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An Investigation of Offshore Wind Installation Strategies

A Discrete-Event Simulation Model Used to Investigate Installation Vessel Operability

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Submission date: June 2017
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Preface

This report provides the Master Thesis, which is the final delivery after five years studying at the Department of Marine Technology, at the Norwegian University of Science and Technology. The report counts as 30 credits, and approval of the Master Thesis results in achieving the title Master of Science in Marine Technology.

The work has been completed during Spring 2017, and the topic of the work was to investigate strategies for improving the installation of offshore wind jacket foundations. A considerable part of the insight into the work, including knowledge about the offshore wind industry and discrete-event simulation, was obtained during Fall 2016, related to the work with the Project Thesis. Additionally, the past five years at NTNU have provided me with a technical understanding and a curious approach towards investigating new topics, which has proven very valuable for the work with the Master Thesis.

I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett, who has provided support and professional discussions concerning the thesis throughout this final year at NTNU. I would also like to thank all industry actors who have supported this work with their insight into installation and operation, including Rune Yttervik from Statoil, Ian Robertsson from Seajacks, and Jens Gengenback from DONG Energy. Additionally, I would like to thank the student assistant in the course TMR4225 Marine Operations, Ragnhild Brekke, for support related to operability analyses.

"Those who fail to bet on the green economy, will be living in a grey future"

United Nations Secretary-General, António Guterres

Trondheim, June 20, 2017

Johanne Tomine Vartdal

Summary

The offshore wind industry has experienced an immense growth during the past years, but one of the main limitations for development is the high installation costs which may account for almost 20 % of total life cycle costs. The objective of the thesis is to assess installation methods for jacket foundations, and investigate how vessel operability impacts total installation time. The results can be used as a decision tool for offshore wind farm developers, when evaluating the best installation strategy during the planning phase.

The development of the industry is trending towards distances farther from shore, larger turbines and increased offshore wind farm sizes. This means that new technology for foundations is being introduced, that is able to support larger loads in deeper waters. Due to the increased distance from shore, the logistics connected to installation must be assessed, to ensure efficient installation at low cost levels.

Several installation scenarios are investigated, including installation with a jack-up vessel, installation with a jack-up installation vessel and feeder vessels to support component transportation, and installation with a DP-vessel. The installation scenarios are tested with case studies in discrete-event simulation models, to evaluate the best strategy for installation. The case studies includes changes in offshore wind farm size, from 50 to 500 turbines, and distances from shore, from 10 to 100 kilometers.

The discrete-event simulation models were created using MATLAB *SimEvents*. The stochastic impact of the weather is implemented into the models by using Markov Chain simulated weather states for wind and wave data, gathered from the FINO1 weather station outside Germany. The operability of the models is verified by comparing the results with an operability study made from the observed weather data, showing a correlation between expected and simulated operability.

The results from the operability study show that the use of feeder vessels is valuable to increase the installation rate. However, this is assumed to increase both the cost levels and the risk of collisions, because more assets are being introduced in the system. The scenario with only one jack-up vessel for installation and transportation provides the

lowest installation rate, but this solution will probably provide the least cost intensive solution. The scenario where a DP-vessel performs all operations has high operability during positioning, thus increasing installation efficiency offshore. Introducing feeder vessels to this solution is likely to increase installation efficiency, but will include high day rates due to the increased number of vessel assets, and the high day rates for the DP-vessel.

Operability during lifting operations is observed to be the governing limitation for installation. Both operations with loading in- and offshore, and installation of the jacket foundation, are depending on wind-limitations, and measures to improve installation efficiency should be taken within the area of lifting operations.

The most effective installation strategy should be chosen based on information about the required installation rate, when distance from shore and number of turbines have been decided. The decision tool presented in this Master Thesis may present a valuable contribution for the project developers, and provides insight for evaluating the best installation strategy, considering how weather impacts vessel operability and installation efficiency.

Sammendrag

Havvindindustrien har gjennom de siste årene opplevd en enorm vekst, men en av hoved begrensingene for videre utvikling har vært høye installasjonskostnader, som kan utgjøre nesten 20 % av totale livssykluskostnader. Formålet med denne oppgaven er å vurdere ulike installasjonsmetoder for jacket fundamenter, og undersøke hvordan installasjonsfartøyets operabilitet påvirker installasjonstiden. Resultatene kan benyttes som et beslutningsverktøy for vindutviklere, i vurderingsfasen for å bestemme den beste installasjonsstrategien.

Utviklingen innenfor næringen viser tendenser mot lengre avstander fra land, større turbiner og økt størrelse på feltene. Dette innebærer at ny fundamentteknologi introduseres, som kan stå imot økte krefter i dypere vann. På grunn av den økte avstanden fra land, må også logistikken knyttet til installasjon vurderes for å sikre effektiv installasjon ved lave kostnader.

Flere installasjonsscenarier har blitt undersøkt, og disse inkluderer installasjon med et jack-up fartøy, installasjon med et jack-up fartøy for installering og et feeder-fartøy for komponent transport, og installasjon med et dynamisk posisjonerings (DP) fartøy. Installasjonsscenariene testes for ulike case-studier, i diskret-hendelse simuleringsmodeller, for å evaluere den beste strategien for installasjon. Case-studiene inkluderer endringer i havvindfeltet, fra 50 til 500 turbiner, og avstander fra land, fra 10 til 100 kilometer.

Simuleringsmodellene med diskrete hendelser ble opprettet i MATLAB *SimEvents*. Den stokastiske påvirkningen av været implementeres i modellene ved å benytte Markov Chain simulering av værtilstander for vind- og bølgedata, hentet fra observasjoner ved værstasjonen FINO1 utenfor Tyskland. Operabiliteten til modellene er verifisert ved å sammenligne resultater med en operabilitetsstudie av de observerte værdataene, som viser en sammenheng mellom forventet og simulert operabilitet.

Resultatene fra undersøkelsen av operabilitet viser at bruk av feeder fartøy er verdifull for å øke installasjonsraten. Dette antas derimot også å øke både kostnadsnivåer og risikoen for kollisjoner, fordi flere resurser introduserer i systemet. Scenariet med bare ett jack-up fartøy for installasjon og transport gir den laveste installasjonsraten, men

denne løsningen vil trolig gi den minst kostnadskrevende løsningen. Scenariet der et DP-fartøy utfører alle operasjoner har høy operabilitet under posisjonering, og oppnår en høyere installasjonseffektivitet. Å innføre feeder fartøy til denne løsningen vil sannsynligvis øke installasjonsraten, men vil inkludere høyere dagrater på grunn av økt antall fartøyressurser, og den forventede høye dagraten til DP-fartøyet.

Operabilitet under løfteoperasjoner er observert til å være den styrende begrensingen for installasjon. Både lasteoperasjoner ved havn og ute på feltet, og installasjonsaktiviteter, er begrenset av vindforhold, og tiltak bør iverksettes for å forbedre installasjonseffektiviteten innenfor løfteoperasjoner.

Den mest effektive installasjonsstrategien bør velges basert på informasjon om nødvendig installasjonsrate, når avstand fra land og størrelsen på vindparken har blitt besluttet. Beslutningsverktøyet som presenters i denne oppgaven kan presentere et verdifullt bidrag for utviklere, og bidrar med innsikt for å bestemme den beste installasjonsstrategien, med tanke på hvordan været påvirker fartøyets operabilitet og installasjonseffektiviteten.

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List of Abbreviations and Symbols

Abbreviations

AHC	Active Heave Compensation System
BMWi	German Federal Ministry for Economic Affairs and Energy
CTV	Crew Transfer Vessel
DP	Dynamic Positioning
EU	European Union
EWEA	Previous European Wind Energy Association, now WindEurope
GBF	Gravity Based Foundation
HLV	Heavy Lift Vessel
LCOE	Levelised Cost of Energy
OSV	Offshore Supply Vessel
OWF	Offshore Wind Farm
PHC	Passive Heave Compensation System
PNR	Point of No Return
RNA	Rotor and Nacelle Assembly
SPIV	Self-Propelled Installation Vessel
TIV	Turbine Installation Vessel
TP	Transition Piece (between foundation and tower)
WTG	Wind Turbine Generator

Symbols

α	Alpha Factor

β	Beta Weibull Parameter
τ_c	Notation of Calms
τ_s	Notation of Storms
H_s	Significant Wave Height
$H_{s,c}$	Characteristic Significant Wave Height
OP_{LIM}	Limiting Design Criteria
OP_{WF}	Forecasted Operational Criteria
T_C	Contingency Time
T_R	Reference Period
T_{POP}	Planned Operation Period

Chapter 1

Introduction

The world sees an increased demand for energy as the population, and the degree of industrialization, is growing. Climate change is a well-documented threat towards the future of our planet, and the world is depending on action concerning the increasing greenhouse gas emissions, according to the United Nations (2017). The effects of climate change are likely to cause severe impacts on the worlds food production, fresh water access, ocean life and sea levels, threatening both the economy and human life. Sustainable solutions and renewable energy sources play a prominent part in the development of our energy consumption, and offshore wind represents a renewable energy source which will be important in the future development of our world.

This report is the result of the master thesis work. It will investigate vessel operability and installation methods for jacket foundations, and review the installation strategies with the help of a discrete-event simulation model to guarantee efficient installation.

Background

The offshore wind industry has seen an immense growth during the past years. The growth in the European wind markets is much caused by the European Union 2030 targets to increase the use of renewable energy sources to at least 27 % of final energy consumption, and due to the developments within commercial solutions for the industry. However, the cost of offshore wind is still the main restrictive factor for developers, especially due to the high installation costs compared to its equivalent industry onshore. To ensure sustainable operation and future growth, it is important to develop new solutions for driving down costs, and provide an investment basis at acceptable cost levels.

According to Barlow et al. (2015), it was normal to acquire vessels from the oil&gas industry in the beginning of the offshore wind developments. Since there was already a high demand in this market, it resulted in high day rates for vessels with capacities above the requirements of the installation project. The demand from the oil&gas market eventually went down, and so did the costs, but the need for more purpose-built vessel had appeared. The European Wind Energy Association (2016) states that the offshore wind industry in Europe experienced a growth in capacity of 1500 MW in 2016, increasing the number of offshore turbines to a total of 338. The total installed capacity in Europe was in the beginning of 2017 at 12.631 MW, where monopile foundations was the chosen solution for about 81 % of the turbines in operation.

With relation to both installation and operation, it is of interest for the industry to develop new solutions for offshore wind turbines. As the turbines keep increasing in size, stronger foundations are needed to support the increased weight of the turbines. The expected development of the industry is towards locations farther from shore, and at deeper waters. This will again impact both the structure of the foundation, and the logistics for installation. A monopile foundation has a relatively large steel-weight, and for large water depths the steel weight will eventually become too large to handle by conventional installation vessels. Jacket foundations have been presented as an alternative foundation for deeper waters, but the installation of these requires additional marine operations and might be more time-demanding. This exemplifies the need for improved installation solutions, to assure future installation with efficient logistics and reduced cost. Driving down the cost level is important to reduce investment expenditures, which again is necessary to develop an industry without subsidies.

The basis for the work with this thesis was made during fall 2016, with the work connected to the Project Thesis (Vartdal, 2016). The Project Thesis report includes an introduction to the offshore wind industry, and a review of installation methods for turbine top-structures. A discrete-event simulation model was created, and a parametric analysis was performed to investigate what system parameters that had the largest impact on installation efficiency. Parts of the thesis, the summary and the system description, is included in Appendix H, and the results from this work will also have relevance for sub-structure installation. The model created in the Project Thesis served as a basis for the simulation models created in this thesis, and the learning outcome from the previous work enabled the modelling in this report.

Motivation

As the industry is expanding towards larger turbines, deeper water and locations farther from shore, new technology and knowledge is needed to provide basis for efficient installation. The expanding turbine size leads to greater strength requirements for the foundations, and the deeper waters will increase foundation size below the waterline. When distance from shore is increasing, the installation phase requires new logistical solutions, according to Barlow et al. (2015). Over the next years, we are likely to observe further growth in the industry, with an increased number of installed turbines, and the work in this thesis aims to improve knowledge of installation to ensure growth at acceptable cost levels.

The work in this thesis provides a deeper investigation into installation solutions for offshore wind foundations. The generic approach ensures that the study can be applied for several installation projects, and will give guidance for logistical planning. The decision tool will have a scientific value for future projects, where the work performed in this thesis can be reviewed and investigated for choosing the most efficient installation approach, thus ensuring cost-efficient installation.

State of the Art

Previous work within the area of improving installation efficiency have been done in terms of system evaluation and fleet optimization. Barlow et al. (2015) presents a simulation tool for evaluating how innovations in design impacts operability, with a parametric change in operational criteria, while Barlow et al. (2014) assesses how changes in vessel characteristics impacts total installation time. Natskår et al. (2015) provides methods for estimating the workable weather windows prior to installation, in order to create an expected installation schedule. A literature study on previous work is presented in Chapter 3.

This thesis aims to create a generic model used for installation of jacket foundations to investigate the best installation solution to improve efficiency, an area that is yet to be thoroughly covered in the literature. The specific focus on jacket foundations is assumed to be a valuable contribution for the future developments of the industry, where monopiles have been the main objective in most literature related to installation models until now. The work also includes a weather implementation that is assumed to give representative weather series, using Markov Chain simulation of forecasted weather.

Objective

The objective of the master thesis is to evaluate possible solutions for installation of jacket foundations, as a tool for improving the planning of the given operations. It includes the evaluation of installation vessels, and how vessel operability will impact total installation time for a set of jacket foundations. The aim is to provide basis for estimating total installation time, with the specified vessel technology assessed in this work. A review of the installation phase shall be presented in a general manner that can be applied to different installation projects as a decision tool in order to improve the installation phase, and ensure effective operations.

The work should improve the understanding of installation of offshore sub-structures, especially jacket foundations. The problem shall be implemented into a discrete-event simulation model created in MATLAB *SimEvents*, where offshore wind farm case studies are evaluated with different installation scenarios, with emphasis on weather windows and operability. Efficiency of installation will depend on the operability of the process, and weather changes may force activities to a temporary halt, or even postpone the whole operation. A simulation model that implements the stochastic factor of weather will have relevance for industry developers, as a tool for simulating installation during project planning. Moreover, vessel acquirers can use the simulation model for testing how changes in vessel features might impact installation efficiency.

The cheapest solution will in most cases also be the fastest solution. Through analyses of simulation results for total installation time, this thesis wish to investigate what solutions will be the most effective, and which phases of operation during the installation process that are the most sensitive to weather conditions.

Limitations

Installation of offshore wind farms includes a range of activities and components, from planning and manufacturing, to installation and completion. This thesis will only investigate the installation of sub-structures, or more specifically, jacket foundations. It is assumed that if efficient installation of these are fulfilled, this will lead to shorter lead time for offshore wind farm installations, and that the results also can be applied to other parts of installation. Additionally, the focus has been solely on bottom-fixed foundations, even though there are increased developments within the industry for floating foundations.

In addition to the aforementioned limitations regarding foundations, logistics connected to component-supply will not be implemented in the problem. It will be assumed that a constant flow of components will always be accessible for installation at the installation port, and that installation ports and vessels are available throughout the installation. This means that no considerations are taken regarding availability of system features.

Offshore activities are depending on operation during acceptable weather windows, and the operability can be defined in terms of many environmental conditions. However, for the work in this thesis, only the effects of wave and wind loads will be implemented, to simplify the analysis. This is due to the increased complexity when including the effects of wind- and wave directions, currents and the periods of which they appear, which would normally be accounted for when planning a marine operation. They are thus neglected from this work, but are acknowledged as essential for a real project.

Report Structure

The chapters of this thesis are structured so that the reader will be familiarized with the offshore wind industry before the methods and the models are introduced. The offshore wind industry is described in Chapter 2, including an introduction to marine operations and the installation cycle. The purpose is to provide the reader with insight into offshore wind, what restrictions and regulations that apply to operations performed offshore, and what needs to be considered during planning. Different foundation types and their applications are also introduced, to further give basis for the installation activities. Chapter 3 gives a short literature review over previous work in the fields of simulation, installation and marine operations, while Chapter 4 explains the methodology used in the report. The case studies and installation scenarios implemented into the model, that forms the basis for the operability study, are also presented here.

The simulation models that were created in SimEvents and the scripts prepared in MATLAB are introduced in Chapter 5, and the results from the operability study using the simulation models are presented in Chapter 6. To conclude this report, the two last chapters discuss the results and findings found during the work with this thesis, and presents the reader with conclusions and further work.

Chapter 2

System Description

Offshore wind is an industry that is experiencing increased growth. The advantages of producing wind power offshore, compared to onshore, are improved wind conditions and less visual pollution of the environment. Nonetheless, moving an industry offshore also introduces new challenges, as one must include marine operations in the planning, putting installation activities at a higher risk. One of the main challenges is the increased costs related to offshore installation, which are assumed to comprise almost 20% of the total costs of offshore wind turbines, according to Stålhane et al. (2016). Additionally, we see the industry trending towards extended distances from shore and deeper waters. This again leads to the need for less costly and more robust solutions.

The first commercialized concept for offshore wind included smaller turbine sizes and monopile foundations. Recently we see that the turbine capacity and weight are increasing, making it necessary to provide even stronger foundations. As the turbines are moving to deeper waters, new technology for foundations in deeper water is also needed. The use of jacket foundations has been widely explored in the oil&gas industry, and the technology already exists. The main difference between oil&gas- and wind installation is the increased number of installation activities required to complete installation of an offshore wind farm, which introduces a challenge related to planning. Completion of a whole offshore wind farm requires multiple piling and jacket installation operations. This makes it more time consuming, and the installation of one jacket can take up to several days, according to Barlow et al. (2015). It is however an advantage that the jackets used for the wind industry are of a much smaller size.

A preliminary study of installation of offshore wind turbines was performed in the project thesis of Vartdal (2016). Here, the emphasis was on installation of top-structures, and the thesis also gives general insight into installation and technical features of the phase. The system description form the Project Thesis in included in Appendix H.

Figure 2.1: Sheringham Shoal Offshore Wind Farm (Statoil, 2017)

2.1 Offshore Wind Farms

An offshore wind farm (OWF) will typically be located 10 to 100 km from shore, at water depths ranging from 5 to 40 meters. Nevertheless, according to European Wind Energy Association (2016), trends show that as the industry develops, the distance from shore increases, in addition to construction on deeper water. The number of turbines in the OWF will depend on turbine size and power demand. The largest wind farm to be constructed to this date is the Hornsea Project One, consisting of 174 wind turbines. Each turbine has capacities between 5 and 8 MW and it is located 120 km off the UK coast, according to DONG Energy (2017). An example of typical layout and turbine appearance is seen on Figure 2.1, showing a picture of the Sheringham Shoal offshore wind farm, located off the Norfolk coast in the UK.

An offshore wind turbine will in general consist of a foundation, that is either floating, or more commonly, fixed to the seabed. The bottom-fixed foundations include monopiles, which to this date is the most used foundation, jacket structures, gravity based foundations (GBS), tripods and suction buckets. Due to stability and accessibility considerations, a transition piece is often mounted on top of the foundation. The function of the transition piece (TP) is to hold equipment for easy access of technicians from crew transfer vessels (CTV), hold cable lay-ups for exporting power, and be the support for the tower structure. The top-structure of the turbine consists of tower, nacelle, hub and blades. The nacelle is mounted on top of the tower, and the hub is located in front of the nacelle. The hub takes up the power from the rotation of the blades, making the shaft rotate. Normally, offshore wind turbines consist of three blades, and the whole rotor-nacelle assembly (RNA) will rotate in order to catch the wind at the optimal angle. Offshore wind turbines usually operate at wind speeds between 4 and 26 m/s, which are

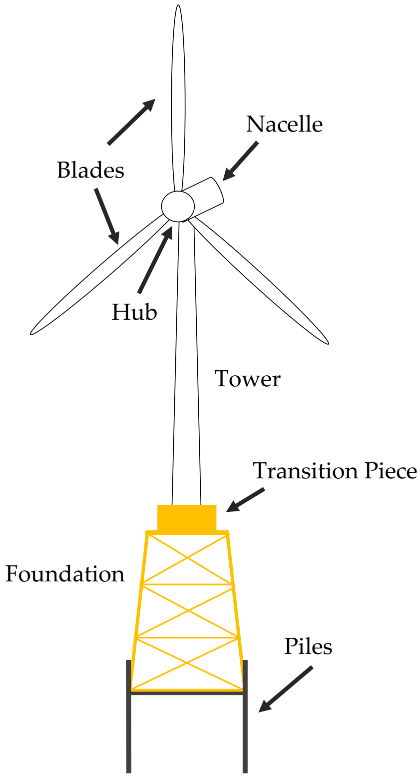


Figure 2.2: Illustration of an offshore wind turbine on a jacket foundation

called cut-in and cut-out speeds, according to Burton et al. (2011). Energinet (2015) states that the rated output of the turbine is normally first reached at wind speeds of 12-14 m/s. An illustration of an offshore wind turbine mounted on a jacket foundation is shown in Figure 2.2.

The OWF also includes one or several offshore substations, that receives power from the turbines through inter-array cables. The power is transformed in the sub-stations and exported to shore through export cables and connected to the onshore power grid. An offshore substation is seen in the middle of Figure 2.1, mounted on a monopile foundation.

2.2 Marine Operations

A marine operation can be classified as a *"non-routine operation of limited duration related to the handling of objects or vessels in the marine environment"*, according to Larsen (2017a). Marine operations can be divided into surface- and subsea operations, where surface operations include towing, lifting, load transfer, station keeping and mooring, and subsea operations can include all installation of subsea equipment, underwater inspection, and pipe laying. It is assumed that the marine operations related to offshore wind installation represent a large cost driver, due to the limited operability offshore, and the strict rules and requirements. Precise planning is very important when performing a marine operation, and it is important to have a great understanding of the risk related to the operation, and how environmental loads may impact it. Most criteria and definitions handled in this section are obtained by investigating the rules and standards of DNV GL.

The document *Marine Operations, General (DNV-OS-H101)* describes a standard covering marine operation, provided to ensure safe operations. In section A200 of the document, environmental loads are listed. These are divided into conditions that are of general importance and phenomena that might be of importance and should be investigated. Of the former category, wind, waves, current and tide is of significance. Regarding the latter, especially soil conditions, temperature, fog and visibility, tide variations and local swell or wave conditions are elements that are essential during installation of offshore wind turbines. For installation in shallow waters many of these factors must be thoroughly reviewed, due to the effect of shallow water operation.

For operations sensitive to long period waves, swell types must be considered and critical swell periods should be identified. In addition, the local tides are important to consider, especially during operation with jack-up vessels. Astronomical tidal range is the difference between the highest and lowest astronomical tides, respectively HAT and LAT, whereas the characteristic water levels also include storm surge effects.

Marine operations should always be designed so that the object being handled is handled from one safe condition to a new safe condition. A *safe condition* is defined as a condition where the object is only exposed to normal risk. In the cases where an operation is not able to be reversed in order to go back to the first safe condition, there should be a well-defined *Point of No Return (PNR)*. It is also important to define the first safe condition reachable after passing a PNR.

When planning marine operations, there are some predefined steps that should be followed to ensure safe operation, stated by Larsen (2017a). It is important to identify the rules, standards and the physical limitations of the operation, both on- and offshore. Then one must plan for and perform risk assessment of all procedures. Before the operational procedures can be prepared, there must be established a design basis, where all environmental conditions and acceptance criteria are stated, in addition to load analysis of the design.

It is normal to divide marine operations between weather restricted and unrestricted

Table 2.1: Weather restricted and unrestricted operations

Operation	**Duration**	**Explanation**
Weather restricted operations	$<$ 72 hrs	Weather forecast considered reliable
Weather unrestricted operations	$>$ 72 hrs	Weather forecast not considered accurate

operations. The definitions of these are stated in Table 2.1. A weather restricted marine operation is said to take place safely within the limits of *favourable weather forecast*, stated in Larsen (2017a). This means that if the forecasted weather is better than the given environmental criteria for operation, in addition to the required duration of the weather window, the operation can be commenced. For unrestricted operations, wave conditions shall be based on long term statistical data. The difference between these is explained in Table 2.1. The characteristic significant wave height, $H_{s,c}$, can in this case be calculated according to Equation 2.1. α and β are Weibull parameters for the probability function of the observed significant wave heights.

$$H_{s,c} = \alpha(\frac{2}{2+\beta} f_1)^{(1/\beta)} \tag{2.1}$$

The α-factor accounts for uncertainty in forecasted weather, which leads to a reduced weather limit for operation compared to design weather conditions. The factor is a number between 0 and 1, where the value 1 reflects perfect weather forecast, which means that the operational and design criteria will be the same. Because weather restricted operations are relying on the forecast, which is an uncertain measure, the α-factor will reduce the operational limits to increase safety in the case the weather observed is worse than forecasted.

Limiting operational environmental criteria shall be established previous to all operations, OP_{LIM}. The criteria must not be chosen greater that the limiting criteria for all equipment and activities in the planned operation, and not greater than the environmental design criteria. The α-factor is introduced to ensure that the probability of exceeding the OP_{LIM} over 50% is smaller than 10^{-4}. DNV GL has provided tables with appropriate α-factors for use in the North Sea and Norwegian Sea. These are found in the DNV GL (2011), section 705-710 for wave calculations and section 712 for wind. The α-factor is read from the tables based on the planned operational period and the design wave height (H_s).

The weather criteria consist of a design criteria and an operational criteria. This is also referred to as the forecasted (monitored) operation criteria, with the notation of OP_{WF}. The design criteria is the acceptable weather condition calculated using the effect of design loads. The operational criteria is connected to the safe working conditions for personnel and equipment, and will be determined during the planning process. Operational criteria is the same as the design criteria multiplied by the α-factor, as seen in Equation 2.2.

$$OP_{WF} = \alpha * OP_{LIM} \tag{2.2}$$

With the use of on-site monitoring systems, the α-factor can be increased towards the value 1, because this increase the quality of the weather forecast. The value will decrease as the duration of the planned operation increase, which makes good forecasting harder. A weather window is a period of sufficient length in order to carry out the planned marine operation in a safe manner. During the weather window, the environmental conditions must remain below the design criteria OP_{LIM}.

2.2.1 Operability

The weather window will have a minimum duration of the reference period T_R, which is the maximal duration of the marine operation, as stated in DNV GL (2011). This includes the planned operation period, T_{POP}, which is based on the predefined schedules for all activities in the operation, and a contingency time, T_C. The contingency time is added to cover uncertainty in the planned operation period, and unpredictable situations that might occur during operation. According to DNV GL (2011), the contingency time should not be lower than 6 hours. During the weather window, it is required that the forecasted weather is calmer or as calm as the OP_{LIM} states. The calculation for the reference period can be seen in equation 2.3.

$$T_R = T_{POP} + T_C \tag{2.3}$$

where T_{POP} is the planned operation period, based on detailed schedules for operations, and T_C is the contingency time, covering uncertainty in the planned operation period.

Expected duration of an operation relies on the expected weather for the period. This is done by establishing the likelihood that an operation can be executed, based on the persistence of the weather, and the expectations related to how long the weather will be better or worse than the operational criteria. Calms, notated τ_c, are periods where the weather is better than the criteria, and storms, τ_s, represents periods where the weather is worse. The occurrence, and duration, of the calm periods can be used to map the operability of the operation, which again can be plotted in an operability plot where the operability for different operational criteria can be read. Figure 2.3 shows an extract from wave data from February 2005, where the red lines marks the periods where the waves are above the operational limit, and green lines where weather enables operation. To commence an operation, one must ensure that the following period of calms is equal to or longer than the required weather window.

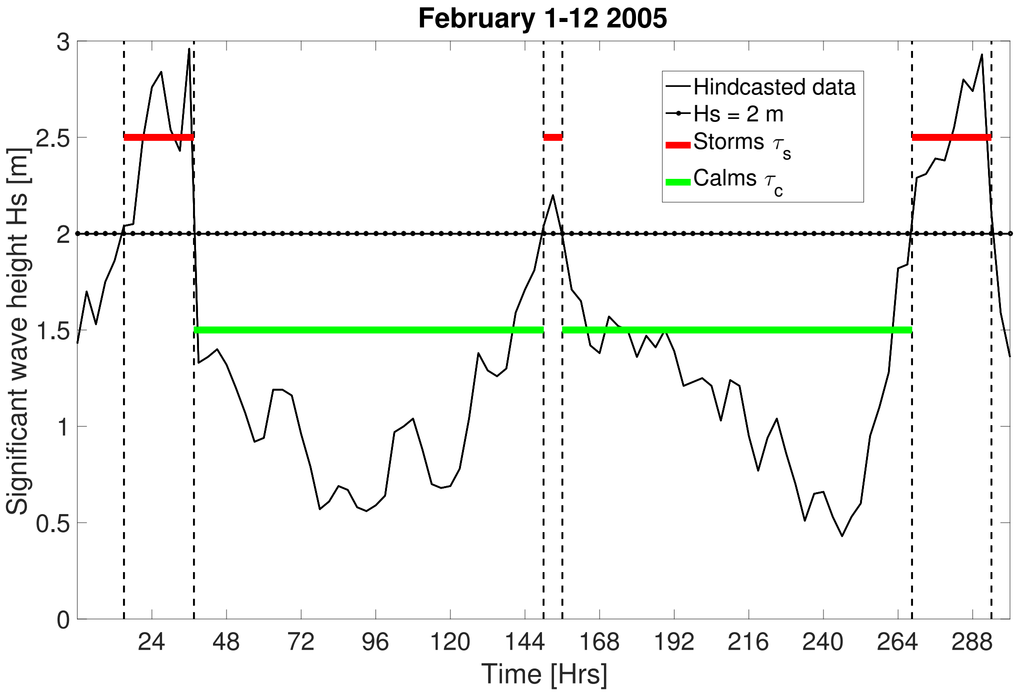


Figure 2.3: Calms and storms plotted over hindcasted weather from FINO1

2.2.2 Transportation

Transportation of special cargoes, such as wind turbine components, must be performed with adequate seafastening to ensure safe transportation and prevent the components of moving due to vessel motions. A change in position of large components can impact the ship stability, which, in a worst-case scenario, can lead to major accidents or even capsizing of vessel. Seafastenings are usually steel-structures that have project-specific design, and these are installed during the mobilization of the vessel. Components are normally welded to the structure for transportation, and this must be removed prior to lifting the components during installation. The weather conditions will also impact the transportation, and the vessel will have limiting criteria for operating in harsh weather.

