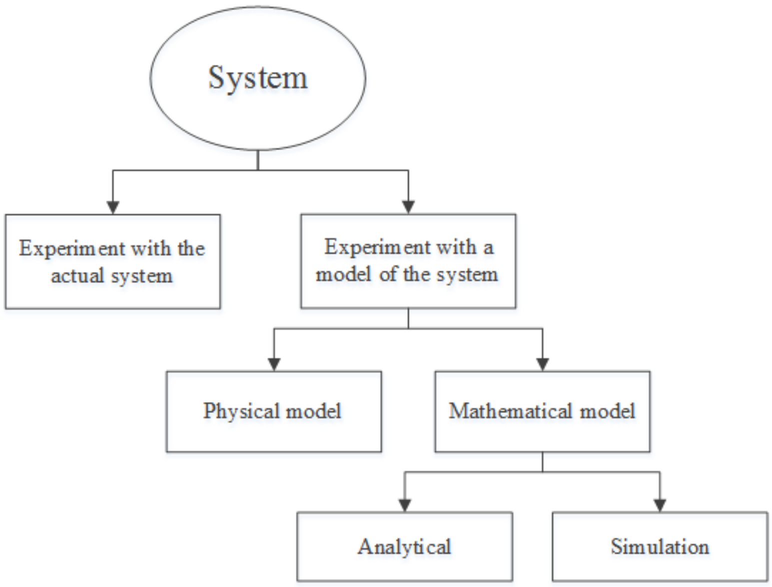


Figure 7.2: Different ways to study a system as suggested by Law (2007).

It is common to categorise systems into two types; *continuous* or *discrete*. A continuous system is one for which the state variables changes continuously over time, while a discrete system is where the variables change instantaneously at specific points in time. A continuous system is not always modelled by a continuous simulation model, and vice versa. The reason is that most systems are not completely continuous or completely discrete. The decision of whether to use a discrete or continuous model to simulate a specific system depends on the objective of the study (Law, 2007). It can be argued that the scenario modelled in this thesis is a continuous system, as the vessel moves through the sea where speed and position in reality changes continuously with respect to time. However, since the objective of the simulation is the performance, movement and characteristics of only one individual vessel, a discrete model is more relevant. A continuous model would be better if a fleet of vessels could be treated "in the aggregate" and the characteristics of the individual vessel was not of interest.

In addition to the classification of discrete and continuous, simulation models are also typically divided into *static* or *dynamic*, and *deterministic* or *stochastic*. A static simulation model represents a system in which time has no impact, while a dynamic model represents a system over time. If a model is deterministic, it does not contain any randomness. In other words, the outcome of the simulation is determined once the input is specified. Most systems, however, must be modelled with some random input components and thus become stochastic. A consequence of stochastic systems is that the outcome of the simulation is random, and only provides estimations of the true system characteristics.

The simulation model developed in this thesis can be characterised as a discrete-, dynamic- and stochastic simulation model. The points in time of which the state variables change are the ones at which *events* occur. An event is by Law (2007) defined as an instantaneous occurrence that may change the state variables of the system. Discrete simulation models driven by events are therefore often referred to as *discrete-event* models.

7.3 Data Input

The input components of a stochastic simulation model is of great significance to the results of an analysis. In this model there are three categories of input; the frequency and duration of service operations to be performed, wave data to specify the sea environment and the operational limits obtained from the vessel response analysis. In the following, each of these will be presented along with necessary assumptions and modifications.

7.3.1 Frequency and Duration of Service Operations

The operations considered in the model are divided into five main categories and eight operations (see Table C.1 in Appendix C). Due to the unpredictable nature of aquaculture production, the frequency and duration of different operations is hard to anticipate (Hansen, 2017). Each individual farming facility is unique in terms of maintenance and support due to variations in environmental conditions, geography and other factors like outbreak of salmon lice and diseases. The questionnaire in Appendix H was given to Hansen (2017) and Oppland (2017), the master and chief officer at M/S "Frøy Fighter", and is used as basis to determine the frequency of occurrence as well as the duration of the service operations. The values applied in the simulation model is shown in Table 7.1.

Table 7.1: Frequency of occurrence and duration of vessel operations. All values are given in hours, as this is the unit time in the simulation model.

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

The frequency of occurrence is to be interpreted as the time between each time a certain operation is requested at a farming facility. The frequencies are modelled according to a normal distribution, with a mean value and standard deviation. The standard deviations depend on the uncertainty related to the different operations, and are determined based on input from the crew at M/S "Frøy Fighter". For example, *inspection of anchor and mooring system* is an operation which is performed about once a year (Oppland, 2017). However, there are no exact regulations for this type of operation, and so there may be a relatively high degree of uncertainty as to when exactly the operations are performed. The same goes for *general support missions*, *cleaning of floating collar and bottom ring* and *installation and removal of nets*, which are all assigned a relatively high standard deviation. Net inspections and tensioning of moorings are performed quite regularly and is therefore specified with a lower standard deviation. Delousing is very hard to predict as it is highly irregular and varies from season to season. Hansen (2017) and Oppland (2017) suggests that each location in the area around Frøya and Hitra require delousing operations approximately 2-3 times per month. Hence a frequency of 12 days is applied.

Regular inspections are fairly predictable with respect to when they are performed and can be modelled according to regulations. Each farming facility is required to have inspections after 3, 6 and 12 months on a regular basis (Hansen, 2017). Hence, for each of the two locations in the simulation model, regular inspections are required at specific times of the simulation. The duration of such inspections vary, and a 12 month inspection is typically more comprehensive than a 3 month inspection. For simplicity and with consultation from Hansen (2017), an average duration of 40 hours is specified for all regular inspections in the model.

As can be seen in the table, the durations for all operations are specified as fixed values. They only concern the actual time of operation at the facility. The durations should ideally be modelled with an element of variation and uncertainty, but are fixed due to restrictions in Simulink regarding entity attribute values. The input values given in the table are determined in days, weeks and months and then transformed to hours since this is the unit time value applied in the simulation. A consequence of this is that the values may seem very specific compared to the high degree of uncertainty present. The assumption in this transformation is that one day corresponds to 24 hours, one month to 30.5 days and a year to 365 days. For an operation performed once a year, the mean value specified is 8,760 hours.

7.3.2 Wave Data From Oceanographic Buoys

The wave data applied in the simulation is the on-site measurements from buoys at the two locations at Valøyan and Salatskjæra. The buoys are located at more exposed locations some distance away from the actual aquaculture facilities, which means that the actual conditions at the facilities may be somewhat different. The data is measured as mean values of the last 15 minutes of every hour. Wave heights, periods and directions as well as currents and wind are measured, but only the significant wave height H_S and the mean wave period T_z are used in the analysis. The measurements, which are still active, began in early 2016. The data series from the two locations have been modified so that they both begin and end at the same date. It stretches from March 9th 2016 to March 28th 2017, and contains a total of 9,109 hours of measured data. Since the data is used as the actual conditions at the two locations in the simulation model, this is also the duration of the simulation analysis.

Before using the data in the analysis, some modification of the wave period should be done. The resolution of the data appears to be discrete with a fixed gap between each measured wave period. The left-hand scatter diagram in Figure 7.3 illustrates this, where a grid-like pattern can be observed. In reality, wave periods may have any continuous value, and is not distributed in discrete values. Andersen (2009) provides a means of solving this problem by randomisation. All wave periods are re-calculated according to

$$T_z = A \cdot \exp\left(B \cdot (i - 0.5 - rnd)\right) \tag{7.1}$$

where A and B are constants, rnd is uniformly distributed in the range 0-1 and i is given by

$$i = ROUND\left[1 + \frac{ln(T_z^*/A)}{B}\right] \tag{7.2}$$

A and B are determined through exponential regression of the measured data and will be unique for each set of data to be modified. The result of the procedure is shown in the right-hand scatter diagram in Figure 7.3, where the data is clearly more noisy and randomly distributed. The discrete spacing of the wave periods prior to the modification was fairly low, and so the difference is not very significant. However, as the spacing increase, the importance of this procedure increase accordingly. This can be explained through an example, where the spacing of the wave periods are 1 second ranging from 3-20 seconds. If the system to be investigated has a natural period of 6.5 seconds, important features may not be accounted for since no data exist between 6 and 7 seconds. By randomising the data as in the right-hand diagram of Figure 7.3, this will not be an issue.

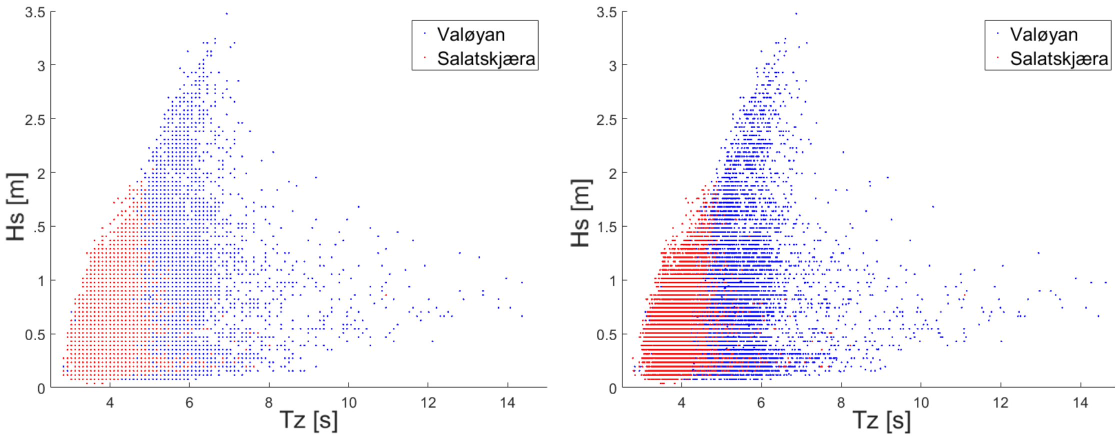


Figure 7.3: Raw data from the two buoys (left) and the same data after modification (right).

7.3.3 Operational Limits from VERES

The operational limits obtained from the hydrodynamic analysis is presented as curves showing the limiting significant wave height, H_S, as a function of mean wave period, T_z. This means that, for each wave heading and T_z, there exist a maximum H_S above which the vessel is not allowed to operate according to the criteria specified in Section 6.4.3. This is illustrated in Figure 7.4, where the curve indicates the limiting H_S for the Macho 40 in zero degrees wave heading, known as head seas. Wave heights above the curve exceeds the operating limit and is therefore characterised as a *non-operating zone*. For all wave heights below the curve the vessel is allowed to operate according to the criteria. This zone is characterised as an *operating zone*. Waves with periods less than three seconds will break at relatively low wave heights and is therefore neglected in the analysis. By including curves for all wave headings, these limits are used in the simulation model to determine whether the operation can be initiated given a certain wave condition at the farming facility.

In order to make use of these limits in the simulation model, the data is exported as XML-files from VERES, and imported into Simulink where they are split into separate variables according to wave heading. This enables the option of analysing and comparing the vessel performance at specific wave headings or sectors in addition to full 360° analyses.

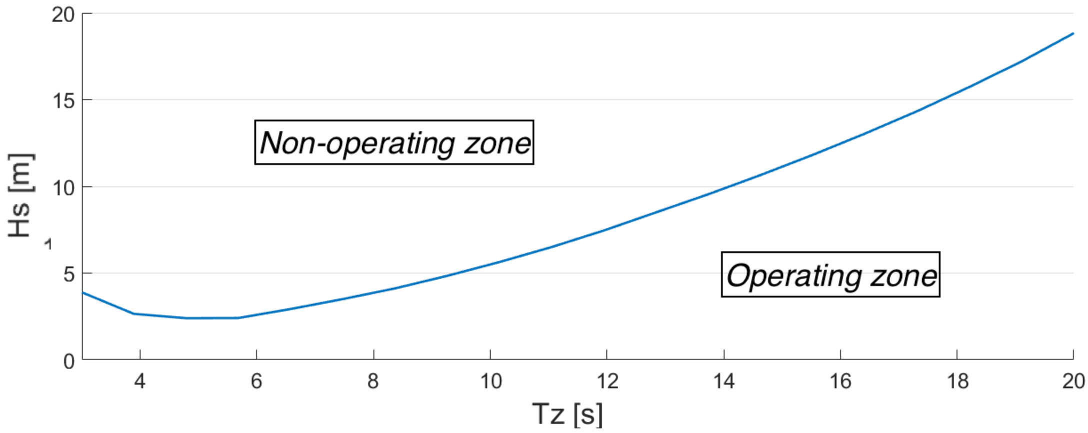


Figure 7.4: The curve represents the limiting wave conditions for the Macho 40 in head seas, with the non-operating zone above and the operating zone below the curve.

7.4 Step-By-Step Model Review

A complete overview of the simulation model is presented in Appendix I. The model is configured into several blocks, each serving different purposes. Figure 7.7 shows the lower half of the model structure presented in the appendix. This is the part simulating the actual operations and sailing between the port and the two farms. The upper half consist of one block generating operation requests at the two farms, one keeping track of the simulation time and another holding the global variables. This section will go through the entire simulation model and describe the functions and content of each part. The blocks in the upper half serve as input to the lower half, and will be covered first.

Service Operation Generator
The service operations to be performed by the vessel is modelled as a separate block in the model. The different operations to be performed are specified by designated entity generator blocks as seen on the left-hand side of Figure 7.5. According to the probability distributions presented in Section 7.3.1, each operation to be performed is generated from these blocks. Once an operation entity is generated, it continues through the entity gate, which is open only if the previous operation is completed, and is arbitrarily assigned to one of the two locations. Once the entity reaches one of the two servers named "Operation Request, a signal containing information on which location the operation is requested to and which type of operation it is, is sent to another server in the model.

Once the operation is performed, the entity continues through the final entity gate before it is terminated.

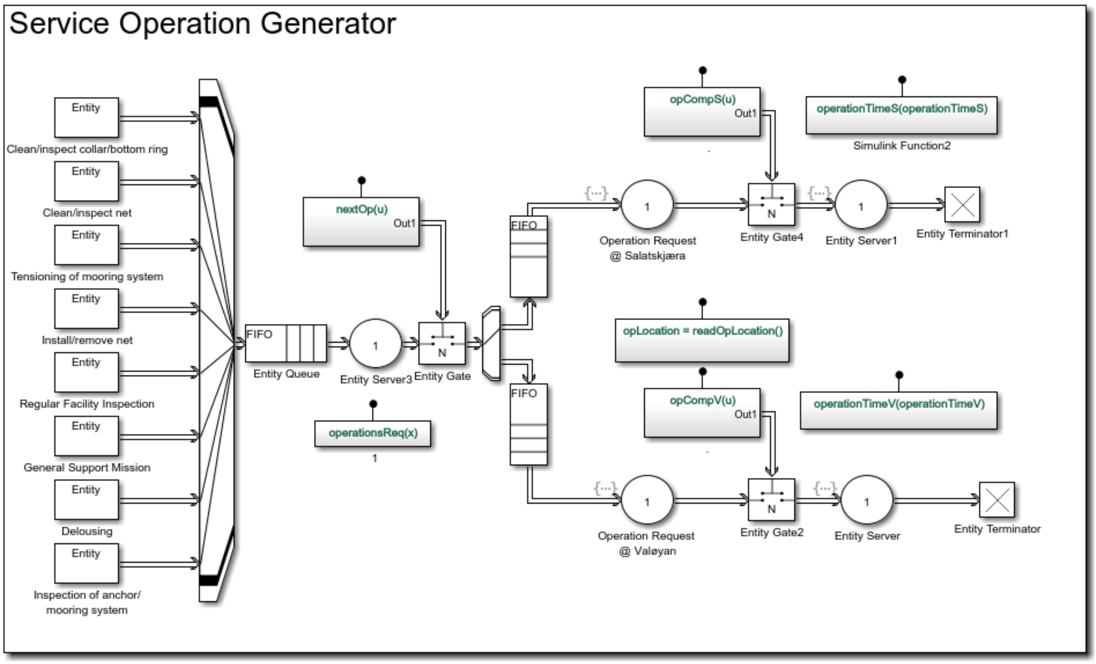


Figure 7.5: This block generates service operations according to specified probability distributions, and assign each operation to either Salatskjæra (upper path) or Valøyan (lower path).

Global Variables

If multiple functions in a simulation model need access to the same variables, these variables are defined as global variables. This means that the variables can be accessed from any server at any time. In this model, seven such variables are defined, as seen in Figure 7.6. The most obvious global variable is the simulation time, which repeatedly updates the point in time of simulation. The simulation time is required as input to assess weather conditions before initiating the operations at the farms. In addition, there are global variables containing information on *where* a certain operation is to be performed and the *duration* of each operation. These variables are used to determine which route the vessel will sail and to assign a service time when performing the operation. The final three variables, operations requested and performed and the vessel utilisation, are used to store statistical information used in the post-processing of the analysis.

The rest of this section will explain the remaining half of the model structure, shown in Figure 7.7. Each block will be covered in a sequential order according to their assigned

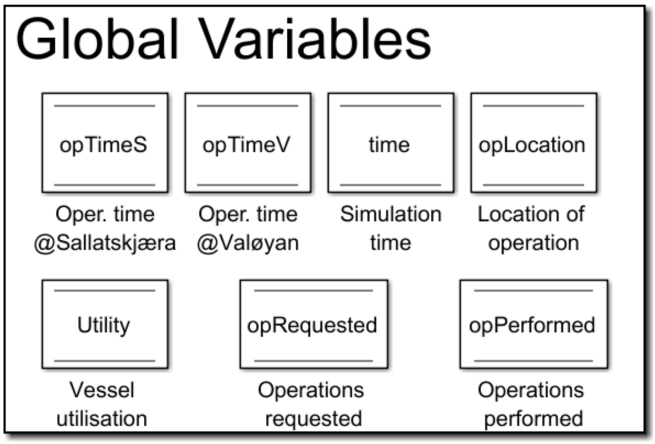


Figure 7.6: Global variables used in the simulation model. These variables can be accessed anywhere in the model and at any time of the simulation.

number as seen in the figure. The numbers indicate their respective order in the simulation cycle. For blocks with equal numbers, the preceding block determines which one will be next.

1. Vessel generation
The simulation starts at block number one where an entity, from here on called the vessel, is generated. The vessel is assigned three different attributes, whose values determine the behaviour of the vessel at certain points in the model. The application of these attributes will be discussed in each designated block. Once the vessel is generated, this block is no longer active in the simulation. An important note of the vessel entity is that not every "movement" in the model corresponds to a physical movement of the vessel. Only the two blocks named with "Sail to" and "Return from" are actual sailings where the vessel moves from one location to another.

2. Wait for new mission
Block number two may be interpreted as the main port in the model. This is where the vessel awaits operation requests from the *service operation generator* block. Once an operation request is generated at one of the locations, a signal is received and the entity gate in block number two opens. Simultaneously with the signal, attribute values are specified depending on the type of operation and at which location the operation is to be performed. The vessel then moves towards block number three where an evaluation of the weather conditions is performed.

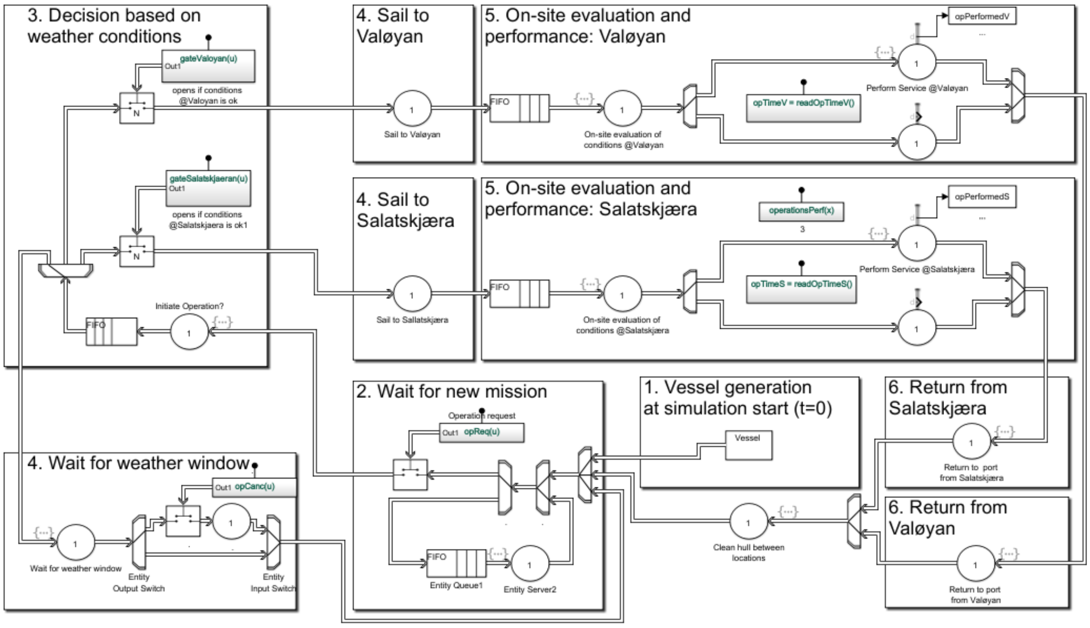


Figure 7.7: Overview of the main part of the simulation model. The blocks are numbered from 1-6 in a sequential order.