Requirements and recommendation for sea transport operations are covered in the *Offshore Standard DNV-OS-H202* (DNV GL, 2015). The standard states that the start and end points for transportation shall be clearly defined *safe conditions*, and the transport operation should be defined within the limits of weather restricted or unrestricted operation. For transportation within the limited duration of a weather restricted operation, the procedures during operation shall be established prior to execution, describing the actions required when observing different forecasted weather conditions. This is a measure taken to ensure a safe and reliable operation. During transit, the direction of weather (currents, waves and wind speeds) may impact the choice of route to reduce vessel motions, and therefore the operation period T_R must be based on the longest required route for transit.

The design loads for seafastening are to be based on the environmental characteristics of the project, in addition to loads caused by risks of collision, waves created by other vessels and sailing restrictions. Especially collisions must be thoroughly considered when transporting components to an offshore wind farm, as there exists risk for colliding with already installed structures in the water, and other vessels used in the installation phase. If expected wave heights during transportation is above $H_s = 0.5m$, the seafastening must also be verified for forces based on the calculated accelerations (DNV GL, 2015).

The purpose of seafastening during transportation is not only to secure the cargo from moving, but also to ensure that components are not destroyed or harmed in any matter. Especially blade components are highly sensitive to movement, and must be secured in a manner that does not damage the component during transportation. It is stated in *DNV-OS-H202* that welded sea fastenings are preferred, but for lighter components, weighing less than 100 tonnes, chains, wire ropes or webbing lashings can be considered acceptable. This might apply to smaller components such as blades, hub and nacelle, but is not applicable for the foundation, as weight normally reaches more than 500 tonnes.

2.2.3 Offshore Lifting

Offshore lifting is normally divided between heavy and light lifts, and the difference is described in the lecture notes by Larsen (2017b). Light lifts are categorized as operations where the object being lifted has a weight of less than 2 % of the vessel displacement, where the vessel behaviour is not affected by the object. In these cases, it is possible to use active and passive heave compensation systems (AHC and PHC). Light lift operations can include foundations, pipelines, and small subsea modules. For large lifts, the mass of the object is above 2 % of the vessel displacement, and typically above 1000 tonnes. These operations normally involve the use of large heavy lift vessels (HLV) or lifting barges, and there will be a considerable dynamic and hydrodynamic interaction between the object and the vessel. Heave compensation systems will not be applicable to heavy lifts. If lifting is done from a jack-up vessel, the dynamic interaction will be neglected, as the jack-up vessel maintains constant position without any accelerations, but these aspects must be considered when performing installation using a DP-vessel.

Important aspects of lifting that must be considered during planning include the vessel motions during operation, hydrodynamic loads, crane characteristics and lifting through splash zone for subsea installation. Special considerations must be made for lifting through the splash zone, because of the changes in weight for the mass when moving from air to water, the added mass, the time dependent buoyancy forces acting on the object, wave excitation and slamming forces. The different phases of subsea installation are shown in Figure 2.4, where all phases are applicable to foundation installation, be-

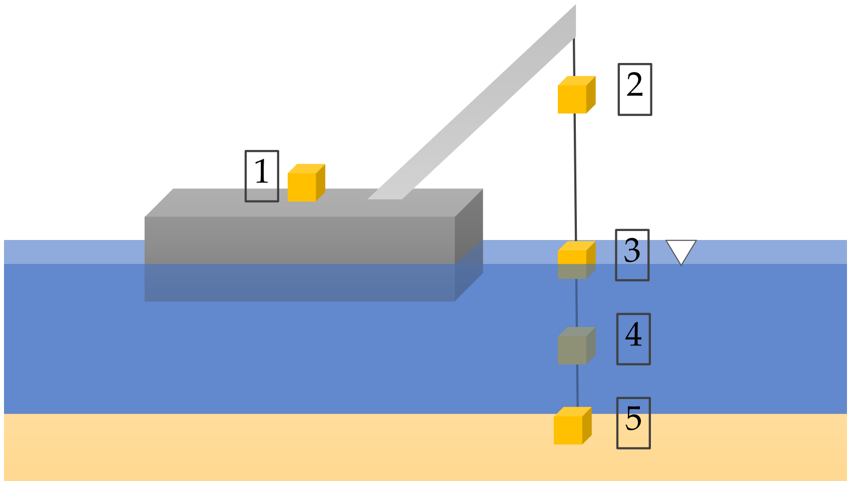


Figure 2.4: The five phases of a subsea lift (Larsen, 2017b)

cause even though the object is only partially submerged, it is also lowered to the seabed. Phases one to five include: lift-off from deck, object hanging in air, crossing of splash zone, object submerged with varying water depth and object landing on seabed. All planning of lifting operations, which includes the design process, documentation and risk management must follow the standards in DNV-OS-H101, section 2B (DNV GL, 2011).

2.2.4 Typical Risks

According to the lecture notes from Larsen (2017a), there are several typical risks related to marine operations, and these needs to be assessed during the planning of operation. Collision risk is very important to assess, when dealing with several vessels in addition to structures in the water. For an installation operation, there can occur collisions between the vessel and the turbine foundation, or between the installation vessel and the feeder vessel. When the two vessels are positioning next to each other, there is a great risk of collision in the phase before jacking-up, and normal operation requires strict DP-regulations or the use of tugs or anchoring. Capsizing during transportation is also a great risk, and this emphasizes the need for proper seafastening. Transit in rough sea can lead to additional motions in the ship, and vessel stability can be suddenly reduced if not proper stability calculations have been performed according to loading.

For operation with DP-vessels or barges, the loss of position introduces a risk to operation. Therefore, it is important to properly plan the operation, and only commence operation when observing a workable weather window. For operation in shallow water or close to shore, grounding present a risk during transportation and maneuvering. Additionally, personnel transfer must also be planned for properly, to reduce the risk of casualties to as low as possible. This is relevant for crew changes offshore, and also when personnel are entering the turbine from crew transfer vessels (CTV). Structural failure can be caused by fatigue in the jack-up legs or on deck. Jack-up legs may buckle when experiencing sudden load changes, or caused by changes in soil conditions.

It is important to identify all possible risks prior to project execution, and discuss the probability of occurrence and the severity of the consequences if it happens. Risk can be reduced by document verification, and all operational procedures should be properly verified, in addition to familiarization of all personnel involved in operation. Safety procedures should be maintained, and the safety manager should survey all operations and verify that they are according to procedure.

An additional risk that must be assessed when planning marine operations, is the stochastic factor of the weather. The weather introduces uncertainties for operation, which must be considered by investigating the proper limiting operational criteria, with the correct α-factor, and with a sufficient required weather window. This is done to reduce the risks connected to operation in harsh weather, and the risk of an operation being executed in weather exceeding the criteria.

2.3 Installation Vessels

In the early development of the offshore wind industry, vessels used for installation and maintenance were often hired from the oil&gas-industry. Due to high demand, the chartering of these vessels was connected to high costs, and not to mention that their features exceeded the requirements for the operation, such as for crane- or carrying capacity (Barlow et al., 2015). To reduce installation costs, more specialized vessel with the required capacities have been introduced to the industry, and there now exists several actors that are specializing in vessels used only for the offshore wind industry, with purpose-built installation vessels.

Vessels most commonly used for installation of wind turbines today include jack-ups, lifting vessels and feeder vessels such as barges or supply vessels (Cradden et al., 2013). The barges are mainly used for the transportation of larger parts, and tugs are needed when the barges are not self-propelled. Jack-up vessels are either self-propelled or platforms, and the self-propelled installation vessel (SPIV) are commonly used for both transportation and installation of components. These are also called turbine installation vessels (TIV). SPIV's can also be used for transportation of parts, and they ensure safe loading offshore as they provide a stable platform when elevated. Jack-up barges used for transportation of components are often slower because they require support from tugs, and might have limited crane capacity and stricter depth restrictions. These have however cheaper chartering costs than the self-propelled vessels.

Heavy-lift vessels (HLV) are used for installation of heavier parts, in cases where the conventional SPIV are lacking the crane capacity, and are normally used for installation of foundations and transition pieces. HLV used for offshore wind installations are usually equipped with dynamic positioning systems, and can be used for both transportation and installation. Because of the more ship-shaped hull of HLV, they can often obtain higher transit speeds, making them a faster asset for transportation of parts than the jack-up vessels.

Crew transfer vessels (CTV) are smaller vessels that are used to transport crew and technicians to the site. Semi-submersible lifting vessels can also be used for installation, but comes at a higher cost and are not normally used in the offshore wind industry.

For larger OWF with long planning horizons placed far from shore, a requirement for accommodation of technicians offshore might arise. This can be solved either by the use of even larger installation vessels with higher accommodation capacities, or by using floatels. The industry already shows tendencies for developing farther from shore at increasing capacities, and in near future one might experience the demand for offshore accommodation, according to Barlow et al. (2015). Novel developments and more project-specific vessels are also being developed in the industry, however mainly still in the conceptual phases at the moment.

Jack-up vessels, also referred to as SPIV, have a quite complex procedure for positioning. A visualization of the procedure is shown in Figure 2.5. The vessel will normally operate on DP to hold the correct position while the legs are being lowered to the seabed, position (A) in the figure. As the legs touch the seabed, a sequence of pre-loading of the legs must be performed to ensure that the legs with the combination of the soil conditions can hold the vessel, and that the legs penetrate the seabed to required depth. An example is for sandy soil conditions, where a jack-up vessel might need a penetration of 2.5 m in the

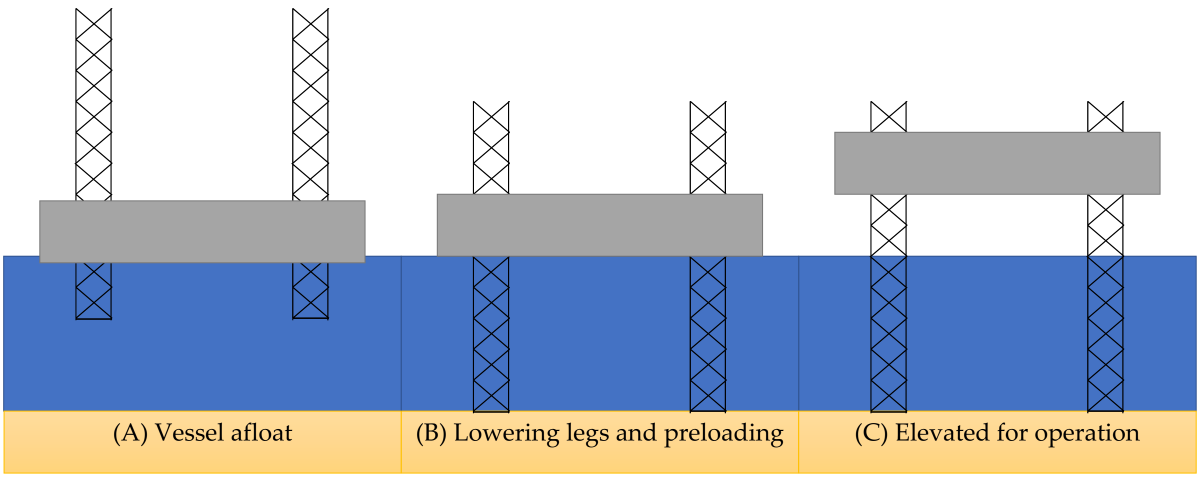


Figure 2.5: The procedure for elevating a jack-up vessel

Table 2.2: Foundation weights and normal depth restrictions

Foundation	Normal depth [m]	Structural weight [mt]
Monopile	5-30	1000-2000
Jacket	30-60	500-700
Gravity based	30-60	4000-8000

seabed (Robertsson, 2017). After pre-loading shown as position (B), the platform can start elevating to the correct position of operation, shown as position (C) in Figure 2.5

2.4 Sub-Structures

Sub-structures include the foundation and the transition piece (TP), where the TP acts as the connection between foundation and tower. The current technology used for foundations for offshore wind turbines is mostly adapted from the offshore oil&gas industry. Foundations are divided into either floating or bottom-fixed, and this section will give a deeper introduction of the bottom-fixed foundations used in the industry. The most common foundation type has until recently been the monopile, used as a foundation for about 81 % of the installed offshore wind turbines according to European Wind Energy Association (2016). It has many advantages, but as the industry is moving to deeper waters, the need for developing new solutions has arisen. The current monopile designs are not suitable for depths above 30 m. The jacket foundation has been used in some projects, but has yet to be commercialized to the same extent.

The chosen foundation solution will depend on structural requirements and water depth. Normal operating depths and weights of monopiles, jackets and gravity based foundations are shown in Table 2.2. The weights represent turbine sizes ranging from 5 to 8 MW, and data is collected from We@Sea (2009). The different solutions are further explained in the following sections. Figure 2.6 illustrates the basic design of the three foundations.

2.4.1 Monopiles

As previously mentioned, monopile foundations are the currently most used solution in the offshore wind industry. They are made of hollow steel cylinders that are piled into the seabed, and are normally suited for water depths up to 30 meters. Even though steel is the most commonly used material for monopiles, they can also be manufactured from concrete (Asgarpour, 2016). The diameter of the cylinder varies for soil conditions, structural requirements due to turbine weight, and water depth, but will typically range from 4 to 6 meters according to Burton et al. (2011). It is normal to place a layer of scour

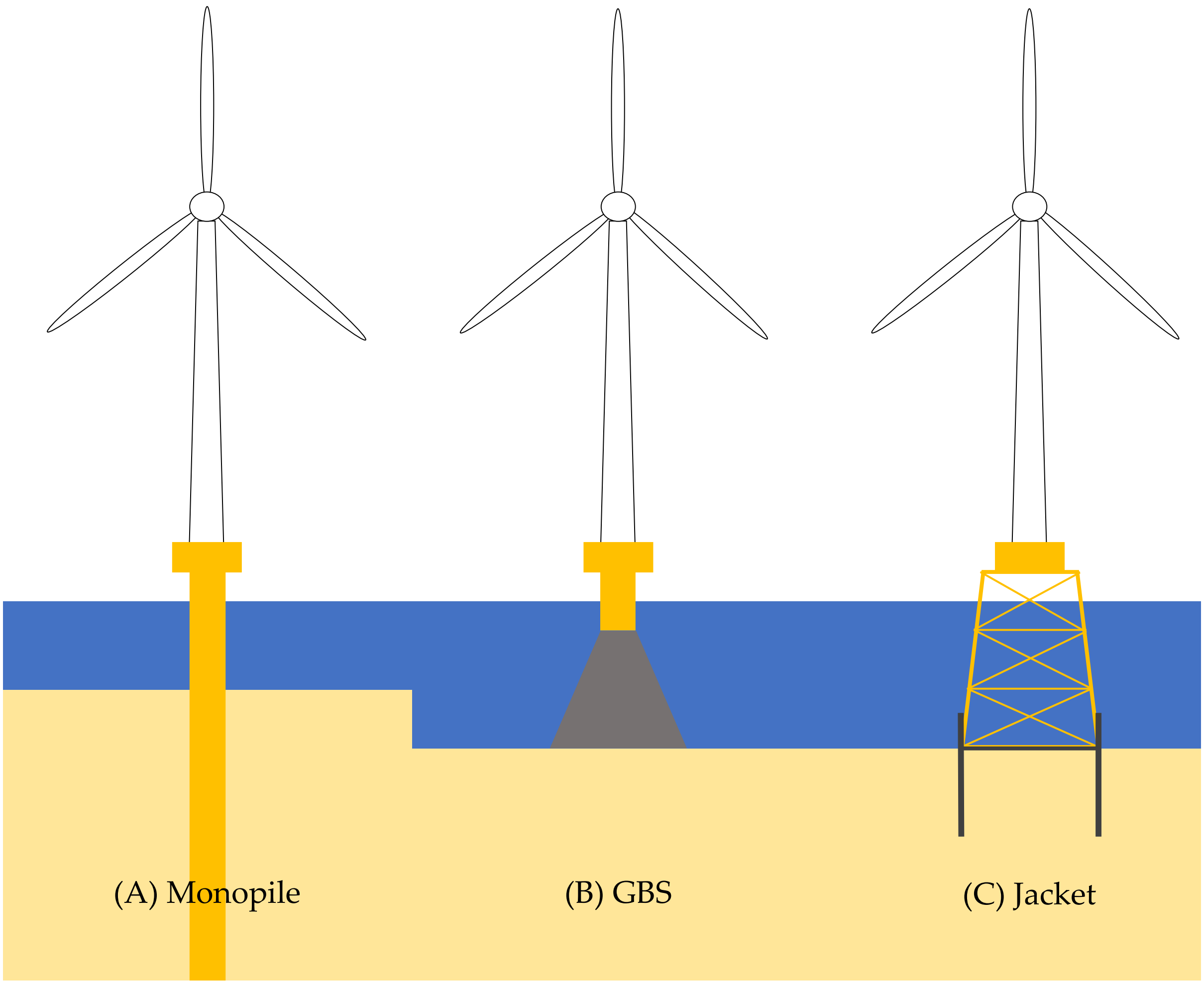


Figure 2.6: (A) Monopile, (B) Gravity Based Structure and (C) Jacket

protection on the seabed before the monopile is piled down into the ground. This is done to prevent erosion of the soil around the monopile. Scour protection is usually stones or stone material that is placed in the area around the foundation. During planning, it is important to evaluate the expected extent of scour to design the appropriate diameter and placement of the scour protection. This will depend on currents, wave activity and soil conditions on the top layers of the seabed, stated by Energinet (2015).

It is normal to install the monopiles using hydraulic hammers for piling. The installation can take one to two days, and might require more than 2000 hammer hits to hammer the monopile to the required depth. The pile depth is constantly monitored during piling to ensure correct positioning of the monopile. Jack-up vessels or barges are often used because they provide stability for the hydraulic hammer. There is a risk of damaging the steel tube when hammering the pile into the seabed. To ensure that the tower is installed on a perfect horizontal surface, a transition piece is mounted on the monopile to connect the pieces. The space between the monopile and the TP is grouted to fasten the piece, while aligning the TP vertically. Other solutions for fastening the TP includes the use of bolted flanges, brackets, and clamping devices (Asgarpour, 2016). The penetration depth will depend on the structural loads, water depth, environmental loads and soil conditions. The latter might account for up to 20 % of the weight requirements for the monopile.

Negative aspects of monopile installations involve the high amounts of environmental pollution in terms of noise. Marine species will be affected by the constant hammering noises, creating a stressful element to their normal life. Grout is a type of cement, used for pile grouting operations, and this also introduces a significant environmental pollution as it can be spilled to the surroundings. Therefore, it is important to ensure minimal grout spills during operation. Excessive force during hammering might lead to buckling of the monopile, and it is thus important to only apply the appropriate force when hammering. It is normal to dispose seabed material collected from inside the monopile during piling within the wind field.

The monopile has a quite simple structure, and needs little welding, but on the other hand has a quite large structural weight, which will increase significantly with increased water depths, thus being more suitable for shallow water installation.

2.4.2 Jackets

A jacket foundation is a lattice structure, normally with 4 legs. An illustration of a typical jacket foundation is shown in Figure 2.6. These are normally used for depths ranging from 30 to 60 meters, whereas not assumed suitable for depths above 80 meters. This is due to the steel weight of the structure being very large. Jacket foundations are considered complex structures due to the high amount of node connections that needs to be welded together.

Even though the steel weight is substantially lower than for a monopile, the required amount of welding will increase the fabrication costs considerably. The fabrication of parts will normally be executed in low-cost countries, while assembly and welding of nodes will be performed close to the installation port. The footprint of the jacket is normally about 15x15 to 40x40 meters, but varies with design and strength considerations, according to Burton et al. (2011). The geometry of the jacket will also depend on soil conditions, turbine size, water depths and expected environmental loads.

Jackets are normally piled to the seabed, on each leg of the structure. While post-piling has been a standard in the oil&gas industry, the offshore wind industry has taken to implement the use of pre-piling for jacket structures. The piles are normally piled prior to the installation of the jackets, and this is performed by laying a template on the seabed to maintain the dimensions between the jacket legs. This procedure is generally used for smaller jackets in the wind-industry, and not applicable for larger jackets due to the required dimension of the template making it physically more complex. Scour is explained in Asgarpour (2016), and it states that scour protection must be considered around the pile-locations, but it is expected to be modest due to the small pile diameter. Some seabed preparation is normally required before piling can commence.

Jacket piles are normally significantly smaller in diameter than the monopiles, but will penetrate even deeper into the seabed. Piling is performed with the use of hydraulic hammers. Piling and installation are considered two different operations, and might be performed with a considerable time gap. However, there is a risk of marine growth and environmental loads changing the position of the piles if the time between the operations is an extended period.

The normal procedure for installation of jackets is to use jack-ups or HLV. An alternative for the installation of larger jackets is to use float-out, where the jacket is simply floated out to the location, and then flipped with the use of floaters and weights. If the pre-piling method has been utilized, the jacket is lifted from the deck of the installation vessel, submerged through the water and positioned on the piles. This operation will normally not take more than one hour, but post-operation, including grouting between the piles and the jacket, can take up to several hours.

Jackets are identified as one of the solutions to be further developed in the future, as the industry develops to deeper water and larger wind turbine generators (WTG). Nevertheless, they are costly to manufacture, and the installation process involves several activities, including piling and grouting for all legs.

2.4.3 GBS

Gravity based structure foundations are normally manufactured in concrete, and are maintaining stability and position for the turbine by its own weight. They are buoyant and can be floated out to the location of the field. When they have reached the correct position of the turbine they are filled with ballast, either rocks or water, in order to obtain stability, and then positioned on the seabed. Seabed preparation is important prior to GBS installation, as it requires a flat seabed and scour protection. This preparation might take days for each GBS, because top layers of the seabed in some cases must be removed to ensure undisturbed soil conditions, and the footprint of the foundation is prepared with gravel or stone.

GBS foundations are suitable for firm seabed conditions, and are more appropriate for operating in areas where larger ice loads can be expected than other foundation types. The conical GBS is appropriate for installation at 20-50 meter depths, and can also hold larger turbine loads. It is anticipated that the conical GBS will be designed for projects involving larger turbines in deep water with perfect seabed conditions, such as in sandy seabeds.

Installation can be performed using a floating crane or crane barge, where the GBS is floated to the site, or semi-floated (partially submerged), and then lowered onto the prepared seabed while being filled with ballast. An illustration of the GBS is shown in Figure 2.6.

2.4.4 Suction Buckets

A suction bucket, or suction caisson, is a method for fastening the foundation to the seabed, and can be applied for both mono-structures or jackets. The procedure for fastening the suction bucket to the seabed is seen in Figure 2.7. The bucket, positioned on the legs of the structure, is placed on the seabed, where pumps are used to create suction inside the bucket. The suction creates a pressure difference between the inside of the bucket and the surrounding water, which pushes the bucket into the seabed. The penetration of the seabed is also supported by the weight of the structure. The diameter and height of the bucket is decided by soil conditions. When the correct penetration depth is obtained, the pump is detached from the bucket, and retracted to the surface, illustrated in Figure 2.7 (C).

The technology can be used as an alternative to piling. When using suction buckets to fasten the structure to the seabed, one avoids the noise from hammering, which is a significant environmental emission to the environment and disturbs the animals living in the sea. However, suction buckets require homogeneous soil, without any hard layers or boulders. The suction bucket can easily be removed by reversing the process and pumping water into the bucket, enabling easy decommissioning.

It is assumed that using suction bucket for seabed fastening of jackets will reduce installation time because the operation is less complex and time-consuming than piling, according to Sparrevik (2017). The total steel used is also lower, because the pile lengths requires more steel than the buckets. However, the total steel weight of the jacket is increased, as the buckets are fastened to the jacket during lifting and installation. The reduction in noise is a considerable effect that improves the solution, but a negative aspect is the sensitivity related to soil conditions.

2.4.5 Environmental Protection

As the sea is a constantly moving mass, the sediments around a structure fastened to the seabed will experience the motions and might move. This can lead do a decreased

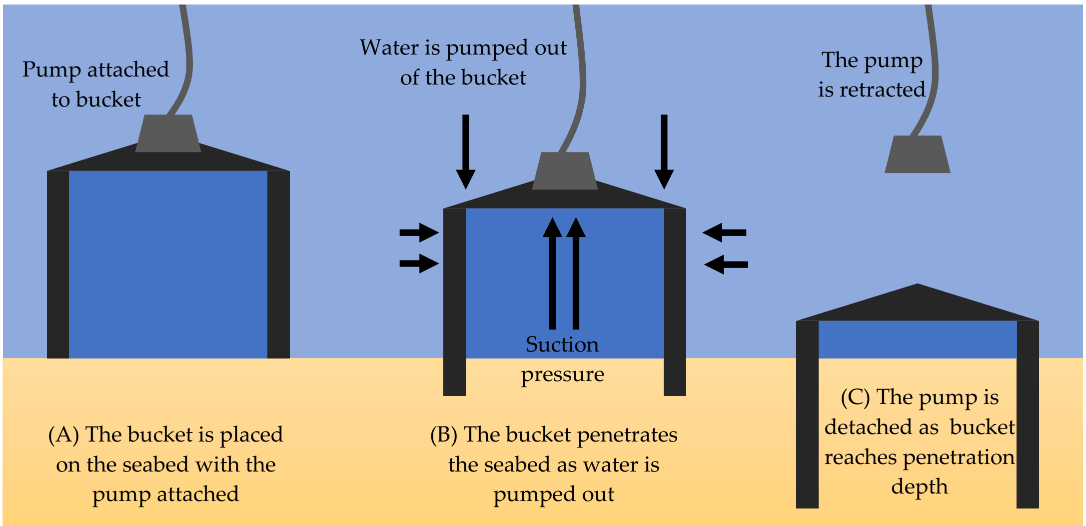


Figure 2.7: The procedure for fastening suction buckets to the seabed

strength of the fastened structures. Scour is the local removal of sediment from seabed in moving water, as explained in Burton et al. (2011), and illustrated in Figure 2.8, where one observe that sediments can build up and be removed around the structure. This can lead to the development of holes around the structure, which again might lead to decreased stability of the structure. Scour protection around the structure, in the shape of rocks, will reduce the risk of scour. It is also possible to account for scouring in the design process. Normal procedure is to use a layer of stones followed by larger rocks as armour. A piled foundation might be designed with a layer that extends 10-15m from the base, with a thickness of up to 2 meter.

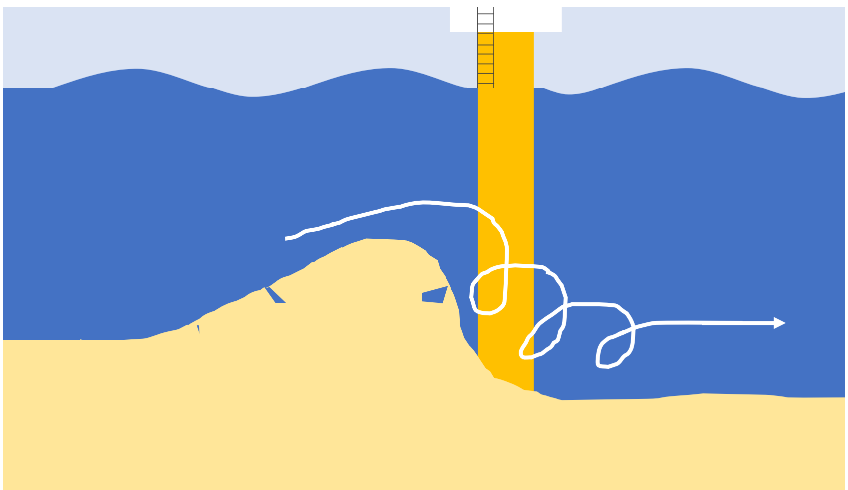


Figure 2.8: Scour on an unprotected seabed around a monopile structure

2.5 Installation Phase

For an offshore wind farm developer, the installation phase will include planning the whole process from manufacturing of parts to completion of the OWF. Planning includes ordering parts and overlooking manufacturing, a logistic system for transportation of the parts and finding a suitable installation port. The procedure for carrying components and technicians to the offshore location of the farm must also be planned for, in addition to procedures for installation.

Installation of offshore wind turbines require several marine operations, and because of the high risk related to these and the required weather window related to each operation, it is desirable to reduce the number of offshore activities and increase pre-assembly onshore. Moreover, offshore man hours are much more expensive compared to onshore work, and reducing the number of offshore operations will reduce costs. In the following sections, the main features for installation of a jacket foundation and a top-structure will be explained.

2.5.1 Mobilization

Prior to project execution, a study of available vessel and installation strategies is performed. It is necessary that the installation vessel has sufficient crane capacity, and that the operational criteria of the vessel ensures project completion within the schedule. Depending on the strategy chosen, the vessel, or vessel, that are to be used for transportation of components, or be used for carrying components at any time, must be mobilized and equipped with seafastening equipment. This is done to ensure safe transportation, both in terms of vessel stability, and to make sure that components are not damaged during transportation.

2.5.2 Installation Port

The installation port is the location where components are loaded onto the vessel. There can also be several installation ports in a project, where they are divided for sub- and top-structure components. When the location of an OWF is to be decided, it is important to assess the availability of installation ports nearby. The distance between the installation port and the OWF will have impact on transit time, which again will impact fuel costs and might increase the total installation time. The port should have good infrastructure concerning both in- and offshore logistics, and have the proper depths for the vessel to dock. There must also be appropriate storage space for storing components before loading, and if a feeder vessel without crane capacity is used for transportation, the port needs to have the required crane capacity available on quay for loading.

According to Robertsson (2017), a normal procedure in the industry is that the jacket structures arrive pre-loaded and ready for lift off at port. When the vessel arrives, it needs only to lift the jacket from the quay, and then position it at deck. Before the vessel leaves, the structures need to be seafastened on the deck. Normally the vessels have been pre-outfitted with equipment for seafastening, and then the components are welded into the templates for a safe transportation offshore. The number of jacket foundations loaded to the vessel depends on the carrying capacity and available deck space on the vessel, and the main restriction for loading at port will be the wind speed when using a jack-up vessel. It is assumed that wind speeds above 8 m/s will be limiting for completing loading, and that the operation of loading and seafastening a jacket will take about 5 hours per jacket.

2.5.3 Jacket Foundation Installation

The installation of the foundation must commence with seabed preparations and piling. Normal procedure for pre-piling is to complete all piling operations prior to foundation installation, to ensure that the installation will not be forced to wait for piles when installation operations has been executed.

The manufactured jacket arrives in port, and will be prepared for transportation before loading can commence. The jacket will then be loaded to the transportation vessel when the forecasted wind allows lifting, related to the required weather window. When vessel is loaded according to procedure, the vessel will leave for transit.

If the installation vessel is transporting the jacket foundations, it will position itself at the location of the first turbine. For jack-up vessels, this involves waiting for the appropriate weather window for jacking-up the vessel, as shown in Figure 2.5, while for DP-vessels means achieving position by using the DP-systems. Additionally, for the DP-vessel, the required weather window must be forecasted prior to execution of operation. There is no point initializing DP-operation if the forecast shows that the weather will worsen before the installation activities have been finalized. Meanwhile, for the jack-up vessel, positioning by jacking-up will be initiated at the first possible weather window, despite not being able to commence installation right afterwards. This is because jacking-up and installation are considered separate activities, and can be executed in different weather windows, while initiating DP-operation without commencing installation is not likely. Carrying capacity of the installation vessel depends on deck strength and space. For larger projects, a method for faster installation can be to use several installation vessels to reduce total installation time.

If a feeder vessel is used for transportation, it must position itself next to the installation vessel for loading offshore, which can commence when the weather allows it. The installation vessel will load all jackets from the feeder vessel and position it on deck, while the feeder will return to port for further loading until all components has been transported to the field. As the feeder vessels normally are smaller than the installation vessels, their carrying capacity is reduced, in addition to the transit speed.

The jacket is installed by lifting it off deck, lowering it through the water and placing it on the pre-piled piles. After the jacket is placed on the piles, the void between the jacket legs and the piles must be grouted to properly fasten the jacket. This is normally done by another vessel, but can also be performed by the installation vessel. The reason why the normal procedure is to use another vessel, is to increase utilization of the installation vessel, and rather use less equipped, cheaper vessels, for the smaller grouting tasks, according to Robertsson (2017).

If a transition piece is used in the wind turbine design, it is normal to complete installation of the TP in the same phase as the foundation. The TP can either be installed in the same stage as the foundation with the same vessel, or after all foundations have been installed. The latter strategy will increase the number of positioning-operations for the vessel, increasing installation time, but since the TP's have a lower weight their installation can be performed using smaller vessels. For jackets, it is however not common to use a TP when pre-piling is executed, as the risk for structural damage of the jacket is low during installation.

2.5.4 Top-Structure Installation

The installation of top-structures includes the tower, nacelle, hub and rotor blades. As these parts not necessarily are the heaviest parts of the structure, the main limiting factor for installation is crane height, because of their height above water, and wind speeds. High wind speeds will delay installation, as especially the blades are highly sensitive for wind. These are designed for moving in the wind, and therefore the most limiting criteria for installation is for the blades. Additionally, sea conditions must be sufficient for the installation vessel to keep position, either through the jack-up phase, or through dynamic positioning for a heavy lift vessel. The installation process is described to a larger extent in the Project Thesis (Vartdal, 2016), which is included in Appendix H.

The degree of pre-assembly of the top-structure parts are highly dependent on installation strategy. Pre-assembly means that parts are assembled onshore, and then installed offshore together. By increasing the degree of pre-assembly onshore, one decreases the required number of offshore lifts to complete installation. Normally, the tower will be divided into several parts because of the large length. The tower parts will then be installed offshore by lifting the parts from a vessel and onto the transition piece. The tower is a typical element where pre-assembly might cause concern, but installation of complete tower sections has been performed. Thorough seafastening is very important when carrying the towers in vertical position to maintain cargo safety.

The nacelle is positioned on top of the tower section, and this can be pre-assembled with the hub while onshore. Regarding the blades, there exists several installation strategies. If no degree of pre-assembly is performed, one needs at least 4 offshore lifts in order to install hub and blades. However, installation strategies exist to reduce the number of offshore lifts related to hub and blades. Due to the design of the blades, they easily move in wind, and therefore strict wind limits are required when performing these operations, and a reduced number of lifting operations will most likely reduce downtime and installation time. The "bunny-ear" configuration is when two blades are connected to the hub, and then installed directly to the nacelle offshore. This requires a lot of deck space, and will easily be caught in the wind. If possible, one can also pre-assemble all blades to the hub, but this will require several configurations on deck to carry the construction safely to the tower section offshore.

Chapter 3

Literature review

General information about the offshore wind industry has been obtained through an extensive investigation on current wind farms, developments in the industry and by assessing industry standards. The *Wind Energy Handbook* written by Burton et al. (2011) has also provided insight into wind turbine and foundation design, general aspects in the industry and planning of installation.

3.1 Simulation

A holistic two-stage simulation tool is proposed in Barlow et al. (2015), where innovations in design and the resulting increase in operability is modelled. The first stage of the model identifies the operations most sensitive to weather, while the second stage explores how innovative solutions (related to increased operability) will reduce weather-sensitivity. The paper use weather data from the German FINO1 weather station, and performs analyses of different installation strategies. The simulation tool developed in the work is used to model the logistics of the installation process, to identify the most critical stages of installation. Validation of new solutions to check for improvements related to weather-sensitivity is emphasized as vital to improve methods and ensure development and reduced installation costs. The paper also introduces industry standards for installation methods of jackets, which this thesis is partly based on. The work concludes that loading operations introduce the most prominent factor for delay during installation, and that there exists a non-linear relationship between the duration of installation and the operational limits for the vessels.

The simulation model used in Barlow et al. (2015) was developed from the initial model created by the author in a paper not yet published. Here, a discrete-event simulation model used for modelling installation over multiple seasons with several parallel streams of operation, such as cable installation, offshore sub-stations and turbines, was introduced for simulation of installation of the whole offshore wind farm. The model provides accurate representation of projects in larger scales, with long duration and high costs. The simulation model used in this thesis has taken some elements from the developed model, but has not implemented all aspects of OWF installation to the same extent.

A stochastic simulation model is presented by Barlow et al. (2014) which is a tool that can be used to model the logistical offshore wind farm installation problem. The model uses a synthetic hourly time-series to model the weather, based on hindcast, and the simulation tool can be used to analyse both schedules for installation vessels, fleet composition and port selection. Barlow et al. (2014) presents an application of the simulation tool, where the objective is to determine the main vessel characteristics to obtain a reduction in installation time. The synthetic weather simulation from this paper has been used as inspiration for the weather-simulation used in this thesis, where synthetic hourly time series are generated from hindcasted data, in order to provide a realistic assessment of expected duration of installation from simulation.

Barlow et al. (2015) and Barlow et al. (2014) probably provide the most detailed simulation tools for evaluating offshore wind installation scenarios found in scientific papers, where the former provides a tool for the whole OWF installation, while the latter only presents a one-vessel model installing only the wind turbine generators (WTG). The aim of this thesis is to provide a tool for assessing installation of jacket foundations. The model is using elements from the models previously created, while on the other side ensuring easy implementation for specific analyses of predicting total installation time and operability analyses for foundation installation. Input can be changed for project-specific studies, thus providing basis for planning.

3.2 Vessel Study

The study of Ahn et al. (2017) provides methods for successful installation of wind turbines, for the Korean coast. The paper is based on studies of installation vessels and operations performed in Europe, and is meant to guide developers in Korea for the growing wind industry in the country. The study in the paper divides installation into six different methods, and compare strategies based on which method was used. The main focus of the paper is top-structure installation, but has a good explanation of the installation vessels used in the European market.

In Barlow et al. (2014), an assessment of vessel properties is presented, providing basis for a comparative study on vessel characteristics and how they impact installation. In concludes that increasing carrying capacity will result in great reductions in total installation time, and that increasing vessel operational criteria is expensive and will only reduce total installation time up to a certain limit.

Additional information about installation vessels and their characteristics has been gathered from technical specifications of vessels, and through direct contact with industry actors. This also applies to the vessel types, where information have been obtained by investigating methods used for already operating and planned offshore wind farms.

3.3 Operability

Operability is a measure for the expected available time an operation can be executed. Background information about operability and marine operations have been gathered from lecture notes written by Larsen (2017b) in the course Marine Operations, and by assessing recommended practice and standards developed by DNV GL (2011). This has provided basis for the operability study, and especially for understanding the practice of marine operations, weather windows and operational criteria.

Natskår et al. (2015) discuss the impact of weather uncertainties on marine operations. The effects of load impacts caused by wind- and wave-loads are studied with regards to the reliability level of the operation. In the paper, differences between forecasted and hindcasted weather is compared in order to describe the uncertainty in weather, and propose a reliability analysis for operations offshore. The paper has a special emphasis on the difference between weather-restricted operations, and weather-unrestricted operations. The difference between these are described in table 2.1.

Guachamin Acero et al. (2016) presents a methodology of the operational limits and operability of marine operations, focusing on the planning phase for offshore wind turbine installation. Here, operational procedures and numerical analysis are assessed for identifying critical events and the corresponding response parameters. By considering all activities, their respective duration and sequential execution, the operational limit is determined for the installation operations. The paper uses the proposed method by Natskår et al. (2015) for forecasted weather models. Natskår et al. (2015) provides methods for assessing the workable weather windows (WOWW) both during planning and project execution. Estimates of the expected operability can be used during the planning phase for feasibility studies of vessels and choice of season. This is also important information for planning the logistics of the installation and determine the time for completion of installation.

Barlow et al. (2017) propose a solution for correlation between wind and waves, by using a correlated autoregression model for creating the synthetic weather time-series. These are generated based on statistical analysis of hindcasted data. Data in each time-step will be expressed based on a linear combination of the previous data points. The method has relevance to the simulated weather states used in this thesis.

Typical operation duration for different activities related to foundation installation has also been gathered through communication with industry actors. Several companies have collaborated and shared general operational data considering operational criteria and required weather windows. These have been compared with the literature, and form the basis for the assumptions and input used in the simulation model.

3.4 Installation Costs

Gonzalez-Rodriguez (2017) reviews the most important economic factors for offshore wind farms, ranging from manufacturing and installation to operation and maintenance. It states that this data is necessary to conduct economic analyses, and predict profitability. The paper concludes that foundation installation costs depends on water depths, seabed characteristics, distance from installation port and vessel rental costs, and that distance from mobilization port also is important to consider taking into account the additional costs of mobilization.

Barlow et al. (2017) emphasize that one method for realizing the necessary lower installation costs, is to pursue the logistical solution that is the most cost-effective. This solution can be identified by properly understanding how costs levels and the duration of operation are affected by the logistical decisions for the installation phase. The models presented in the paper can be used together in order to obtain a realistic understanding of how uncertainties in weather impacts installation, and as decision support for making logistical decisions.

A comprehensive analysis of the levelized cost of energy (LCOE) is performed in Myhr et al. (2014). The authors investigate all cost components for different foundation solutions, over case studies with bottom-fixed and floating foundations. The cost components for predicting LCOE, ranging from steel prices to installation vessel day rates, are presented in the report. It concludes that water depth at site is the governing parameter for deciding the optimal concept for a site, while the distance from shore, load factors and availability for energy production are factors that have the highest impact on the LCOE.

Information about cost elements for installation is essential for performing a cost-benefit analysis of the simulation results. It is difficult to properly decide the specific costs related to each asset and how installation time impacts total costs without having access to the real costs, but an analysis of expected behaviour and assumed costs can be conducted to create a clear image of installation costs.

Chapter 4

Methodology

This chapter presents the methodologies used in order to solve the problem represented in Section 1. To create a realistic representation of the system, the discrete-event simulation engine MATLAB *SimEvents* can be used to model a system that behaves like the real system. This chapter will explain the basics of MATLAB *SimEvents*, how operability is calculated, and at last introduce a cost-benefit analysis, and how it can be evaluated to decide the best solutions for installation.

4.1 Weather Representation

In order to extract relevant data from the model of a real system, the input to the model must be realistic and represent reality. Weather data includes observations of wind and significant wave height, and observations from the German FINO1 Weather Station has been used (German Maritime and Hydrographic Agency, 2016). The weather data was downloaded and used with permission from the Federal Ministry for Economic Affairs and Energy in Germany (BMWi) and the project execution organization, Projekttraeger Juelich (PTJ). The FINO1 weather station is located in the North Sea, north-west of Germany. The location is shown in Figure 4.1, and excerpts from the downloaded data files for wind and waves are shown in Appendices B.6 and B.5.

To have a substantial representation of the weather, hindcasted weather from a 10-year period from the 1^{st} of January 2005 until the 31^{st} of December 2014 was downloaded. The data was then transformed in a text-edit program to the correct format and imported to excel, so that it could easily be read by the *xlsread*-function when imported to MATLAB. This includes placing all relevant information, such as time and dates, in different columns so that it is easily distinguished in MATLAB. This is done with both wind- and wave data, and in the interest of obtaining correlation between wind and wave, data is gathered

Figure 4.1: Location of the FINO1 weather station (Screenshot from Google Maps)

from the same hourly observation from both series. Because it is normal that forecasts are given every third hour, new matrices are created from both 10-year time series in MATLAB where one observation from every third hour is extracted sequentially. In the new weather series, all data are checked for valid values. The range for all values are above zero and below unrealistically high observations. In case of missing values, data from the previous observation is extracted.

The MATLAB-scripts *Hs_series.m* and *wind_series.m* are the scripts where wind and wave data are imported to MATLAB. The Markov Chain simulation of data are performed with the matrices created from these scripts. The matrices created have a column for year, month and day of the observation, in addition to the hour the observation is taken from. The matrices also include the observed significant wave height or wind speed. By also including the month of the observation, the weather data can easily be divided into seasons. This can be used in the simulation model to represent installation over different periods during the year, and also to calculate expected operability. The MATLAB-scripts for importing weather data are included in Appendix B.1 and B.2.

4.1.1 Markov Chain Simulation of Weather

A Markov Chain is a stochastic process, where the definition of the time step X_n, is dependent on the value of the former time step X_{n-1}. For a time-variant simulation over a period, the present value, or state, will always only be depending on the previous value, and a set of probabilities for the transition states. The probability of a transition from one state to another is in the MATLAB-scripts defined by the number of occurrences of the transition. The probabilistic value $P_{i,j}$ represents the probability of the change from one state to another, so there is a probability $P_{i,j}$ that if X_{n-1} is in state i, X_n will make a transition into state j (Ross, 2014).

The theory of Markov Chain simulation is applicable to stochastic processes where one can assume that the present state will depend only on the previous state. An application of this can be implemented for simulating weather. Probabilities for state-changes are set so that the probabilities of staying in the current state and the transition into a neighbouring weather state are set to be high. The transition from a weather state with low values into a weather state of high value, such as a sudden transition from very good weather to very bad weather, will have a low probability. When performing Markov Chain simulations, one can sometimes observe absorbing states. An absorbing state is a condition where a state-transition has happened, and the probability in the transition matrix from this state to any other is zero, therefore it will never change state. To ensure good results, it is very important to investigate this, and remove any instance of absorbing states.

The Markov Chain simulation of the weather can be performed over different seasons, so that the system being simulated can be modelled over different periods of the year. The MATLAB-scripts *MT_Hs_wave.m* and *MT_wind.m* create the weather simulations, and by changing the parameter *seasons* between the values 1, 2, 3 and 4, which corresponds to winter, spring, summer and fall, the scripts output series of states that can be used in a simulation model in MATLAB *SimEvents*. These scripts are included in Appendix B.3 and B.4.

4.2 Installation Scenarios

A representative selection of installation strategies has been chosen to properly evaluate the most suitable method for installation of different configuration of offshore wind fields. Even though several installation strategies exist, and normally will depend on company procedures and experience, three different scenarios has been chosen for evaluation. They include the following:

- Scenario 1: Jack-up vessel used for transportation of components and installation
- Scenario 2: Jack-up vessel used for installation of components, and smaller jack-up feeder vessels used for transportation of components
- Scenario 3: DP-vessel used for transportation of components and installation

The evaluation of the best scenario will include information about total installation time, or the efficiency of installation, and the cost levels related to each solution. Costs will depend on both the length of the operation period, and on the specific operating costs of each vessel. The goal will in many installation projects be to produce first energy quickly, but will also be depending on the budget of the project. Properties for all the vessels used

Table 4.1: Vessel features and properties

Vessel type	Vessel speed [*knots*]	Carrying capacity [nr of turbines]
Jack-up installation vessel	12	4
Jack-up feeder vessel	6	2
DP installation vessel	14	4

are shown in Table 4.1, where vessel properties has been adapted from already existing vessels in the market, such as Fred Olsen Windcarrier (2016), and from conversation and validation from industry actors, including Robertsson (2017) and Yttervik (2017).

To easier present the different scenarios for installation, the operational procedure for the installation phase can be investigated. The operational procedures for all scenarios are presented in Table 4.2, 4.3 and 4.4. For simplicity in the model, it is assumed that the jack-up vessels for installation and feeding have the same operational criteria and will require the same amount of time for jacking up and down.

4.2.1 Operational Procedure Scenario 1

The first scenario includes only the use of one installation vessel, which will be a jack-up vessel. In this scenario, the vessel will first be mobilized and prepared for carrying 4 jackets, which is the assumed capacity of the vessel. She will load the jackets in port, transit to field, and install the jackets before returning to port for new loading until all jackets has been installed. The main limitations of this solution will be the distance from shore, which will affect installation time as the vessel will spend longer time in transit and thus have a smaller utilization for installation.

In Table 4.2 the procedure for Scenario 1 is shown. The jack-up vessel will first be mobilized before the project can commence. The cycle consists of the vessel loading in port, transiting to the field and installing the loaded jackets before returning to port. Before

Table 4.2: Operational procedure for Scenario 1 (Robertsson, 2017)

Operation	Hs [m]	Wind [m/s]	T_{POP}/jacket [hrs]
Jack-up inshore	2	-	3
Lift out in port	-	8	5
Jack-down inshore	2	-	3
Transportation	3.5	-	-
Jack-up offshore	2	-	6
Installation	2	8	2
Grouting	3.5	-	4
Jack-down offshore	2	-	4
Relocating	3.5	-	1

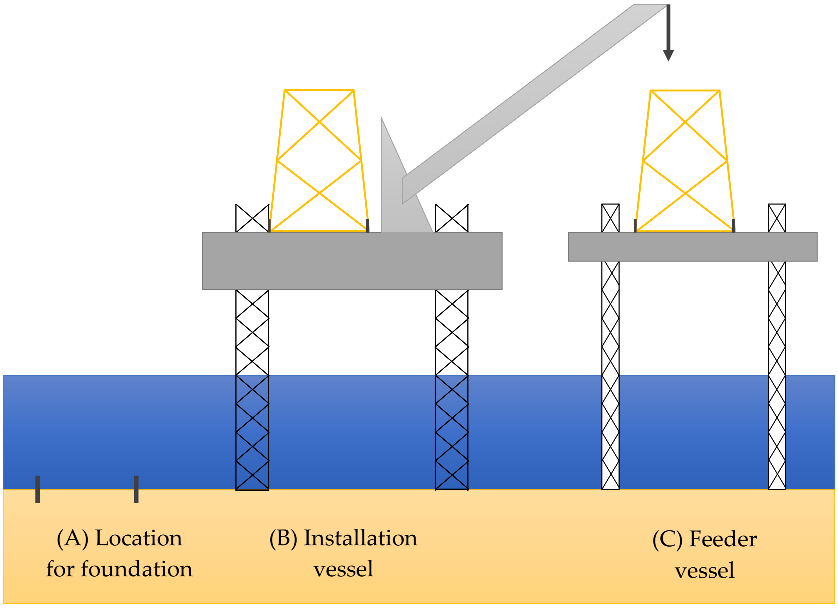


Figure 4.2: Loading of jackets from feeder vessel to installation vessel

every operation, the weather must be checked to verify conduction of operation. If the weather window does not comply with the required length and criteria, the operation must wait until the weather forecast shows calmer weather. Loading in port are 4 separate activities, where the weather-window is checked before loading of each jacket may commence.

4.2.2 Operational Procedure Scenario 2

Scenario 2 will use a jack-up installation vessel for installation, the same vessel as used in Scenario 1, and this vessel will stay on the installation field for the whole duration of installation. One or several feeder vessels are then mobilized for carrying its capacity of jackets, which in this case is assumed to be 2, and then start the campaign of loading jackets in port and transporting them to the installation vessel until the installation of foundations is complete. The feeder vessel will offload both jackets to the installation vessel at the first opportunity, and then return to port for additional loading of components.

For Scenario 2, one or more feeder vessels are used for transporting the components to the installation vessel that is positioned at the installation field, and the procedure is shown in Table 4.3. The feeder vessel will position itself at the designated location for offloading, which will most likely be next to the position of the next foundation that is to be installed. In order to utilize the installation vessel to the fullest, the feeder vessel should be ready for offloading before the installation vessel is done jacking-up. The desired condition of this scenario is that the installation vessel will never wait for the feeder vessel. The

Table 4.3: Operational procedure for Scenario 2 (Robertsson, 2017)

Installation vessel	Feeder vessel	Hs [m]	Wind [m/s]	T_{POP}/jacket [hrs]
	Jack-up inshore	2	-	3
	Lift out in port	-	8	5
	Jack-down inshore	2	-	3
	Transit	3.5	-	-
Jack-up offshore	Jack-up offshore	2	-	6
Loading from feeder	Offload 2 jackets	2	8	1
	Jack-down offshore	2	-	4
	Transit to port	3.5	-	-
Installation		2	8	2
Grouting		3.5	-	4
Jack-down offshore		2	-	4
Relocating		3.5	-	1

feeder vessel will unload the two jackets to the installation vessel, and then jack-down and return to port. The installation vessel will install the first jacket at the location of loading, jack-down and reposition to the next foundation location. After two jackets have been installed, it will move on to the next foundation location and jack-up, where preferably the feeder is positioned and ready for offloading.

The main limitation in this scenario will be the degree of feeding from the support vessels. If the feeders can supply a constant flow of components for the installation vessels and the waiting time offshore for components is at a minimum, the utilization of the installation vessel will be maximized (not including the additional waiting time for weather windows). Here it will be interesting to investigate how many feeder vessels are needed to ensure the constant flow of components, and an increase in distance from shore will also increase the need to operate several feeder vessels. However, all vessels comes at a cost, and operation costs will grow when chartering more vessels, or including more assets to the system. The installation vessel will receive consumables with the support of supply-vessels, and crew exchange with the assistance of crew transfer vessels (CTV). This will also introduce more required assets to the installation phase, which must be accounted for in the cost-benefit analysis.

4.2.3 Operational Procedure Scenario 3

The third scenario has a close resemblance to the first, but it is assumed that a DP-vessel has a slightly higher transit speed. Additionally, the DP-vessel is quicker to obtain position as it does not need to jack up. After installation, the vessel also does not need to spend time jacking down, and can therefore quickly move on for the next foundation installation. Beside this, the DP-vessel will operate with the same wind restrictions

Table 4.4: Operational procedure for Scenario 3 (Robertsson, 2017)

Operation	**Hs [m]**	**Wind [m/s]**	T_{POP}**/jacket [hrs]**
Positioning in port	3	-	2
Lift out in port/jacket	3	8	5
Finish port operation	3	-	1
Transportation	4	-	-
Positioning offshore	3	-	3
Installation/jacket	2	8	2
Grouting/jacket	3	-	4
Finish DP	3	-	1
Relocating	3	-	1

related to jacket installation and loading in port, while wave restrictions will depend on the vessels ability to hold position during operation with dynamic positioning systems.

In Scenario 3, which only contains a DP-vessel for installation and transportation of jackets, the operational procedure is shown in Table 4.4. The vessel must position itself in port, and then loading can commence when the weather-window with wind below the criteria exists. The vessel heads for the field and installs the jackets, and then returns to port for loading of new jackets until all foundations has been installed.

4.3 Operability Plotting in MATLAB

Operability is a measure for the probability of executing an operation, and is an essential tool for understanding how long an operation is expected to last. An operability plot gives out information about how often, during a period, the weather window is open for operation at different operational criteria, and can also show operability over different seasons. The plots can be used to evaluate the operability of a certain activity, when the required weather-window and operational criteria is given. An example of an operability plot is seen in Figure 4.3. This is a plot for a required weather-window of 3 hours, and the vertical line intersects the operability plots for winter, spring, summer and fall at the expected operability of the activity.

The weather series range from 2005 to 2014, and to create the operability plot, all observations from the observed data are used. The MATLAB-scripts *Hs_series.m* and *wind_series.m* imports the weather series and recreates the matrix of all the observations from every third hour, while the scripts *op_wave.m* and *op_wind.m* divides all data into seasons and checks for each observation if the weather will stay below the given weather criteria. In order to make the operability plot in Figure 4.3, operability is checked for wave heights between zero and five, with increments of 0.1, to create a smooth plot.

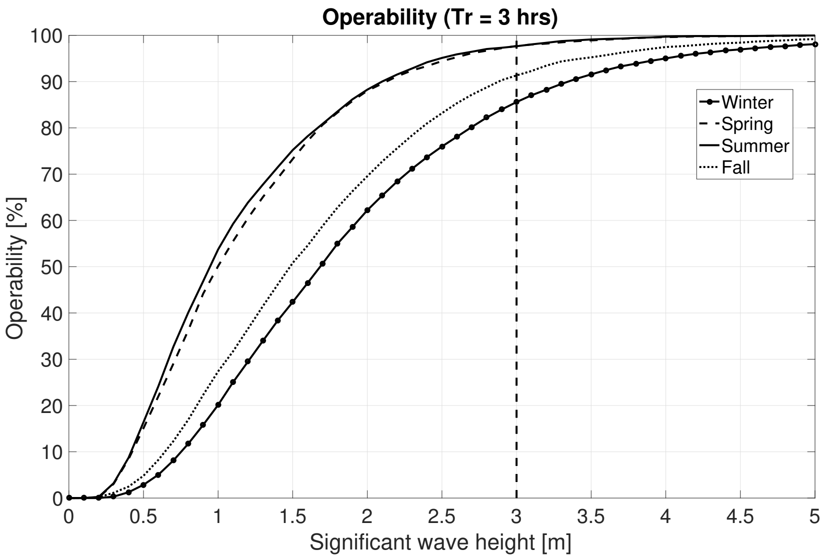


Figure 4.3: Example of operability plot for a required weather-window of 3 hours

It is possible to change the required duration for the calm each time the script is ran, to create plots for different weather-windows. The results can then be plotted together to compare the operability for different seasons. The scripts where this was performed are included in Appendix C.1 and C.2.

The results from the calculated operability can be used to validate the model. Information about when operation must wait for weather from each activity in the simulation model can be extracted and the operability of the activity should be compared with the expected results from the MATLAB-plots.

4.4 Simulation of Installation

Creating a simulation model for a system is an easy way of checking the functionality of the operation during a design process, and can be used in order to optimize the system for the proper purpose. A simulation model should be a realistic representation, and should implement all external factors that can affect the model or impact system behaviour. For the work in this thesis, simulation models have been created using MATLAB *SimEvents*. The models are used for understanding how different installation scenarios behave over different field configurations, or cases. The cases are described in Chapter 4.6. The results from the simulations can be used to find the most effective method for installation for each case, and should also be evaluated using a cost-benefit analysis to consider the costs of the different strategies.

Table 4.5: Commonly used blocks in MATLAB SimEvents

Block	Description
Entity Generator	Generates entities and assignes attributes
Entity Terminator	Terminates entities when no longer useful
Entity Queue	Stores entities when not possible to proceed
Entity Server	Serves entities and event actions
Entity i/o Switch	Combines or divides entity routes
Entity Gate	For controlling the flow of entities
Scope	Easy visualization of results
Simulink Function	For implementation of MATLAB-functions
Data Store Write	Writes data to Data Store Memory
Data Store Memory	Created a shared data store
Data Store Read	Copies data from a memory to an output source
From Workspace	Loads signal data from the workspace of MATLAB
To Workspace	Writes data to the workspace of MATLAB

4.4.1 MATLAB SimEvents

MATLAB *SimEvents* is a discrete-event simulation tool where entities are generated, then ran through blocks to simulate action, and the program in properly described in MathWorks (2017). Event-driven simulation means that the state of the system is changed through events. Entities in the system can be generated, moved, processed or terminated, and these represents the dynamic factors of the system that is being modelled. The entities can be assigned characteristics in the form of attributes, which holds information about the entities. The most common blocks used during the modelling of the system in this thesis are shown in Table 4.5, and will be further explained in the following sections.

Simulation models created in MATLAB SimEvents can easily be ran through the Workspace in MATLAB. Before a simulation can be executed, the necessary parameters and inputs to the model must be created in the Workspace. This can include constants, such as distance from shore and the number of turbines in the field, and the assigned weather series that simulation is to be tested for. The model is loaded with the function *load_system('ModelName')* and a simulation will be executed with the function *SimulationOutput=sim('ModelName')*. All input to the model must be set before the model can run. After the model has been ran, information about the simulation can be extracted through the *To Workspace* blocks in the model, where all pre-assigned information is saved in the Workspace in MATLAB. This configuration for simulation facilitates running several simulations over different inputs, by using *for-loops*, where information about each run can be saved consequently in matrices for further analyses.

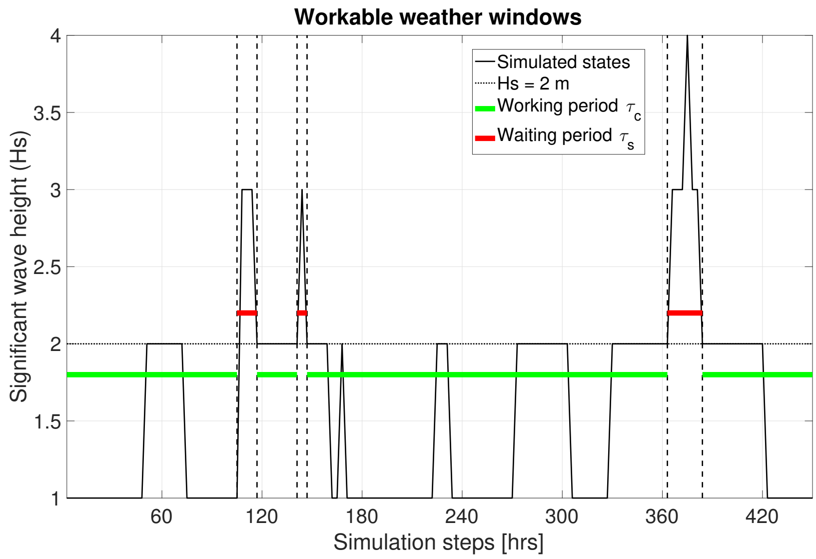


Figure 4.4: Illustration of working and waiting periods during July 2005

4.4.2 Workable Weather Windows

The workable weather windows are one of the main features of the simulation model, and this is the stochastic factor that influence the total installation time. The workable weather windows in the model are decided by comparing the assigned operational criteria and required weather-windows with the actual weather forecasts at all time. This is done by using *Entity Gates*, which will open and proceed the entity when receiving a positive signal. The signal is decided in a new entity-system, where an entity is generated at every time step, and proceeded to a server. In the server, the forecasted weather will be checked and evaluated for the assigned period of operation, and if the weather is below the operational criteria, the weather-window is valid and a positive signal is sent to the *Gate Control* of the *Entity Gate*. Figure 4.4 illustrates the workability of the simulated weather, where the red lines define that the weather state is above the criteria for operation, and the green lines define periods where work can be performed, if the remaining work period allows it, which is checked in the *Entity Gates*.