3. Decision based on weather conditions

Once the vessel arrives at the server in block number three, the process of evaluating weather conditions at the particular location begins. The wave data is imported and compared to the operational limits from VERES. A decision of whether to initiate or postpone the operation is then made. Once the decision is made, the appropriate entity gate is opened and the vessel sails towards its intended location. If the conditions are found too rough for operation, the operation is postponed by one hour until the conditions are acceptable. The vessel then goes in a loop between block two and three, via block four (*4. Wait for weather window*) in the bottom left corner of Figure 7.7. However, if the operation is delayed by more than six hours, the operation is cancelled and the entity gate in block two close. The vessel then returns to block number two and awaits a new operation request. The full MATLAB script for this process is attached in Appendix J.

4. Sail to farms

If the weather conditions are acceptable for operation, the vessel sails towards the farm. The sailing is modelled with a fixed distance for each location, and the sailing time is determined by the specified distance and the vessel's speed. To obtain a more realistic sailing time, variation in weather conditions along the route could have been included. However, due to lack of weather data and the fact that the sailing is not emphasised in this analysis, this has not been emphasised.

5. On-site evaluation and performance

When the vessel arrives at the farm, another weather evaluation is performed before the operation can be initiated. The reason is that during the time the vessel use to sail from the port to the location, the weather conditions may have changed. The procedure for evaluation is similar as in block number three, and contains only minor modifications to the MATLAB script shown in Appendix J. If the operation is performed, the duration of the operation is determined from the attribute value of this specific operation type. If the conditions are not acceptable for operation, the vessel advance straight to the final block of the model.

6. Return to port

When the operation at one of the farms is completed (or cancelled due to weather), the vessel returns to the port. The routes are deterministic and identical to the ones in block four where the vessel sails from port to the farms. Additional functions in this block is that signals are sent to open the final entity gate in the "Service Operation Generator" block and close the entity gate in block number two. This is done to make room for the next operation request, and also to stop the model from beginning a new cycle before a new operation request is made.

Regulations require the vessels in certain geographic areas to clean the hull between operations at different locations. Since this is the case in the area around Hitra and Frøya, this process is included in the model between block six and two. With this server, the simulation loop is completed, and the next operation will be initiated once a new request is made from either one of the farms.

Chapter 8

Results

This chapter is dedicated to the presentation of results from the analyses. The operational limits from the vessel response analysis are presented in Section 8.1, followed by the results from the simulation in Section 8.2. To keep the report organised and readable, it has been decided not to include all resulting plots in the main part. Additional and complimenting results are therefore presented in appendices, and referred to throughout the chapter.

8.1 Operational Limits

This section presents the results obtained from the vessel response calculations in VERES. The aim of the analysis is to obtain a set of limiting wave conditions for the Macho 40 based on the specified criteria. The program allows for a wide variety of plots to visualise the results from the analysis. Not all are directly relevant for the input in the simulation model, but can be of interest to compare the effect of the different criteria or to study transfer functions. Hence, additional plots related to limiting wave conditions are presented in Appendix L and transfer functions for heave, roll and pitch in Appendix K .

All results are obtained with the applied wave spectrum as described in Section 6.4.2, i.e. short-crested JONSWAP spectrum with a cosine squared distribution and a wave spreading angle of $\pm 90°$. Figure 8.1 shows the limiting significant wave height (H_S) for headings from $0 - 180°$ when all criteria are included. The remaining wave headings from $180 - 360°$ are not included to make the plot more readable. It follows that, due to the symmetric geometry of the vessel along the longitudinal axis, the operational limits from this sector are very similar. This can be seen in Figure L.1 (Appendix L), where all headings are included.

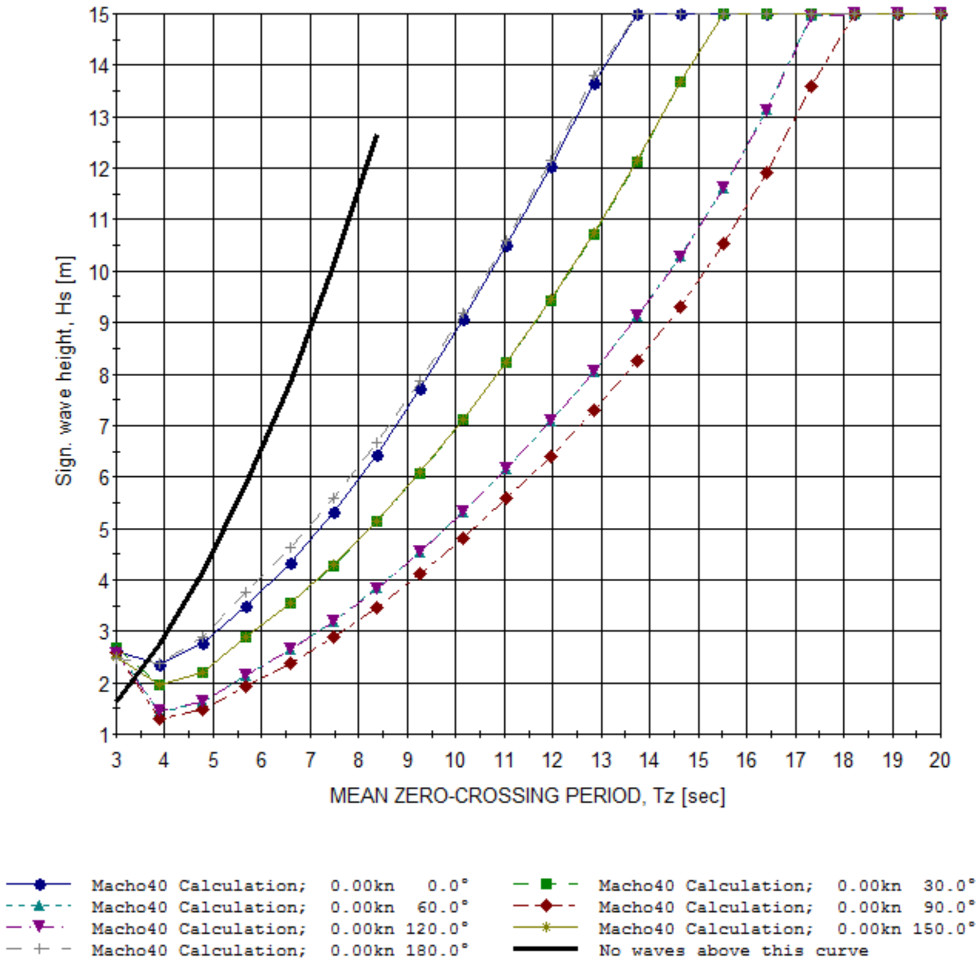


Figure 8.1: Limiting significant wave height H_S [m] for headings from $0-180°$ when all criteria are included. The black curve indicates the wave breaking limit, above which no waves occur.

The curves in Figure 8.1 show the maximum significant wave height, H_S, as a function of the mean wave period, T_z. This is to be interpreted as the maximum H_S by which the vessel is allowed to operate for a given T_z and wave heading. Since a cosine-squared power spreading is applied in the analysis, it is important to note that the wave headings given is the *primary* wave headings, and thus have a distribution of wave headings according to the illustration in Figure 6.6b. It can be seen that the lowest values are obtained for a wave heading of 90°, where the allowable H_S for $T_z = 4\,\mathrm{s}$ is about 1.2-1.3 m. For wave periods below 3 s, the limits exceed the theoretical limit for breaking waves, hence there are no operational restrictions for $T_z < 3\,\mathrm{s}$.

Polar curves can be useful to get a more intuitive impression of the results. The polar curve in Figure 8.2 shows the maximum allowable H_S for each wave heading, corresponding to the global minimum of each graph in Figure 8.1. From the polar curve it is clear that wave headings close to beam sea (90° and 270°) are most critical with respect to wave height, with a maximum allowed H_S of approximately 1.2-1.3 m. This is in accordance with the minimum value for the 90° curve in Figure 8.1. The highest values are obtained for head and following sea at 2.2-2.3 m. It can also be observed that the plot is not completely symmetric. A few minor deviations can be seen in a ±30° sector of head sea. The deviations are most likely caused by the position of work station 2 and 3 defined in Section 5.2, which are located a few metres off the centreline.

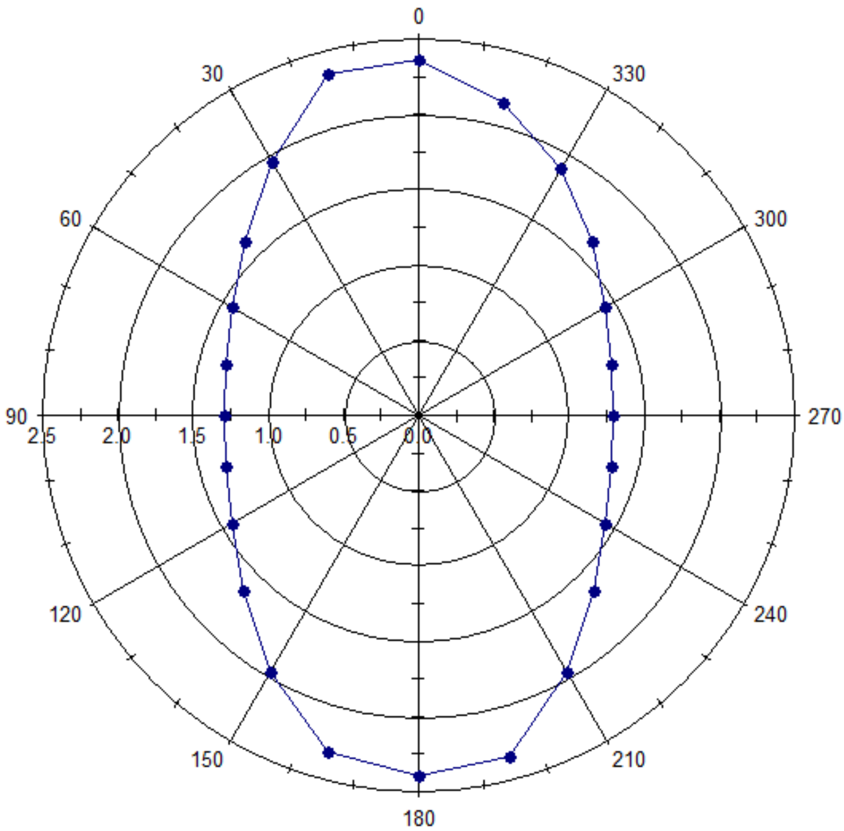


Figure 8.2: Limiting significant wave height H_S [m] for all wave headings when all criteria are included. Zero degrees heading is head sea.

8.2 Simulation

The objective of the simulation model is to analyse the long-term performance of the Macho 40 given the operational limits from VERES and the wave data from the oceanographic buoys. Depending on the objective and area of interest of the study, different statistics and results can be obtained from the simulation model. In this case, the vessel's ability to perform its intended missions is of primary interest, and the results presented is therefore related to operability.

During operations at a facility, the service vessels may encounter incident waves from all directions. Favourable wave headings are endeavoured by the vessel's master, but operational and structural factors often restrict the ability to manoeuvre freely (Hansen, 2017). This constitutes a challenge in the analysis since the operational limits are defined for discrete wave headings and must be compared to wave headings accordingly. To overcome this issue, wave heading *sectors* are introduced in the analysis. The next section will present the results from analyses of each individual wave heading, while Section 8.2.2 addresses the simulation of the sectors.

8.2.1 Individual Wave Headings

Initial simulation analyses are performed where it is assumed that all vessel operations during the entire endurance of the simulation are performed at the same, fixed wave heading. Even though this is not a realistic assumption, it can be useful to see which headings are more critical with respect to the vessel's ability to perform the missions. For each wave heading, an analysis is performed and the results are shown in Figure 8.3.

The operability represents the fraction of operations completed throughout the simulation. The remaining fraction is the requested operations which are cancelled or aborted due to rough weather conditions. From the figure it can be seen that the operability is lowest for wave headings of 90° and 270°, with values of 91.5 % and 91.7 %. A clear trend can be observed with respect to wave heading. The operability gradually decrease as the wave heading approaches beam sea, while increasing towards head and following sea. The highest operability is obtained for 0° and 180°, with 98.9 % and 99.0 %, respectively.

Forty simulations are performed for each wave heading to have a sufficient sample size for

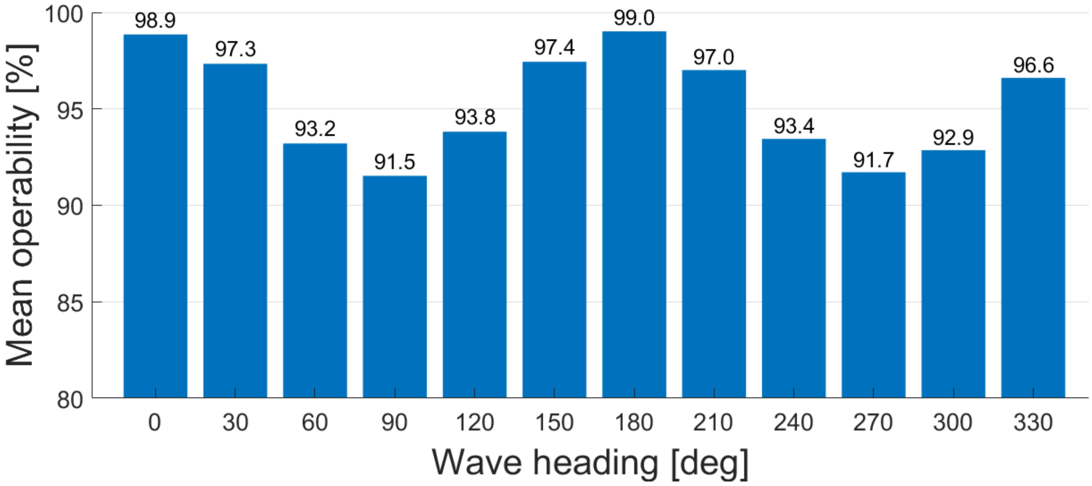


Figure 8.3: Mean operability for each individual wave heading.

calculating statistical properties. The frequency of occurrence of each service operation is normally distributed, which means the standard deviation along with a confidence interval can be derived from the results. The standard deviation, σ, is a measure for the level of variation from the mean value and is given in the same unit as the data. Confidence intervals define a range of values of which an estimated parameter lies within with a specified probability, and is calculated according to Equation 8.1. Here, $\bar{x}$ is the mean value, z^* is a constant from the standard normal distribution defined by the confidence level and n is the sample size. In this case $n = 40$ and $z^* = 1.96$ is applied, corresponding to a 95% confidence interval.

$$\bar{x} \pm z^* \frac{\sigma}{\sqrt{n}} \tag{8.1}$$

Table 8.1 shows the mean operability for all headings and the corresponding standard deviation. The largest standard deviation is 1.5, for a wave heading of 240°, while the smallest is 0.5 for a wave heading of 180°. In general it can be seen that there is a larger standard deviation, and thereby a greater variation in operability for wave headings close to beam sea than for head and following sea. Only three significant digits and one decimal place are included in the statistical calculations due to the high level of uncertainty in the model input.

Table 8.1: Mean operability and corresponding standard deviation and 95% confidence interval for each wave heading.

Wave heading [deg]	**Mean operability [%]**	**St.dev. [%]**	**Confidence interval [95 %]**
0	98.9	0.6	98.9 ± 0.2
30	97.3	1.0	97.3 ± 0.3
60	93.2	1.0	93.2 ± 0.3
90	91.5	1.3	91.5 ± 0.4
120	93.8	1.0	93.8 ± 0.3
150	97.4	0.9	97.4 ± 0.3
180	99.0	0.5	99.0 ± 0.1
210	97.0	1.2	97.0 ± 0.4
240	93.4	1.5	93.4 ± 0.5
270	91.7	1.2	91.7 ± 0.4
300	92.9	1.0	92.9 ± 0.3
330	96.6	1.3	96.6 ± 0.4

8.2.2 Wave Heading Sectors

In reality, the vessel is not able to operate at the same wave heading at all times, but it may be able to slightly adjust the position to avoid the least favourable wave headings. To reflect this in the simulation, six different wave heading sectors are defined. A presentation of the sectors can be seen in Figure 8.4, where the blue shaded areas indicate the respective sector. For each case, the vessel is assumed to operate in wave headings within the extension of the sector throughout the simulation time. This means that for Sector 1, the vessel always operate in wave headings within $\pm 30°$ of head sea, while for Sector 2 the range is extended to $\pm 60°$ and so on. As can be seen from the figure, a wide variety of sectors are analysed. To which extent each sector reflects the vessel's true condition during the operations is uncertain, and should be subject to further consideration. It is, however, assumed that by analysing this range of sectors the vessel's sensitivity to certain wave headings may be revealed. This issue is further discussed in Chapter 9.

An assumption made in this process is that the operability limits considered in the assessment of weather conditions in the simulation model is always chosen as the most conservative (lowest) within the sector. This can be seen in the MATLAB script in Appendix J, where the limiting H_S is determined by taking the minimum of the interpolated values for the current sector.

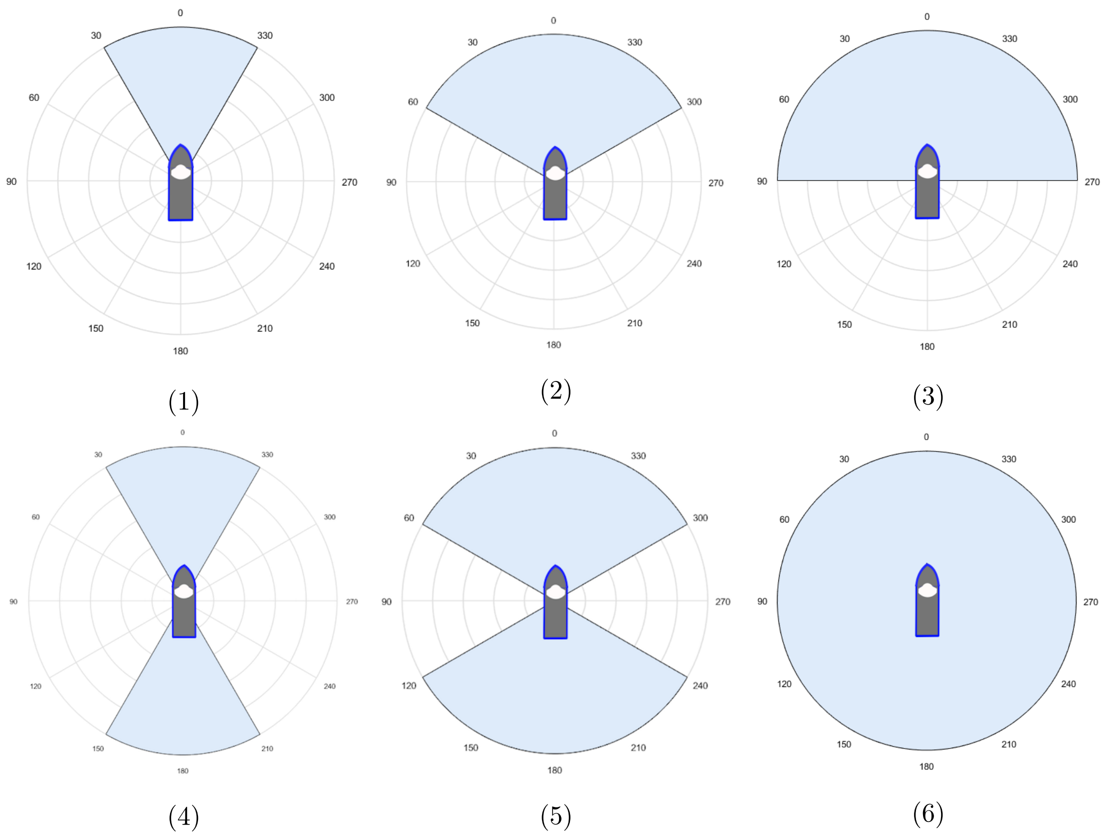


Figure 8.4: Illustration showing the wave headings sectors compared in the analysis.