4.5 Cost-Benefit Analysis

The best installation strategy is in many cases considered the most effective strategy, which is assumed to also be the cheapest one. But the cost of the assets must be included, to compare the benefits and cost levels for each strategy. To complete an analysis of the costs of a solution and the corresponding benefits, it is important to assess the assumed expenditures to map the cost levels. The benefits of an installation strategy are most likely to depend on the obtained reductions in installation time, but the related risk levels

Table 4.6: Estimated vessel day rates (Myhr et al. (2014) and We@Sea (2009))

Vessel type	**Day rate [1000 €]**
Jack-up installation vessel	161 - 231
Jack-up feeder vessel	115 - 140
DP-vessel (HLV)	431 - 631

should also be considered. If installation can be completed fast but at high risks, the consequence of an accident and the probability must be added to the cost calculations.

The cheapest solution might be the most time-consuming, but one should also analyze the daily expenditures for installation, or the installation costs per component. If one component can be installed very quickly, but at a high cost level, it might not be worth it if the rest of the operation does not depend on the early completion.

According to Barlow et al. (2015), the optimal strategy for installation can be an analysis of the balance between the direct installation costs related to the duration of installation. These include operational expenditures (OPEX), the number of vessels acquired and their costs over the installation time, and the benefit of the solutions include the financial benefits from early completion (Cradden et al., 2013). The cost drivers during installation includes chartering costs for vessel, operating costs, port costs, and the costs of technicians and crew.

A comparative study of the different installation strategies will have relevance for deciding on the best solution, according to criteria for developers. The value of the benefit connected to each solution must be compared with the cost of the solution, and this analysis can be a valuable decision tool for project developers.

An assessment of vessel day rates is presented in Myhr et al. (2014), and these are used as basis for evaluating the costs of each scenario in this report. Additionally, day-rates for smaller jack-up vessels, used as feeders in Scenario 2, are gathered based on data from We@Sea (2009). Here, the vessel with the lowest day rate has sufficient capacity for carrying two jacket foundations, but as the wave criteria is lower than what is assumed for the feeder vessel in this report, the smallest feeder vessel with limiting wave criteria of 2 meters is added as the maximum range for feeder day rate. The estimated day rates for the significant vessels used in the simulation model are shown in Table 4.6.

4.6 Case Studies

In order to complete a comparative study of the installation strategies, to evaluate the best strategy fir different OFW projects, the simulation models are to be applied to several

Table 4.7: Case studies

	Number of turbines	Distance from shore
Case 1	50	
Case 2	100	10 - 100 km
Case 3	500	

case studies. The case studies vary in terms of distance from shore and the number of turbines in the field. Three cases for number of turbines have been decided on: either a small field comprised of 50 turbines, a larger field to model the more commonly field sized today of 100 turbines, or a scenario for the future comprising of 500 turbines.

The distances have been set to range between 10-100 km from shore. Even though it is stated that the distance is from shore, the more practical implementation of the distance is that it will model the distance from the field to installation port. For Model 2, another parameter in the case study is the number of feeder vessels, that can be changed to evaluate the necessary degree of component flow to ensure efficient use of the installation vessel. The cases evaluated are listed in Table 4.7.

Several parameters in the model can be changed for project-specific simulation, such as carrying capacity, transit speed and operational criteria, and the use of one or several feeder vessels. Additionally, the number of turbines and distance to port can also easily be changed to comply with real conditions.

The three scenarios given in 4.2 are tested for all case studies, to check what installation method is the most suitable. It will also be relevant to investigate the operability of the operation to expected operability computed in MATLAB with the real data. The comparative case studies will prepare basis for evaluating the best solution for installation.

4.6.1 Jacket Dimensions

The jackets that are to be simulated for installation in this thesis, are the same type as for the Alpha Ventus projects, and the dimensions are described in Burton et al. (2011). These are created for 5MW turbines, have a footprint of 20x20 meters, and are 46 meters tall in total The total weight is 523 tonnes, including a pre-mounted TP, where the jacket itself weights 360 tonnes. The geometry is shown in Figure 4.5.

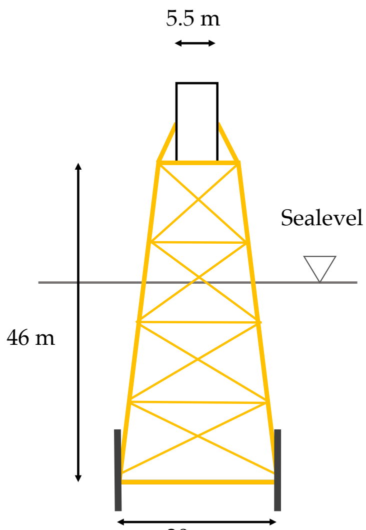


Figure 4.5: Jacket foundation dimensions

Chapter 5

Discrete-Event Simulation Model

This chapter explains the simulation models used for simulation of installation in this thesis. The models will simulate three different methods for installation, and this chapter describes the model structure and the input and outputs of the model. It is important that the models properly represent the real-life system, and that input data is chosen in order to model the physical features.

The basic model structure is shown in Figure 5.1, which shows that the model needs input and constraining weather for running simulation, and gives out a designated output. The models are developed using MATLAB *SimEvents*, and most blocks used in the model are explained in Table 4.5. Three models are created to simplify the specific model structure, another approach could have been to create a more generic model to represent all scenarios, specified by changing the input.

5.1 Model Input

The model input includes both system-specific information such as vessel characteristics and offshore wind farm structure, in addition to the simulated weather states that are used to model physical weather. This acts as a constraining factor, because decisions

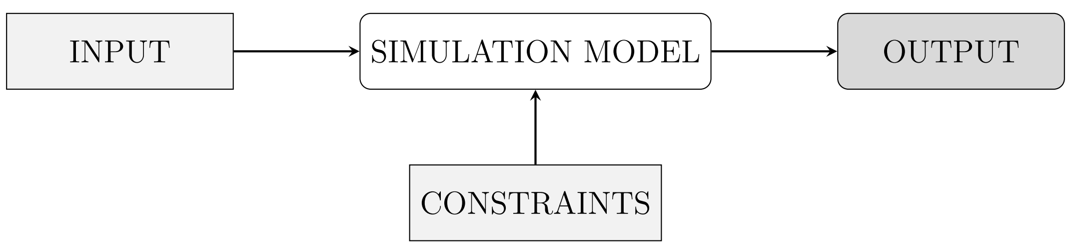


Figure 5.1: Overall description of the model structure

Table 5.1: Model input from Excel (# means that input can be changed)

Parameter	**Value**	**Unit**
Vessel type	#	-
Speed	#	m/s
Capacity	#	-
Nr of turbines currently on vessel	#	-
Wave criteria 1 [H_s]	#	m
Wave criteria 2 [H_s]	#	m
Wind criteria	#	m/s

related to operation are made based on forecasted weather during simulation. Vessel specific information is imported to the simulation model by using the function *xlsread* in the *Event Actions* environment in the *Entity Generator*, where vessels are generated. The input from the Excel-sheet is eight columns of information for the vessel, shown in Table 5.1, where multiple rows are added when different vessels are to be generated. The vessel type will vary depending on the model composition, and enables the use of different vessels that can be routed differently or be entitled for different tasks during simulation. Most of the input are assigned to the vessel-entity in the model as *attributes*, but also saved as *Global Variables.* The specific excel-sheets are also included in Appendix E.

5.1.1 Global Variables and Parameters

Global Variables are variables that can be called for and changed from an *Event Action* environment in the model. These can be assigned by importing data from an excel-sheet the same way vessel attributes are created, through an *Entity Generator*, *Server* and *Entity Terminator*, whose sole purposes are to read the information from the excel-sheet. The excel-sheet is imported in the *Entity Generator* block, whereas the values from the excel sheet are assigned to the attributes of the entity. In the *Service Action* in the *Server*-block, the values of the attributes, which can include wave- and wind-criteria and the vessel speed, are assigned to *Simulink*-functions, and made global by using *Data Store Memory* and *Data Store Read* blocks.

Additional input that is to be changed for every simulation can be assigned as a variable in the *Workspace* environment in MATLAB and read into the model. These are imported using a *From Workspace*-block, that reads the current variable value directly from the MATLAB *Workspace.* The value then needs to be written to a memory block with a *Data Store Write* block. This is done for deciding the number of turbines and the distance from shore, the parameters of the case studies, enabling simulation and parameter changes without entering the actual simulation model physically.

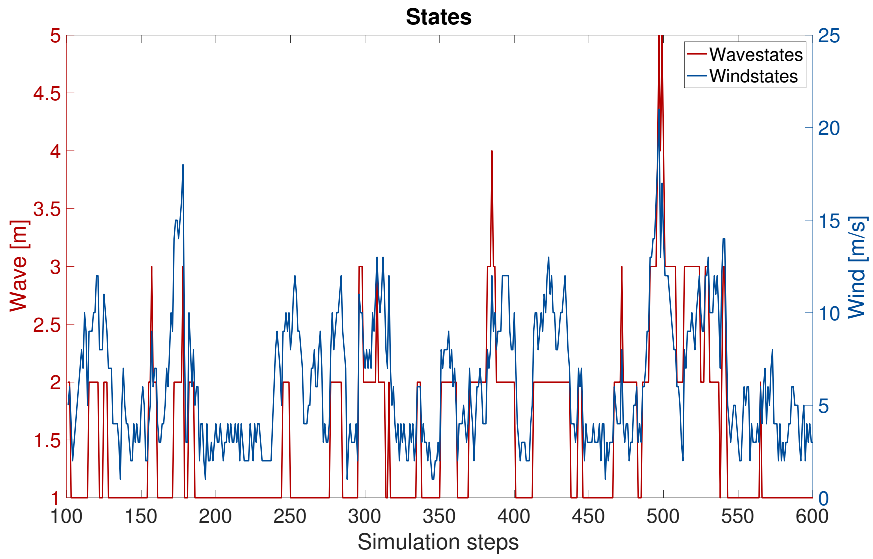


Figure 5.2: Simulated wind and wave states

5.1.2 Weather Simulations

The Markov Chain simulated weather series are imported to the model by using *Simulink Functions*. In each of these functions, the weather state is retrieved from the weather state vectors in MATLAB *Workspace*, by accessing the correct position of the weather according to the assigned time of simulation. Each step in simulation represents an hour of real-life behaviour, and a *Digital Clock* in the simulation model is used to keep track of the time-steps. When simulation is started from MATLAB, the script reads in the correct weather state from the three-hour forecast, according to season.

The weather states are synthetic weather representations, and are assigned integer values. For each weather state, the integer value represents wave observations between the two states, meaning that weather state 1 represents weather with values between 0 and 1, and weather state 2 represents weather with values between 1 and 2. Figure 5.2 shows the correlation between the wind and wave states, from an excerpt of the simulated states. The script showing how the weather simulations were performed are included in Appendix B.3 and B.4.

5.1.3 Attributes

The attributes which are assigned to each entity are given in Table 5.2. The first seven attributes are given by changing the entries in the excel-sheet that is imported in the model. These include vessel specific information, that can be changed to describe the given choice of vessel type and configurations. The two latter attributes are assigned to the vessel entity as it passes through the system. The *Current Load* is a measure of how

Table 5.2: Attribute values for the vessel entities

Attribute	Installation vessel	Feeder vessel	DP-vessel	Unit
Type (vessel)	1	2	3	-
Speed	12	6	14	*knots*
Capacity	4	2	4	-
Wave criteria 1	3.5	3.5	3	*m*
Wave criteria 2	2	2	2	m/s
Wind criteria	8	8	8	m/s
Current load	#	#	#	-
Output port	#	#	#	-

many components that are currently loaded on the vessel during simulation. The value of this is used to decide if the vessel entity will continue the installation cycle during simulation, for installation of the remaining components, or if it will return to port for loading. The *Output Port* will at the initialization of simulation be assigned a value according to the type of vessel for Scenario 2. This is to route the installation vessel directly for the field, while the feeder vessel is routed to port.

5.2 Running Simulation from MATLAB

All simulation runs were executed from a MATLAB-script. This enhances parametric changes for each simulation, and the actions for post-processing of results as the output from simulation is stored in their dedicated matrices after each run. The MATLAB-Scripts used for running simulations are called *run_sim_model#*, and several are created to reduce required action in each script. The scripts used for running simulations from MATLAB is included in Appendix D. For each simulation, the season for simulation must be specified, and the configurations for the number of turbines and distances that are to be simulated. *load_system('model_master2');* and *simOut=sim('model_master2');* are ran for every simulation, where the former loads the model into MATLAB, and the latter runs simulation and saves the output.

5.3 Model Structure

The basic model composition consists of vessels portrayed as *Entities* being generated in the *Entity Generator* block, and then assigned to the designated route according to model input. For Scenario 1 and 3 there is only one route, or cycle, but the routes consists of several sub-routes to model the installation of several components on the field. The basic structure of Model 1 is shown in Figure 5.5, but Model 3 has a very similar appearance.

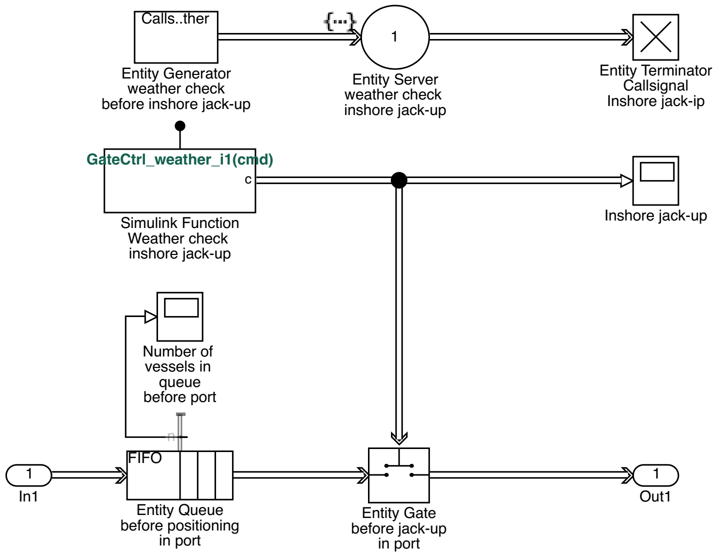


Figure 5.3: Weather check before jacking up in port (before loading)

The difference is further explained in the specific sections for the models.

The vessels will load up with components in the installation port, modelled as an *Entity Server*. Before loading can commence, the forecasted weather for the required operation is checked, and the entity is only proceeded through the *Entity Gate* from the *Entity Queue* when the weather forecast shows a weather window of the required size. The configuration for checking weather before jacking-up in port is shown in Figure 5.3, and this configuration is repeated every time a weather restricted operation is simulated, with changes in the *Entity Server* for when an *Entity* is to be proceeded according to the weather window and the limitations.

The required weather window must be assigned in the *Entity Server* for the *Entity Gate*, and if changes are to be made, the current configuration of the models indicates that this must be changed by modifying the *Event Action* in the server. In order to proceed the entity, the forecasted weather is examined with relation to the operational criteria for the activity, either wind speeds or significant wave height. Before each loading operation, the required weather window is checked, and loading of each jacket is performed in assigned *Entity Servers*. The loading procedure is shown in Figure 5.4. During the loading-event, the *Attribute* called *Current Load*, or *Nr* in the model, is assigned a value according to the number of components loaded.

After loading, the vessel entity is proceeded to the field for transit if the weather allows it. Positioning at the field can commence only when the forecasted weather allows it, and installation of a jacket is commenced when the forecasted wind speeds for the required weather window are lower than the operational criteria. The vessel entity has an attribute that decides the output-port when passing the *Output Port*-block after installation of one jacket is performed. This attribute will be changed according to the number of jackets still loaded on the vessel, saved in the *Current Load*-attribute. When all jackets that were loaded on the vessel has been installed, the vessel will be routed in the *Output Port* to return to port, but will continue installation as long as there are components loaded. When all jackets in the offshore wind farm has been installed, according to the input from running the simulation, the vessel is routed for demobilization, and terminated in an *Entity Terminator*.

A detailed overview and graphical representations of the three simulation models that were created are explained in the following sections. The operational procedure of all scenarios were thoroughly explained in Section 4.2. For all models, the wind-criteria for loading in port has been increased by two in the *Entity Serves* that check the weather. This is done to consider that the weather inshore is calmer than offshore, because the weather series are given for a offshore location. The model structure from *SimEvents* is included for all models in Appendix F.

5.3.1 Model 1

This model represents the installation method for Scenario 1, and the simulation model is shown in Figure 5.5. The entity is in this case an installation vessel with jack-up features. The vessel is created in the *Entity Generator*, and then routed to the installation port for loading for components. The vessel first passes an *Entity Gate* that only proceeds the vessel if the weather is good enough to jack up in port. There is also an *Entity Gate* after loading, that proceeds the vessel to transit to the field.

The loading operations in port is shown in Figure 5.4, and a graphical representation of the model is illustrated in the flow chart in Figure G.1 in Appendix G, where the loading operation has been slightly simplified. The loading operations in port includes one *Entity Server* for jacking up, and then several separated *Entity Servers* to load the components to the entity. There is also a configuration for checking the weather, before positioning

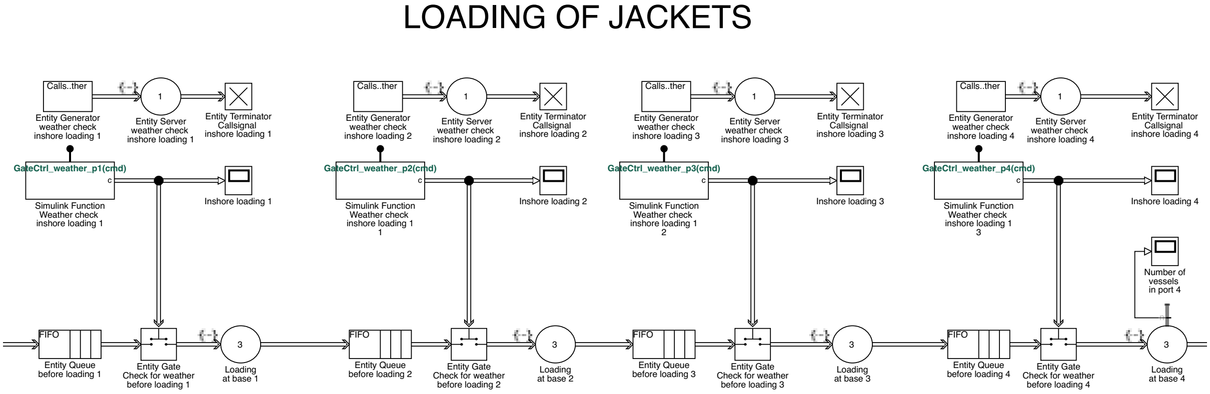


Figure 5.4: Loading in port

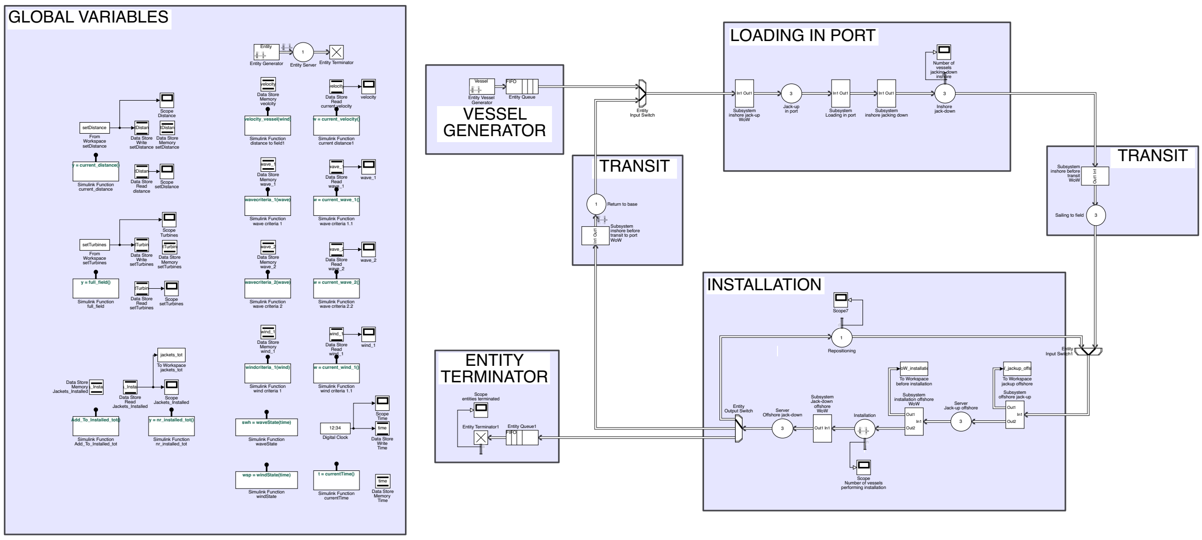


Figure 5.5: Simulation Model 1

and each loading, and also before jacking-down.

Installation in modelled in a cycle, where the vessel entity will continue in the installation cycle until all components that were loaded to the vessel have been installed. Every time the vessel enters the *Entity Server* for installation, a component is installed, which is simulated by subtracting an integer from the *Current Load*-Attribute. When this attribute has the value zero, the attribute *Output Port* is changed and the vessel is routed for new loading operations in port. When all components in the field has been installed, the vessel is routed to the *Entity Terminator*, and is terminated from the system.

5.3.2 Model 2

In this model, representing Scenario 2 as illustrated in Figure G.2 in Appendix G, it is possible to decide the number of feeder vessels used for installation. The entities that are generated are routed to different cycles according to the attribute for vessel type. This way, the installation vessel is routed directly to the location of the field, while the feeder vessel is routed for loading in port. The feeder vessel will travel to the field when loading is completed, and will jack-up at the designated position next to the installation vessel, or where the installation vessel is going to be positioned, when the weather allows for jacking-up. When both vessels are positioned, components will be loaded from the feeder to the installation vessel.

The simulation model for Scenario 2 is shown in Figure 5.6, and a larger picture is also included in Appendix F.2. The main difference between this and Model 1 and 3 (shown in Figure 5.5) is that there are two different entity cycles, one for the feeder and one for the installation vessel. In the simulation model, the upper cycle represents the loading for

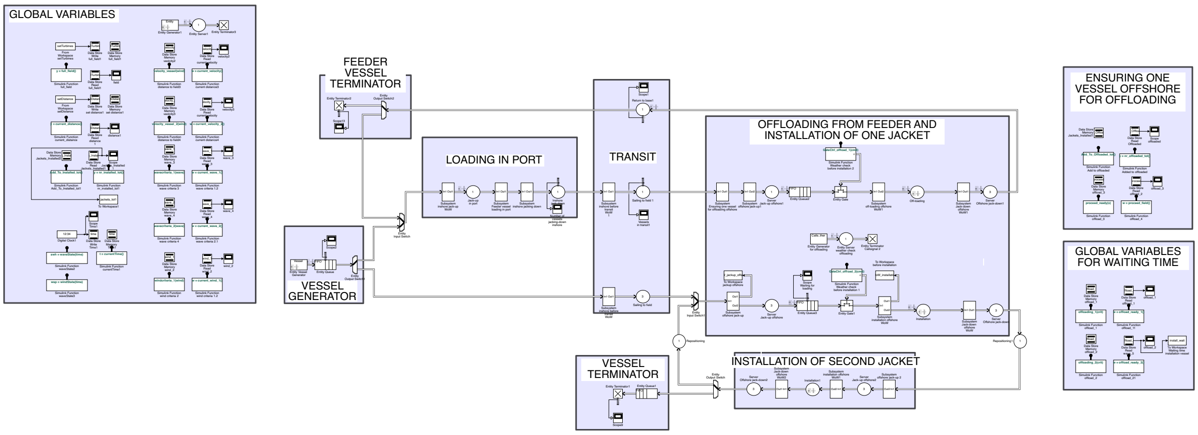


Figure 5.6: Simulation Model 2

the feeder vessels, while the lower is the installation vessel that stays at the offshore wind farm. An addition to this model for handling several feeder vessels, is the *Entity Gate* and *Global Variables* that ensures that only one feeder vessel is jacking-up for offloading of components. This means that if several feeder vessels have loaded in port and have headed for the installation field, only one vessel at a time will position itself next to the installation vessel, while the other will wait until the installation vessel have installed both components on board.

When this model is ran in MATLAB *SimEvents*, two different models, that are practically the same, are saved with the correct configurations for one and two feeder vessels. This was done to save time during the execution of simulation, and the models created in MATLAB *SimEvents* are called *Model2* and *Model22*, where the latter represents two feeder vessels.

5.3.3 Model 3

The third model created in *SimEvents*, Model 3, is included in Appendix F.3, and Figure G.3 in Appendix G illustrates the model composition of Scenario 3. The procedures in the model are quite similar to those of Model 1, but with the entity being a DP-vessel instead of a jack-up vessel. This means that there is no need for jacking up or down prior to loading and installation, the entity only needs to obtain position with the dynamic position system, which is modelled as an event with a duration of the intended length. The entity is passed through *Entity Gates* before all operations with operational criteria, and the criteria are given in Table 4.4.

5.4 Model Output

The output from the simulation models are exported by using the *To Workspace* block in MATLAB *SimEvents*. For all models, the output includes time to complete installation of all jacket foundations, the operability for jacking up or positioning before installing, and the operability to perform installation. For Model 2, the output also comprises a measure for utilization of the installation vessel. This is done by exporting data from the *Entity Gate* where the installation vessel waits for the feeder vessel for loading of components. A global function is assigned the value 1 in every simulation-step when the installation vessel is waiting, and by summarizing the vector containing the values of the output over the total installation time, the percentage of installation time that the installation vessel spends waiting for the feeder vessel can be calculated. This is also the method used for calculating the operability of positioning and installation. In the MATLAB-scripts where the simulation is performed, a post-processing code is written that saves the installation time and calculated operability and waiting time for every simulation. These scripts are included in Appendix D.

Chapter 6

Operability Study

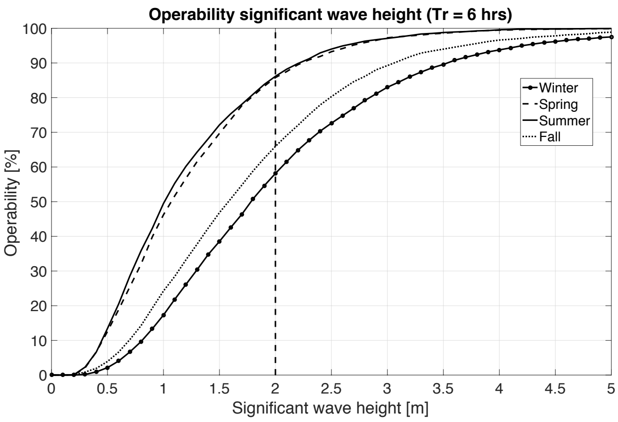
This chapter presents the results found from operability plotting in MATLAB and the simulation models in MATLAB *SimEvents*. The chapter starts with a presentation of the operability plots, then continues with simulation results, an investigation of the efficiency of installation by comparing installation time per jacket, and concludes with a cost-benefit analysis. It will be relevant to compare the operability results from simulation with the expected operability from the MATLAB-scripts.

The output of the model is saved as total installation time, operability for jacking up or positioning offshore, and operability for installation. The former depends on significant wave heights, while the latter is limited by wind speeds. Additionally, for Scenario 2, the waiting time offshore for the installation vessel is also recorded.

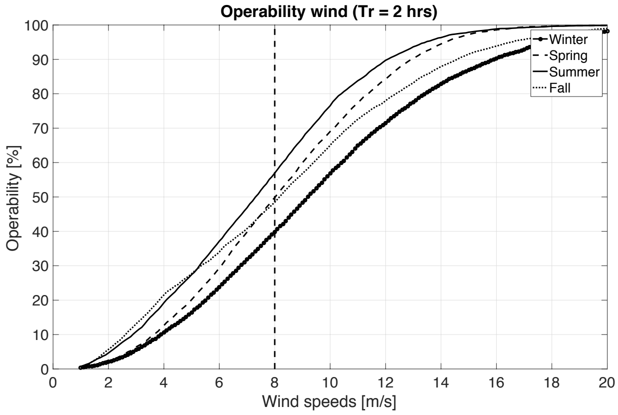
In order to perform an analysis of what parameter that influences the choice of installation strategy the most, parameters for distance from shore and number of turbines were changed sequentially, and the corresponding total installation time was recorded. The simulations were performed with parameter values which are reasonable for installation operations today, related to vessels already in use. The criteria for vessels are explained in Section 4.2, and were given in Table 4.2, Table 4.3 and Table 4.4. Attribute values for the vessel entity are explained in Chapter 5.1.3.

6.1 Operability Analysis

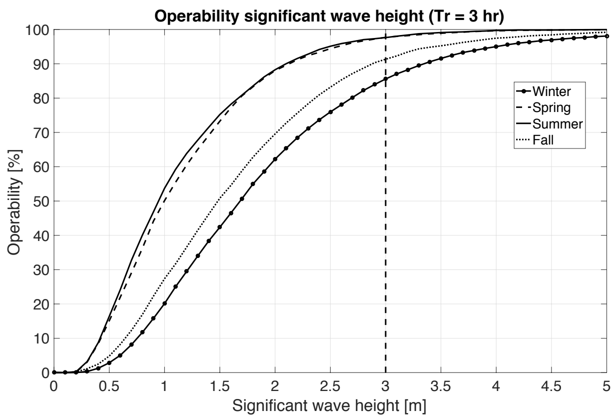
An operability analysis of the weather series is performed by examining all observed wave- and wind values from the years 2005 to 2014. The parameters for the analysis include the required weather window for performing a given operation, and the criteria for operation. The operability plot shows the operability for an operation with a given duration during



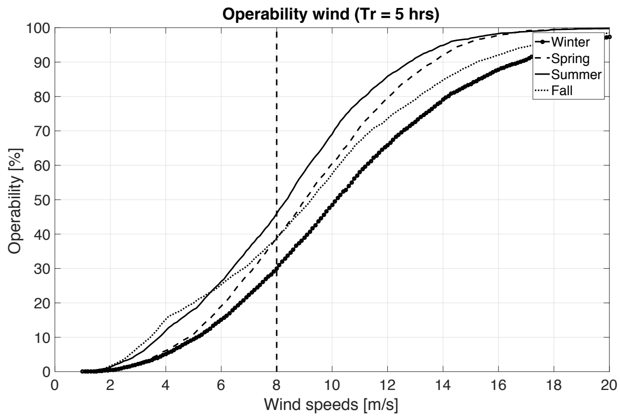
(a) Expected operability jacking up (T_r = 6hrs)



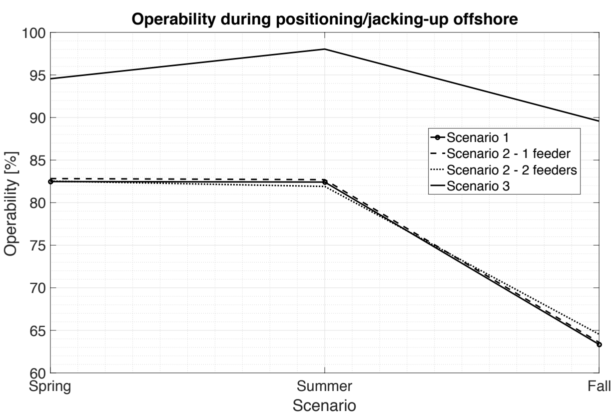
(b) Expected operability installation (T_r = 2hrs)



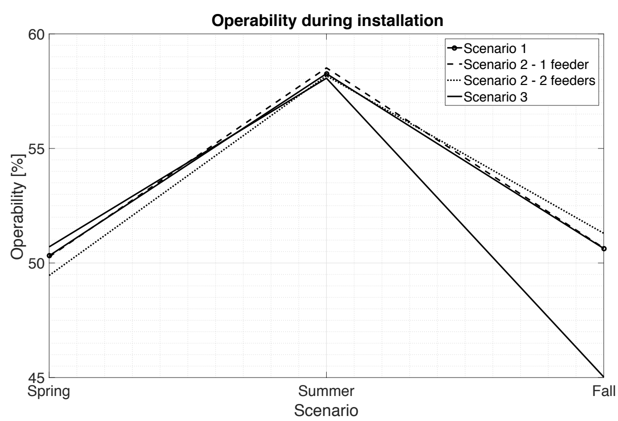
(c) Expected operability positioning (T_r = 3hrs)



(d) Expected operability inshore loading (T_r = 5hrs)



(e) Simulated operability positioning/jacking-up



(f) Simulated operability installation

Figure 6.1: Expected and simulated operability

a specific season over the limiting weather criteria. The operability from the simulation models is used for comparing the simulated operability with expected operability, as a validation tool for the model.

Table 6.1: Expected and simulated operability for jacking-up offshore (Scenario 1 and 2)

$OP_{LIM} = 2$ $[m]$ $T_R = 6$ [Hrs]	**Expected Operability** [%]	**Simulated Operability** [%]
Spring	85	82-83
Summer	85	82-83
Fall	66	63-64

Table 6.2: Expected and simulated operability for positioning with DP-vessel offshore (Scenario 3)

$OP_{LIM} = 3$ $[m]$ $T_r = 3$ [Hrs]	**Expected Operability** [%]	**Simulated Operability** [%]
Spring	98	94
Summer	98	98
Fall	91	89

6.1.1 Operability for Limiting Wave Heights

The operability output from the simulation model includes positioning and installation, where both operations are depending on the wave height being lower than the criteria. To compare the operability from positioning offshore with jack-up vessels and DP-vessels, operability plots were made in MATLAB based on the 10-year weather series with the required duration of operation as the weather window (T_r) and the wave criteria shown as a vertical line. The limiting significant wave criteria for the different scenarios are shown in Table 6.1 for Scenario 1 and 2, and in Table 6.2 for Scenario 3, where also the expected and simulated operability is shown. The simulated operability shown in Table 6.1 has some slight variances, because the results are for several models. The resulting operability plots made in MATLAB for wave data are shown in Figure 6.1a and 6.1c, which is where the expected operability shown in the tables are collected from.

Figure 6.1a shows the expected operability for jacking-up offshore, with a required weather window of 6 hours, and the vertical line at $H_s = 2m$ intersects the expected operability for operation during the different seasons. As can be seen in the Figure, and read from Table 6.1, it is expected that the vessel will be able to position itself and jacking-up at an operability of about 85 % during both summer and spring, while the operability during fall is only at about 66 %. For the DP-vessel, Figure 6.1c and Table 6.2 shows that the expected operability for positioning offshore during summer and spring is at about 98 %, and 91 % during fall. The higher operability for the DP-vessel is due to the higher operational criteria, meaning that it is expected that waves are unlikely to be above 3 meters for longer periods during summer.

The operability from simulation for jacking up offshore can be seen in Figure 6.1e. The plot is made by taking the average of all results from the case-studies, varying the number of jackets to be installed from 50 to 500, and the distance from shore from 10 to 100 kilometers. The plot shows that for summer, the model experiences an average operability of about 83 % during summer and spring, and 64% during fall, for all scenarios where a jack-up vessel is used. This is in accordance with the expected operability of 85 % and 66 %, respectively, shown in Figure 6.1a. For positioning with the DP-vessel, the operability experienced in during simulation is at 94 and 98% for spring and summer respectively, and 89 % for fall. This is also consistent with the expected operability from MATLAB shown in Figure 6.1c. The close correlation between expected and simulated operability displayed in Table 6.1 and Table 6.2 shows that the simulation model has relevance for modelling real-life behaviour with relation to vessel behaviour and operation in waves.

6.1.2 Operability for Limiting Wind Speeds

Operability plots for wind has been made in accordance with the criteria for loading inshore and install offshore. However, as the only output from the model related to wind limitations is for installation offshore, only this operability will be possible to compare. The plot showing inshore loading has been included only to show that the expected operability for inshore loading is as low as 45 % during summer, as can be seen in Figure 6.1d. This means that measures should be taken to improve this operability, and increase the efficiency of loading. The reason for the low operability is probably due to the long required weather window, of 5 hours.

For offshore installation, the criteria and required weather window is equal in all scenarios, and the resulting operability is shown in Table 6.3, for all seasons. The expected operability over different seasons in seen in Figure 6.1b, and calculated by examining wind data from the years 2005 to 2014. From the simulation model, the operability results from installation are shown in Figure 6.1f. These results cover the average operability from all simulation runs over 50 to 500 jackets for installation and a distance of 10 to 100 kilometers from shore. The highest operability is attained during summer, where the probability that an installation can be performed is at 58 %, for all scenarios. For spring, the simulated operability is at about 50 %, whereas the largest difference is during fall, where Scenario 1 and 2 have simulated operability around 51 %, while Scenario 3, with a DP-vessel for installation, has an operability of only 45 %. Even though these results differ from each other, they are still within compliance with the expected operability of 50, 57 and 48 %, for spring, summer and fall respectively, which are shown in Table 6.3.

Table 6.3: Expected and simulated operability for installation offshore (Scenario 1, 2 and 3)

$OP_{LIM} = 8$ $[m]$ $T_R = 2$ [Hrs]	**Expected Operability** [%]	**Simulated Operability** [%]
Spring	50	49-51
Summer	57	58
Fall	48	45-51

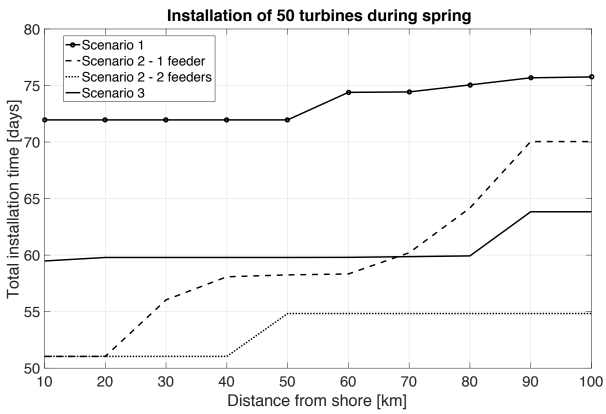
6.2 Simulation Results

From each simulation, the recorded output includes the total installation time, operability for jacking up or positioning, and operability for installation. Moreover, for simulation with Scenario 2, the utilization of the installation vessel is recorded. The results from case studies where the distance is changed from 10 to 100 kilometers are plotted for all scenarios where the plots are divided into the number of turbines installed, 50, 100 or 500. This is plotted for each of the seasons spring, summer and fall. The efficiency of installation is also investigated, to map the most efficient installation method by comparing the time spent to install one jacket foundation. An additional investigation of Scenario 2 is also performed, to find the limiting distance for the feeder vessel to maintain supply, and the utilization of the installation vessel.

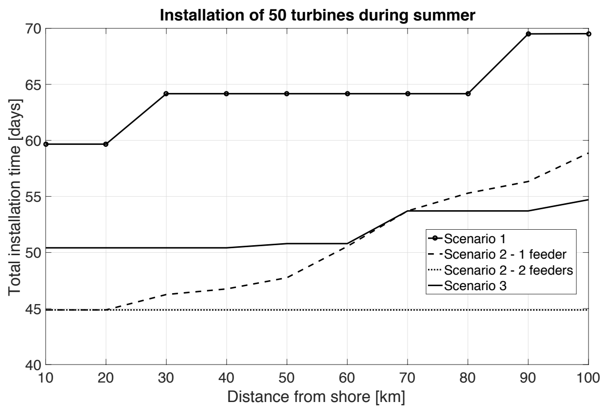
The cases introduced in Chapter 4.6 were all ran in the three models created in *SimEvents*. Additionally, the model for Scenario 2 was ran two times, with one and with two feeder vessels.

6.2.1 Case 1 - Installation of 50 Jacket Foundations

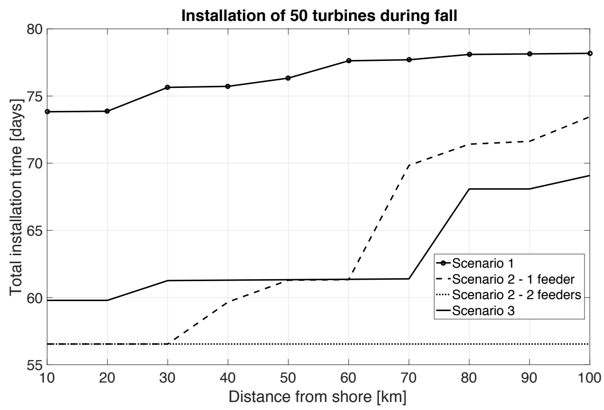
The results from simulation of installation of 50 jacket foundations over distances ranging from 10 to 100 kilometers are shown in Figure 6.2. The results in the plot show that the fastest installation is performed over the seasonal weather from summer, where installation with Scenario 2 as the installation method will complete the installation of 50 turbines in only 45 days. For all three seasons, the fastest installation method with a short distance from shore, ranging between 10 to 20 kilometers for spring and summer, and 10 to 30 kilometers for fall, will be Scenario 2, and equal installation time despite the number of feeder vessels used. When distance from shore increases, Scenario 2 with only one feeder vessel will have an increase in installation time, and eventually intersect the plot of installation time for Scenario 3 with a DP-vessel. For Scenario 2 with two feeder vessels, the total installation time in almost linear. The reason is that for these relatively short distances, the two feeder vessels maintains supply of all components, ensuring a high



(a) Total installation time during spring



(b) Total installation time during summer



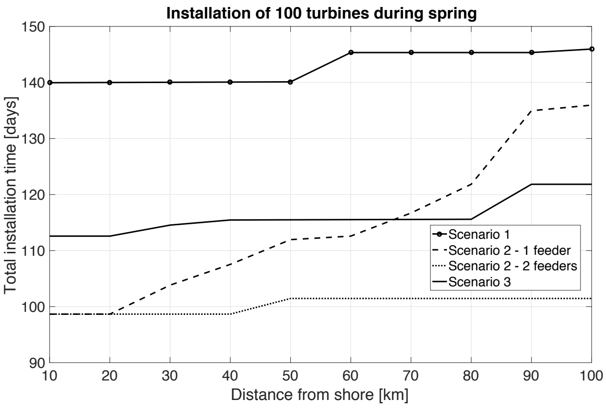
(c) Total installation time during fall

Figure 6.2: Case 1 - Simulation results for installation of 50 jacket foundations

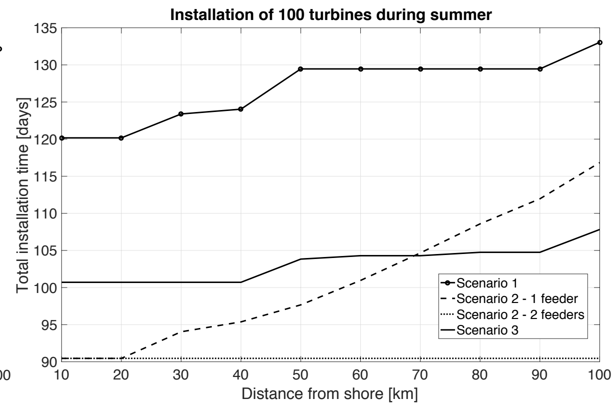
utilization of the installation vessel, and therefore installation time is not affected by an increase of distance up to 100 kilometers. Scenario 1 has the overall highest installation time, but the advantage for this solution is that is only includes one vessel asset.

The reason behind the linearity, or the low gradient, in some of the graphs, such as for Scenario 1 in Figure 6.2a, is probably due to the weather windows. Even though the vessel spends longer time performing transit for longer distances, it might have to wait for the correct weather window when reaching the field for installation, leading to weather wait. The plots also show that increasing the distance from shore in most cases does not affect installation time substantially for Scenario 1 and 3, which probably means that the main restrictive factor for operation is not the distance from shore, but the operational criteria and required weather windows. The latter is emphasized by the increase in installation time when installing over weather series that have worse weather, because total installation time is higher for all scenarios during spring and fall compared to summer.

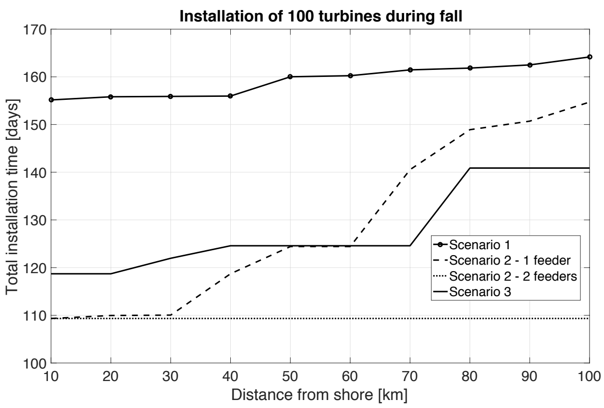
6.2.2 Case 2 - Installation of 100 Jacket Foundations



(a) Total installation time during spring



(b) Total installation time during summer



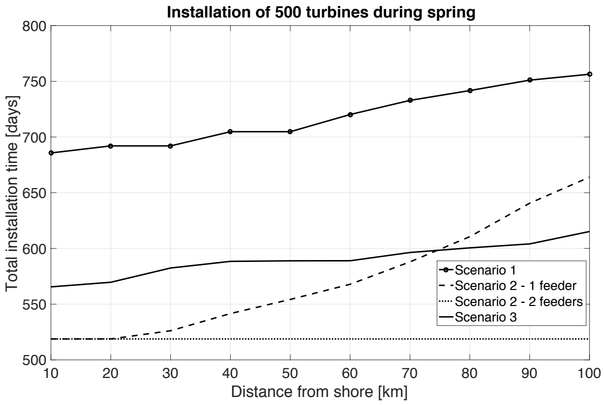
(c) Total installation time during fall

Figure 6.3: Case 2 - Simulation results for installation of 100 jacket foundations

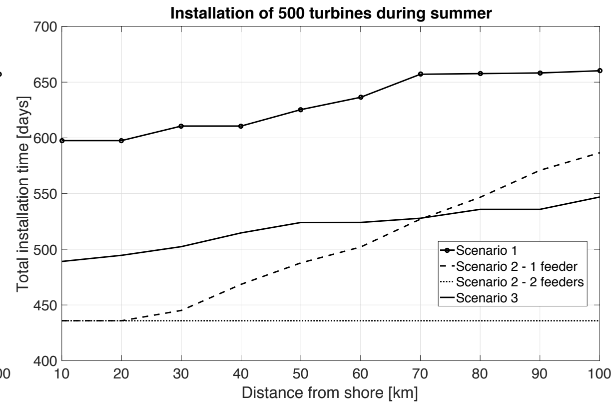
For installation of 100 jackets foundations the results are shown in Figure 6.3. We see the same trends in all the plots compared to the installation of 50 jackets seen in Figure 6.2, and here Scenario 2 with two feeder vessels keeps the highest rate of installation. There is an equal trend for Scenario 2 with one feeder, where the feeder vessel maintains supply for smaller distances, while installation increases with a high rate when increasing the distanced from shore above 20 kilometers for spring and summer, and above 30 kilometers for fall.

6.2.3 Case 3 - Installation of 500 Jacket Foundations

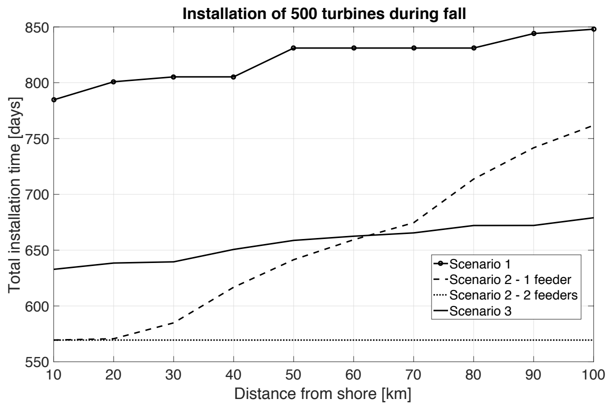
The results from installation of 500 jackets for all scenarios are shown in Figure 6.4, where results from spring, summer and fall are shown in Figure 6.4a, 6.4b and 6.4c respectively. The same trends as for case 1 and 2 are also observed here, where Scenario 2 with two feeder vessels performs the most efficient installation, while Scenario 1 performs the least



(a) Total installation time during spring



(b) Total installation time during summer



(c) Total installation time during fall

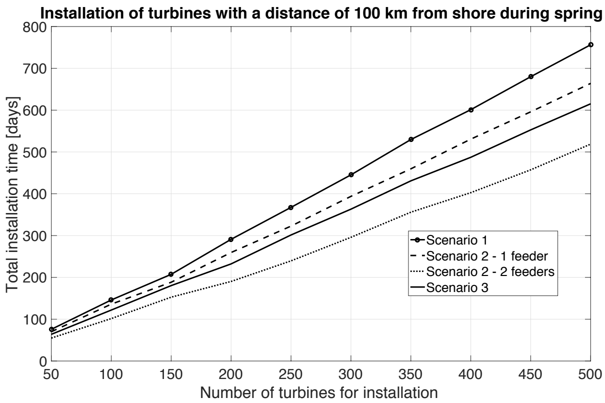
Figure 6.4: Case 3 - Simulation results for installation of 500 jacket foundations

efficient over all distances. Scenario 2 with only one feeder vessel also shows the same trends as for the other cases, with a steep increase in total installation time when distances increase over 20 and 30 kilometers.

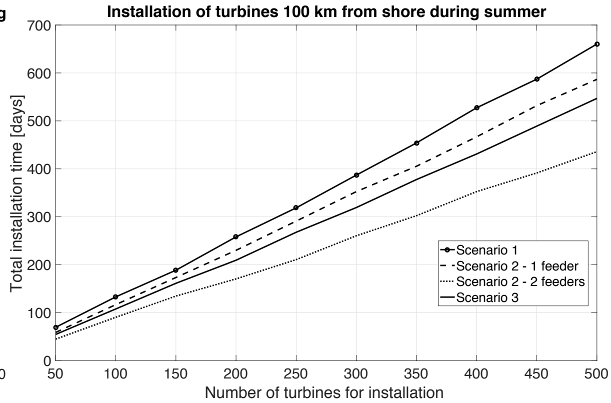
An interesting behaviour seen from the graphs in Figure 6.4, is that there is a more linear increase in total installation time than for the other case studies. This is probably due to the increase installation time when installing 500 jacket foundations. This means that operation will be depending on longer weather series, which seems to reduce local variations in the weather series, thus creating more smooths installation rates.

6.2.4 Linearity for Increased OWF Size

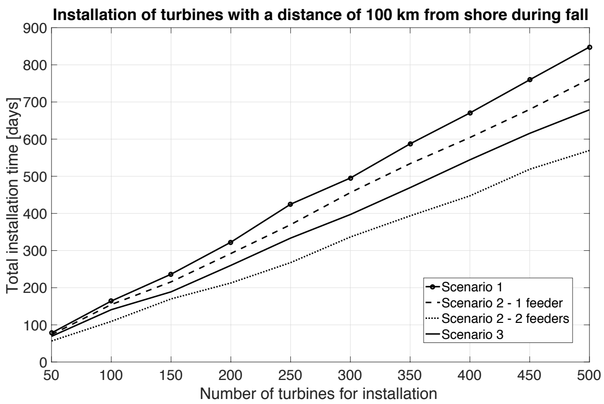
Simulations were also executed with a constant distance from shore, while increasing the number of turbines in the OWF. By plotting these results, it is possible to observe the linearity in installation over an increase in offshore wind farm size. The plots are shown in Figure 6.5, where all results show total installation time for a set distance of 100



(a) Total installation time during spring



(b) Total installation time during summer



(c) Total installation time during fall

Figure 6.5: Simulation results of installation for increased OWF size

kilometers from shore. The plots show a linearity, but not necessarily with the same rate of growth in installation time. The plots also show that total installation time depends significantly on the season when OWF increases in size. By comparison, one spends about 560 days installing 500 turbines using *Scenario 2 - 2 feeders* during fall, seen in Figure 6.5c, compared to 430 days installing during summer, seen in Figure 6.5b. The resulting improvement in operability by choosing the optimal season to perform installation will therefore lead to savings of about 130 days. This is however not applicable in the real world, where an installation ranging over 430 days would span over more than a year, but is a useful tool for measuring efficiency.

The plots in Figure 6.5 show that total installation time increases linearly with an increased OFW size. This is thus not a parameter that has high impact on deciding the installation strategy, except from choosing the most efficient alternative.

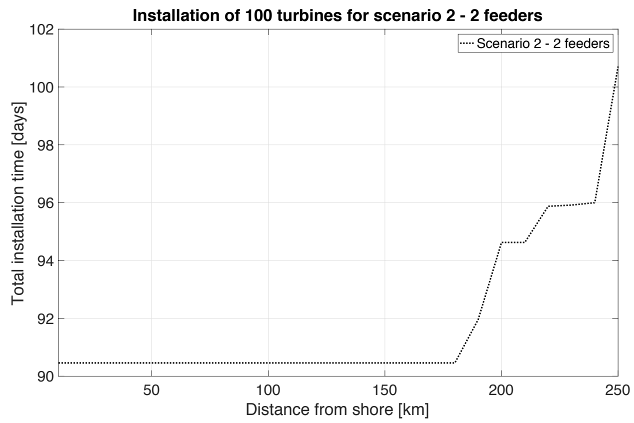
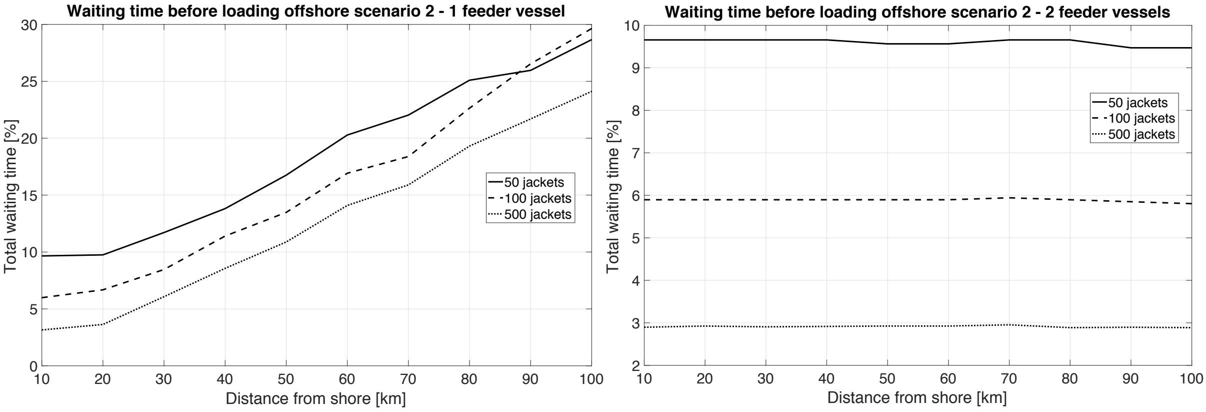


Figure 6.6: Total installation time for 100 turbines (Scenario 2 with 2 feeders vessels)

6.2.5 An Investigation of Scenario 2

As can be seen from the plots of all results in Figure 6.2, 6.3 and 6.4, one can observe a close to constant installation time for Scenario 2 with 2 feeders. This is due to the high supply of components from the feeder vessel when there are two operating. By running simulations over even higher distances from shore, one can observe a significant change in total installation time for larger distances. The total installation time will increase for distance above 180 kilometers, as seen in Figure 6.6. With distances from 190 kilometers and above, two feeder vessels will no longer be sufficient to keep the utilization of the installation vessel at a maximum, and therefore it will occur instances when the installation vessel will have to wait for the feeder vessel to arrive, and therefore total installation time will increase.

The rate of utilization for the installation vessel can be found by investigating how much time the vessel spends waiting for components offshore. If no time is spent waiting, it means that the feeding of components is unsaturated and one obtains a higher degree of efficiency for installation. If the installation vessel however needs to spend longer time waiting for components, it reduces the utilization and the project developer will spend more money per installed jacket due to the longer chartering period. The waiting time for the installation vessel before loading components from the feeder vessel offshore is shown in Figure 6.7, and the results are from summer. The waiting time is the percentage of the installation time that the vessel spends waiting for the feeder vessel for loading. Results from seasons spring and fall shows the same trends, hence the reason why the plots are not displayed here. In Figure 6.7a one can observe that the waiting time increases with increased distance from shore, despite the number of jackets installed. This increase is due to increased time spent in transit, which makes the availability of vessel offshore decrease. The waiting time for using two feeder vessels over distances from 10 to 100 kilometers is shown in Figure 6.7b. This shows that there is an almost constant waiting



(a) Waiting time before loading offshore with 1 feeder vessel

(b) Waiting time before loading offshore with 2 feeder vessels

Figure 6.7: Installation time per jacket

time offshore for the installation vessel, because the flow of components is ensured to fulfill the demand up to 100 kilometers from shore. This is also shown in the results from the case studies, shown in Figure 6.2, 6.3 and 6.4, where the total installation time for Scenario 2 with two feeder vessels is practically constant for all cases.

Another interesting result related to the waiting time offshore for two feeder vessels, is observed when plotting the average waiting time for installation of 50, 100 and 500 turbines over distances from 10 to 100 kilometers, for the different seasons. The average value is chosen in this plot because of the nearly constant values for waiting times for two feeders. This is plotted in Figure 6.8, and shows that the highest average waiting time is observed for summer, when installing 50 turbines. The total installation time for spring and fall is higher than for summer, even though waiting time is lower. The reason for this is probably because the limiting factor for installation during spring and fall is bad weather, leading to weather wait before executing an operation. The average waiting time decreases when increasing the number of turbines for installation. A feasible reason for this is that as total installation time increase, the influence of the weather is reduced as the system reaches a steadier state.

6.3 Efficiency of Installation

An investigation of the efficiency of the installation in terms of average time spent installation one jacket can be interesting for both practical and financial purposes. The installation time per jacket for installation of 100 turbines during summer is shown in Figure 6.9a. The plot correlates with the total installation time for 100 jackets, as an

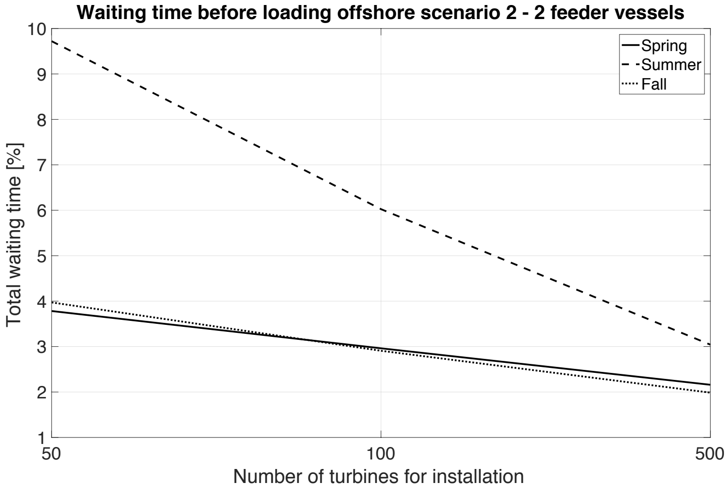


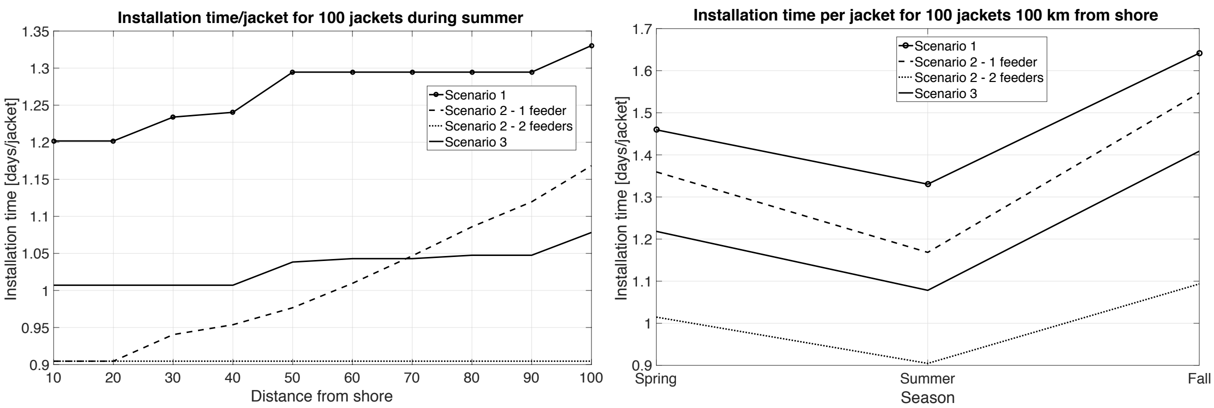
Figure 6.8: Utilization of installation vessel, with two feeder vessels, 100 km from shore

installation time of 120 days for 100 jackets is the same as an average of 1.2 days per jacket. This shows that average installation time per jacket increases with the distance from shore for all scenarios, except for Scenario 2 with two feeders that maintains the installation efficiency of approximately 0.9 days per turbine. This is considered quite high compared to industry standards.