The results from the analysis of each wave heading sector is presented as a bar chart in Figure 8.5. It can be seen that the highest operability is obtained for Sector 1 and 4, with mean operability of 96.8% and 97.4%, respectively. The lowest operability is obtained for Sector 3 and 6, with mean operability of 93.2% and 91.3%, respectively. Considering the results from the individual wave headings, it is also expected that the sectors including the lateral wave headings provide the lowest operability results.

As for the simulation runs presented in Section 8.2.1, forty runs are performed for each wave heading sector. This allows for calculation of mean values and standard deviations. The results presented in Table 8.2 show that the standard deviation, and consequently range of the confidence intervals, are quite similar for all sectors. Sector 2 has the highest

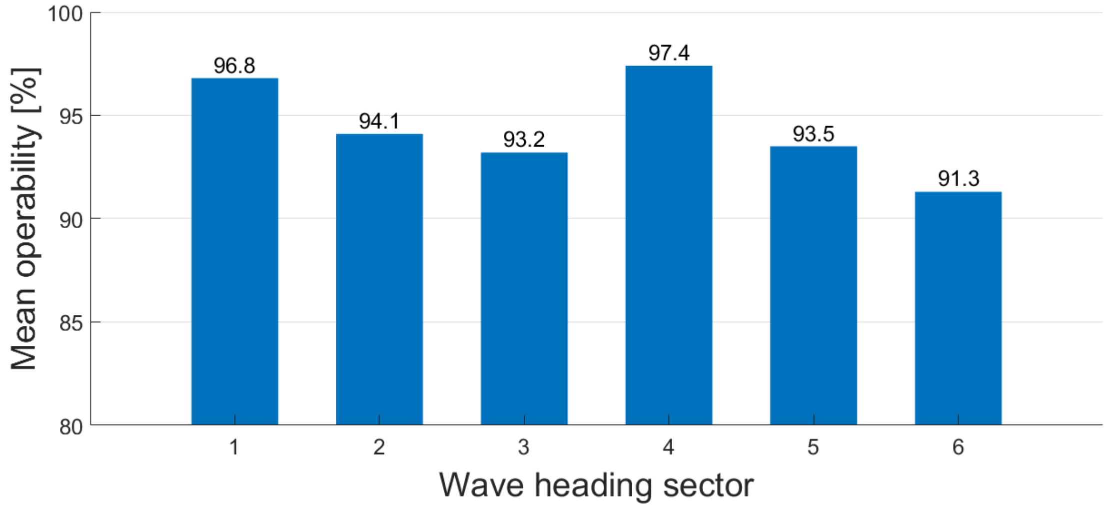


Figure 8.5: Mean operability for the six different wave heading sectors.

standard deviation with 1.2%, while Sector 4 has the lowest with 0.8%.

Table 8.2: Mean operability and corresponding standard deviation and 95% confidence interval for each wave heading sector.

Wave heading sector	**Mean operability [%]**	**St.dev. [%]**	**Confidence interval [95 %]**
1	96.8	0.9	96.8 ± 0.3
2	94.1	1.2	94.1 ± 0.4
3	93.2	1.0	93.2 ± 0.3
4	97.4	0.8	97.4 ± 0.2
5	93.5	0.9	93.5 ± 0.3
6	91.3	0.9	91.3 ± 0.3

8.2.3 Seasonal Variations

Service vessels operate in the physical environment and are affected by changing weather and wave conditions. The winter months are often characterised by harsher and more unstable weather conditions than the rest of the year. Since many aquaculture production sites are located in sheltered coastal areas, the impact of seasonal variations may not always be considerable. However, as the industry moves towards more exposed locations, this becomes an increasingly important factor to consider. In the offshore industry, peak season for vessel operations is during the summer months since, in general, this is the time of year with the most favourable weather conditions.

The impact of seasonal variations on the performance of the Macho 40 has been assessed. Figure 8.6 shows the variations of H_S from the measurements at the two oceanographic buoys close to the facilities at Valøyan and Salatskjæra. The high density of data points makes it difficult to read exact values from the graphs, but some trends may be observed. The significant wave height is in general higher at Valøyan. This is further confirmed by the mean values, which are 0.81 m and 0.57 m, respectively. Also, an increase of H_S can be seen from November-March compared to the summer months June-August.

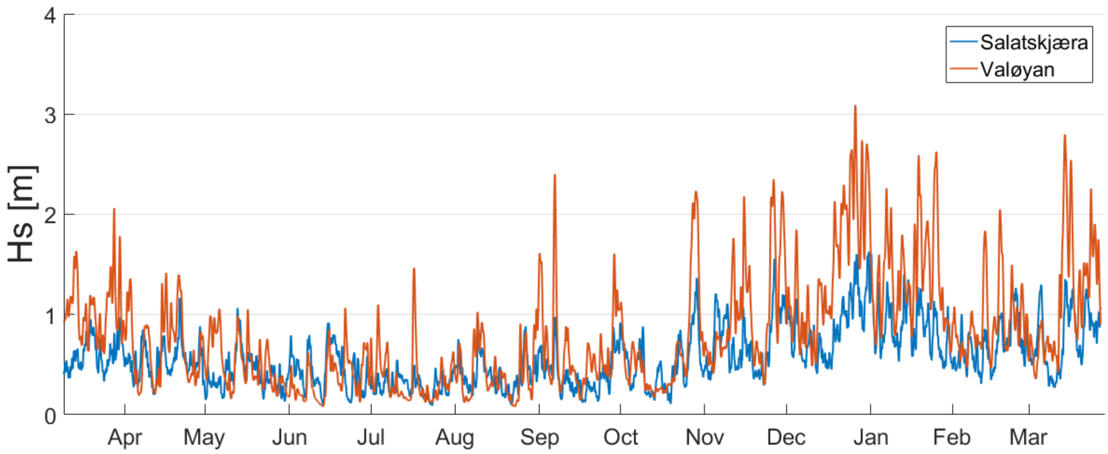


Figure 8.6: Seasonal variations in significant wave height (H_S) at Valøyan and Salatskjæra.

Figure 8.7 shows the number of operations performed at each of the two locations through the year and the number of operations cancelled or aborted as a consequence of rough weather conditions. A total of 252 operations were carried out by the vessel at the two farms. It can be seen that the number of operations performed at both farms are quite equal from the simulation start until October-November, from which fewer operations are performed at Valøyan than at Salatskjæra. The difference evolving means that operations are more frequently cancelled at Valøyan due to harsh weather conditions. This is further supported by the graph showing the number of cancelled operations, which remains low until it starts to increase in November.

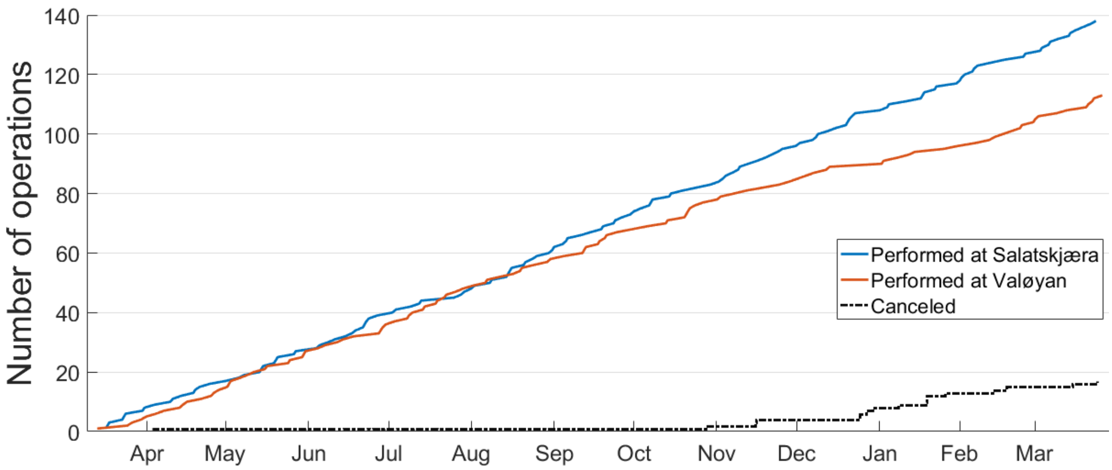


Figure 8.7: Number of operations performed at each location, and the total number of cancelled operations due to harsh weather conditions.

Rough weather conditions can affect the ability to perform operations, which again may lead to cancelled operations and decreasing vessel operability. To assess the seasonal variations in operability for the Macho 40, each wave heading sector is analysed and compared. Figure 8.8 shows a comparison of the operability of all six sectors from mid May to the end of March. The impact of seasonal variations seems to vary depending on wave heading. Sector 1 and 4 show significantly less variation throughout the year than the other sectors.

The first few months of simulation are not included in Figure 8.8 because the operability curves in the start-up region are influenced by lack of calculation points and thus do not reflect the true operability. This can be seen in the figure in Appendix M, where the curves show a high level of fluctuation before stabilising after some time of simulation.

From Figure 8.8 it can be seen that Sector 6 shows the most significant drop in operability as the winter months approaches. The curves clearly show that the negative effect of seasonal variations is larger for the sectors including wave headings close to beam sea. A more detailed comparison of the most and the least affected wave sectors is shown in Figure 8.9. While the operability drops from about 98% to 93% for Sector 6, it only drops from 99% to 98% for Sector 1.

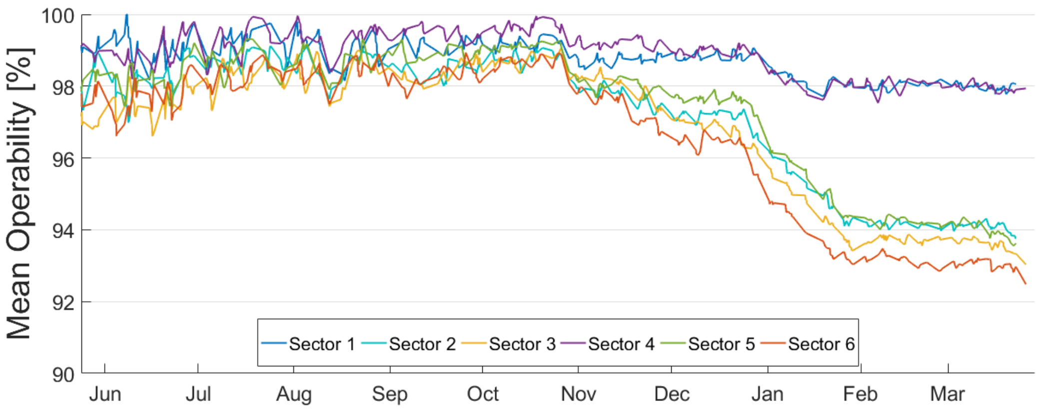


Figure 8.8: Development of mean operability from mid May to the end of March for the six wave heading sectors.

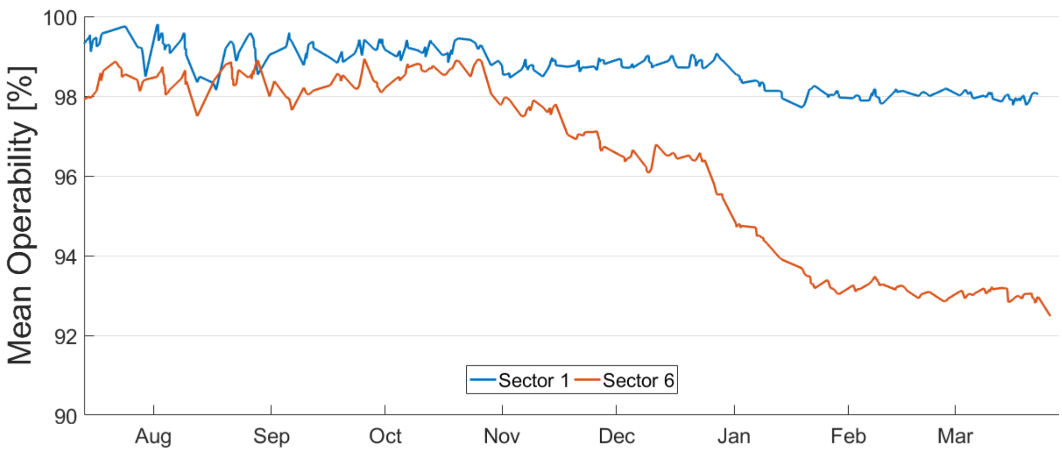


Figure 8.9: Comparison of Sector 1 and 6, the least and most affected wave heading sectors, from July to the end of March.

Chapter 9

Discussion

This chapter will discuss the approach of the thesis work and how the methods applied have contributed to fulfil the objectives of the thesis. Further, an evaluation of the results along with a discussion on their reliability are presented. This chapter also seeks to relate the results to recognised findings in the literature and, wherever relevant, suggest alternative approaches or methods.

9.1 Method of Approach

The objective of this thesis is to increase the knowledge and insight of service vessel operations in exposed aquaculture, with a particular focus on vessel behaviour and performance during vessel-structure interaction. The work towards this objective has addressed several aspects regarding hydrodynamics and system design. Vessel response calculations have been used by ship designers and developers for a long time to compare and evaluate different designs. Simulation of marine systems related to evaluation and optimisation of fleet sizes and logistical processes is also widely used in the maritime industry. Through the literature review, however, no studies combining the hydrodynamic domain with a simulation approach to assess vessel performance has been found. The work of this thesis may therefore to some extent be considered an exploratory approach of combining previously recognised methods in a new area of application.

Vessel-structure interaction in exposed aquaculture was extensively studied in the project thesis, and has been further considered in this thesis through a study of service operations and corresponding specification of operability criteria. It was made a decision at an early stage to only consider operations involving vessel-structure interaction and zero forward speed. This meant excluding operations like towing and moving of plants, supply and transport and deployment of anchors. The decision was made to reduce the complexity of the model and at the same time increase the focus on the vessel-structure interaction. If the overall performance of the vessel is within the scope of interest, including parameters like power consumption and fuel efficiency, some or all of these operations should be considered in the analysis.

The software VERES, developed by SINTEF Ocean, was used to perform the vessel response analysis. The objective of this analysis was to evaluate the response motions of the Macho 40 and to obtain a set of limiting wave conditions to be used as input in the simulation model. The analysis and the specification of operability criteria have provided knowledge on the vessel behaviour in different sea conditions, as well as identification of critical motions with respect to operability. The program also allows for long-term operability assessment of a vessel. This approach calculates the percentage operability based on the operational limits and a wave scatter diagram for a specific geographic area. Calculations of percentage operability in the program are based on sea states that occurs independently and with a typical duration of three hours. This means that, in calculations of long-term statistics, the percentage operability is obtained under the assumption that the vessel is able to operate within the duration of a single sea state. The duration of most service vessel operations is significantly longer, and a sufficiently long weather window where the weather conditions are acceptable is required. This method for operability assessment in VERES is therefore likely to provide inaccurate estimates for this particular application. The importance of weather windows was pointed out by Shyshou et al. (2009), who suggested that to account for uncertainties in weather forecasts, weather windows must be at least 1.5 times longer than the expected time of the operation. Even though this study concerns offshore anchor handling operations, similarities can be drawn towards vessel operations in exposed aquaculture. In order to overcome this problem, the operability assessment in this thesis was done through a simulation model in Simulink which, by use of measured wave data from the oceanographic buoys, enabled evaluation of weather windows at the particular farm locations prior to each operation.

The aim of the simulation model was to analyse the vessel's long-term ability to perform its intended missions, known as operability. In addition to more flexibility regarding operability assessments, the combination of vessel response analysis and simulation allows for evaluation of vessel performance as part of a system, rather than as an individual. The simulation model may also be modified for different scenarios or purposes by adding or removing vessels, farms or other components. There are, however, some drawbacks with this particular approach. The relatively high number of manual processes makes it time consuming to make significant changes to the model. In the case of changing the vessel design, the entire process in VERES must be redone in accordance with the new loading condition(s), new operability criteria must be specified and manually implemented, and the operational limits used in the simulation model must be updated. Minor changes like additional farms, sailing routes or other factors only influencing on the operational scenario are, on the other hand, much easier to implement, as it only requires modifications in the simulation model structure.

The main reason for choosing a simulation model for assessment of the vessel operability rather than the built-in procedure in VERES, was the ability to capture a wider aspect of factors affecting the vessel operations, study weather windows and the opportunity to use measured wave data from actual aquaculture locations. The fact that the wave data reflects the true conditions at the locations also contributes to increase the scientific value of the analysis towards the aquaculture industry.

9.2 Evaluation and Reliability of Results

Chapter 8 presents the results from the vessel response analysis and the simulation. This section considers a more thorough evaluation of the results and discuss their reliability and confidence, as well as suggestions on model improvements and alternative approaches.

9.2.1 Operational Limits

The results from the vessel response analysis show that the wave heading is of major significance to the vessel's operational limits. The highest operating wave heights are obtained for head and following sea, while the lowest are obtained for beam sea. The lowest operational limits for most wave headings are constrained by the roll motion criteria, as shown in Figure 9.1. It can also be seen from the figure that for head and following sea, deck wetness and motion sickness are the criteria constraining the operational limits. The criticality of roll was expected prior to the analysis, as the crew at M/S "Frøy Fighter" identified this as the most critical and challenging motion during the operations. The fact that the roll criterion is not the most critical for head and beam sea is also expected, since these particular wave headings induce very little roll motion on the vessel. Similar results were found by Tello et al. (2010) while studying the seakeeping performance of fishing vessels. The study pointed at roll and pitch as the most critical motions, and that the location of reference design points had a significant influence on the performance. Reference design points were addressed in Section 5.2, where three working stations were specified as reference points for evaluation of the criteria. A sensitivity study on these points should be considered to determine whether further efforts should be put in addressing the working locations for each type of operation.

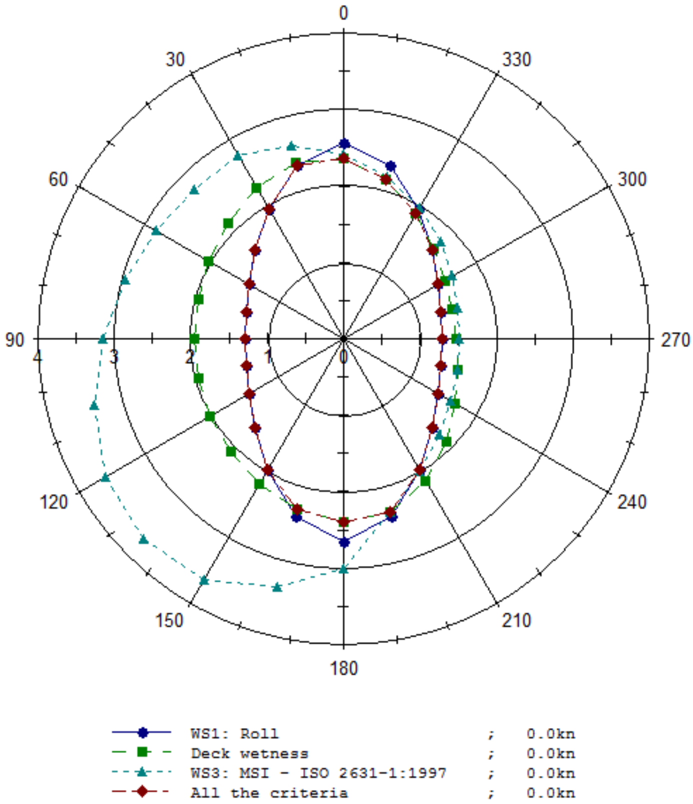


Figure 9.1: A comparison of the criteria constraining the overall limiting wave heights H_S [m].

For vessel operations limited by roll motion, the metacentric height GM is particularly important. A change of GM will change the resonant period of roll, which in turn can coincide with the wave period and cause resonance motions. During an operation this can lead to dangerous situations both for the crew and the equipment, as well as for the structural integrity of the aquaculture facility. Since the value of GM varies depending on loading condition, the choice of loading condition may have a large influence on the vessel's operability. Analysing the vessel in different loading conditions could therefore be considered to provide a broader evaluation of the vessel's performance.

When using programs for calculation of vessel motions, it is important to be aware of limitations and assumptions that may affect the validity of the results. As discussed in Section 6.2, the theoretical background for the calculations in VERES are based on strip theory using linear potential theory. This theory is developed for moderate wave heights inducing moderate motions on a slender vessel geometry. Hence, the validity of the results depend on the accuracy of these assumptions. Experiments show, however, that the program also provides good results for wave conditions stretching outside the theoretical limits (Fathi, 2012). The wave heights considered in this thesis are relatively small (<4 m) and so the results from the vessel response analysis are considered reliable.

The vessel response analysis only concerns what happens beneath the water surface. Consequently, wind forces acting on the vessel are not considered. Another aspect which is not considered and may have an influence on the vessel performance is ocean currents. According to Hansen (2017), the Master on M/S "Frøy Fighter", the combination of wind and currents may in some cases be a greater challenge than wave loads. This is especially the case if the vessel is equipped with containers or other large volume components on deck, acting as windbreaks. The fact that these effects are not accounted for is therefore a limitation of the analysis that should be further considered to improve the overall authenticity of the analysis.

9.2.2 Long-term Vessel Performance

The simulation results for individual wave headings clearly show how the long-term vessel operability depends on wave heading. It can be seen that the lowest operability is obtained for beam sea and the highest for head and following sea. The trend is somewhat expected considering the operational limits obtained in the vessel response analysis, which shows lower operational limits for lateral wave headings. This particular representation of operability is, however, purely theoretical as the analyses are performed under the assumption that all vessel operations are performed at a fixed wave heading. Despite this fact, the results are useful to identify the most critical headings with respect to operability.

Additional operability assessments were conducted by defining six wave heading sectors. For each sector, an analysis was performed under the assumption that the vessel is able to keep the wave heading within the particular sector during the operations. According to Hansen (2017), the concept of sectors could be a realistic approach as the vessels often seek to orientate in favourable directions with respect to weather conditions. That being said, external factors like facility structures, moorings or crane operations often limits the freedom to manoeuvre freely. Hence, to imitate different degrees of manoeuvring restriction, the configuration of sectors varies from a narrow 60° sector to a full 360° sector. When making the decisions of whether or not to initiate the operations, a conservative approach is applied by always evaluating the wave heading within the sector with the lowest operational limit. This ensures that the operational limits are never exceeded as long as the vessel keeps the wave heading within the sector.

The results show that as the sector is "focused" towards head and following sea, the operability tends to increase. Sector 6, covering the full 360°, shows the lowest while Sector 1 and 4 shows the highest operability. This is expected, since for Sector 6 the overall lowest operational limits are always considered in the decision process. An interesting observation is that Sector 4 shows a higher operability than Sector 1. In principle, this indicates that in terms of operability, following sea is more favourable than head sea for this particular vessel. However, a comparison of Sector 2 and 5 gives indications of the opposite. Thus, considering the fairly low sample size of the analyses, no conclusive remarks should be taken regarding this particular matter.

The seasonal variations of the vessel's operability seems to correlate with the variations in significant wave height, H_S. An increase in wave height can be observed from around October, which is also when the operability starts to decrease. This indicates that an increase in H_S leads to a decrease in operability. Higher waves means that the vessel is more likely to exceed the operational limits and end up in the *non-operating zone*, as defined in Figure 7.4. During the simulation, a noticeable difference between the two farm sites can be observed. Only about 5% of the cancelled operations are located at Salatskjæra. The reason is most likely related to the difference in H_S at the two farms. While Valøyan has a maximum significant wave height of 3.48 m and a mean of 0.81 m, the corresponding values at Salatskjæra is 2.03 m and 0.57 m.

The reliability of the simulation results is uncertain, which is first of all a consequence of the nature of simulation. A general drawback of studying complex stochastic systems through simulation is that each run, no matter the quality of the input or model structure, is an estimate of the true characteristics of the system. For this reason, simulation models are generally more useful at comparing different system designs than for optimising one design in particular (Law, 2007). However, other factors also affect the confidence of the simulation results in this particular case. The simulation time is limited by the amount of measured wave data from the oceanographic buoys, which extends for about one year. Since weather conditions vary from year to year, assessing seasonal variations in vessel performance based on a single year of data will only provide indications of the true characteristics. This is a deficiency of the analysis, and is important to be aware of when assessing the results. To obtain true estimations of seasonal variations a number of consecutive seasons of measurements should be analysed. This will ensure that phenomena like storms and extreme weather conditions are accounted for, and statistical values may be estimated with a much higher accuracy. According to Faltinsen (2005), about 100,000 observations are needed to get reliable results. The sample size of the data series used in this simulation is only 9-10,000. Hence, at least ten years of measurements would be preferred to obtain reliable results accounting for extreme value statistics.

The degree of accuracy in weather forecast is another important aspect. DNV (2011) accounts for the uncertainty in weather forecasts by including a factor, α. This assures that the operational limit is less than the limit obtained in design. A study by Natskår et al. (2015) of the uncertainty in weather forecasts for marine operations shows that the uncertainty in the forecasts decrease with decreasing lead time. The study also pointed out that there is a lower correlation between forecasted and experienced data for wave periods than for significant wave heights. In the simulation model the uncertainty is accounted for by multiplying the actual wave height and period at the locations by a factor larger than one, depending on the lead time of the forecast. For a three hour forecast, a factor of 1.1 and 1.05 were applied for wave period and significant wave height, respectively. Increasing the lead time will consequently increase the multiplication factors.

The simulation model itself is subject to simplifications and assumptions that may affect the confidence of the results. The most significant source of uncertainty is the input of frequency and durations of the operations. The mean values and standard deviations of the normal distributions are based on discussions and educated guesses from the crew on M/S "Frøy Fighter", and is therefore subject to uncertainty. In addition, a lot of the operations are not performed in a regular manner. Logging the frequency and duration of real operations over a long period of time would thus contribute to increase the reliability of the input and thereby also the results.

In reality, service vessels operate at a large number of fish farms spread over a large area, and multiple vessels often cooperate to perform demanding operations. The operational scenario constructed for this analysis (see Section 2.3) is therefore not a true reflection of the day-to-day operation of a typical service vessel. But as discussed in Section 9.1, the model can easily be modified with additional farms, vessels and routes. According to Law (2007), a common pitfall of simulation studies is to include too many components and variables at an early stage of the model development. It was therefore determined to develop a simplified scenario that could be further developed at a later stage.

Even though the results from the assessment of seasonal variations should be read with care, they are based on true weather conditions in the vicinity of two actual aquaculture locations. Disturbing local factors like bathymetry, islets and skerries are thus accounted for, making the data more precise than for instance hindcast data for the same geographic region. Compared to a long-term analysis of the same vessel using hindcast data, these results may therefore prove to be more accurate and realistic. The results from the individual wave heading assessments should also be taken only as indications of the vessel's sensitivity to the different wave headings and not as its true long-term performance. The wave heading sectors, on the other hand, are likely to provide more realistic estimations of the operability, as they account for multiple incident wave headings during the operations. To which degree each of the sectors reflect the vessel's actual ability to manoeuvre during the operations is, however, uncertain, and should be subject to further research.

The combination of vessel response analysis in VERES and a simulation model has provided an increased knowledge on the vessel's performance in the true physical conditions of two exposed aquaculture facilities. As discussed above, the model contains simplifications and drawbacks that affects the confidence of the results. However, the analyses provides indications of the vessels operational robustness in different wave headings as well as estimations of operability and seasonal variations. With a larger amount of wave data and further research regarding frequency of operations and wave heading sectors, the model could be useful in assessing and comparing the long-term performance of different vessel designs. If further developed, the model may also be combined with real-time measurements of vessel responses in a similar manner as the system developed by Hoffman and Petrie (1980). This could enable improved planning and performance of operations and in that way increase the vessel utilisation and reduce operational costs.

Chapter 10

Conclusion

The results from the vessel response analysis show that wave headings are important when considering the vessel's operational limits. In general, lateral wave headings have a more constraining effect on the maximum allowable operating wave heights than head and following sea. It is also found that roll is the most critical motion with respect to the vessel's operability.

The results from the simulation indicate that the vessel's long-term operability depends on its operational limits. Six different wave heading sectors are analysed and compared. It seems clear that the more the vessel is able to avoid operating in lateral wave headings, the higher the operability. Further, seasonal variations in performance show that the vessel's ability to perform its intended operations is reduced in periods with increased wave height, and vice versa.

The validity of the simulation model and the reliability of the output have not been tested or verified. In order to obtain a reliable model that can be trusted by users, a study on validation of the model is encouraged. Despite the uncertainty in the model input, the results provide useful indications on the vessel's sensitivity to incident wave headings, as well as estimations of long-term operability and seasonal variations. In accordance with the thesis objective, it can be concluded that an increased knowledge on service vessel operations in exposed aquaculture has been obtained and that, with further research and longer wave data series, the combination of hydrodynamic analysis and simulation could prove to be a useful approach in assessing and comparing the long-term performance of different vessel designs.

Chapter 11

Further Work

As discussed in Chapter 9, the simulation model is subject to simplifications that affects the authenticity and reliability of the results. This chapter presents suggestions for further work that may contribute to improve the quality of the model output and also discuss the possibility of involving alternative software and methods for assessment of vessel performance in exposed aquaculture.

11.1 Operability Criteria

To determine the operability criteria for the Macho 40, the research project by Nielsen (1987) was used as basis. The criteria related to motion sickness are determined based on ISO 2631-1:1997, and are defined in the regulations for a mixed population of unadapted adults. The criteria stated in the standard is therefore not accurate for service vessel crews who, in general, are adapted to vessel motions. The modifications applied in this thesis are based on subjective considerations regarding the type of work performed by the crew, and is not necessarily perfectly accurate. An increased effort should therefore be made towards this particular criterion, and the question should be raised of whether there should even be a criterion related to motion sickness due to the high degree of adaptiveness amongst the crew.

It was previously mentioned that the EXPOSED project has initiated on-board measurements of accelerations on a service vessel. The measurements will hopefully provide information on vessel motions and limiting sea states during different operations. The results from these measurements could provide valuable information on the current vessel design, which can be used to improve the accuracy of operability criteria. If similar measurements are initiated on M/S "Frøy Fighter", the results could be compared to the criteria specified in this thesis and necessary modifications applied.

The structural integrity of fish cages are also an aspect which could be interesting to consider in the process of defining operational limits. This could for instance be analysed through the SIMA workbench, a software for simulation and analysis of marine operations and floating systems (SINTEF Ocean, 2017). The output from the analysis could then be used as input in the simulation model, similarly to the operational limits from VERES used in this thesis.

11.2 Weather Forecasting

A weakness of the simulation model used in this thesis is the limited length of the wave data series from the oceanographic buoys. With only about one year of measurements, long-term statistics on seasonal variations can not be estimated properly. An alternative approach may be to develop a forecasting model based on the measured data from the current sites. In simulation, Markov chains are typically used for this purpose. Markov chains are stochastic processes describing a sequence of possible events. The possibility of each event is only based on the state of the previous event, i.e. the model is memoryless.

A number of sea states must be predefined in the forecasting model, and the historical data is categorised within these states. A transition matrix, P, is then created based on the number of transitions from one state to another.

$$
P = \begin{array}{c c} & \begin{array}{ccc} S1 & S2 & S3 \end{array} \\ \begin{array}{c} S1 \\ S2 \\ S3 \end{array} & \begin{bmatrix} 0.5 & 0.4 & 0.1 \\ 0.4 & 0.5 & 0.1 \\ 0.1 & 0.6 & 0.3 \end{bmatrix} \end{array}
$$

This matrix forms the basis for the forecasting, as it tells the probability of going from one sea state to another. In the example matrix above, the probability of going from sea state 1 (S1) to sea state 2 (S2) is 0.4. The probability of remaining in S1 is 0.5, and so on. Random number sampling determines whether or not a transition will occur based on the probabilities in the transition matrix. Sea states are typically updated every three hours, thus a forecasting of for instance the next nine hours can be done by sampling three subsequent sea states.

The suggestion for a forecasting model above, only considers wave conditions. In Chapter

9, the importance of wind and currents during vessel operations was pointed out. Hence, involving these factors would add to the overall authenticity of the analysis and should be considered, also with regards to a forecasting model.

11.3 Alternative Software and Approaches

In addition to VERES and Simulink, alternative software have been attempted during the work on this thesis. FhSim is a program developed by SINTEF Ocean for simulation and visualisation of marine operations and systems (Reite et al., 2014). It is compatible with both VERES and Simulink, and can analyse vessel motions as well as mooring loads. In collaboration with Føre (2017), an attempt was made to import the vessel response characteristics of the Macho 40 into FhSim along with a fish cage structure and a JONSWAP wave spectrum. The simulation worked, and provided data on vessel motions as a function of time (see Figure 11.1). It was decided to not go any further with this process as it was somewhat outside the scope of the thesis. A further exploration of this software should, however, be considered for future research on the subject.

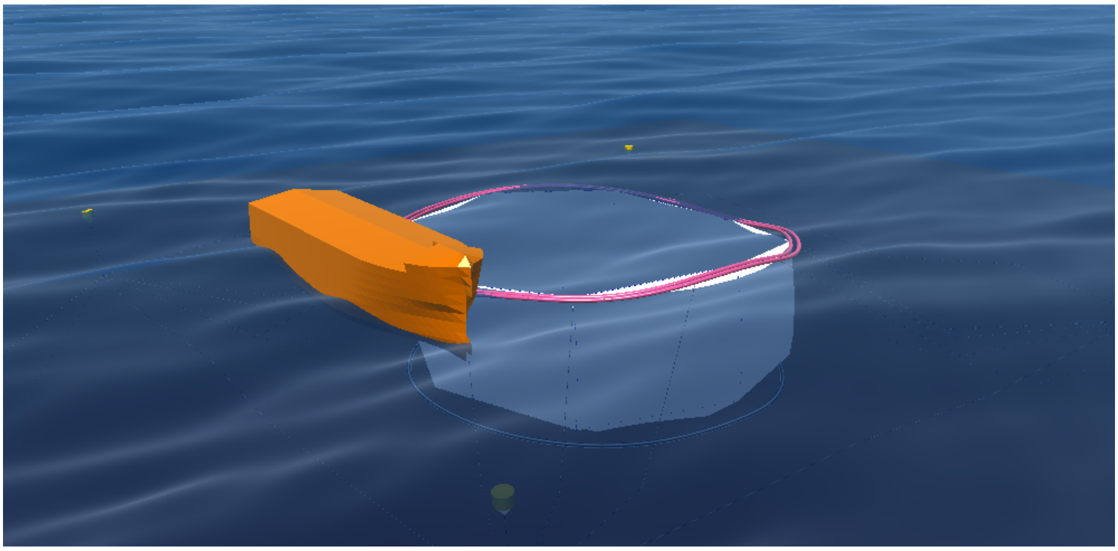


Figure 11.1: Screen caption from FhSim, where the motion characteristics of the Macho 40 are analysed based on output from VERES.

As mentioned in Section 11.1, SIMA would add another dimension to the model by analysing the structural integrity of cage structures during operations. SINTEF Ocean is currently developing Gymir, a workbench providing a common platform upon which many different components may be hosted. This includes modules for metocean data, geography and sailing routes, hydrodynamic analyses from VERES and possibly also SIMA. A joint platform like Gymir for the implementation of multiple modules may prove to be a better and more complete way of assessing the long-term performance of vessels in the aquaculture industry. The approach was also considered at the initial stages of the thesis work, but a decision was finally made to narrow the scope of the thesis and continue the work on the model in Simulink. Thus, for further work Gymir is a platform that should be investigated and considered as an alternative for a simulation model in Simulink.

The importance of model validation and verification was briefly discussed in the literature review in Chapter 3. For a model to be actively used as a tool for support and decision-making, the users of the model are likely to be concerned of the model reliability. This issue can be addressed through a study on model validation and reliability, and should be emphasised in further work on the subject.

References

Andersen, O. J. (2009). *The peak period in the WAM10 hindcast archive.* Statoil.

Antão, P. & Soares, C. G. (2004). Analysis of accidents of Portuguese fishing vessels.

Applebee, T. & Baitis, A. (1984). *Seakeeping Investigation of the U.S. Coast Guard 270-ft Medium Endurance Class Cutters: Sea trials aboard the USCGC Bear (WMEC 901).* Ship Performance Department.

AQS AS. (2017, May 3). AQS Loke. Retrieved from https://aqs.no/fartoyer/aqs-loke/

Bjelland, H. V. (n.d.). Project 3: Vessels-Structures Interaction. Retrieved from http://exposedaquaculture.no/en/project-3-vessels-structures-interaction/

Bjelland, H. V. (2015). *EXPOSED Aquaculture Operations - Annual Report 2015.* SINTEF Ocean.

Bjelland, H. V. (2017, March 22). E-infrastructure. Retrieved from http://exposedaquaculture.no/prosjekt-8-e-infrastruktur/

Bjelland, H. V., Føre, M., Lader, P., Kristiansen, D., Fathi, D., Oppedal, F., . . . Schjølberg, I. (2015). *Exposed Aquaculture In Norway.* EXPOSED Aquaculture Operations Centre.

Darzentas, J. & Spyrou, T. (1996). *Ferry Traffic in the Aegean Islands: A Simulation Study.* Department of Mathematics, University of Aegean.

Directorate of Fisheries. (2017, March 20). Map - aquaculture. Retrieved from https://kart.fiskeridir.no/akva

DNV. (2011). *DNV-OS-H101: Marine Operations, General.*

EXPOSED. (2017, April 21). Buoy data. Retrieved from http://exposedaquaculture.no/wp-content/uploads/MHWave.png?refresh=1

Faltinsen, O. (1999). *Sea Loads On Ships and Offshore Structures.*

Faltinsen, O. (2005). *Hydrodynamics of High-Speed Marine Vehicles.*

Fathi, D. E. (2012). *ShipX Vessel Responses (VERES) - Ship Motions and Global Load - Users' Manual.*

Fathi, D. E. (2017, April 24). Head of Research, SINTEF Ocean. Interviewer: R. Stemland.

Fathi, D. E. & Hoff, J. R. (2014). *ShipX Vessel Responses (VERES) - Theory Manual.*

Fonsenca, N. & Soares, C. G. (2002). Sensitivity of the expected ships availability to different seakeeping criteria.

Food and Agriculture Organization of the UN. (2016). *The State of World FIsheries and Aquaculture.*

Føre, M. (2017). Research Scientist at SINTEF Ocean.

Frøy Gruppen. (2017, March 7). Frøy fighter. Retrieved from http://froygruppen.no/tjenester/storbater/froy-fighter

Goto, D. (1983). *Characteristics and Evaluation of Motion Sickness Incidence on-board Ships.*

Hansen, B. (2017, April 6). Master on M/S "Frøy Fighter". Interviewer; Runar Stemland.

Haward, B. M., Lewis, C. H., & Griffin, M. J. (2009). *Motions and crew responses on an offshore oil production and storage vessel.*

Heide, M. A., Moe, H. K., Lien, A. M., & Sunde, L. M. (2013). *Servicefartøy 2010 - Sammenfatning av prosjektets aktiviteter [Service Vessels 2010 - Summary of the project activities]*. SINTEF Fisheries and Aquaculture.

Hersoug, B. & Revold, J. (2012). *Assessment criteria for Norwegian assistance to aquaculture in developing countries.* The Norwegian College of Fishery Science, Univeristy of Tromsø.

Hoffman, D. & Petrie, G. L. (1980). Integraded Computer Systems for Weather Bound Vessel Operations.

Holmen, I. M., Utne, I. B., & Haugen, S. (2016). *Safety and risk management in exposed aquaculture operations.* Norwegian University of Science and Technology, SINTEF.

Holmer, M. (2010). *Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs.* Institute of Biology, University of Southern Denmark.

ISO 2631-1. (1997). *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration.*

Johnsen, V. (2017, April 5). Project Manager, Møre Maritime AS. Interviewer: R. Stemland.