Figure 6.9b shows the average installation time for installation of 100 jackets 100 kilometers from shore, comparing results from the different seasons. As can be expected, the highest installation rate is obtained during summer, while the lowest rates are obtained during fall. Results for larger distances from shore are expected to be larger, assumed by comparing with the results from Figure 6.9a, and by comparing both plots it is assumed that the highest rate of installation is obtained with short distances to shore, independent of the number of turbines for installation. This is however not the case for Scenario 2 with two feeders, where it can be assumed that the low rate of installation will continue until the flow of components is saturated, at about 190 kilometers from shore as shown in Figure 6.6. In real projects, one should also include the factor of learning curves, leading to increased installation rates as the installation progresses.

6.4 Comparative Cost-Benefit Analysis of the Installation Scenarios

The simulation results from the case studies in Section 6.2.1, 6.2.2 and 6.2.3 shows that the lowest rate of installation is attained for installation Scenario 1, using only one installation vessel to perform all operations. This strategy involves however only one asset, and the choice of vessel can be made based on required carrying- and lifting capacity, in addition



(a) Installation time per jacket for 100 jackets during summer

(b) Installation time per jacket for 100 turbines 100 km from shore

Figure 6.9: Installation time per jacket

to the transit speed required to install the foundations within the time frame. Crew changes and loading of consumables can be performed as the vessels docks for loading, neglecting the need for supply offshore.

This is also realized for Scenario 3, where a DP-vessel performs all activities. Installation is obtained at a higher rate, as the vessel spends less time for positioning before loading in port and installing offshore, and often the DP-vessel will have the capacity to hold a higher transit speed. For long distance from shore, Scenario 3 provides a lower total installation time than Scenario 2 with one feeder vessel. This can possibly provide a cheaper solution, as the strategy only includes one vessel asset compared to Scenario 2, but must be compared with specific operating costs for the vessel.

There is an equal trend for Scenario 2 with one feeder for all the case studies, where the feeder vessel maintains supply for smaller distances, while installation increases with a high rate when increasing the distances from shore above 20 kilometers for spring and summer, and above 30 kilometers for fall. The increased installation time for using one feeder vessel compared to two, must be compared with the expected return of earlier completion. If operation costs (OPEX) are significantly larger for using two vessels compared to using one feeder, the effect of earlier completion with relation to profit must be investigated. It is assumed that cost levels are increasing considerably when introducing more assets to the system, and must therefore be compared to the expected return of investment caused by shorter installation time, to ensure acceptable cost levels and profit.

In order to decide the best installation strategy for each project, a complete analysis of the resulting cost compared to the benefit of the method must be achieved. The most efficient strategy is likely to come at higher daily costs, but if installation can be completed in shorter lead time, this might reduce total installation costs and lead to profit due to earlier completion.

Chapter 7

Discussion

This chapter provides the discussion of the results and findings in this thesis, and will also address the assumptions made during the work, and how this has impact on the results.

7.1 Assumptions for Installation

The simulation models created in this thesis, does not include pre-piling of the jackets, or other possibilities for fixing the foundation to the seabed. It is assumed that pre-piling has been completed prior to installation of the jackets. The models have excluded this task to create a less complex model, due to concerns related to the results. It was assumed that a simpler model, only focusing on the installation of the foundation, would provide better basis for analysis related to the logistics of installation for this specific operation. An extension of the model where pre-piling is included can be performed, but these tasks normally are considered two different operations. An extension could have provided information about pre-piling operations, but this is not assumed to impact installation efficiency for foundations, and is therefore considered irrelevant for foundation installation phase.

The suction-bucket method for fixing a jacket foundation to the seabed was explained in the system description, but was not further investigated in this thesis. There has been performed an installation of the suction-bucket jacket by DONG Energy, which until now has proven successful. However, as limited information exists regarding this operation, it was assumed that this procedure would be difficult to model properly, and yet harder to measure in a cost-benefit analysis when comparing to pre-piling for seabed fastening. The use of a suction-bucket for seabed-fastening would include different procedures during installation, and little experience exists in the industry. This is however a novel development that can be further investigated for future projects.

When including several vessels that interacts during installation, an increased risk for collision is introduced. Robertsson (2017) stated that during normal installation, SeaJacks avoids the use of feeder vessels without excellent DP-systems, because the consequences of a collision with their expensive installation vessels are considered severe. The use of jack-up feeder vessels with DP-systems introduces a large cost driver, and would normally be avoided if possible. Nevertheless, the installation scenario including this type of vessel, Scenario 2, has been investigated because it contributes to increasing the installation efficiency, and the resulting cost-benefit factor can be assessed.

The features of the installation vessels used as input in the simulation model, are assumed to be relevant for the industry based on information from industry actors, and procedures used for installed wind farms. They can however be changed according to specific projects, and the model is considered to give relevant results related to installation efficiency based on the current features. The vessel characteristics are considered general for the industry, and features for specific vessels and operations can easily be implemented to investigate real projects in a later stage.

In Scenario 2, the installation vessel stays on the OWF during the whole installation phase in the simulation model. The vessel will require support for supply of consumables and crew change, but the logistics related to this is not included in the model. The reason behind this decision is that this is not assumed to be a limiting factor for installation. Crew changes and vessel supply can be provided on a regular basis, and will most likely only experience delay due to lack of sufficient weather windows which has already been accounted for by the vessel operability. The additional costs related to supply and increased vessel assets in the system are however necessary to consider when calculating the total operational costs.

Related to installation efficiency, daylight-restrictions has not been accounted for, and operations are executed regardless of the time of day. Proper investigation related to industry standards in terms of daylight restrictions have not been performed, which is a limitation of the simulation and should be considered implemented in a development of the work in this thesis.

The weather used for the operability study from simulation is limited to only include spring, summer and fall. Winter-weather has not been tested in the simulation model. The reason for this is due to the expected lower operability, that is shown in the expected operability plots, and also to limit the operability study. It was assumed that limiting the scope and reducing the number of simulations to include three out of four seasons was necessary, and that sufficient results were obtained from the three seasons. However, simulation results from the whole year might have been valuable for project developers for planning installation over a whole year.

7.2 Weather Representation

The weather states used as input for the simulation model were simulated by using Markov Chain simulation, based on a 10-year forecast from the southern North Sea. The wind- and wave states are plotted in Figure 5.2, which shows a certain correlation between the states. It is however impossible to obtain perfect correlation, based on statistical behaviour of wind and waves, using the method in this thesis. This is because the simulation of wind and wave were performed in individual operations, and the states obtained are depending on the transition matrix based on observed values. Nevertheless, as the states show a similar behaviour over time, it is assumed that they demonstrate a representative performance of weather for the simulation model. Additionally, the states are representing a forecast for every third hour. This has been implemented into the simulation model by creating a code that converts the time-step in simulation to the corresponding location of the forecasted states.

Another implementation of the weather that interacts with real-system behaviour, is the difference between off- and inshore weather. In the simulation model, the same weather series have been used for performing weather checks both in port and while operating on the offshore wind farm. However, it is unlikely to always observe the same weather in these different locations. A solution for this would have been to create different weather-state series for operations in port and at the OWF, with correlation between values. In this case, the inshore weather should in most cases behave calmer than offshore, but should additionally be based on statistical values. This was however considered too complex for this thesis, and the solution to the problem has been to increase the inshore wind-criteria in the assigned *blocks* by 2, meaning that offshore wind criteria has had the value of 8 m/s, while inshore loading has had an operational limit of 10 m/s.

A method for better correlation between the wind- and wave simulated states could have been investigated, for improved weather representation. A method is shown for this in Barlow et al. (2015), and for future work the work from this paper can be reviewed and implemented for synthetic weather simulation. Barlow et al. (2015) also introduces possibilities for coupled weather series for in- and offshore weather, that should be further investigated for extensions of this work.

During transit, the weather impact of ship performance and speed was not applied to the transit time. Changes in weather directions will in real operation impact the chosen vessel route, to reduce motions and improve performance, and it is also normal to reduce speed when experiencing rough weather conditions. The transit time in the model has been set to a constant relationship between vessel speed and distance, but with operational criteria ensuring that the vessel will not leave for transit if forecasted weather is over the criteria. A more real approach would have been to also include the effect of weather direction and intensity to calculate transit time.

7.3 Operability and Cost-Benefit Study

It has been mentioned that the simulated operability should have proximity to the expected operability calculated in MATLAB. Comparing the operability is a measure for validating the simulation model, to ensure that the model represents the real behaviour. The operability results in Table 6.1, 6.2 and 6.3 show that the operability from simulation are close to the expected values, and therefore it can be assumed that the models give a good depiction of the real system. Additionally, it validates the Markov Chain simulated weather states, and proves that this method is a sufficient representation of weather.

The operability plots shown in Figure 6.1 shows that the operability plot for significant wave height are shifting towards the left, meaning that an increase in operational criteria will not have large effects on the operability for installation. The operability plots for wind are however shifting towards the right, and a significant increase in operability can be obtained by enabling an increase in operational limit. This applies to lifting operations during the installation phase. Even though lifting operations rely on both wind and wave limitations, wind is the governing factor. This means that measures should be taken to increase the operability for lifting, either by changing procedures or vessels. Procedures that can be investigated for increasing installation operability can include new methods for installation, such as float-out of the jackets, or skidding instead of lifting from the vessel. Barlow et al. (2015) concluded that lifting operations introduce the most prominent factor for delay during installation, which the results from this operability study also proves. This can be seen in Figure 6.1b, where an increase in operational criteria from 8 to 10 m/s will result in an increase in operability from 57 to 77 %, and an additional increase to 12 m/s gives an expected operability of 90 %. This means that by only introducing new technology, or optimizing the limiting criteria, is likely to reduce weather wait in the system, thus reducing total installation time.

By comparison, increasing the limiting wave criteria for jacking up from 2 to 2.5 m, only increases the operability during summer from 85 % to 93 %. Because of the already high operability, increasing the wave criteria is not likely to cause large reductions in total installation time, but should be considered if the cost of the change is reasonable compared to the benefit of the higher installation rate.

The expected day rates for the vessels used in this report were presented in Table 4.6, and these are used as guidance for evaluating the costs of each scenario, used for the comparative study. The numbers show that the DP-vessel is much more expensive than the jack-up installation vessel, while the feeder vessels operate at lower costs than the installation vessels. Scenario 1 present the largest total installation time for all case studies, but the corresponding cost levels for this scenario are assumed to be the lowest. This means that this might be a good option where early completion is not highly valued. Installation with Scenario 3, using only one DP-vessel, will provide higher installation rates than Scenario 1, but comes at much higher prices. However, the operability for installation in this scenario is much higher, and might be beneficial in some instances.

For Scenario 2, the day rates will include the use of several vessels. Here one must evaluate the savings in installation time connected to the increased expenditures for vessel chartering costs. Even though total installation time is reduced at longer distances from shore when using two feeder vessels, the corresponding expenditures are higher than for using one feeder. Project developers must therefore evaluate how much they value the benefit of earlier completion, and predict what profit they can make in relation to the increased costs of several vessels.

For installation of more than 100 jacket foundations, the total installation time exceeds the duration of a season. The operability measured for these cases will therefore only apply for a limited duration of time in a real project. This means that the results connected to increased OWF sizes are not applicable to real projects, but the operability can be used as a measure to predict total installation time. Another option would be to increase the number of installation vessel to reduce total installation time. It can be assumed that two installation vessels can perform installation at the same rate, and therefore an addition of one installation vessel will lead to a resulting doubling of the installation rate. This way, installation can be performed in one season, by increasing the number of installation assets to obtain the correct lead time. Nevertheless, the simulation results can be used to predict total installation time, and as guidance for a decision tool for planning installation during seasons with high operability.

Related to positioning offshore, the DP-vessel provides the highest operability. This is due to the lower required weather window, and that the limiting criteria for positioning is higher than for jacking up.

7.3.1 Installation Efficiency

From the plotted results for installation efficiency, shown in Figure 6.9a, it is quite evident that Scenario 2 provides the fastest solution for installation of foundations. For shorter distances to shore, it is only necessary to include one feeder vessel to ensure fast installation with the scenario, while with increasing distances the need for two feeder vessels to ensure the rate of installation is required. For all the results shown in the three cases, Scenario 1 provides the slowest installation rate, while Scenario 3, with the DP-vessel, provides the second highest installation rate at large distances from shore.

Total installation time for increasing number of turbines at a constant distance from shore was investigated, and the corresponding plots are shown in Figure 6.5. The plots show a nearly linear increase in installation time over increased number of turbines for all scenarios. This means that additional number of turbines does not have a large impact on operability, but can lead to a slight reduction in installation rate as the simulation model reaches a steady state. The installation rate is larger during summer as operability is higher, which is expected. This result is emphasized in Figure 6.9b, where the difference in installation time over the seasons spring, summer and fall is shown. This shows that Scenario 2 with two feeders provides the highest installation rate, followed by Scenario 3, for installation of 100 jacket foundations at a distance of 100 km from shore. The installation rate of 0.9 days per jacket for Scenario 2 during summer is considered quite high by industry standards, but the resulting cost level is assumed to be higher than for Scenario 3, which again is considered higher than for Scenario 1 and Scenario 2 with one feeder vessel.

For Scenario 2 with two feeder vessels, the almost constant installation time from all case studies means that a constant flow of components is ensured at the current configuration of the model, with the given vessel features. To investigate how far from shore the offshore wind farm would have to be placed before component flow is reduced, installation with distances from 10 to 250 km was plotted, and Figure 6.6 shows that a constant installation rate in ensured at distances up to 180 km from shore. There does not, at this time, exist any project developments at these distances from shore, but as the industry is developing, one might see the distance expanding to these lengths, introducing the need for additional feeder vessels.

Introducing feeder vessels to Scenario 3 will probably provide the most efficient solution. The DP-vessel maintains a higher installation rate than the jack-up vessel, because they do not need to jack-up. When also being able to neglect the transit time for Scenario 3, this will be the most efficient solution, but comes at much higher costs due to higher day rates and increased number of vessel assets.

Chapter 8

Conclusion

The objective of this thesis was to evaluate installation strategies for jacket foundations, and investigate possible solutions to provide insight into the industry. Installation efficiency was assessed with relation to how vessel operability impacts total installation time, with the aim to provide improved installation solutions in order to drive down cost levels. The intention behind the work was to contribute to driving down installation costs in the industry, which might account for about 20 % of total life cycle costs.

The discrete-event simulation models are proven to provide representative results regarding vessel operability. The similarities between expected operability calculated from observed weather data, and the simulated operability found from the simulation models, confirms that the models give a correct simulation of the system. This also validates the weather states used as input for the models, which were created using Markov Chain simulation.

By studying the results from the simulation models, an assessment of the most effective installation scenario shows that the use of feeder vessels increase the rate of installation. If the feeder vessels maintain supply at a constant rate, ensuring high utilization of the installation vessel offshore, the distance from shore will not impact total installation time. However, Scenario 2, with feeder vessels, introduces more vessel assets to the system, thus increasing the operational costs, and increasing the risk of collisions offshore.

Scenario 3, with a DP-vessel, provides a much more efficient installation strategy than Scenario 1, with a jack-up vessel. This is much due to the required weather windows for jacking up offshore, where the operability of the DP-vessel is much higher for positioning. The DP-vessel is also assumed to have higher transit speeds, causing shorter transit time and reduced total installation time at distances farther from shore, than for the jack-up vessel in Scenario 1. Nevertheless, chartering the DP-vessel will lead to much larger installation costs, due to the high day rates.

The operability assessed in the operability study shows that operability is low during lifting operations, which are performed when loading in port and installing offshore. Installation also relies on wave criteria, but results show that the wind criteria is governing during installation offshore. This is due to the stability provided by the jack-up vessel, that offers a stable platform for loading, and also the high stability obtained during DP-operation with the DP-vessel. Components are highly dependent on safe conditions during lifting to ensure safe installation when lifted from deck. This means that measures should be taken to improve the operability for lifting operations, because this is assumed to limit installation the most. An alternative here would be to use different methods for transportation and installation, such as float-out or skidding systems.

It can be concluded that the optimal installation strategy must be decided based on evaluations of required operability for operations and total installation time. The optimal installation strategy for a specific project will normally be assessed after the distance from shore and OWF size has been decided. The benefits of the solution, or the reduced benefits related to increased costs, for the system must also be assessed. The results from the operability study showed however that the size of the offshore wind farm does not impact total installation time significantly, other than the linear increase in total installation time, while installation rate is depending on system operability. The decision tool presented in this Master Thesis may present a valuable contribution for the industry. It provides insight for evaluating the best installation strategy, when considering the extent of how weather impacts operation, with a special focus on jacket foundations.

8.1 Further Work

During the work with this thesis, some limitations to the work has been performed due to restricted information provided by the industry and workload. Limited literature exists related to jacket foundation installation, and most novel developments, such as the suction bucket for seabed fastening and methods for installation, are kept classified by industry actors. Due to this, installation of suction bucket fastening was not addressed in the study, but it would have been interesting to investigate how this method could have improved installation for an extension of the thesis where also seabed fastening was included. In this thesis, the pre-piling was assumed performed prior to jacket installation, but a comparative study with these two solutions would probably provide grounds for future development in the industry.

Additionally, this thesis did not consider how learning curves interacted with total installation time. Most industry actors account for how learning develops the installation strategies, increasing the installation rate as project progresses. An extension of the models could have been to map the progress during installation as installation time was reduced towards the end of the project.

An implementation of the weather representation, introducing a better correlation between wind- and wave data, would have provided a more realistic simulation. Additionally, coupled sets of weather series for on- and offshore operations would have been preferred over the solution chosen in this work, where the criteria for inshore loading instead have been increased to account for the assumed reduction in weather strength inshore.

From the work with the Project Thesis (Vartdal, 2016), a parametric analysis of vessel features resulted in insight about how vessel features interacted with installation efficiency. This method could have proven valuable also for the operability study in this thesis, and can be considered as an extension of the work. Project developers can use these kinds of results for practical evaluations of vessel acquisitions.

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Appendix A

Problem Description

A.1 Master Thesis Problem Description

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

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2017

For stud.techn.

Johanne Tomine Vartdal

An Investigation of Offshore Wind Installation Strategies

A Discrete-Event Simulation Model Used to Investigate Installation Vessel Operability

Background

Installed production capacity from offshore wind is increasing; from less than 50 MW in year 2000 to more than 11 GW in the end of 2015. The European Union has stated that the total energy consumption should contain 20% energy from renewable sources within year 2020 (EU 20-20-20 targets), and wishes to increase energy production from the offshore wind segment.

New offshore wind projects are in the planning stages, and some are already being installed. It is expected that there will be an increase in installed capacity to 24 GW within 2020, and the trend shows that new projects are increasing both in capacity and distance from shore.

The installation process of offshore wind fields is challenging and the activities are relying on weather conditions to be completed. There exist several installation strategies in the offshore segment, in addition to an increase in available installation vessels and technology. Based on this, project planners need access to decision tools to improve the evaluation of possible installation strategies. This can also be implemented into vessel design and installation technologies, to evaluate how new concepts will handle the designated logistic system.

Objective

The objective of the master thesis is to evaluate possible solutions for installation of jacket foundations, as a tool for improving planning of the given operations. It includes the evaluation of installation vessels and the impact of installation vessel operability, on installation time for a set of jacket foundations. A review of the installation phase shall be presented in a general manner that can be applied to different installation projects as a decision tool in order to improve the installation phase, and ensure effective operations.

The work should improve the understanding of installation of offshore sub-structures, especially jacket foundations. The problem shall be implemented into a discrete-event simulation model, where offshore wind farm case studies are evaluated with different installation scenarios, with emphasis on weather windows and operability.

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Norwegian University of Science and Technology
Department of Marine Technology

The Project Thesis that was delivered in December 2016, served as the basis for the work connected to the Master Thesis, and defined a preliminary scope for the Master Thesis work.

Tasks

The candidate shall/is recommended to cover the following tasks in the project thesis:

a. Review state of art within the topic. That means to document what others have done and published previously, regarding stochastic programming, operability and installation for operations related to offshore wind.
b. Perform a review of existing literature related to simulation, operability and cost components.
c. Review problems related to the maritime challenges within installation of offshore wind fields, with an emphasis on risk and vulnerability of maritime operations.
d. Investigate installation strategies for offshore wind sub-structures, and their corresponding operability.
e. Create a discrete-event simulation model where different installation scenarios for installation are implemented.
f. Perform case studies of the installation of jacket foundations, and a comparative analysis of the different installation solutions
g. Perform a cost-benefit analysis of the installation solutions
h. Calculate operability, and compare expected operability with simulation results

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.

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Department of Marine Technology

Deliverables

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

Supervision

Main supervisor: Bjørn Egil Asbjørnslett

Deadline: 25.06.2017

Appendix B

Weather States Simulation

B.1 Hs_series.m - Importing Wave Data to Matlab

```
%% This function will import the Hs weather data
% Excel file Hs_05_14 inclues weather data from 2005 to 2014
% Output is an M-vector with:
% year - month - day of month - time of hindcast - Hs

A=xlsread('Hs_05_14');

S=size(A,1);
Hs=zeros(S,1);
for i = 1:S
    Hs(i,1)=A(i,7);
end
for i = 1:S
    if Hs(i)<=0
        Hs(i)=Hs(i-1);
        A(i,7) = A(i-1,7);
    elseif Hs(i) >= 100
        Hs(i) = Hs(i-1);
        A(i,7) = A(i-1,7);
    end
end

% The data matrix wil consist data from each 3rd hour,
% and the month the observation is taken from

M=0;
count=1;
```

```

for i=1:12
    for k=1:S
        for j=1:3:22
            if A(k,2) == i && A(k,4) == j
                if A(k,4) ~= A(k-1,4)
                M(count,1) = A(k,1);
                M(count,2) = A(k,2);
                M(count,3) = A(k,3);
                M(count,4) = A(k,4);
                M(count,5) = A(k,7);
                count=count+1;
                end
            end
        end
    end
end

% Change the data into a 4-column matrix

l = length(M);
count = 0;
N = 0;
for i=1:l
    if M(i,1) ~= 0
        count = count + 1;
        N(i,1) = M(i,2);
        N(i,2) = M(i,3);
        N(i,3) = M(i,4);
        N(i,4) = M(i,5);
    end
end
```

B.2 wind_series.m - Importing Wind Data to Matlab

```
%% This function will import the wind weather data
% Excel file wind_05_14 inclues weather data from 2005 to 2014
% Output is an Q-vector with:
% year - month - day of month - time of hindcast - wind


tic;
```

```
W=xlsread('wind_05_14_22');
% this weather series have been fixed to save time every time the script is
% ran, meaning that 3rd hour forecast have already been extracted. This was
% done by using the code commented out below:

%count = 0;
% Ww = W;
% for i = 1:S
%     if W(i,5) >= 100
%         W(i,5) = W(i-1,5);
%     end
% end
%
% for i=1:S-2
%     if W(i,7) == W(i+2,7)
%        W(i,7) = W(i,7) + (3*rand(1,1) + 1);
%     end
% end

S=size(W,1);

XX = [1 1.2 1.4 1.6 2 2.4 2.6 2.6 2.8 2.8 3];

count = 1;
for i = 2012:2014
    for j = 1:S
        if W(j,1) == i && W(j,2) == 12
            W(j,5) = W(j,5) * XX(count);
            if count == 11
                count = 1;
            else
                count = count + 1;
            end
        end
    end
end

% The data matrix wil consist data from each 3rd hour,
% and the month the observation is taken from

count=1;

Q = W;
l = length(Q);
count = 0;
```

```
R = 0;
for i=1:l
    if Q(i,1) ~= 0
        count = count + 1;
        R(i,1) = Q(i,2);
        R(i,2) = Q(i,3);
        R(i,3) = Q(i,4);
        R(i,4) = Q(i,5);
    end
end
toc;
```

B.3 MT_Hs_wave.m - Markov Chain Simulation of Wave Data

```
%% MT_Hs_wave.m
% This function use Markov Chain simulation to create weather states
% The function must be ran before simulation can start
% Hindcasted data from FINO1 is used to create a Markov Chain simulation
% of significant wave height
% states is the output vector used as input for simulation
clear all;
tic;

% Run the Hs_series.m to import the recorded wave series
Hs_series;
size_series = size(M,1);

% Choose for what season the simulation will use
% Either winter = 1, spring = 2, summer = 3, fall = 4

season = 4; % change this parameter for different seasons

% Create a vector that imports only the Hs-values from the correct season
if season == 1
    season_m = [1 2 12];
elseif season == 2
    season_m = [3 4 5 ];
elseif season == 3
    season_m =[6 7 8 ];
else
    season_m =[9 10 11];
end
```

```

% Add all wave data from selected season into a vector, Hs
Hs = zeros(1);
count = 1;
for i = 1:3
    for j = 1:size_series
        if M(j,2) == season_m(i)
            Hs(count,1) = M(j,5);
            count = count + 1;
        end
    end
end

% Quick fix for the dataset Hs_05_14 to remove absorbing states
if season == 4
    Hs(3831) = Hs(3831)-2;
end

% Find upper limit for significant wave height
ul = max(Hs);
% Round the upper limit to create states
ul_r=round(ul);
% Number of states equals the rounded upper limit
numStates = ul_r;
% Create a range for the states, and setting the different states
stateRange = ul_r / numStates;
stateValues = stateRange:stateRange:ul_r;
% Create a vector to hold states of each vector point
HsState = zeros(length(Hs),1);

% Transform data point (Hs) to its corresponding state
for i = 1:length(Hs)
    % For each data point
    for j = 1:numStates
        % For each state
        if Hs(i) <= stateValues(j)
            % Data point is in state j
            HsState(i) = j;
            % This data point is categorized, so we break and move to the
            % next data point
            break;
        end
    end
end

```

```
% Remove instances of states being zero
for i=1:length(HsState)
    if HsState(i)<=0
        HsState(i)=HsState(i-1);
    end
end

% Quick fix for dataset Hs_05_14, to avoid absorbing states
if season==2
    HsState(182)=6;
end


% Find transitions for Markov Chain simulation
transitions = zeros(numStates);
for t = 1:length(HsState)-100
    % HsState(t) represents the state and HsState(t+1) represents the state
    % it transitions to
    transitions(HsState(t),HsState(t+1)) = transitions(HsState(t),HsState(t
        +1)) + 1;
end

P = transitions;
% Normalize each row in the transition matrix so each row sums to 1
for i = 1:numStates
    P(i,:) = P(i,:) / sum( P(i,:) );
end


% Check to see if there are any absorbing states
% i.e. P(i,j) == 1 where i=j
absorbstate = zeros(numStates);
for i = 1:numStates
    for j = 1:numStates
        if P(i,j) == 1
            absorbstate(i,j) = absorbstate(i,j) + 1;
        end
    end
end

if sum(sum(absorbstate)) >= 1
    error('Absorbing states. Stopping. Consider reducing number of states
        or check data.');
end

```

```
% Transition matrix is now ready in P

% Decide the number of performed transitions
numReplications = 10000;

% Random number seed
rng(12345);

% Set starting state - should sample randomly
state = randi(numStates);

states = zeros(numReplications,1);

for i = 1:numReplications
        % Sample a new random value in range [0,1]
    r = rand();

    for j = 1:numStates
        prob = 0;
        % Accumulate probabilities
        for k = 1:j
            prob = prob + P(state,k);
        end

        if r <= prob
            % New state is found, j
            state = j;

            % Store the state we transition to
            states(i) = j;

            % Break ends the current for loop, and returns to the outer
            % loop, which will sample a new random value and start over
            break;
        end
    end
end

% If needed, Hs can be compared directly to the simulated results
simValues = zeros(numReplications,1);
for i = 1:numReplications
    simValues(i) = (states(i) * stateRange) - stateRange/2;
end
```

```
% Plot the distribution for the original data points and the simulated sea
% states. The number of samples won't correlate, but the general shape
% should correlate somewhat.

% Distribution of original data points
figure(1);
hist(Hs,numStates);
title('Data points');
% Plot of the number of each state
figure(2);
hist(simValues,numStates);
title('Simulation results');

% Timeseries plot
figure(3);
plot(simValues(1:1000));


toc;
```

B.4 MT_wind.m - Markov Chain Simulation of Wind Data

```
%% MT_wind.m
% This function use Markov Chain simulation to create weather states
% The function must be ran before simulation can starte
% Here hindcasted data is used to create a Markov Chain simulation
% of wind speeds
clear all;
tic;

% Run the wind_series.m to import the recorded wave series
wind_series;
size_series = size(Q,1);
% Choose for what season the simulation will use
% Either winter = 1, spring = 2, summer = 3, fall = 4

season = 4; % change this parameter for different seasons

% Create a vector that imports only the wind-values from the correct season
if season == 1
    season_m = [1 2 12];
elseif season == 2
```

```
    season_m = [3 4 5 ];
elseif season == 3
    season_m =[6 7 8 ];
else
    season_m =[9 10 11];
end

% Add all wave data from selected season into a vector, wind
wind = zeros(1);
count = 1;
for i = 1:3
    for j = 1:size_series
        if Q(j,2) == season_m(i)
            wind(count,1) = Q(j,5);
            count = count + 1;
        end
    end
end

if season == 1
     wind(61,1) = wind(61,1)-5;
elseif season == 2
    wind(748,1) = wind(748,1) - 7;
    wind(637,1) = wind(637,1) - 1;
elseif season == 3
     wind(6302,1) = wind(6302,1) - 3;
elseif season == 4
     wind(5119,1) = wind(5119,1) + 12;
     wind(5120,1) = wind(5120,1) + 13;
     wind(5121,1) = wind(5121,1) - 2;
 end


% Find upper limit for significant wave height
ul = max(wind);
% Round the upper limit to create states
ul_r=round(ul);
% Number of states equals the rounded upper limit
numStates = ul_r;
% Create a range for the states, and setting the different states
stateRange = ul_r / numStates;
stateValues = stateRange:stateRange:ul_r;
% Create a vector to hold states of each vector point
windState = zeros(length(wind),1);