Law, A. M. (2007). *Simulation Modeling and Analysis.*

Lien, A. M. (2017, March 27). Research Scientist, SINTEF Ocean. Interviewer: R. Stemland.

Longo, F., Huerta, A., & Nicoletti, L. (2013). Performance Analysis of a Southern Mediterranean Seaport via Discrete-Event Simulation.

McCauley, M., Royal, J., Wylie, D., O'Hanlon, J., & Mackie, R. (1976). *Motion sickness incidence: exploratory studioes of habituation, pitch and Roll, and the refinement of a mathematical model.* Office of Naval Research, Department of the Navy.

Møre Maritime AS. (2014). *Specification Macho 40 - 40.00 m Aquaculture Service Vessel.*

Natskår, A., Moan, T., & Alvær, P. Ø. (2015). Uncertainty in forecasted environmental conditions for reliability analyses of marine operations.

Nielsen, I. R. (1987). *NORDFORSK - Assessment of Ship Performance In a Seaway.*

Ochi, M. (1964). *Prediction of Occurence and Severity of Ship Slamming at Sea.* Fifth Symposium on Naval Hydrodynamics, Bergen.

O'Connor, M., Lewis, T., & Dalton, G. (2012). Weather window analysis of Irish west coast wave data with relevance to operations & maintenance of marine renewables.

Oppland, G. (2017, April 4). 1st Officer on M/S "Frøy Fighter". Interviewer: R. Stemland.

Payne, P. (1976). *On Quantizing Ride Comfort and Allowable Accelerations.*

Reite, K., Føre, M., Aarsæther, K., Jensen, J., Rundtop, P., Kyllingstad, L., ... Fredheim, A. (2014). FhSim - Time Domain Simulation of Marine Systems.

Rusu, L. & Soares, C. G. (2013). Forecasting fishing vessel responses in coastal areas.

Salvesen, N. & Faltinsen, O. (1970). *Ship Motions and Sea Loads.*

Sandberg, M. G., Lien, A. M., Sunde, L. M., Størkersen, K. V., Stien, L. H., & Kristiansen, T. (2012). *Erfaringer og analyser fra drift av oppdrettsanlegg på eksponerte lokaliteter [Experiences and analyses on operation of exposed aquaculture facilities].* SINTEF Ocean.

Sargent, R. G. (1998). *Validation and Verification of Simulation Models.* Department of Electrical Engineering and Computer Science, Syracuse University, NY.

Schmidt, J. & Taylor, R. (1970). *Simulation and Analysis of Industrial Systems.*

Senneset, G. (2017a, May 3). Senior Research Scientist, SINTEF Ocean. Interviewer: R. Stemland.

Senneset, G. (2017b, March 11). SustainFarmEx – Towards Sustainable Fish Farming at Exposed Marine Sites. Retrieved from http://www.sintef.no/prosjekter/sustainfarmex-towards-sustainable-fish-farming-at-/

Shyshou, A., Gribkovskaia, I., & Barceló, J. (2009). A simulation study of the fleet sizing problem arising in offshore anchor handling operations.

SINTEF Ocean. (2017, May 30). SIMA. Retrieved from https://www.sintef.no/en/software/sima/

St. Denis, M. (1976). *On the Environmental Operability of Seagoing Systems.* The Society of Naval Architects and Marine Engineers, New York.

Statistics Norway. (2017, March 8). Aquaculture. preliminary numbers. Retrieved from https://www.ssb.no/266921/akvakultur.forelopige-tall

Steen, S. (2014). *Experimental Methods in Marine Hydrodynamics.*

Svåsand, T., Boxaspen, K. K., Karlsen, Ø., Kvamme, B. O., Stien, L. H., & Taranger, G. L. (2015). *Risikovurdering norsk fiskeoppdrett 2014 [Risk Assessment of Norwegian Aquaculture 2014].* Havforskningsinstituttet.

Tello, M., Silva, S. R., & Soares, C. G. (2010). Seakeeping performance of fishing vessels in irregular waves.

Tupper, E. C. (2013). *Introduction to Naval Architecture (Fifth Edition).*

Vugts, J. (1968). *The Hydrodynamic Coefficients for Swaying, Heaving and Rolling Cylinders in a Free Surface.* Laboratorium voor Scheepsbouwkunde, Technische Hogeschool Delft.

Waagbø, S. K. (2014). MACHO - The Size Matters - the contours of future service vessels.

Wang, J., Pillar, A., Kwon, Y., Wall, A., & Rodríguez, C. L. (2005). An analysis of fishing vessel accidents.

Appendix A

Problem Statement

MASTER'S THESIS IN MARINE TECHNOLOGY

SPRING 2017

For stud.techn.
Runar Stemland

Assessment of Service Vessel Operability In Exposed Aquaculture

Background
The aquaculture production in Norway has gradually moved towards more exposed location, but large parts of the coast is unavailable to production activity due to harsh environmental conditions. A better interaction between vessel and structure components, operability criteria and tools for decision-making, have been identified as key issues to develop safe and reliable production in exposed aquaculture.

Objective
The objective of this thesis is to increase the knowledge and insight of service vessel operations in exposed aquaculture, with a focus on vessel behavior and performance during vessel-structure interaction. Through a vessel response analysis and specification of operability criteria, quantitative limits of operation will be determined. Operational limits may improve the ability to plan operations ahead based on weather forecasts, and thereupon increase the overall utilisation and operability of the vessel. Further, this thesis will develop a simulation model that uses operational limits obtained from the vessel response analysis and wave data series from oceanographic buoys as input to analyse the long-term operability of a service vessel. By testing and comparing different vessel designs, a simulation model can also provide valuable information on vessel performance for decision-making in the early phase of a design process, which in turn could contribute to develop new and improved designs with increased operability.

Tasks
- Conduct a literature review on previous work on relevant subjects like vessel operability, metocean conditions, weather forecasting and simulation of marine systems.
- Perform a vessel-response analysis and specify operability criteria for a chosen vessel design.
- Develop a simulation model to assess the long-term operability of the vessel.
- Present and discuss the results
- Conclusions and recommendations for further work.

General
In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work. Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

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

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

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated. The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverables
The thesis shall be submitted electronically (pdf) in DAIM:
- Signed by the candidate
- The text defining the scope (signed by the supervisor) included
- Computer codes, input files and other electronic appandages that cannot be bound should be organized and uploaded in a separate folder in DAIM.

Supervisor **:** Professor Bjørn-Egil Asbjørnslett, IMT
Co-supervisor **:** Dariusz Eirik Fathi, SINTEF Ocean
Start-up **:** 15.01.2017
Deadline **:** 11.06.2017

Appendix B

Description of Software

A short description of relevant software considered in the report. Only MATLAB, Simulink and VERES have been actively used in the thesis work, while the remaining software are considered in Chapter 11 on further work.

FhSim	a program developed by SINTEF Ocean for simulation and visualisation of marine operations and systems.
Gymir	a workbench capable of hosting, testing and applying different modules and research algorithms to data sets.
MATLAB	a programming language for numerical computing.
SIMA	a workbench developed by SINTEF Ocean for simulation and analysis of marine operations and floating systems.
Simulink	add-on to MATLAB, which enables graphical programming for simulation and analyses of dynamic systems.
VERES	a vessel response program for calculating ship motions and loads, short- and long-term statistics and operability.

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Appendix C

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

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Appendix D

Vessel Specification - 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

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Appendix E

Stability Report - Loading Cond.: Ballast,departure

Figure E.1 and E.2 shows the stability report on the selected loading condition for the Macho 40 (M/S "Frøy Fighter"). The information is useful to compare and verify the hydrostatic data obtained in VERES.

Frøy Fighter

Condition No: 7 :Ballast, Departure

Water sp.gravity (t/m3) 1.0250 Intact ship SS=1-20, Shell=6 Date: 14 DEC 2015

App2=1-6,9-23,31-34,37-44

Pos	Description	TNo	TCode	DWc	Vol. (m3)	Spg. (t/m3)	Weight (t)	LCG (m)	VCG (m)	TCG (m)	Spg*IT (t*m)	Length (m)
1	Crew			CRE	0.60	1.0000	0.60	30.000	6.600	0.000	0.0	1.00
2	Provision			PRO	1.00	1.0000	1.00	36.500	6.000	0.000	0.0	1.00
3	Storage			STO	1.00	1.0000	1.00	30.000	6.000	-2.500	0.0	1.00
5	WB Forepeak tank #71-Stem	1 T	100%	WB	16.60	1.0250	17.01	36.339	3.228	0.000	0.0	2.25
6	WB DB tank #45-65 Port Side	2 T	100%	WB	46.40	1.0250	47.56	26.821	1.010	-1.952	0.0	10.00
7	WB DB tank #45-65 Starboard	3 T	100%	WB	46.40	1.0250	47.56	26.821	1.010	1.952	0.0	10.00
8	WB DB tank #23-45 Port Side	4 T	100%	WB	74.74	1.0250	76.61	16.997	0.949	-2.466	0.0	11.00
9	WB DB tank #23-45 Starboard	5 T	100%	WB	74.74	1.0250	76.61	16.997	0.949	2.466	0.0	11.00
10	WB Stern tank Stern-#5 PS	6 T	100%	WB	27.92	1.0250	28.61	0.410	3.743	-3.570	0.0	4.54
11	WB Stern tank Stern-#5 SB	7 T	100%	WB	27.92	1.0250	28.61	0.410	3.743	3.570	0.0	4.54
13	FW tank #45-58 Port Side	8 T	100%	FW	26.19	1.0000	26.19	26.178	2.703	-3.888	31.6	6.25
14	FW tank #45-58 Starboard	9 T	100%	FW	26.19	1.0000	26.19	26.178	2.703	3.888	31.6	6.25
16	MDO Side tank #23-44 PS	10 T	100%	MDO	44.33	0.8600	38.13	16.787	3.059	-5.251	2.5	10.50
17	MDO Side tank #23-44 SB	11 T	100%	MDO	41.13	0.8600	35.37	17.162	3.033	5.251	2.5	10.50
18	MDO Daytank #23-25 SB	12 T	100%	MDO	3.21	0.8600	2.76	11.985	3.394	5.249	0.0	1.00
20	Sludge tank DB #19-21 SB	13 T	100%	SLU	2.47	0.9000	2.22	10.022	1.177	3.355	0.0	1.00
21	Sewage tank #65-67 Center	16 T	100%	SEW	4.80	1.0000	4.80	32.981	1.036	0.000	0.0	1.00
22	Bilge water tank #16-19 SB	19 T	100%	BW	2.34	1.0000	2.34	8.839	1.289	3.197	0.0	1.50
	Dead weight:						463.16	18.857	1.969	0.027	68.2	
	Light ship:						466.00	17.910	3.920	0.061		
	TOTAL for the condition:						929.16	18.382	3.021 *	0.044	ITc=	0.073

Description	Filling (%)	DWc	Volume (m3)	Spc.gr (t/m3)	Weight (t)
Crew		CRE	0.6	1.0000	0.6
Man Provision Storage		STO	1.0	1.0000	1.0
Fresh Water		FW	52.4	1.0000	52.4
Sluge oil		SLU	2.5	0.9000	2.2
Bilge Water		BW	2.3	1.0000	2.3

Description	Filling (%)	DWc	Volume (m3)	Spc.gr (t/m3)	Weight (t)
Provision		PRO	1.0	1.0000	1.0
Water Ballast		WB	314.7	1.0250	322.6
Marine Diesel Oil		MDO	88.7	0.8600	76.3
Septic / Sewage		SEW	4.8	1.0000	4.8

Condition's VCG (m): 3.021 * (2.947 + 0.073) GMT (m): 3.568 KMT (m): 6.589

Max allowed VCG (m): 4.791

WATERLINE	DA (m)	DF (m)	MEAN (DA+DF)/2	TRIM (DA-DF)	HEELING (°SB/PS)	TPC (t/cm)	MCT1CM (tm/cm)	Wet Surf (m2)
Draft at MARK:	-0.213	-0.217						
Draft above BASE:	3.337	3.333	3.335	0.003	0.55 SB	4.14	11.18	588.84

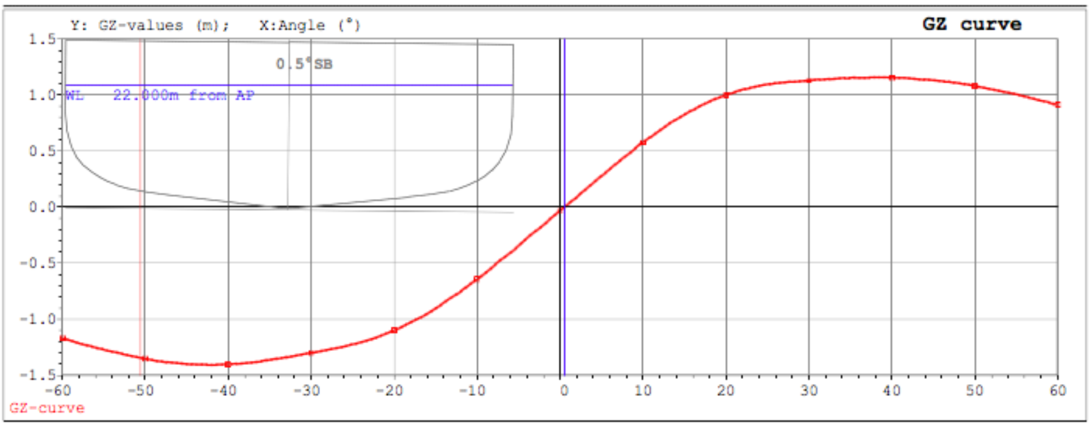
Figure E.1: Hydrostatic data from the stability report on loading condition 7: Ballast, departure. The data is presented with consent from Møre Maritime AS.

Frøy Fighter

Condition No: 7 :Ballast, Departure

Water sp.gravity (t/m3) 1.0250 Intact ship SS=1-20, Shell=6 Date: 14 DEC 2015

App2=1-6,9-23,31-34,37-44



Displ.=929.163T \LCG=18.382M \VCG=3.021M \TCG=0.044M
GMt = 3.568M

Angles (-PS°)	GZ (M)	Angles (+SB°)	GZ (M)
0.0	-0.034	0.0	-0.034
-10.0	-0.642	0.5	Equilibrium
-20.0	-1.100	10.0	0.576
-30.0	-1.302	20.0	1.000
-40.0	-1.402	30.0	1.131
-42.1	-1.406*Max*	38.1	1.158*Max*
-50.0	-1.353	40.0	1.156
-60.0	-1.169	50.0	1.080
		60.0	0.913

Angles (-PS°)	Area (MR)
0.5 > -20	0.215
0.5 > -30	0.428
0.5 > -40	0.665
-30.0 >-40.0	0.237
0.5 >-42.1	0.717

Angles (+SB°)	Area (MR)
0.5 > 20	0.190
0.5 > 30	0.379
0.5 > 40	0.580
30.0 > 40.0	0.201
0.5 > 38.1	0.542

Flood angles: Used points:1-2

PS/SB	Angles (°)	GZ (M)	Ab.WL (M)	Type	No:Description
PS	-50.6	-1.346	6.128	T3	2:ER ventilation
SB	> 60.0		5.727	T3	1:ER ventilation

STABILITY CRITERIA: (Column WC="Worst Case" use: SB=SB, PS=PS or SP=SB&PS)

Set name: INTACT: Supply & Towing ship (Rev.2008-11-04)

Comment	Left/Expression	Value	R	Right/Req.	WC	OK/Not
Area (0-15/30) >= 0.07/0.	CHOOSE(FirstGZMaxAngle <=15, GetGZArea(0,15) , CHOOSE(FirstGZMaxAngle >15 AND FirstGZMaxAngle <30, GetGZArea(0,FirstGZMaxAngle), GetGZArea(0,30)))	0.3789	>=	0.0550	SB	OK
Area(30-40/FA3)° >= 0.030	CHOOSE(Min(40,FloodAngle3) >30 ,GetGZArea(30,Min(40,FloodAngle3)),0)	0.2007	>=	0.0300	SB	OK
Turningpoint >= 15°	GZMaxAngle	38.1381	>=	15.0000	SB	OK
Min.GM>0.15	GMT	3.5681	>=	0.1500	SP	OK
GZ >= 0.2m at angle >=30	GetGZMax(30, LastAngle)	1.1579	>=	0.2000	SB	OK

Result for used variables:

RAD2DEG=57.2958	DEG2RAD=0.0175	K=0.1000
WD=0.0034	H=-0.8731	KA1=0.4750
KA2=-0.0305		

Figure E.2: GZ curve from the stability report on loading condition: Ballast, departure. The report is presented with consent from Møre Maritime AS.

Appendix F

VERES: Hydrostatic Report

ShipX	DATA-CHECK PROPERTIES	ENCL. A.431
		REPORT
		DATE 26.04.2017
		REF.

Run name: VERES Calculation

```
Ship name: Macho 40
Loading condition description: Design waterline

ShipX exported data
Main dimensions (from input):
_____________________________________________________________

Length between perpendiculars     (m)      37.870
Breadth                           (m)      12.000
Draught, midship                  (m)       3.335
Sinkage                           (m)       0.000
Trim, + = aft                   (deg)       0.000
_____________________________________________________________

Coefficients for data check etc.:
Type                                  Specified    Calculated
_____________________________________________________________

Displacement                 (tonnes)      929.00        932.60*
Vertical center of bouyancy,      KB                     1.971*
Vertical center of gravity,       VCG       3.021*
Longitudinal center of bouyancy,  LCB                   18.319*
Longitudinal center of gravity,   LCG      17.058       18.319*
Block coefficient,                Cb        0.601        0.600
Water plane area coefficient,     Cw        0.837        0.884
Prismatic coefficient,            Cp                     0.688
Mid section area coefficient,     Cm        0.887        0.873*
Longitudinal metacentric height,  GMl                   47.184*
Transverse metacentric height,    GMt                    3.528*
Roll radius of gyration,          r44       4.200*
Pitch radius of gyration,         r55      10.000*
Yaw radius of gyration,           r66      10.000*
Roll-yaw radius of gyration,      r46       0.000*
_____________________________________________________________

* - Applied in the hydrodynamic calculations
```

Figure F.1: Calculated hydrostatic data in VERES.

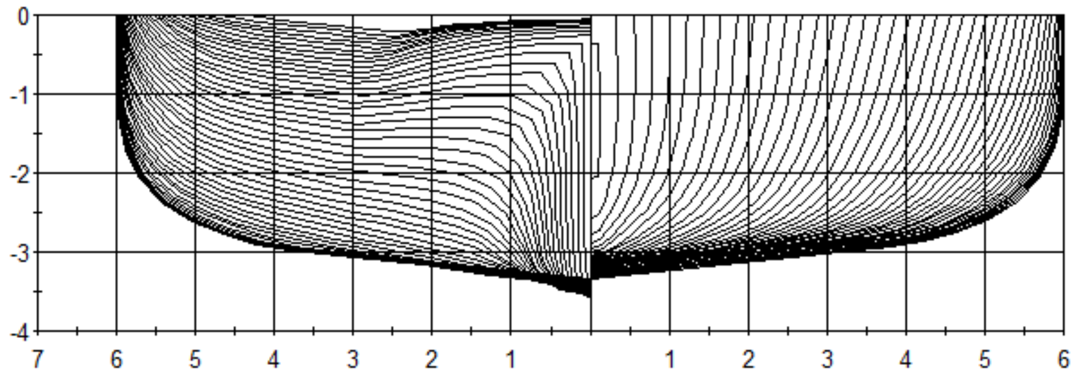


Figure F.2: Lines plan of the hull geometry. Forward half on the right, aft half on the left.

Appendix G

Operability Criteria

Table G.1 shows which parts of the ship is considered when estimating the limiting criteria of motions. This is information provided by Nielsen (1987), and was used in their project on assessing ship performances in a seaway. It is relevant for this thesis as well, since many of the findings from this report has been applied in the VERES analysis. It can be seen that while the vertical acceleration is affecting all four categories, slamming and deck wetness only concern hull safety. An important note on the slamming, is that for passenger vessels, vibrations from slamming may cause discomfort and thus require a reduction in critical values.

Table G.1: Points of view considered in the criteria (Nielsen, 1987).

Criterion	**Hull safety**	**Equip. Operation**	**Cargo safety**	**Personnel safety and efficiency**
Vert. acc.	•	•	•	•
Lateral acc.		•	•	•
Roll		•	•	•
Slamming	•			
Deck wetness	•			

Table G.2 shows limiting criteria for vertical and lateral acceleration and roll motion in terms of comfort and seasickness for the crew and passengers. The information provided in the table is useful to see the varying limits for different cases. For the purpose of the Macho 40, heavy manual work and intellectual work has been applied to describe the typical work during the operations. An important note is that the intellectual work in this table considers humans not well adapted to vessel motions, meaning the values will be somewhat lower than the ones applied in this thesis.

Figure G.1 shows the severe discomfort boundaries according to ISO 2631-3:1985 with regard to vertical acceleration as a function of exposure time (Nielsen, 1987). The findings

Table G.2: Criteria with regard to accelerations and roll motion (Nielsen, 1987).

Root mean square criterion			**Description**
Vert. acc.	Lat. acc.	Roll	
0.20 g	0.10 g	6 deg	Light manual work
0.15 g	0.07 g	4 deg	Heavy manual work
0.10 g	0.05 g	3 deg	Intellectual work
0.05 g	0.04 g	2.5 deg	Transit passengers
0.02 g	0.03 g	2 deg	Cruise liner

from the laboratory experiments done by McCauley et al. (1976) is also presented, along with a standard proposal from Goto (1983). The values from ISO 2631:3-1985 is based on a mixed population of unadapted male and female adults ($K_m = 1/3$).

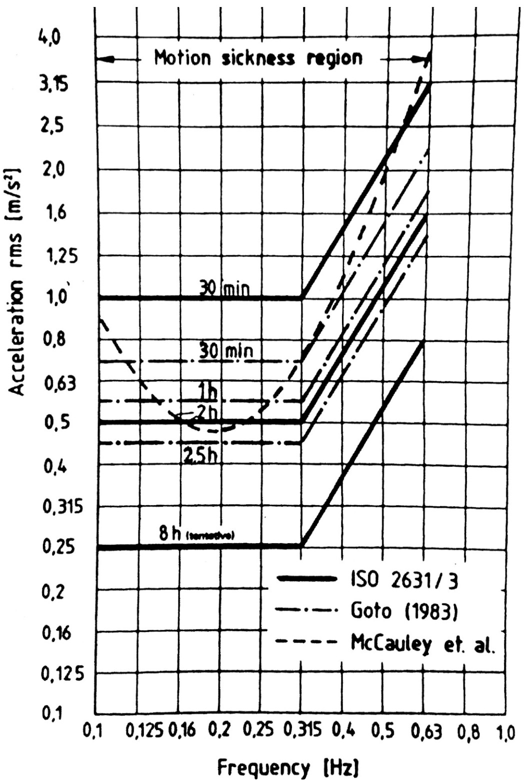


Figure G.1: Boundaries for severe discomfort according to ISO 2631:3-1985, Goto (1983) and McCauley, Royal, Wylie, O'Hanlon, and Mackie (1976).

Appendix H

Questionnaire: Vessel Operations

	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

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Appendix I

Simulation Model

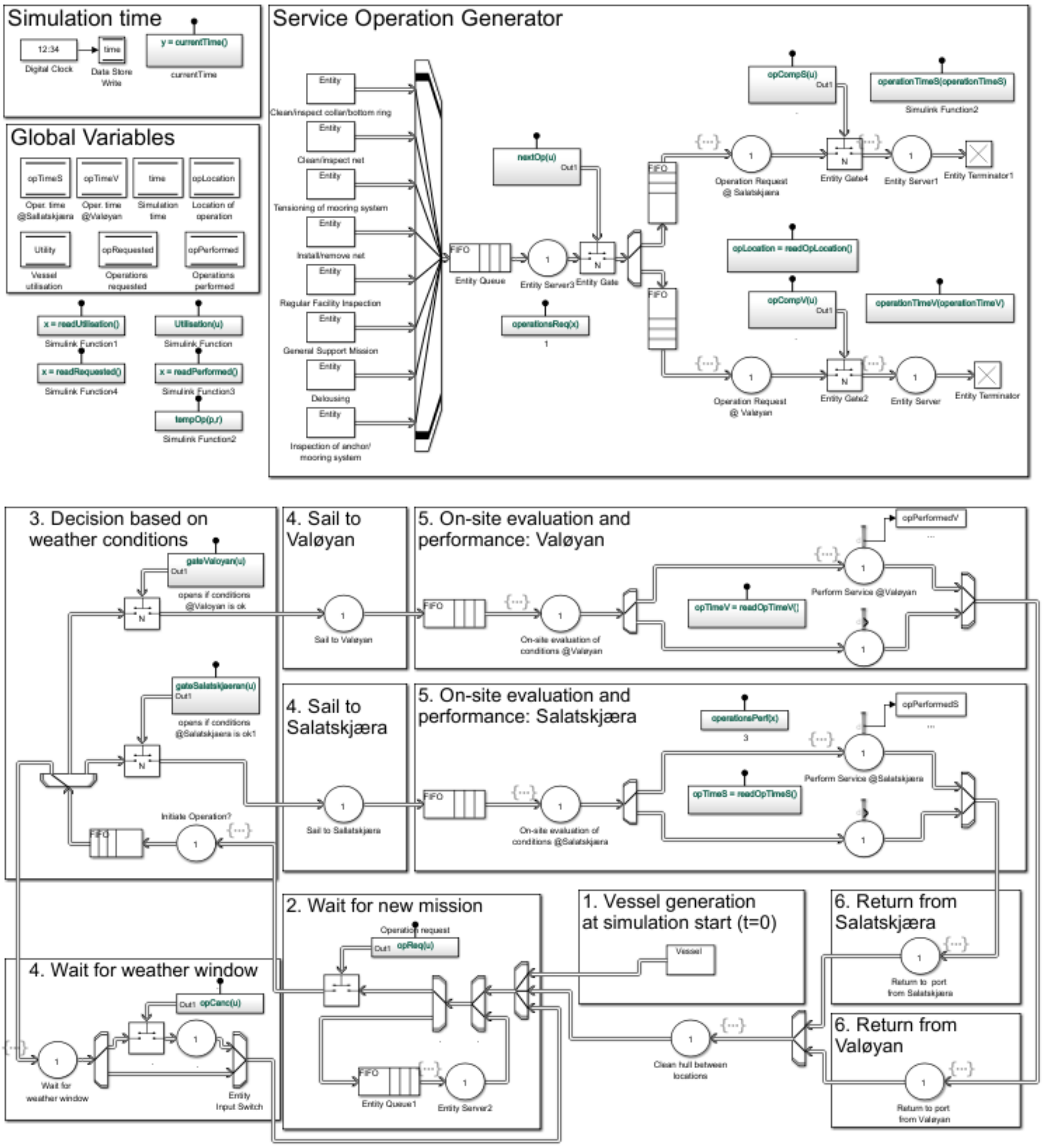

Figure I.1: Overview of the simulation model. The lower half concers the vessel sailing and operations. The upper half blocks are additional input and global variables.

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Appendix J

MATLAB Scripts: Simulation Model

Main Script

This script is an external MATLAB script that defines the required variables prior to the simulation in Simulink. The post-processing is done after the simulation is completed and consists of the definition of different variables, calculation of average values and standard deviations. Sector 1-6 in the script corresponds to the wave heading sectors defined in Section 8.2.

```

%% Define variables
operabilityAccumulated = 0;
operabilityMean = 0;
operability = 0;
temp = zeros(40,1);

for j = 1:40
%% SECTOR 1
opLim = [operationLimits(:,1),operationLimits(:,2),operationLimits(:,3) ,...
         operationLimits(:,13)];
sim('DES_MultipleDir1');     % Run simulation for Sector 1

%% SECTOR 2
opLim = [operationLimits(:,1),operationLimits(:,2),operationLimits(:,3) ,...
         operationLimits(:,4),operationLimits(:,12),operationLimits(:,13)];
sim('DES_MultipleDir2');    % Run simulation for Sector 2

%% SECTOR 3
opLim = [operationLimits(:,1),operationLimits(:,2),operationLimits(:,3) ,...
        operationLimits(:,4),operationLimits(:,5),operationLimits(:,11) ,...
        operationLimits(:,12),operationLimits(:,13)];
sim('DES_MultipleDir3');    % Run simulation for Sector 3

```

```
%% SECTOR 4
opLim = [operationLimits(:,1),operationLimits(:,2),operationLimits(:,3),...
         operationLimits(:,7),operationLimits(:,8),operationLimits(:,9),...
         operationLimits(:,13)];
sim('DES_MultipleDir4');   % Run simulation for Sector 4

%% SECTOR 5
opLim = [operationLimits(:,1),operationLimits(:,2),operationLimits(:,3),...
         operationLimits(:,4),operationLimits(:,6),operationLimits(:,7),...
         operationLimits(:,8),operationLimits(:,9),operationLimits(:,10),...
         operationLimits(:,12),operationLimits(:,13)];
sim('DES_MultipleDir5');   % Run simulation for Sector 5

%% SECTOR 6
opLim = [operationLimits(:,1),operationLimits(:,2),operationLimits(:,3),...
         operationLimits(:,4),operationLimits(:,5),operationLimits(:,6),...
         operationLimits(:,7),operationLimits(:,8),operationLimits(:,9),...
         operationLimits(:,10),operationLimits(:,11),...
         operationLimits(:,12),operationLimits(:,13)];
sim('DES_MultipleDir6');   % Run simulation for Sector 6

%% POST-PROCESSING

% Number of operations performed at Valoyan
    numOpV = opPerformedV.Data;
    timeOpV = opPerformedV.Time;

% Number of operations performed at Salatskjaera
    numOpS = opPerformedS.Data;
    timeOpS = opPerformedS.Time;

% Total number of operations performed
    opPerformed = numOpV(length(numOpV)) + numOpS(length(numOpS));

% Number of operation requests at Valoyan
    opRequestV = operationsRequestedV.Data;
    timeOpReqV = operationsRequestedV.Time;

% Number of operation requests at Salatskjaera
    opRequestS = operationsRequestedS.Data;
    timeOpReqS = operationsRequestedS.Time;

% Total number of operation requests
```

```
    operationsReqVS = operationsRequested.Data;
    totOperationsReq = operationsReqVS(length(operationsReqVS));

% Update operability matrix (temp) for each loop
    operability = opPerformed/totOperationsReq*100;
    temp(j) = operability;
    operabilityAccumulated = operabilityAccumulated + operability;
    operability = zeros(1,12);
end

% Calculate mean operability and standard deviation
operabilityMean = operabilityAccumulated/j;
standardDev = std(temp);
```

Script for assessing weather conditions

This script is located in the server of block number three in the simulation model. The necessary data to assess the weather conditions at the locations are imported and compared to the operational limits. A decision is then made whether the operation is to be initiated or postponed. The following script is modified for *sector 6* as defined in Section 8.2.2, hence all wave headings are included in the interpolation process.

```
readUtilisation();              % update global variable "Utility"
location = readOpLocation();% location of next operation
Hs_V = dataV(:,1);              % import Hs @Valoyan
Tz_V = dataV(:,2);              % import Tz @Valoyan
Hs_S = dataS(:,1);              % import Hs @Salatskjaeran
Tz_S = dataS(:,2);              % import Tz @Salatskjaeran

simTime = currentTime();        % current simulation time
if simTime == 0
    simTime = simTime +1;
end

if location == 1                % 1 = Valoyan 2 = Salatskjaera

    %% Current sea state at Valoyan + three hours forecast incl.
    uncertainty

    currentWaveHeight_V = Hs_V(simTime);
    currentWavePeriod_V = Tz_V(simTime);

    currentWaveHeight_V3 = Hs_V(simTime+3)*(0.05*rand()); % + 5.0 percent;
    currentWavePeriod_V3 = Tz_V(simTime+3)*(0.1*rand()); % + 10.0 percent;

    %% Interpolate limiting sea state at Valoyan

    if currentWavePeriod_V < 3  % small wave approximation
        Hs_lim_V = currentWaveHeight_V;
        gateValoyan(1);         % opens entity gate to Valoyan
        entity.Route = 2;       % specify route to Valoyan
        return
    else
        % interpolate limiting sea states for all 12 headings
        % oplim() = operation limits from VERES
```

```
        Hs_lim_V0 = interp1(opLim(:,1),opLim(:,2),currentWavePeriod_V);
        Hs_lim_V30 = interp1(opLim(:,1),opLim(:,3),currentWavePeriod_V);
        Hs_lim_V60 = interp1(opLim(:,1),opLim(:,4),currentWavePeriod_V);
        Hs_lim_V90 = interp1(opLim(:,1),opLim(:,5),currentWavePeriod_V);
        Hs_lim_V120 = interp1(opLim(:,1),opLim(:,6),currentWavePeriod_V);
        Hs_lim_V150 = interp1(opLim(:,1),opLim(:,7),currentWavePeriod_V);
        Hs_lim_V180 = interp1(opLim(:,1),opLim(:,8),currentWavePeriod_V);
        Hs_lim_V210 = interp1(opLim(:,1),opLim(:,9),currentWavePeriod_V);
        Hs_lim_V240 = interp1(opLim(:,1),opLim(:,10),currentWavePeriod_V);
        Hs_lim_V270 = interp1(opLim(:,1),opLim(:,11),currentWavePeriod_V);
        Hs_lim_V300 = interp1(opLim(:,1),opLim(:,12),currentWavePeriod_V);
        Hs_lim_V330 = interp1(opLim(:,1),opLim(:,13),currentWavePeriod_V);

        Hs_lim_V = [Hs_lim_V0,Hs_lim_V30,Hs_lim_V60,Hs_lim_V90, ...
                    Hs_lim_V120,Hs_lim_V150,Hs_lim_V180,Hs_lim_V210,...
                    Hs_lim_V240,Hs_lim_V270,Hs_lim_V300,Hs_lim_V330];
    end

    % Determine the direction of which has the lowest limiting Hs
    Hs_lim_V_min = [Hs_lim_V(1)];
    for i = 2:length(Hs_lim_V)
        if Hs_lim_V(i) < Hs_lim_V_min
            Hs_lim_V_min = Hs_lim_V(i);
        end
    end
    Hs_lim_V = Hs_lim_V_min;

    %% Check whether the sea state is within operational limits

    if Hs_lim_V >= currentWaveHeight_V && Hs_lim_V >= currentWaveHeight_V3
        gateValoyan(1);     % opens entity gate to Valoyan
        entity.Route = 2;   % specify route to Valoyan
    else
        entity.Route = 1;   % operation postponed due to weather
    end

elseif location == 2 % 1 = øValyan 2 = Salatskjaera

    %% Current sea state at Salatskjaera + three hours forecast incl. uncertainty

    currentWaveHeight_S = Hs_S(simTime);
    currentWavePeriod_S = Tz_S(simTime);
```

```
    currentWaveHeight_S3 = Hs_S(simTime+3)*(0.05*rand()); % + 5.0 percent;
    currentWavePeriod_S3 = Tz_S(simTime+3)*(0.1*rand()); % + 10.0 percent;

    %% Interpolate limiting sea state at Salatskjaera

    if currentWavePeriod_S < 3 % small wave approximation
        Hs_lim_S = currentWaveHeight_S;
        gateSalatskjaeran(1);   % opens entity gate to Salatskjaera
        entity.Route = 3;       % specify route to Salatskjaera
        return
    else
        Hs_lim_S0 = interp1(opLim(:,1),opLim(:,2),currentWavePeriod_S);
        Hs_lim_S30 = interp1(opLim(:,1),opLim(:,3),currentWavePeriod_S);
        Hs_lim_S60 = interp1(opLim(:,1),opLim(:,4),currentWavePeriod_S);
        Hs_lim_S90 = interp1(opLim(:,1),opLim(:,5),currentWavePeriod_S);
        Hs_lim_S120 = interp1(opLim(:,1),opLim(:,6),currentWavePeriod_S);
        Hs_lim_S150 = interp1(opLim(:,1),opLim(:,7),currentWavePeriod_S);
        Hs_lim_S180 = interp1(opLim(:,1),opLim(:,8),currentWavePeriod_S);
        Hs_lim_S210 = interp1(opLim(:,1),opLim(:,9),currentWavePeriod_S);
        Hs_lim_S240 = interp1(opLim(:,1),opLim(:,10),currentWavePeriod_S);
        Hs_lim_S270 = interp1(opLim(:,1),opLim(:,11),currentWavePeriod_S);
        Hs_lim_S300 = interp1(opLim(:,1),opLim(:,12),currentWavePeriod_S);
        Hs_lim_S330 = interp1(opLim(:,1),opLim(:,13),currentWavePeriod_S);

        Hs_lim_S = [Hs_lim_S0,Hs_lim_S30,Hs_lim_S60,Hs_lim_S90, ...
                    Hs_lim_S120,Hs_lim_S150,Hs_lim_S180,Hs_lim_S210,...
                    Hs_lim_S240,Hs_lim_S270,Hs_lim_S300,Hs_lim_S330];
    end

    % Determine the direction of which has the lowest limiting Hs
    Hs_lim_S_min = [Hs_lim_S(1)];
    for i = 2:length(Hs_lim_S)
        if Hs_lim_S(i) < Hs_lim_S_min
            Hs_lim_S_min = Hs_lim_S(i);
        end
    end
    Hs_lim_S = Hs_lim_S_min;

    %% Check whether the sea state is within operational limits

    if Hs_lim_S >= currentWaveHeight_S && Hs_lim_S >= currentWaveHeight_S3
        gateSalatskjaeran(1);   % opens entity gate to Salatskjaera
```

```
        entity.Route = 3;        % specify route to Salatskjaera
    else
        entity.Route = 1;        % operation postponed due to weather
    end
end

%% Update operability variable
    p = readPerformed();
    r = readRequested();
    tempOp(p,r);
```

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Appendix K

Transfer Functions

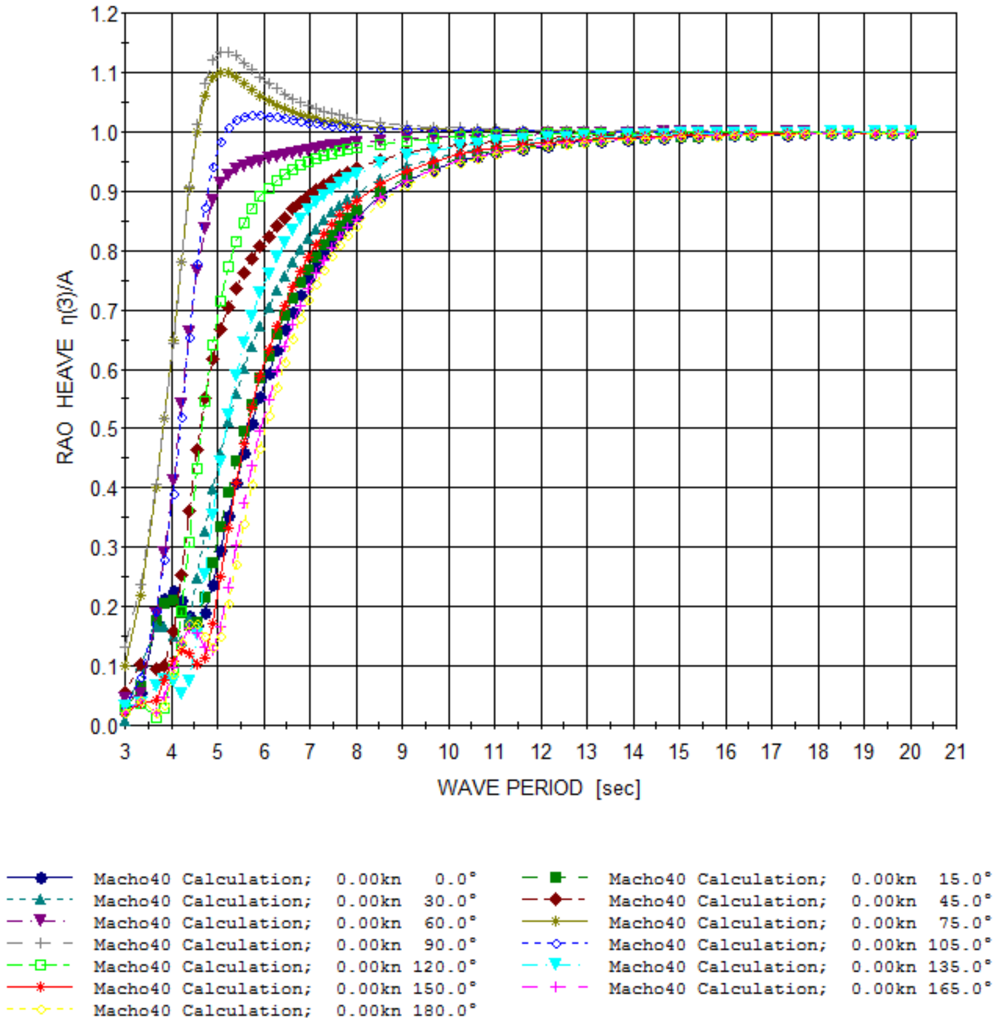

Figure K.1: Response amplitude operator in heave. Cancellation effects can be seen for wave periods around 3-4 s and small resonance effects around 5 seconds.