```

```
% Assign wach vector point (Hs) to a state
for i = 1:length(wind)
    % For each data point
    for j = 1:numStates
        % For each state
        if wind(i) <= stateValues(j)
            % Data point is in state j
            windState(i) = j;
            % This data point is categorized, so we break and move to the
            % next data point
            break;
        end
    end
end

% Romove instances of the state being zero
for i=1:length(windState)
    if windState(i)<=0
        windState(i)=windState(i-1);
    end
end


% Find transitions in the Markov Chain simulation
transitions = zeros(numStates);
for t = 1:length(windState)-100
    % HsState(t) represents the state and HsState(t+1) represents the state
    % it transitions to
    transitions(windState(t),windState(t+1)) = transitions(windState(t),
       windState(t+1)) + 1;
end

P = transitions;
% Normalize each row in the transition matrix so each row sums to 1
for i = 1:numStates
    P(i,:) = P(i,:) / sum( P(i,:) );
end


% Check to see if there are any absorbing states
% i.e. P(i,j) == 1 where i=j
absorbstate = zeros(numStates);
for i = 1:numStates
    for j = 1:numStates
        if P(i,j) == 1
```

```
            absorbstate(i,j) = absorbstate(i,j) + 1;
        end
    end
end

if sum(sum(absorbstate)) >= 1
    error('Absorbing states. Stopping. Consider reducing number of states or check data.');
end

% Transition matrix is now ready in P

% Decide the number of performed transitions
numReplications = 10000;

% Random number seed
rng(12345);

% Set starting state - should sample randomly
state = randi(numStates);

windstates = zeros(numReplications,1);

for i = 1:numReplications
        % Sample a new random value in range [0,1]
    r = rand();

    for j = 1:numStates
        prob = 0;
        % Accumulate probabilities
        for k = 1:j
            prob = prob + P(state,k);
        end

        if r <= prob
            % New state is found, j
            state = j;

            % Store the state we transition to
            windstates(i) = j;

            % Break ends the current for loop, and returns to the outer
            % loop, which will sample a new random value and start over
            break;
        end
```

```
    end
end

% If needed, Hs can be compared directly to the simulated results
simValues = zeros(numReplications,1);
for i = 1:numReplications
    simValues(i) = (windstates(i) * stateRange) - stateRange/2;
end


% Plot the distribution for the original data points and the simulated sea
% states. The number of samples won't correlate, but the general shape
% should correlate somewhat.

% Distribution of original data points
figure(1);
hist(Hs,numStates);
title('Data points');

% Plot of the number of each state
figure(2);
hist(simValues,numStates);
title('Simulation results');

% Timeseries plot
figure(3);
plot(simValues(1:1000));


toc;
```

B.5 Extract of Raw Wave Data From FINO1 Weather Station

```
# Station- FINO1
# Parameter- Signifikante_Wellenhoehe_Boje
# Unit- m
# Titles-
Time Value        Minimum  Maximum  Deviation  Quality
# Data-
2005-01-03 12-00-003.81  -999.99   -999.99   -999.99   2
2005-01-03 13-00-003.68  -999.99   -999.99   -999.99   2
2005-01-03 14-00-003.6   -999.99   -999.99   -999.99   2
2005-01-03 15-00-003.57  -999.99   -999.99   -999.99   2
2005-01-03 16-00-003.51  -999.99   -999.99   -999.99   2
2005-01-03 17-00-003.19  -999.99   -999.99   -999.99   2
2005-01-03 18-00-003.15  -999.99   -999.99   -999.99   2
2005-01-03 19-00-003.15  -999.99   -999.99   -999.99   2
2005-01-03 20-00-003.27  -999.99   -999.99   -999.99   2
2005-01-03 21-00-003.33  -999.99   -999.99   -999.99   2
2005-01-03 22-00-003.48  -999.99   -999.99   -999.99   2
2005-01-03 23-00-003.69  -999.99   -999.99   -999.99   2
2005-01-04 00-00-003.81  -999.99   -999.99   -999.99   2
2005-01-04 01-00-003.58  -999.99   -999.99   -999.99   2
2005-01-04 02-00-003.27  -999.99   -999.99   -999.99   2
2005-01-04 03-00-003.6   -999.99   -999.99   -999.99   2
2005-01-04 04-00-003.48  -999.99   -999.99   -999.99   2
2005-01-04 05-00-003.5   -999.99   -999.99   -999.99   2
2005-01-04 06-00-003.34  -999.99   -999.99   -999.99   2
2005-01-04 07-00-003.52  -999.99   -999.99   -999.99   2
2005-01-04 08-00-003.36  -999.99   -999.99   -999.99   2
2005-01-04 09-00-003.71  -999.99   -999.99   -999.99   2
2005-01-04 10-00-003.65  -999.99   -999.99   -999.99   2
2005-01-04 11-00-003.67  -999.99   -999.99   -999.99   2
2005-01-04 12-00-003.39  -999.99   -999.99   -999.99   2
2005-01-04 13-00-003.44  -999.99   -999.99   -999.99   2
2005-01-04 14-00-003.55  -999.99   -999.99   -999.99   2
2005-01-04 15-00-003.47  -999.99   -999.99   -999.99   2
2005-01-04 16-00-003.55  -999.99   -999.99   -999.99   2
2005-01-04 17-00-003.6   -999.99   -999.99   -999.99   2
2005-01-04 18-00-003.43  -999.99   -999.99   -999.99   2
2005-01-04 19-00-003.01  -999.99   -999.99   -999.99   2
2005-01-04 20-00-002.75  -999.99   -999.99   -999.99   2
2005-01-04 21-00-002.37  -999.99   -999.99   -999.99   2
2005-01-04 22-00-002.28  -999.99   -999.99   -999.99   2
2005-01-04 23-00-002.1   -999.99   -999.99   -999.99   2
2005-01-05 00-00-002.24  -999.99   -999.99   -999.99   2
2005-01-05 01-00-002.04  -999.99   -999.99   -999.99   2
2005-01-05 02-00-002.05  -999.99   -999.99   -999.99   2
2005-01-05 03-00-001.95  -999.99   -999.99   -999.99   2
2005-01-05 04-00-002.01  -999.99   -999.99   -999.99   2
2005-01-05 05-00-002.04  -999.99   -999.99   -999.99   2
2005-01-05 06-00-002.12  -999.99   -999.99   -999.99   2
2005-01-05 07-00-002.2   -999.99   -999.99   -999.99   2
```

B.6 Extract of Raw Wind Data From FINO1 Weather Station

```
# Station- FINO1
# Parameter- Windgeschwindigkeit_U_Anemometer_40m
# Unit- m/s
# Titles-
Time Value        Minimum  Maximum  Deviation  Quality
# Data-
2005-01-01 00-00-000      -999.99     -999.99     0     2
2005-01-01 00-10-005.6    -999.99     -999.99     .29   2
2005-01-01 00-20-006.31 -999.99     -999.99     .45   2
2005-01-01 00-30-006.84 -999.99     -999.99     .37   2
2005-01-01 00-40-007.04 -999.99     -999.99     .45   2
2005-01-01 00-50-008.25 -999.99     -999.99     .55   2
2005-01-01 01-00-007.69 -999.99     -999.99     .48   2
2005-01-01 01-10-007.09 -999.99     -999.99     .42   2
2005-01-01 01-20-007.21 -999.99     -999.99     .3    2
2005-01-01 01-30-006.58 -999.99     -999.99     .56   2
2005-01-01 01-40-007.18 -999.99     -999.99     .53   2
2005-01-01 01-50-007.38 -999.99     -999.99     .53   2
2005-01-01 02-00-007.23 -999.99     -999.99     .52   2
2005-01-01 02-10-007.66 -999.99     -999.99     .54   2
2005-01-01 02-20-007.42 -999.99     -999.99     .48   2
2005-01-01 02-30-007.49 -999.99     -999.99     .6    2
2005-01-01 02-40-007.83 -999.99     -999.99     .51   2
2005-01-01 02-50-008.43 -999.99     -999.99     .57   2
2005-01-01 03-00-008.41 -999.99     -999.99     .68   2
2005-01-01 03-10-007.51 -999.99     -999.99     .59   2
2005-01-01 03-20-006.48 -999.99     -999.99     .55   2
2005-01-01 03-30-006.72 -999.99     -999.99     .7    2
2005-01-01 03-40-007.26 -999.99     -999.99     .35   2
2005-01-01 03-50-006.95 -999.99     -999.99     .62   2
2005-01-01 04-00-007.45 -999.99     -999.99     .51   2
2005-01-01 04-10-008.22 -999.99     -999.99     .49   2
2005-01-01 04-20-007.77 -999.99     -999.99     .47   2
2005-01-01 04-30-008.32 -999.99     -999.99     .56   2
2005-01-01 04-40-008.31 -999.99     -999.99     .49   2
2005-01-01 04-50-008.91 -999.99     -999.99     .6    2
2005-01-01 05-00-008.52 -999.99     -999.99     .47   2
2005-01-01 05-10-009.26 -999.99     -999.99     1.28  2
2005-01-01 05-20-0010.51      -999.99     -999.99     .61   2
2005-01-01 05-30-009.49 -999.99     -999.99     .69   2
2005-01-01 05-40-009.11 -999.99     -999.99     .59   2
2005-01-01 05-50-009.8    -999.99     -999.99     .68   2
2005-01-01 06-00-008.9    -999.99     -999.99     .54   2
2005-01-01 06-10-008.63 -999.99     -999.99     .65   2
2005-01-01 06-20-009.17 -999.99     -999.99     .55   2
2005-01-01 06-30-009      -999.99     -999.99     .69   2
2005-01-01 06-40-008.81 -999.99     -999.99     .59   2
2005-01-01 06-50-008.78 -999.99     -999.99     .55   2
2005-01-01 07-00-008.52 -999.99     -999.99     .68   2
2005-01-01 07-10-009.49 -999.99     -999.99     .61   2
```

Appendix C

Operability Plotting in Matlab

C.1 op_wave.m - Operability for Significant Wave Heights

```
%% This function will create an operability plot for significant wave
% height, sorted by seasons
clear all;
tic;

% Criteria for operation, and duration of operation
Hs_crit = 3;
T_r = 3 ;
gap = 3 ; % duration between each weather measurement

% Import the Hs-series from the Hs_series plot, in the vector N
Hs_series;

% Count the duration of calms for all seasons
l_new = count;

% ------ WINTER ------
% Start with calculating for winter, december, january and february
% calmtime_wi consists of the durations of each calm
row = 0;
for i=0:0.1:5
    count_calm = 0;
    row = row + 1;
    column = 0;
    for j=1:l_new
        if N(j,1) == 1 || N(j,1) == 2 || N(j,1) == 12
```

```
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_wi(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_wi(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_wi = size(calmtime_wi);
row_wi = size_wi(1);
column_wi = size_wi(2);

calms_wi = 0;
for i=1:row_wi
    for j=1:column_wi
        if calmtime_wi(i,j)*gap >= T_r
            calms_wi(i,j) = 1;
        end
    end
end

op_wi = zeros(row_wi, 1);
for i = 1:row_wi
    op_wi(i,1) = sum(calms_wi(i,:))/column_wi*100;
end

x1=0:0.1:5;
y1=op_wi;


% -----SPRING------
% Start with calculating for spring, march, april and may
% calmtime_sp consists of the durations of each calm
row = 0;
for i=0:0.1:5
    count_calm = 0;
    row = row + 1;
    column = 0;
    for j=1:l_new
        if N(j,1) == 3 || N(j,1) == 4 || N(j,1) == 5
```

```
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_sp(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_sp(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_sp = size(calmtime_sp);
row_sp = size_sp(1);
column_sp = size_sp(2);

calms_sp = 0;
for i=1:row_sp
    for j=1:column_sp
        if calmtime_sp(i,j)*gap >= T_r
            calms_sp(i,j) = 1;
        end
    end
end

op_sp = zeros(row_sp, 1);
for i = 1:row_sp
    op_sp(i,1) = sum(calms_sp(i,:))/column_sp*100;
end

hold on
%figure(2)
x2=0:0.1:5;
y2=op_sp;


% -----SUMMER------
% Start with calculating for june, july and august
% calmtime_su consists of the durations of each calm
row = 0;
for i=0:0.1:5
    count_calm = 0;
    row = row + 1;
    column = 0;
```

```
    for j=1:l_new
        if N(j,1) == 6 || N(j,1) == 7 || N(j,1) == 8
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_su(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_su(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_su = size(calmtime_su);
row_su = size_su(1);
column_su = size_su(2);

calms_su = 0;
for i=1:row_su
    for j=1:column_su
        if calmtime_su(i,j)*gap >= T_r
            calms_su(i,j) = 1;
        end
    end
end

op_su = zeros(row_su, 1);
for i = 1:row_su
    op_su(i,1) = sum(calms_su(i,:))/column_su*100;
end


x3=0:0.1:5;
y3=op_su;


% -----FALL------
% Start with calculating for september, october and november
% calmtime_fa consists of the durations of each calm
row = 0;
for i=0:0.1:5
    count_calm = 0;
    row = row + 1;
```

```
    column = 0;
    for j=1:l_new
        if N(j,1) == 9 || N(j,1) == 10 || N(j,1) == 11
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_fa(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_fa(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_fa = size(calmtime_fa);
row_fa = size_fa(1);
column_fa = size_fa(2);

calms_fa = 0;
for i=1:row_fa
    for j=1:column_fa
        if calmtime_fa(i,j)*gap >= T_r
            calms_fa(i,j) = 1;
        end
    end
end

op_fa = zeros(row_fa, 1);
for i = 1:row_fa
    op_fa(i,1) = sum(calms_fa(i,:))/column_fa*100;
end

x4=0:0.1:5;
y4=op_fa;

%% Plot the results with the criteria for wave

figure(8)
plot(x1,y1,'k-o','linewidth',3);

hold on
plot(x2,y2,'k--','linewidth',3);

```

```
grid on
plot(x3,y3,'k-','linewidth',3);

plot(x4,y4,'k:','linewidth',3);
legend('Winter', 'Spring','Summer','Fall');
set(gca,'FontSize',24)
title('Operability significant wave height (Tr = 3 hr) ');
xlabel('Significant wave height [m]');
ylabel('Operability [%]');
set(gca,'FontSize',30);

y_crit = [0:5:100];
x_crit = Hs_crit*ones(1,length(y_crit));
plot(x_crit, y_crit, 'k--', 'linewidth', 3);
```

C.2 op_wind.m - Operability for Wind Speeds

```
%% This function will create an operability plot for wind speeds,
% sorted by seasons
clear all;
tic;

% Criteria for operation, and duration of operation
wind_crit = 8;
T_r = 2 ;
gap = 3 ; % duration between each weather measurement


% Import the wind-series from the wind_series plot, in the vector R
wind_series;

N = R;
N(:,4) = K(:,5);
M = K;

max = 20;
min = 1;

% Count the duration of calms for all seasons
l_new = count;

% ------ WINTER ------
% Start with calculating for winter, december, january and february
% calmtime_wi consists of the durations of each calm
```

```
row = 0;
for i=min:0.1:max
    count_calm = 0;
    row = row + 1;
    column = 0;
    for j=1:l_new
        if N(j,1) == 1 || N(j,1) == 2 || N(j,1) == 12
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_wi(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_wi(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_wi = size(calmtime_wi);
row_wi = size_wi(1);
column_wi = size_wi(2);

calms_wi = 0;
for i=1:row_wi
    for j=1:column_wi
        if calmtime_wi(i,j)*gap >= T_r
            calms_wi(i,j) = 1;
        end
    end
end

op_wi = zeros(row_wi, 1);
for i = 1:row_wi
    op_wi(i,1) = sum(calms_wi(i,:))/column_wi*100;
end

x1=min:0.1:max;
y1=op_wi;


% -----SPRING------
% Start with calculating for spring, march, april and may
% calmtime_sp consists of the durations of each calm
```

```
row = 0;
for i=min:0.1:max
    count_calm = 0;
    row = row + 1;
    column = 0;
    for j=1:l_new
        if N(j,1) == 3 || N(j,1) == 4 || N(j,1) == 5
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_sp(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_sp(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_sp = size(calmtime_sp);
row_sp = size_sp(1);
column_sp = size_sp(2);

calms_sp = 0;
for i=1:row_sp
    for j=1:column_sp
        if calmtime_sp(i,j)*gap >= T_r
            calms_sp(i,j) = 1;
        end
    end
end

op_sp = zeros(row_sp, 1);
for i = 1:row_sp
    op_sp(i,1) = sum(calms_sp(i,:))/column_sp*100;
end

x2=min:0.1:max;
y2=op_sp;


% -----SUMMER------
% Start with calculating for june, july and august
% calmtime_su consists of the durations of each calm
```

```
row = 0;
for i=min:0.1:max
    count_calm = 0;
    row = row + 1;
    column = 0;
    for j=1:l_new
        if N(j,1) == 6 || N(j,1) == 7 || N(j,1) == 8
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_su(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_su(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_su = size(calmtime_su);
row_su = size_su(1);
column_su = size_su(2);

calms_su = 0;
for i=1:row_su
    for j=1:column_su
        if calmtime_su(i,j)*gap >= T_r
            calms_su(i,j) = 1;
        end
    end
end

op_su = zeros(row_su, 1);
for i = 1:row_su
    op_su(i,1) = sum(calms_su(i,:))/column_su*100;
end

x3=min:0.1:max;
y3=op_su;

% -----FALL------
% Start with calculating for september, october and november
% calmtime_fa consists of the durations of each calm
row = 0;
```

```
for i=min:0.1:max
    count_calm = 0;
    row = row + 1;
    column = 0;
    for j=1:l_new
        if N(j,1) == 9 || N(j,1) == 10 || N(j,1) == 11
            column = column + 1;
            if N(j,4) <= i
                count_calm = count_calm + 1;
                calmtime_fa(row,column) = count_calm;
            elseif N(j,4) > i
                count_calm = 0;
                calmtime_fa(row,column) = count_calm;
            end
        end
    end
end

% Calculating how many occurences of working windows for each season
size_fa = size(calmtime_fa);
row_fa = size_fa(1);
column_fa = size_fa(2);

calms_fa = 0;
for i=1:row_fa
    for j=1:column_fa
        if calmtime_fa(i,j)*gap >= T_r
            calms_fa(i,j) = 1;
        end
    end
end

op_fa = zeros(row_fa, 1);
for i = 1:row_fa
    op_fa(i,1) = sum(calms_fa(i,:))/column_fa*100;
end

x4=min:0.1:max;
y4=op_fa;

%% Plot the results with the criteria for wave

figure(9)
plot(x1,y1,'k-o','linewidth',3);

```

```
hold on
plot(x2,y2,'k--','linewidth',3);

grid on
plot(x3,y3,'k-','linewidth',3);

hold on
plot(x4,y4,'k:','linewidth',3);
legend('Winter', 'Spring','Summer','Fall');
set(gca,'FontSize',24)
title('Operability wind (Tr = 2 hrs) ');
xlabel('Wind speeds [m/s]');
ylabel('Operability [%]');
set(gca,'FontSize',30);

y_crit = [0:5:100];
x_crit = wind_crit*ones(1,length(y_crit));
plot(x_crit, y_crit, 'k--', 'linewidth', 3);
```

Appendix D

Running Simulation from Matlab

D.1 run_sim_model12.m - Model 1

```
%% This scripts rund simulation model 1
% The output includes total simulation time, operability during
% jacking-up offshore, and installation offshore
tic;
season = 4; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
results_1_fa = 0; % change this according to season

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
end

turb = [ 50 100 500];
 for i=1:3
     for j=10:10:100
         nr_turb = turb(i);
         dist = j;
```

```

         setDistance = [0 0 ; 0 dist];
         setTurbines =[0 0; 0 nr_turb];

         load_system('model_master12');
         simOut=sim('model_master12');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
tot_fall=jackets_tot.time(step);
inst_fall=sum(WoW_installation.signals.values(1:tot_fall));
jackup_fall=sum(WoW_jackup_offshore.signals.values(1:tot_fall));

results_1_fa(run,1)=tot_fall;
results_1_fa(run,2)=inst_fall;
results_1_fa(run,3)=inst_fall/tot_fall*100;
results_1_fa(run,4)=jackup_fall;
results_1_fa(run,5)=jackup_fall/tot_fall*100;

        run = run + 1;


     end
 end
toc;

%% Simulation with model 1, over different distances

tic;
season = 2; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
results_1_turbines_sp = 0; % change this according to season

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
```

```
end

%turb = [50];
 for i=50:50:500 % turbines
     for j=100       % distance
         nr_turb = i; % turb(i);
         dist = j;

         setTurbines =[0 0; 0 nr_turb];
         setDistance = [0 0 ; 0 dist];

         load_system('model_master12');
         simOut=sim('model_master12');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
tot_fall=jackets_tot.time(step);
tot_fall=jackets_tot.time(step);
inst_fall=sum(WoW_installation.signals.values(1:tot_fall));
jackup_fall=sum(WoW_jackup_offshore.signals.values(1:tot_fall));

results_1_turbines_sp(run,1)=tot_fall;
results_1_turbines_sp(run,2)=inst_fall;
results_1_turbines_sp(run,3)=inst_fall/tot_fall*100;
results_1_turbines_sp(run,4)=jackup_fall;
results_1_turbines_sp(run,5)=jackup_fall/tot_fall*100;

        run = run + 1;


     end
 end
toc;
```

D.2 run_sim_model21.m - Model 21

```
%% This scripts rund simulation model 2, with one feeder
% The output includes total simulation time, operability during
% jacking-up offshore, installation offshore and utiilzation of
% installation vessel

tic;
season = 4; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
```

```
results_21_fa = 0; % change this according to season

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
end

turb = [ 50 100 500];

 for i=1:3
     for j=10:10:100
         nr_turb = turb(i);
         dist = j;

         setDistance = [0 0 ; 0 dist];
         setTurbines =[0 0; 0 nr_turb];

         load_system('model_master21');
         simOut=sim('model_master21');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
tot_fall=jackets_tot.time(step);
inst_fall=sum(WoW_installation.signals.values(1:tot_fall));
jackup_fall=sum(WoW_jackup_offshore.signals.values(1:tot_fall));
install_wait=sum(install_wait.signals.values(1:tot_fall));

results_21_fa(run,1)=tot_fall;
results_21_fa(run,2)=inst_fall;
results_21_fa(run,3)=inst_fall/tot_fall*100;
results_21_fa(run,4)=jackup_fall;
results_21_fa(run,5)=jackup_fall/tot_fall*100;
results_21_fa(run,6)=install_wait/tot_fall*100;

        run = run + 1;

```

```

     end
 end
toc;

%% Simulation with model 2, over different number of turbines

tic;
season = 4; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
results_21_turbines_fa = 0;

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
end

%turb = [ 50 100];
%dist_ = [10 50 100];
 for i=50:50:500   % turbines
     for j=100      % distance
         nr_turb = i;
         dist = j;

         setTurbines =[0 0; 0 nr_turb];
         setDistance = [0 0 ; 0 dist];

         load_system('model_master21');
         simOut=sim('model_master21');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
tot_fall=jackets_tot.time(step);
inst_fall=sum(WoW_installation.signals.values(1:tot_fall));
jackup_fall=sum(WoW_jackup_offshore.signals.values(1:tot_fall));
install_wait=sum(install_wait.signals.values(1:tot_fall));
```

```
results_21_turbines_fa(run,1)=tot_fall;
results_21_turbines_fa(run,2)=inst_fall;
results_21_turbines_fa(run,3)=inst_fall/tot_fall*100;
results_21_turbines_fa(run,4)=jackup_fall;
results_21_turbines_fa(run,5)=jackup_fall/tot_fall*100;
results_21_turbines_fa(run,6)=install_wait/tot_fall*100;

        run = run + 1;


     end
 end
toc;
```

D.3 run_sim_model22.m - Model 22

```
%% This scripts rund simulation model 2, with two feeders
% The output includes total simulation time, operability during
% jacking-up offshore, installation offshore and utiilzation of
% installation vessel
tic;
season = 4; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
results_22_fa = 0; % Change this according to season

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
end

turb = [ 50 100 500];
 for i=1:3                  % turbines
     for j=10:10:100      % distances
         nr_turb = turb(i);
```

```
         dist = j;

         setDistance = [0 0 ; 0 dist];
         setTurbines =[0 0; 0 nr_turb];


         load_system('model_master22');
         simOut=sim('model_master22');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
tot_fall=jackets_tot.time(step);
inst_fall=sum(WoW_installation.signals.values(1:tot_fall));
jackup_fall=sum(WoW_jackup_offshore.signals.values(1:tot_fall));
install_wait=sum(install_wait.signals.values(1:tot_fall));

results_22_fa(run,1)=tot_fall;
results_22_fa(run,2)=inst_fall;
results_22_fa(run,3)=inst_fall/tot_fall*100;
results_22_fa(run,4)=jackup_fall;
results_22_fa(run,5)=jackup_fall/tot_fall*100;
results_22_fa(run,6)=install_wait/tot_fall*100;

        run = run + 1;


     end
 end
toc;

%% Simulation with model 2, over different number of turbines

tic;
season = 4; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
results_22_turbines_fa = 0;

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
```

```
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
end

%turb = [ 50 100];
%dist_ = [10 50 100];

 for i=50:50:500   % turbines
     for j=100      % distance
         nr_turb = i;
         dist = j;
%
         setDistance = [0 0 ; 0 dist];
         setTurbines =[0 0; 0 nr_turb];

         load_system('model_master22');
         simOut=sim('model_master22');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
tot_spring=jackets_tot.time(step);
inst_spring=sum(WoW_installation.signals.values(1:tot_spring));
jackup_spring=sum(WoW_jackup_offshore.signals.values(1:tot_spring));
install_wait=sum(install_wait.signals.values(1:tot_spring));

results_22_turbines_fa(run,1)=tot_spring;
results_22_turbines_fa(run,2)=inst_spring;
results_22_turbines_fa(run,3)=inst_spring/tot_spring*100;
results_22_turbines_fa(run,4)=jackup_spring;
results_22_turbines_fa(run,5)=jackup_spring/tot_spring*100;
results_22_turbines_fa(run,6)=install_wait/tot_spring*100;

        run = run + 1;


     end
 end
 %save('results_22_distances', 'results_22_distances');
toc;
```

D.4 run_sim_model3.m - Model 3

```
%% This scripts rund simulation model 3
% The output includes total simulation time, operability during
% positioning offshore, and installation offshore
tic;
season = 4; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
results_3_fa = 0; % Change this according to season

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
end

turb = [50 100 500];
 for i=1:3
     for j=10:10:100
         nr_turb = turb(i);
         dist = j;

         setDistance = [0 0 ; 0 dist];
         setTurbines =[0 0; 0 nr_turb];

         load_system('model_master3');
         simOut=sim('model_master3');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
tot_fall=jackets_tot.time(step);
inst_fall=sum(WoW_installation.signals.values(1:tot_fall));
positioning_fall=sum(WoW_positioning_offshore.signals.values(1:tot_fall));

results_3_fa(run,1)=tot_fall;
results_3_fa(run,2)=inst_fall;
results_3_fa(run,3)=inst_fall/tot_fall*100;
results_3_fa(run,4)=positioning_fall;
results_3_fa(run,5)=positioning_fall/tot_fall*100;
```

```

        run = run + 1;


    end
 end
toc;

%% Simulation with model 2, over different number of turbines

tic;
season = 4; % 1 == winter, 2 == spring, 3 == summer, 4 == fall
run = 1;
results_3_turbines_fa = 0;

if season == 1
    load('states_winter.mat');
    load('windstates_winter.mat');
elseif season == 2
    load('states_spring.mat');
    load('windstates_spring.mat');
elseif season == 3
    load('states_summer.mat');
    load('windstates_summer.mat');
else
    load('states_fall.mat');
    load('windstates_fall.mat');
end

%turb = [ 50 100];
%dist_ = [10 50 100];
 for i=50:50:500   % turbines
     for j=100        % distance
         nr_turb = i;
         dist = j;


         setTurbines =[0 0; 0 nr_turb];
         setDistance = [0 0 ; 0 dist];

         load_system('model_master3');
         simOut=sim('model_master3');

kk=find(jackets_tot.signals.values>=nr_turb);
step = kk(1);
```

```
tot_fall=jackets_tot.time(step);
inst_fall=sum(WoW_installation.signals.values(1:tot_fall));
jackup_summer=sum(WoW_jackup_offshore.signals.values(1:tot_fall));


results_3_turbines_fa(run,1)=tot_fall;
results_3_turbines_fa(run,2)=inst_fall;
results_3_turbines_fa(run,3)=inst_fall/tot_fall*100;
results_3_turbines_fa(run,4)=jackup_summer;
results_3_turbines_fa(run,5)=jackup_summer/tot_fall*100;

        run = run + 1;


     end
 end
toc;
```

Appendix E

Model Input from Excel

E.1 Input File Description

Vessel type	Speed	Capacity	Current load	Output port	Wave crit 1	Wave crit 2	Wind crit 1