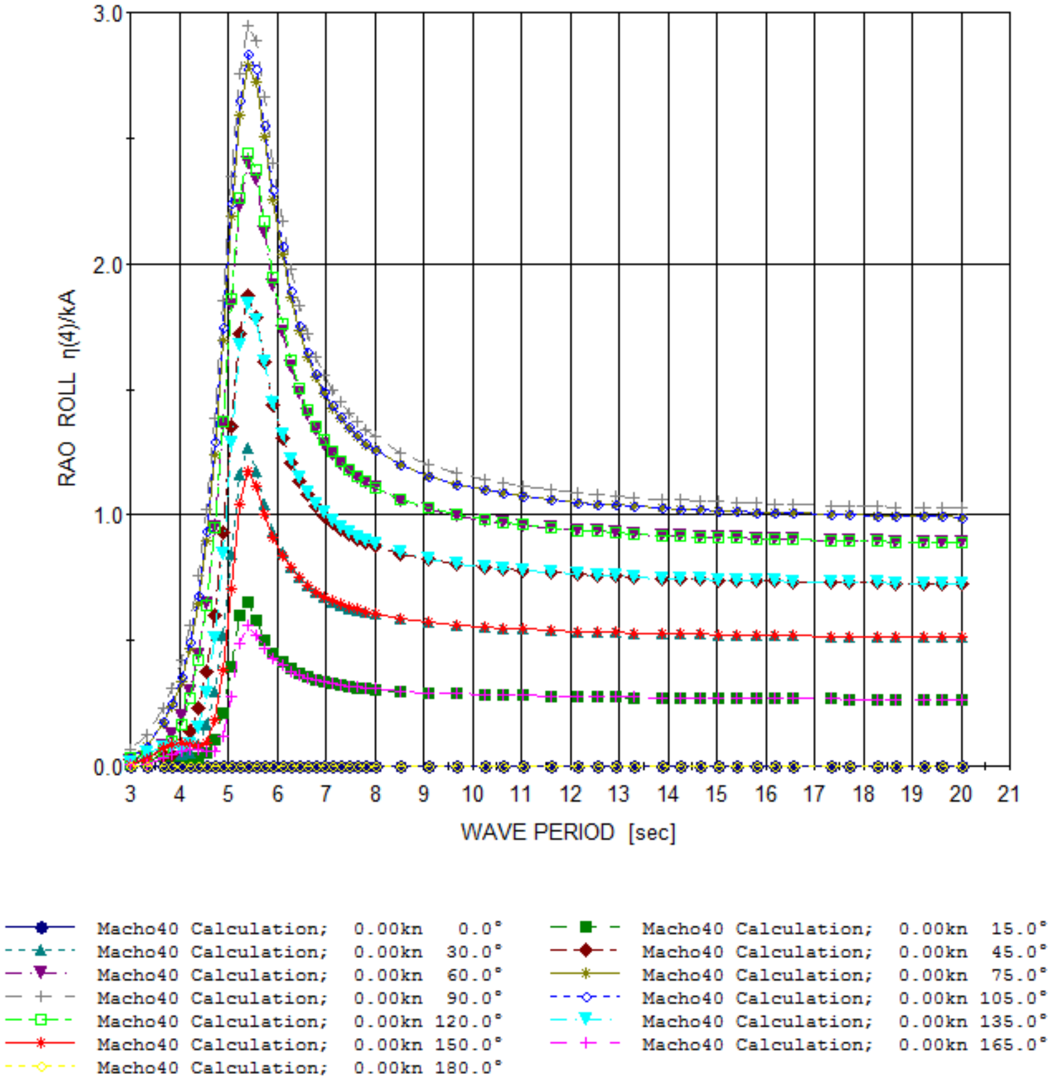

Figure K.2: Dimensionless response amplitude operator in roll. The asymptotes indicate the roll motion for long waves. For 90° the RAO converge towards unity, i.e. the vessel follows the wave.

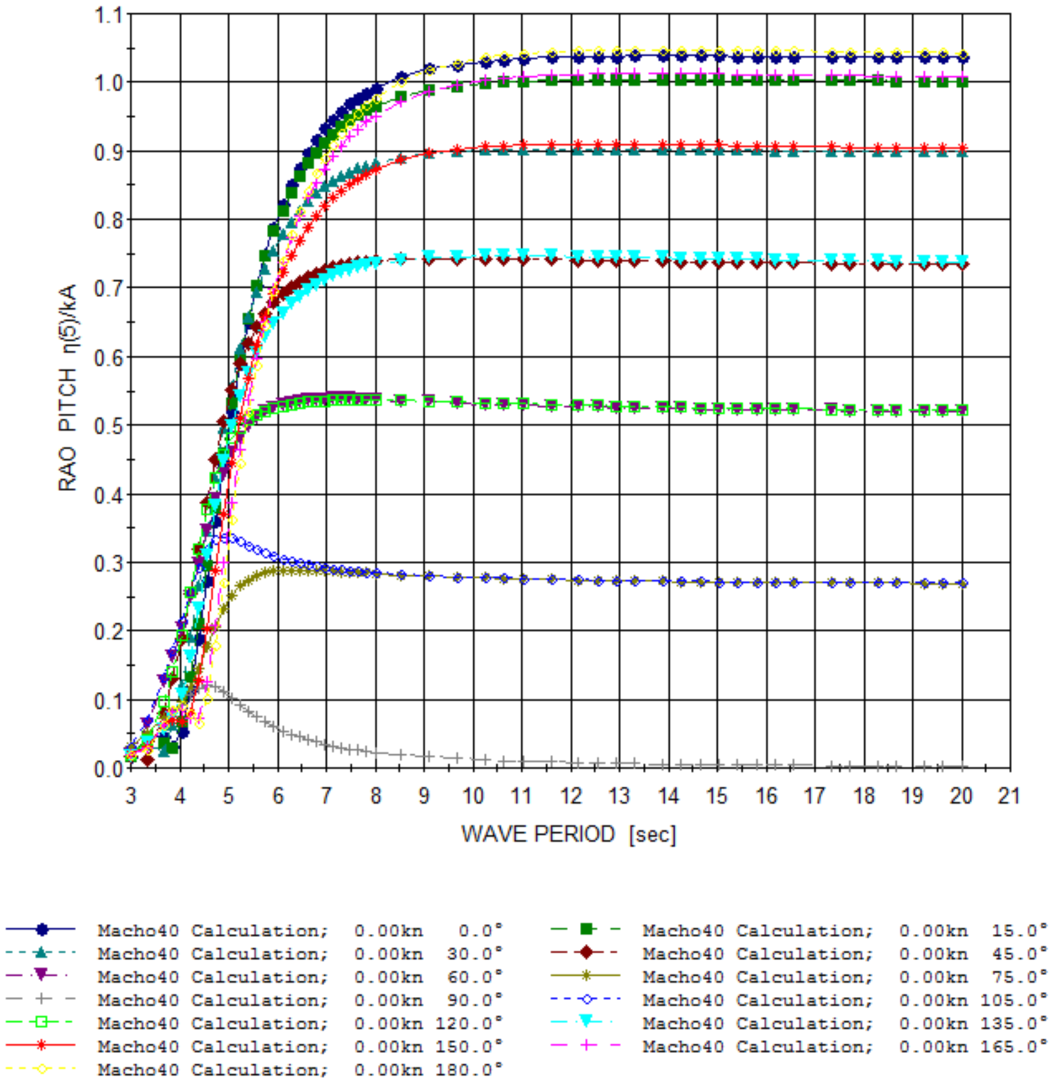

Figure K.3: Dimensionless response amplitude operator in pitch. Beam sea cause little pitch motions, while head and following sea cause the most significant motions.

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Appendix L

Operational Limits

In addition to the results presented in Section 8.1, the following plots provides a more detailed insight into each criterion applied and their impact on the three specified working stations (see Section 5.2). All results are obtained with the same applied wave spectrum, i.e. short-crested JONSWAP with a cosine squared distribution and a wave spreading angle of ±90°. Zero degree heading in the polar curves corresponds to head sea. A short, explanatory comment to each graph is found in the captions.

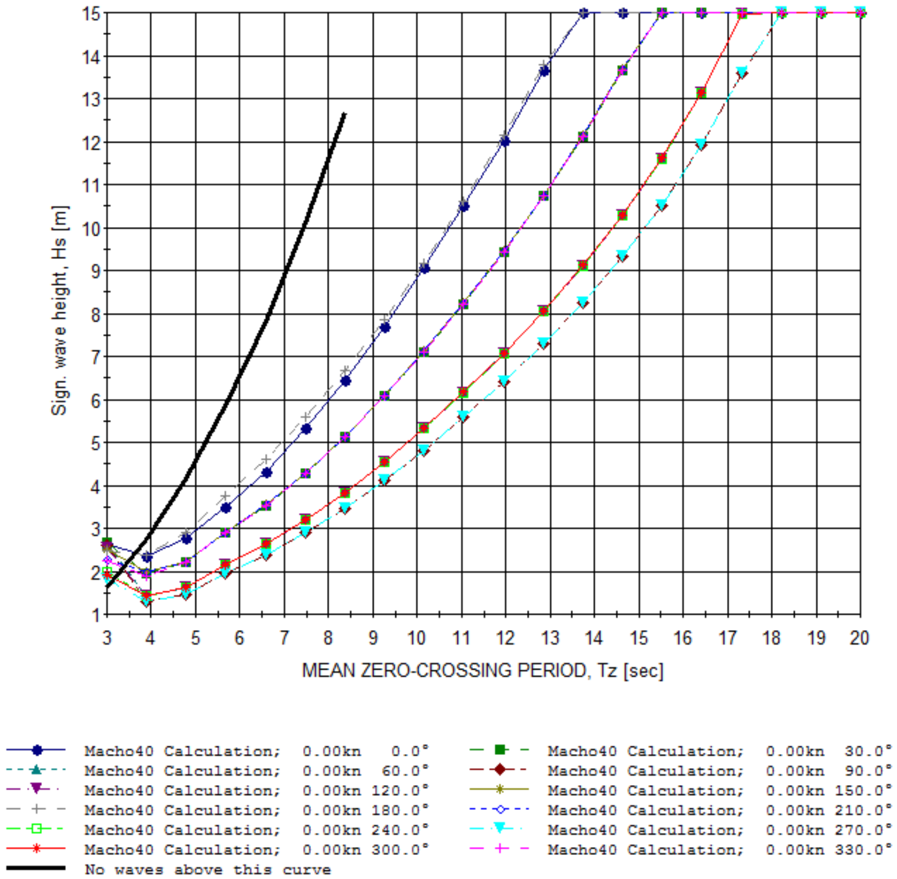

Figure L.1: Limiting wave height H_S [m] for all headings when all criteria are included. The black curve indicates the wave breaking limit, above which no waves exist.

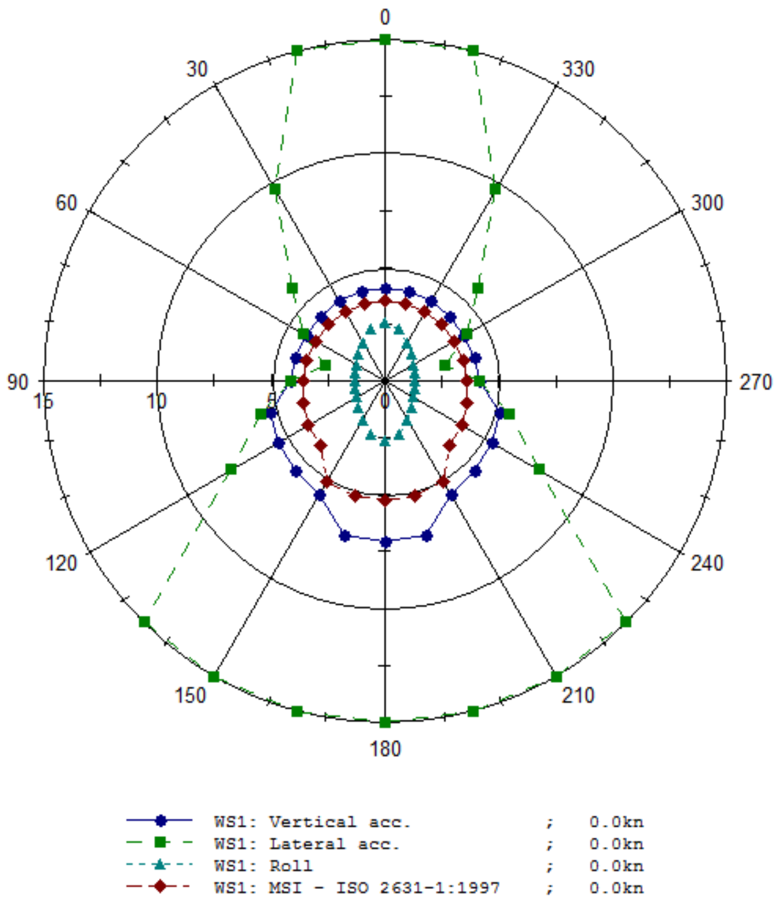

Figure L.2: Limiting wave heights H_S [m] for all headings according to criteria specified at workings station 1 (WS1). Roll motion is identified as the limiting criterion for all wave headings at WS1.

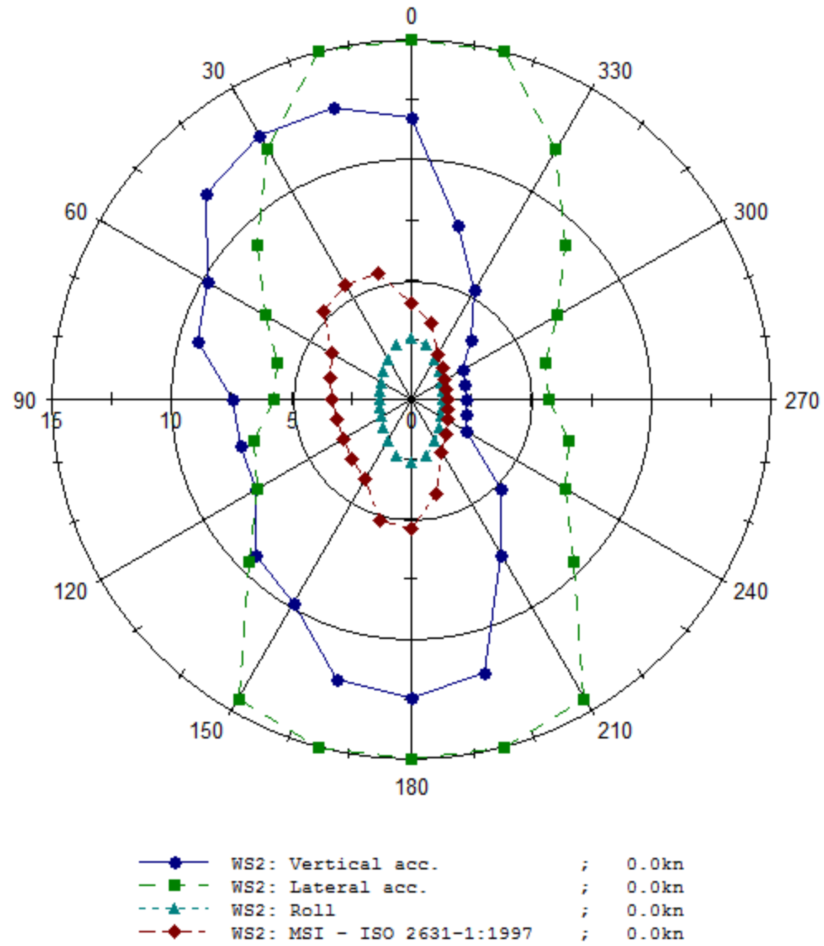

Figure L.3: Limiting wave heights H_S [m] for all headings according to criteria specified at workings station 2 (WS2). Roll motion and (possibly) the MSI criterion are identified as the limiting criteria for WS2.

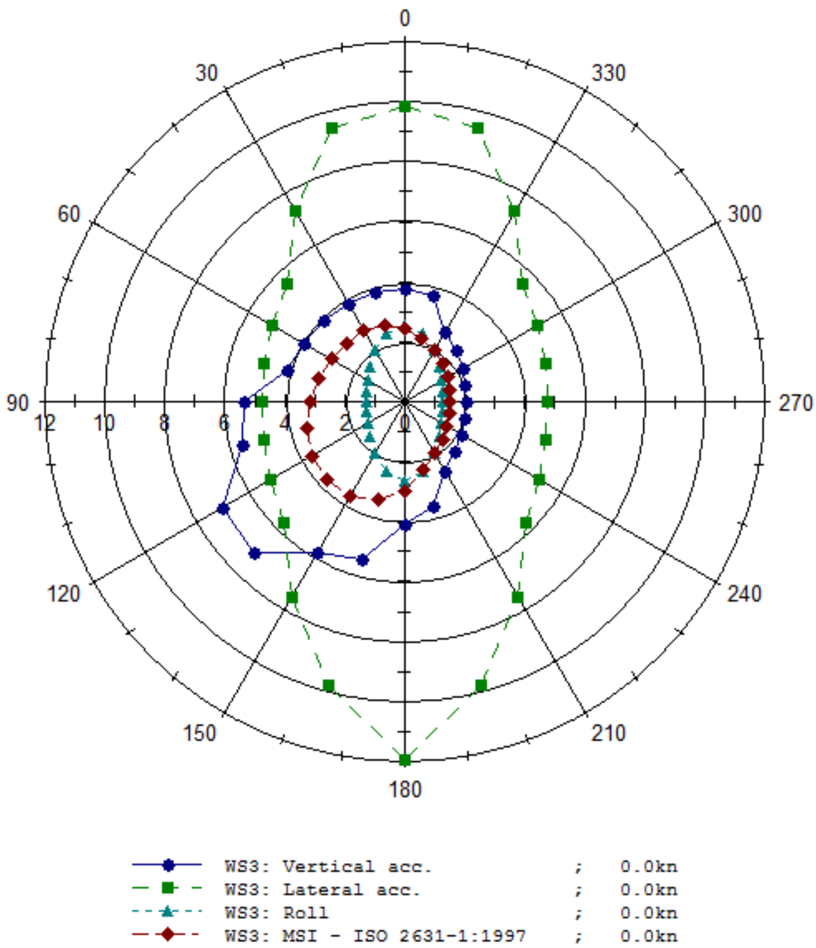

Figure L.4: Limiting wave heights H_S [m] for all headings according to criteria specified at workings station 3 (WS3). Roll motion and the MSI criterion are identified as the limiting criteria for WS3.

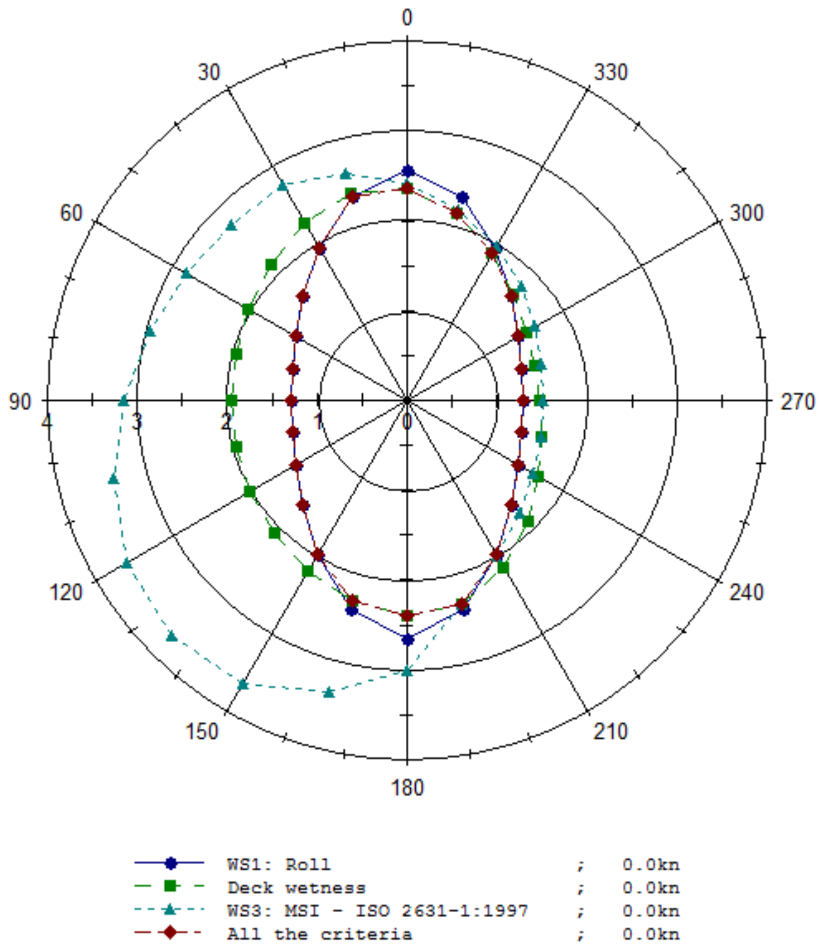

Figure L.5: A comparison of the criteria constraining the overall limiting wave heights H_S [m]. Roll motion is clearly the most limiting criterion for the Macho 40 when all criteria are applied, except at head and following seas.

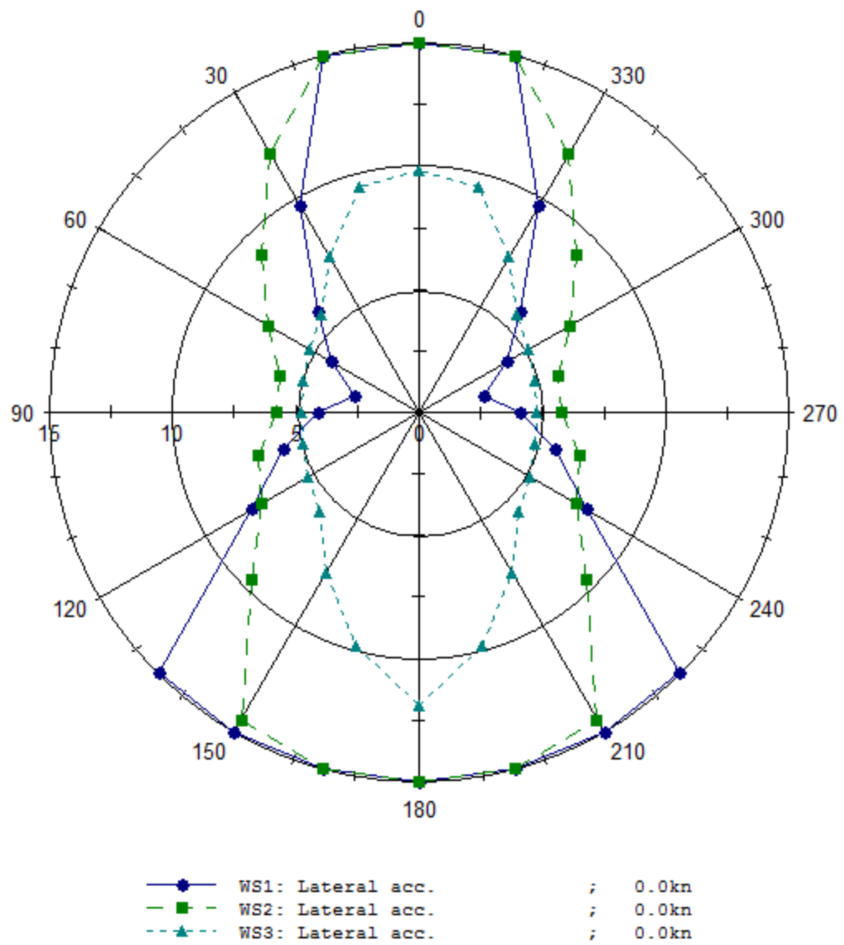

Figure L.6: The effect of lateral acceleration criterion at the three specified working stations. In general WS3 seems most affected, but for beam sea the bridge (WS1) is more affected.

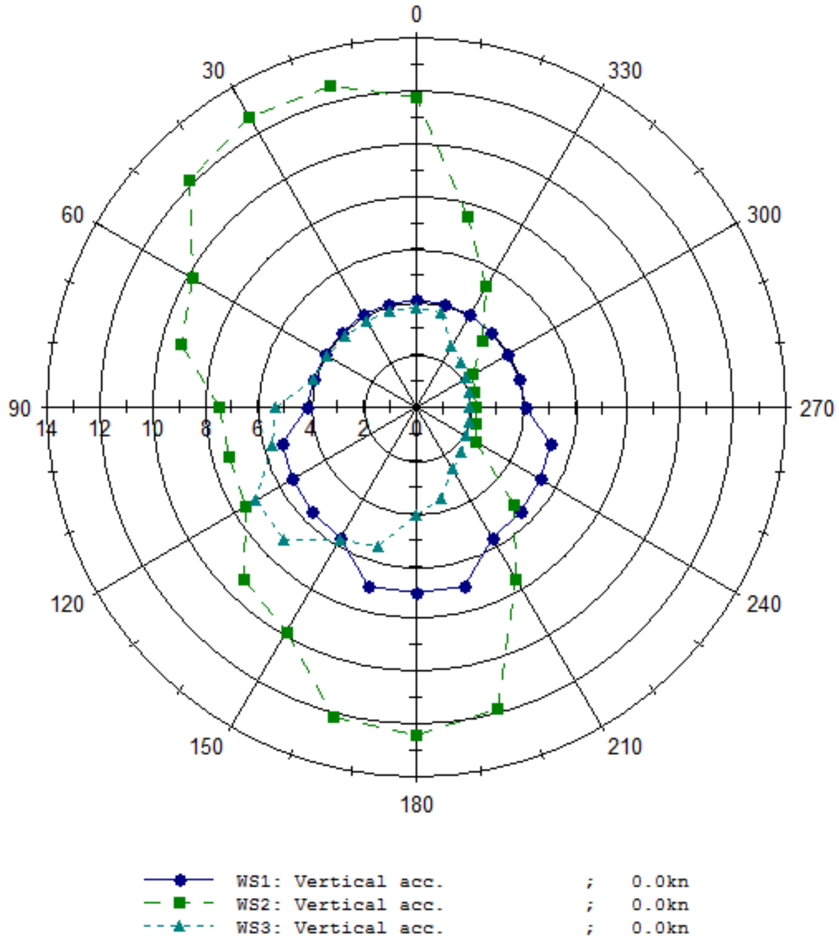

Figure L.7: The effect of vertical acceleration criterion at the three specified working stations. In general WS3 seems most affected, but for headings about $90-150°$ the bridge (WS1) is more affected.

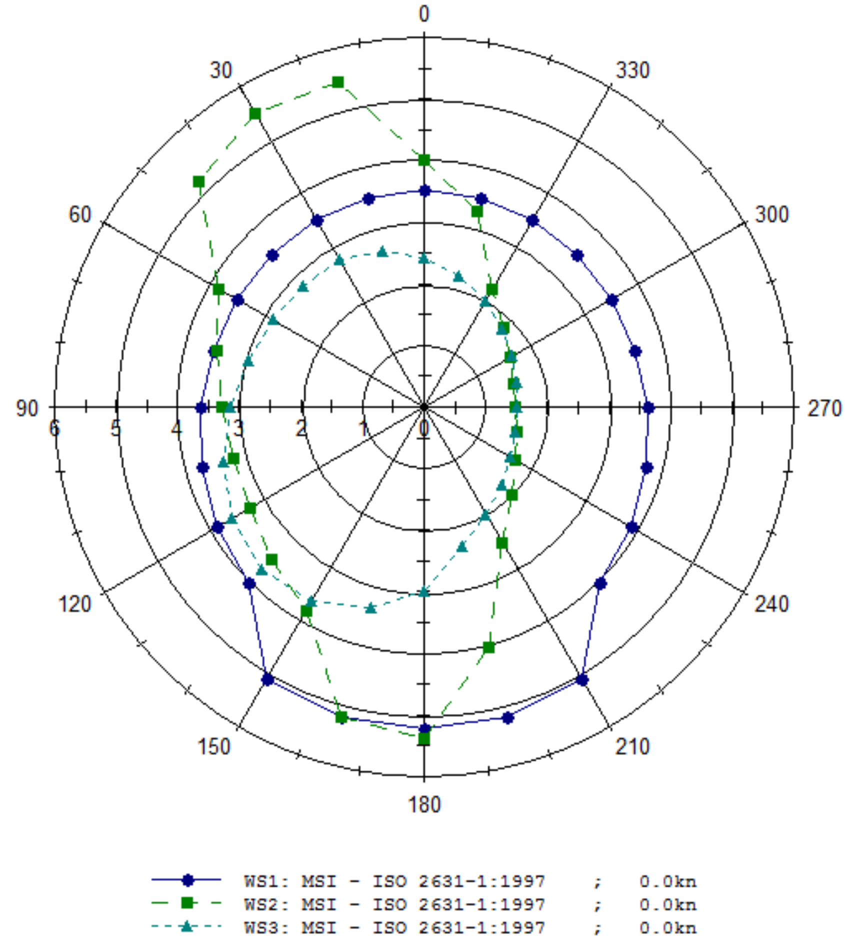

Figure L.8: The effect of motion sickness index (MSI) criterion at the three specified working stations.

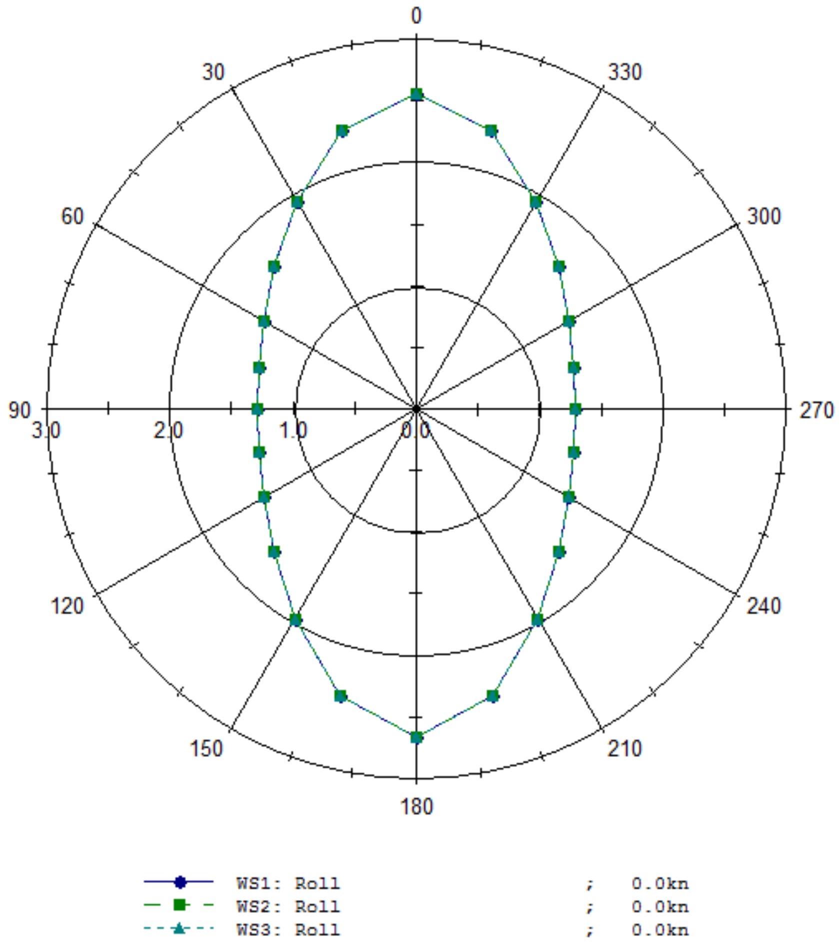

Figure L.9: The roll criterion has an equal effect on all three specified working stations.

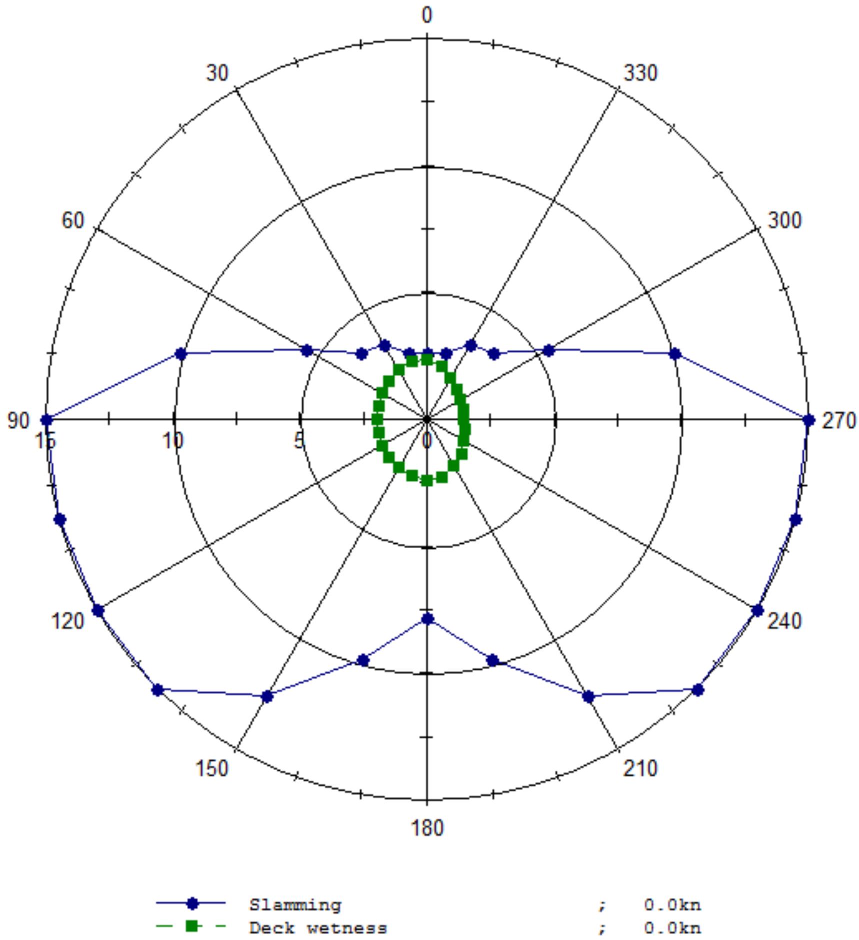

Figure L.10: Limiting wave heights H_S [m] according to deck wetness and slamming criteria.

Appendix M

Simulation: Vessel Operability

The mean operability for all six wave heading sectors (see Section 8.2.2 for definition of sectors) are presented in Figure M.1. The initial part of the curves are a result of the simulation warm-up period, and is not representative. After some time of simulation, the curves stabilise and provide more reliable estimates of the vessel's true operability. During the summer months the operability remains very high for all sectors, but as the winter months approaches the operability drops quite significantly for Sector 2, 3, 5 and 6. Sector 1 and 4 show a small tendency of reduced operability, but are in general not much affected by seasonal variations.

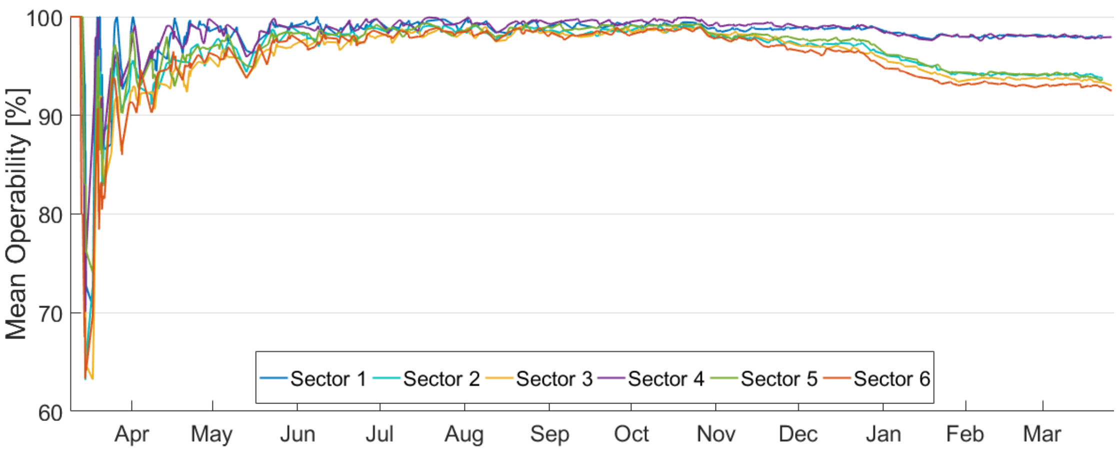

Figure M.1: Development of mean operability for the six wave heading sectors.

Figure M.2-M.7 shows the mean operability development for each wave heading sector from April to the end of March the following year. It should be noted that the axes are modified which makes the difference between the sectors more evident than in Figure M.1.

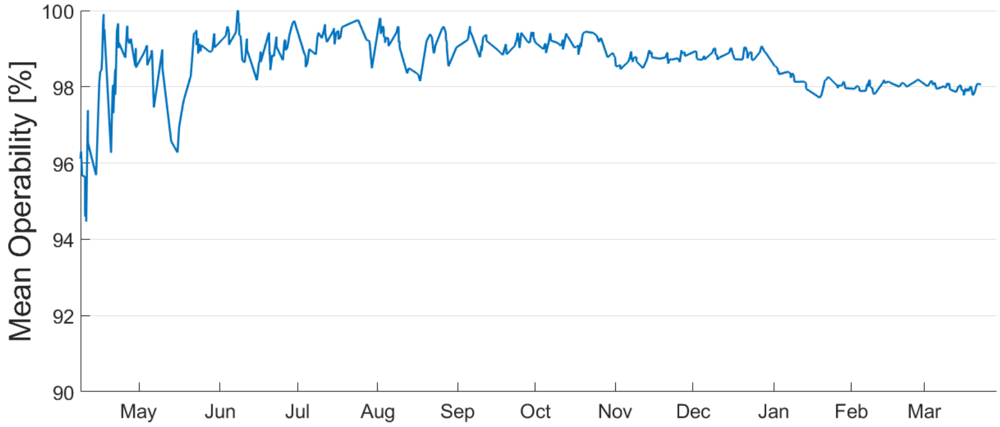

Figure M.2: Development of mean operability for Sector 1.

Figure M.3: Development of mean operability for Sector 2.

Figure M.4: Development of mean operability for Sector 3.

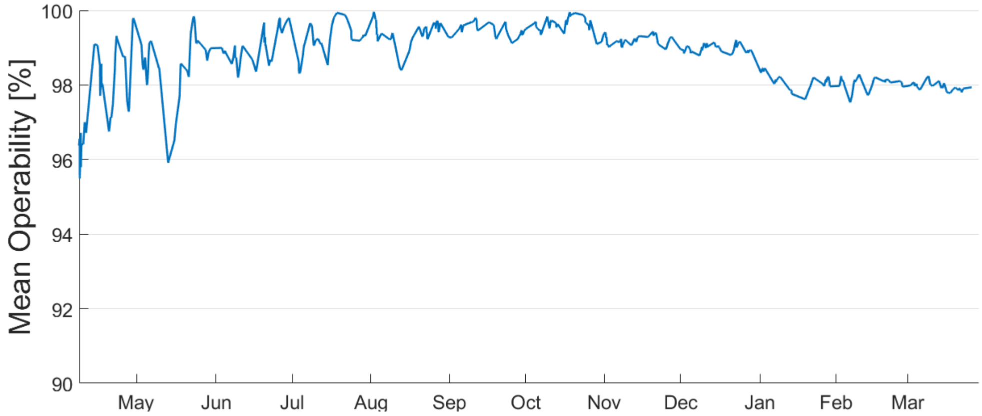

Figure M.5: Development of mean operability for Sector 4.

Figure M.6: Development of mean operability for Sector 5.

Figure M.7: Development of mean operability for Sector 6.