E.2 Input Model 1

1	22	4	0	0	3,5	2	8

E.3 Input Model 2

2	22	4	0	0	3,5	2	8
1	11	2	0	0	3,5	2	8
1	11	2	0	0	3,5	2	8

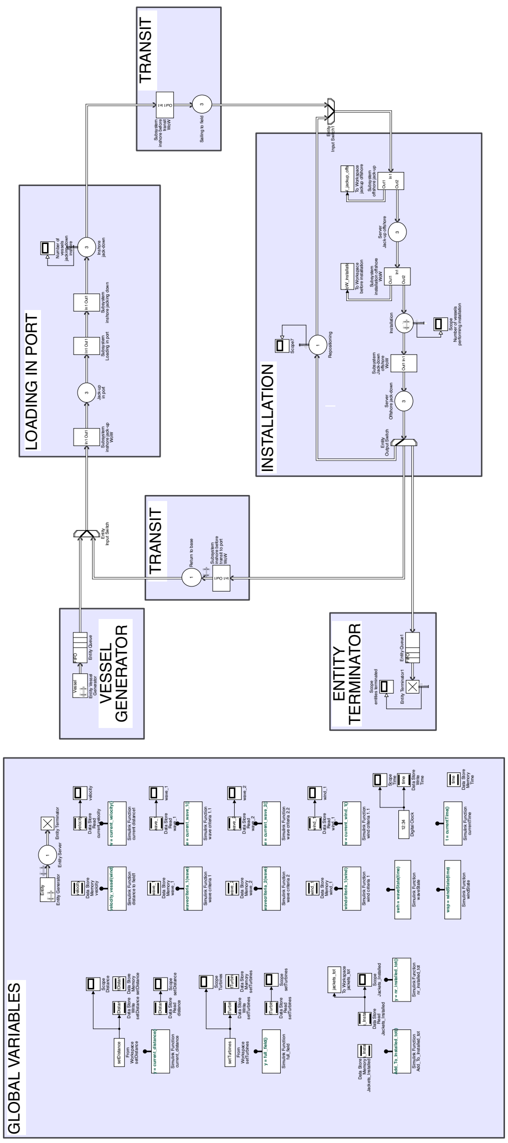
E.4 Input Model 3

1	26	4	0	0	3	2	8

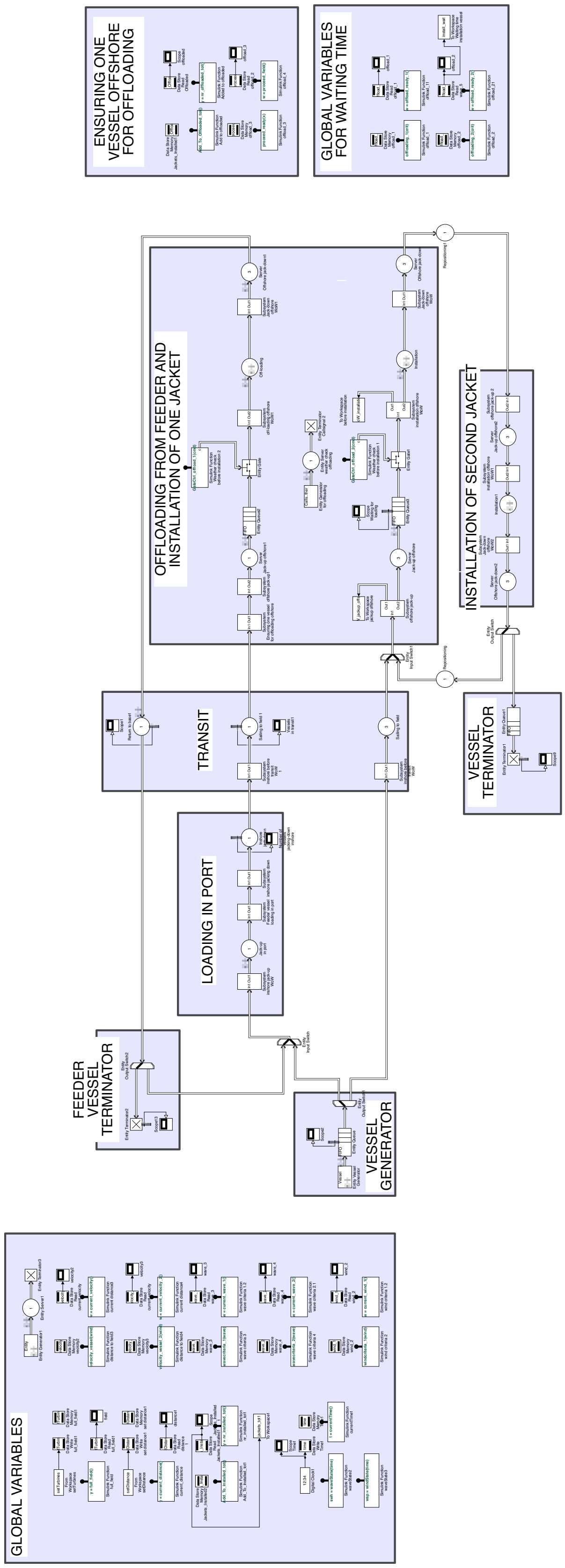
Appendix F

Simulation Models from SimEvents

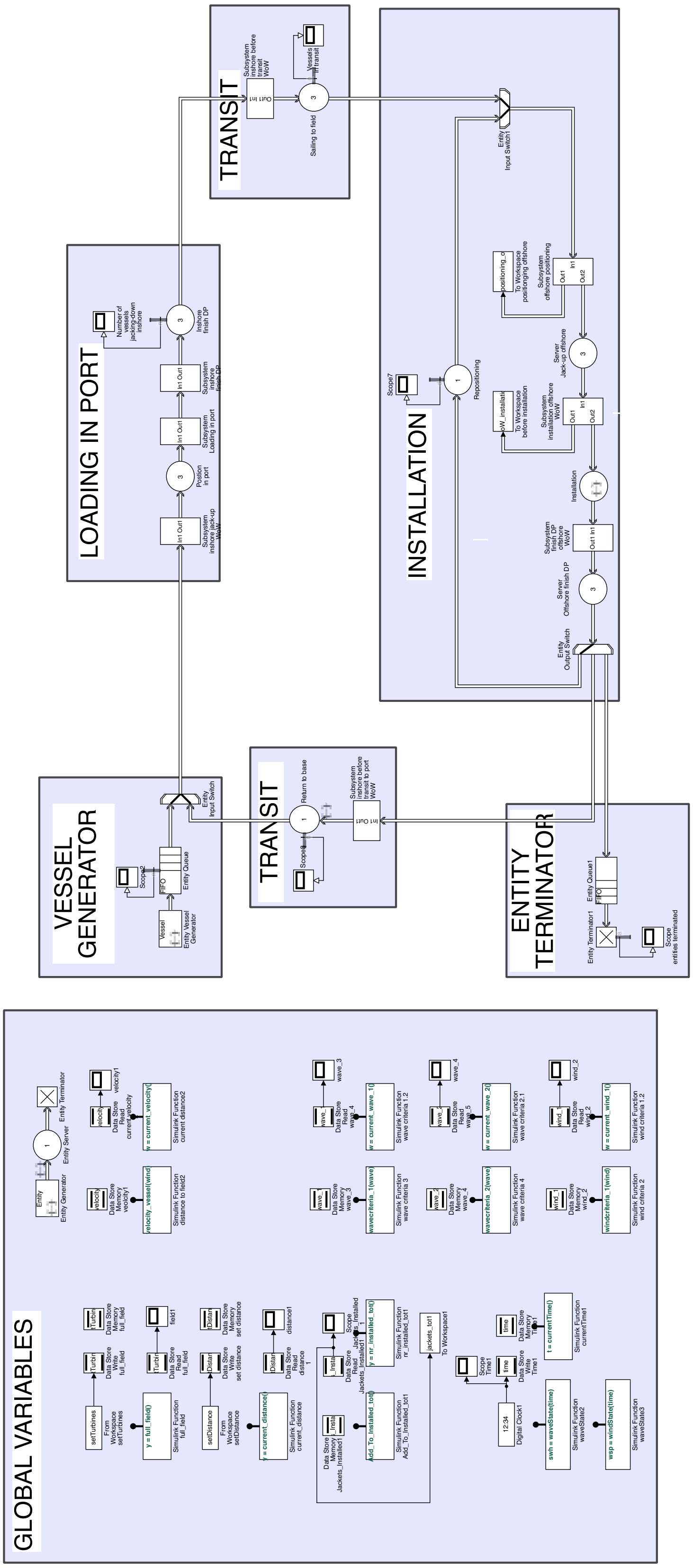
F.1 Model 1



F.2 Model 2


ENSURING ONE VESSEL OFFSHORE FOR OFFLOADING
GLOBAL VARIABLES FOR WAITING TIME
OFFLOADING FROM FEEDER AND INSTALLATION OF ONE JACKET
INSTALLATION OF SECOND JACKET
TRANSIT
VESSEL TERMINATOR
LOADING IN PORT
FEEDER VESSEL TERMINATOR
VESSEL GENERATOR
GLOBAL VARIABLES

F.3 Model 3


TRANSIT
LOADING IN PORT
INSTALLATION
VESSEL GENERATOR
TRANSIT
ENTITY TERMINATOR
GLOBAL VARIABLES

Appendix G

Graphical Presentation of the Simulation Models

G.1 Simulation Model 1

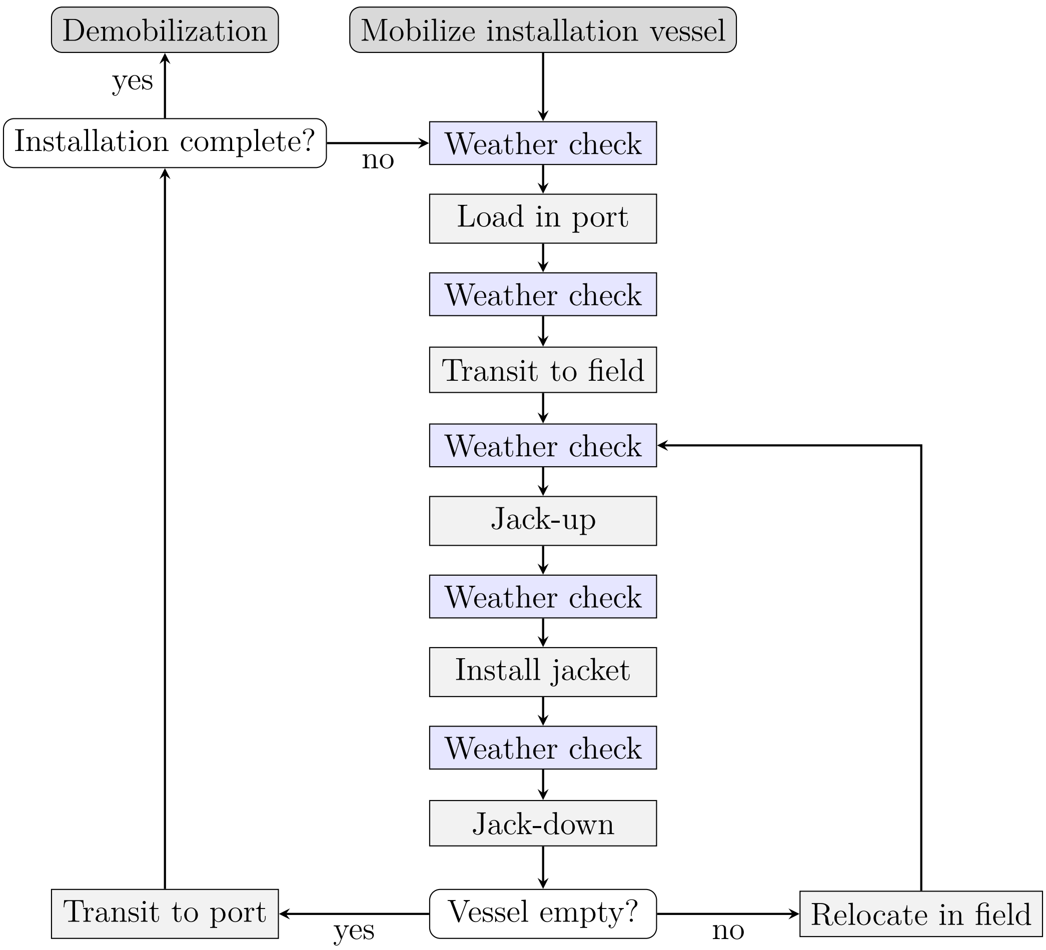


Figure G.1: Flow chart for Scenario 1

G.2 Simulation Model 2

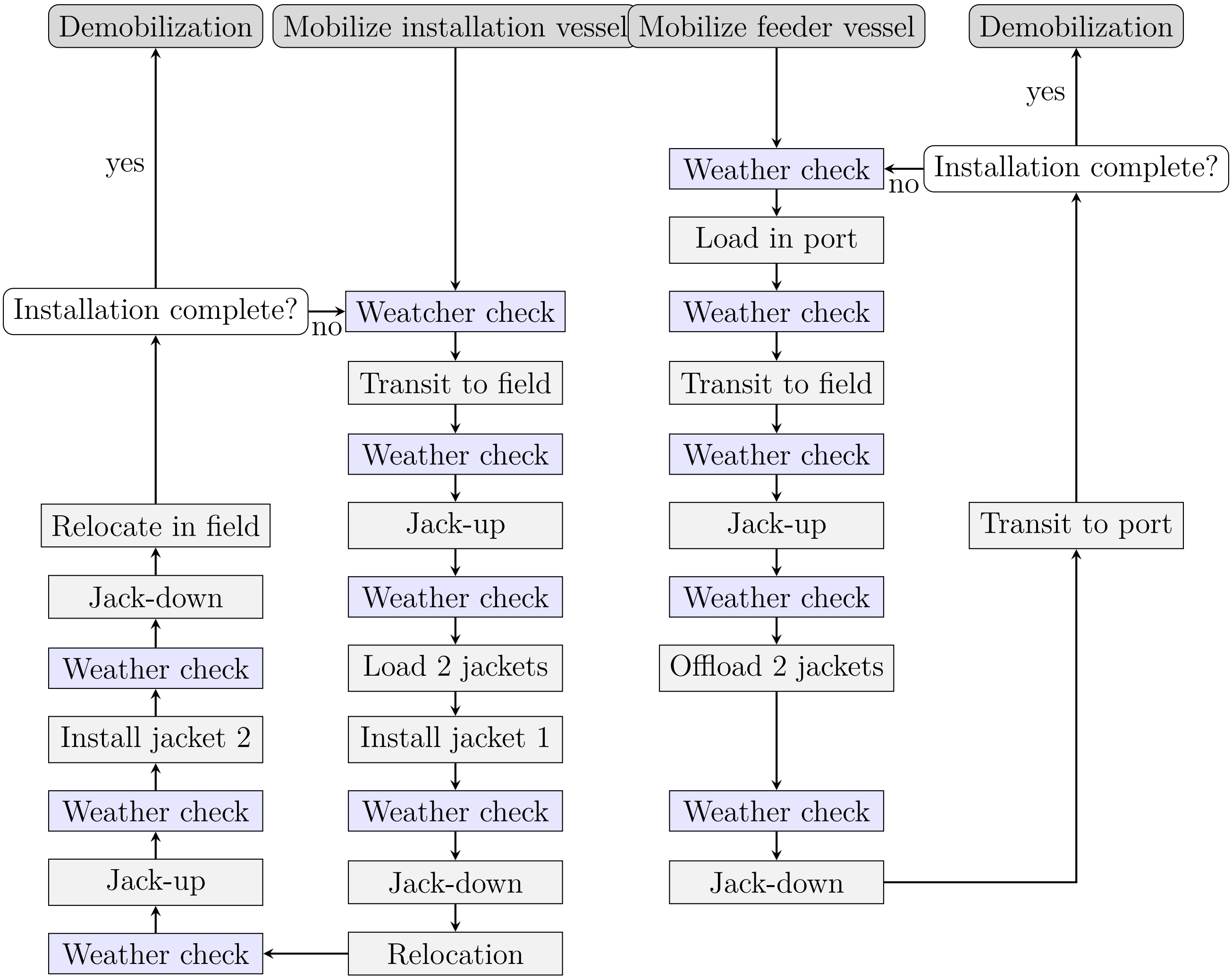


Figure G.2: Flow chart for Scenario 2

G.3 Simulation Model 3

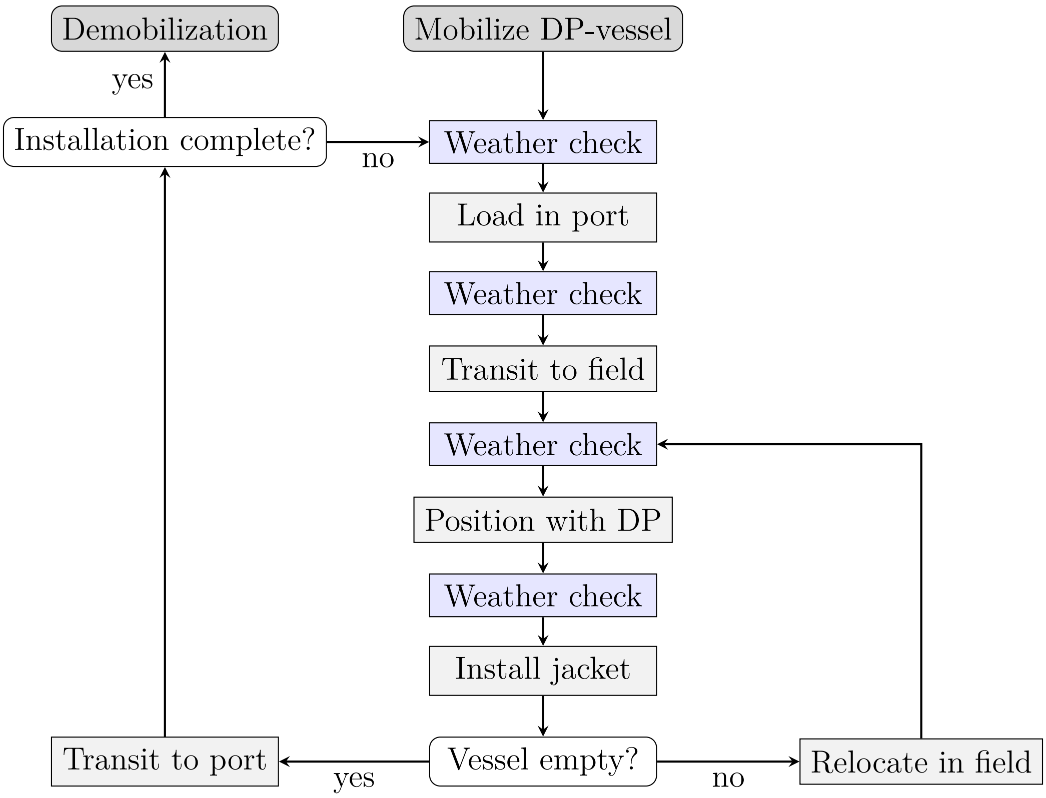


Figure G.3: Flow chart for Scenario 3

Appendix H

Project Thesis

H.1 Summary Project Thesis

Summary

The offshore wind industry is novel compared to its equivalent onshore, but is a growing industry with immense potential. One of the main restrictive factors for the industry is the high cost levels for installation of offshore wind farms. It is assumed that installation accounts for about 20-25% of total life cycle costs. Additionally, installation in rough environments offshore has introduced new challenges to the wind industry.

The objective of this report is to provide insight into the installation phase for offshore wind, and investigate different operational profiles for installation. Important factors include how vessel operability impacts installation, and how these can be changed in order to improve the efficiency of installation. The insight obtained was used to implement the system into a simulation model in Matlab SimEvents. The simulation model was used for analysing system behaviour.

The offshore wind turbine is divided into two main parts, sub- and top-structure. The former consists of the foundation and transition piece, while the latter contains tower, nacelle, rotor and blades. The transition piece connects tower with foundation, whereas the hub connects the blades to the nacelle. Vessels that are normally used in the installation phase include jack-up vessels, heavy lift vessels and feeder vessels. The jack-ups are mainly used for installation of top-structures, and the heavy lift vessels are used for sub-structure installation.

Weather impact on the system is related to both operability criteria and the state of uncertainty related to providing sufficient forecasts. Weather is in the simulation model imported from hindcasted data, and Markov Chain simulated states are imported to the model to represent current weather conditions during simulation time.

Through an analysis of vessel parameters, such as speed, capacity and weather criteria, the behaviour of the system was evaluated. Vessel criteria were changed sequentially, and results were compared. The analysis showed that the operability criteria for wind and waves have the greatest potential related to reducing total installation time, but it can however be assumed that transit speed and capacity constraints will have a more significant impact if the wind farm is located farther from shore.

Results provided in this report are subject to validation, as simulations were only performed over one weather scenario. The simulation model also has some limitations, as it only involves two installation strategies, performed with one heavy lift vessel and one jack-up vessel. Model extensions can cover more vessel types, additional configurations of component assembly and increased distances from shore.

Recommendations for further work also include a wider investigation of operability related to the installation phase, and current and future solutions to match the expanding industry.

H.2 System Description Project Thesis

2 Installation of Offshore Wind Farms

The installation of offshore wind farms (OWF) includes a wide variety of system components, which range from onshore logistics and manufacturing, to offshore installation at the field. Central system components include installation ports for storage and loading, all vessels that serve in the phase, the uncertain factor of weather and of course the operation of installation. Aspects concerning the installation phase and its cycle will be further explained in the following sections.

2.1 Wind Turbine Components

The wind turbine consists of the following parts: foundation, transition piece, tower, nacelle and rotor. The nacelle and rotor together are often described as a rotor and nacelle assembly (RNA), where the rotor consists of hub and blades. Figure 1 shows the different parts of the turbine. The tower is the part of the turbine unexposed to water where the RNA is mounted, the foundation provides stability for the turbine as it connected to the seabed. The transition piece connects the tower to the foundation. Regarding the configuration of offshore turbines, several descriptions exists in literature related to the components, but this report will use the naming system from Cradden et al. (2013), sub- and top-structure. Sub-structure consists of foundation and transition piece, while top-structure covers the tower, nacelle, hub and blades.

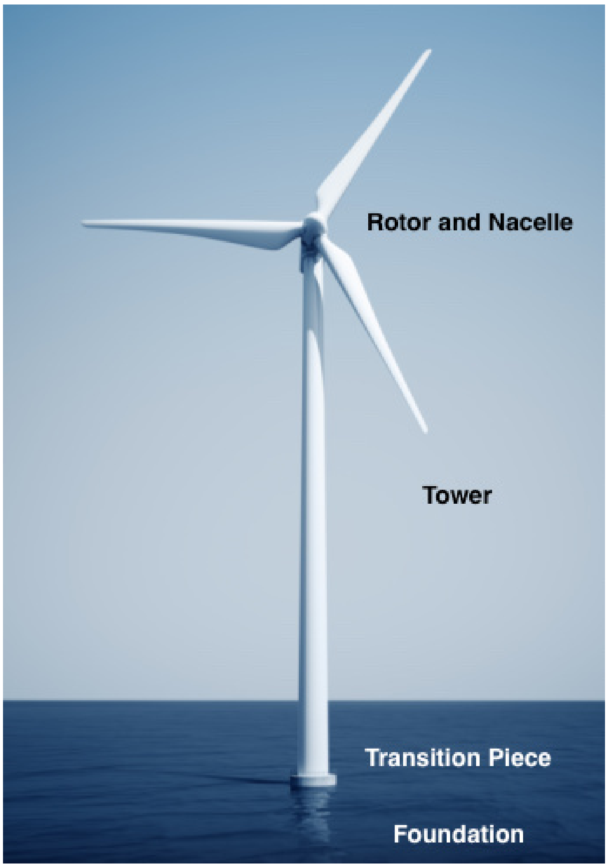


Figure 1: Overview over the turbine and its components (NAW Staff, 2015)

A closer description of the RNA can be seen in figure 2. Normally a turbine consists of three blades, connected to the hub. The hub is then connected to the nacelle, where the gearbox and generator are situated. These control the speed of the rotation, and transforms the mechanical energy of the rotation to electrical energy, that is exported to shore in export cables and can be connected to the electrical grid.

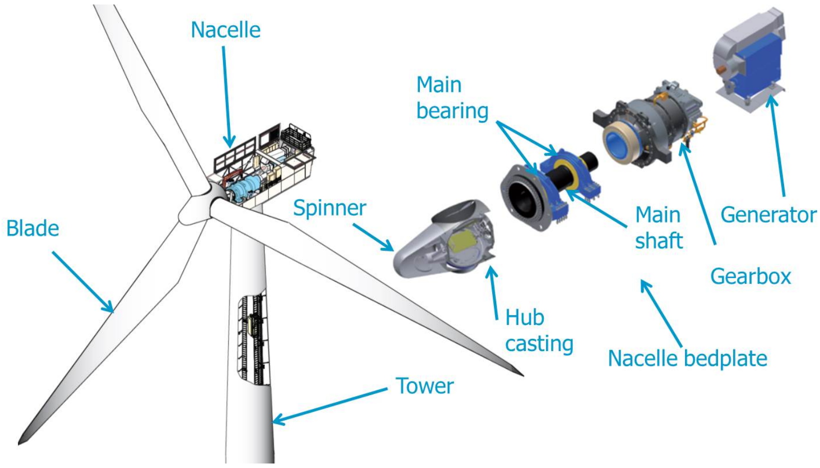


Figure 2: Overview over nacelle, hub and blades (Kent Wind Energy, 2016)

2.2 Installation Cycle

For the installation cycle, the system consists of all components of installation both at shore and offshore. Project planners must design a system that consists of manufacturing for the turbine components and a logistic system to transport the parts to a suitable installation port. This is where components are loaded on vessels, and transported to site, either by a feeder vessel or by the installation vessel. When the location of the turbine field is to be decided, the availability of an installation port should be considered. The port ought to have good infrastructure concerning both onshore and offshore logistics, and have the proper configurations for vessels to load. Opportunities for storage of components is an important factor, in order to minimize waiting time at port. The port must also have adequate size and depth to ensure that vessels of the required size can visit port. Operations in port are also depending on equipment, and the availability of them. There need to exist sufficient crane capacity, either on board the vessel or on the quay, for the lifting operations that are to be carried out.

During the installation phase, a lot of time will be spent by vessels and technicians travelling in transit between port and field. This means that great consideration should be taken when deciding where to put the installation port, and also when choosing strategy. If transit to port for the installation vessel is to be performed between every turbine installation and the distance is great, it is not hard to predict that transit will have a great impact on total installation time for the OWF. Not to mention the additional operating costs concerning fuel consumption and extra hours spent on work for the technicians. The transit is also affected by weather, but not as critical as operations on field during installation.

Transportation of components depends on the choice of vessels. The installation vessel can either both transport parts and perform installation, or a feeder vessel can transport components from installation port to turbine field. Current weather conditions will be a limiting factor for performing operations. A simple illustration of the system is shown in figure 3. In the illustration, it is shown that there might exist several possible installation ports for the operation, and that installation vessels and possible feeder vessels will transit between port and location of the OWF. Both inter-array cables between the turbines and export cables must also be installed in order to export the energy to the onshore electrical grid. This report will however not include the installation of cables.

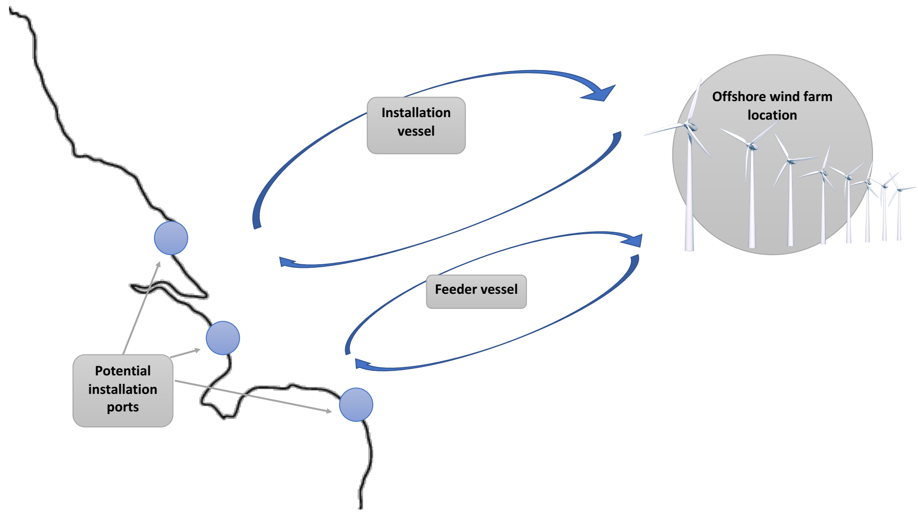


Figure 3: System overview over the installation phase

2.3 Installation Strategies

There exists several strategies for the installation phase of an offshore wind farm. Depending on lifting capacity of vessels, transit time and weather conditions, one can choose between multiple configurations. Normally, the sub-structure and top-structure are installed in different phases, so that all sub-structures on the field are completed before installation of top-structures can commence.

2.3.1 Sub-Structure

As previously mentioned, the installation strategy will be affected by the type of turbine to be installed. There are many different types of offshore wind turbines, but they can be divided into either floating or bottom-fixed. Different types of foundations are illustrated in figure 4. Bottom-fixed turbines are the most common, and these are used for offshore wind farms on rather shallow waters, with less than 50 m depth. These can have either jacket-foundations or be mono-piles. For the floating foundations, there exist today only one concept that is under construction for commercial use, the Statoil Hywind Pilot Project at Buchan Deep. The field consist of 5 6MW turbines that will be completed in 2017 (Statoil, 2016).

It is normal to complete installation of foundation and transition piece in the same phase.

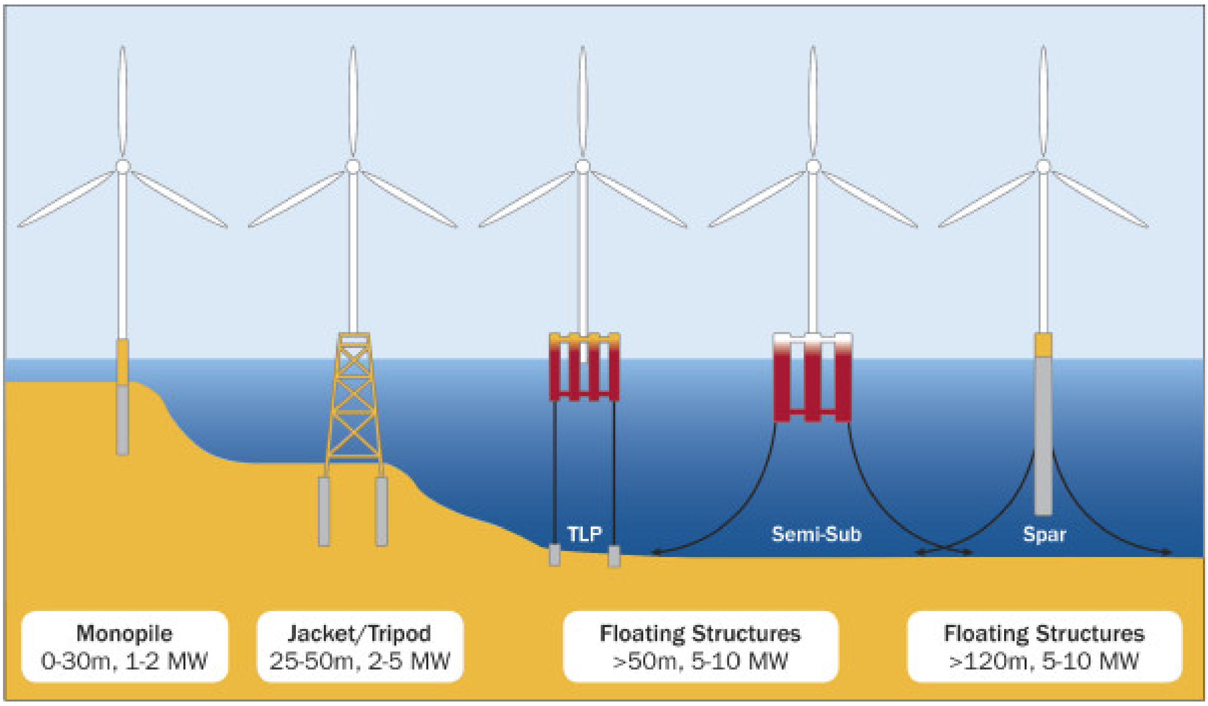


Figure 4: Overview over different turbines foundations and their respective depths (Principle Power, 2016)

For the installation of monopile foundations, a vessel with great lifting capacity is required, as these are normally very heavy. An installation vessel can transport out parts, normally for 3-8 foundations depending on deck space and carrying capacity, and install all foundations before returning to base for loading and repetition of the cycle. Often the transition pieces are installed together with the foundation, or the vessel will install these at a later stage when all foundation installations are finished. A feeder vessel might also be used, which is a vessel that is used solely for the purpose of transporting components. This will reduce transit time, as the installation vessel does not have to return to base for loading. For jacket or tripod foundations, it is more normal to transport the components directly from fabrication yard to the installation site, according to Cradden et al. (2013). On site, a heavy lift vessel (HLV) or an installation vessel will complete the installation of the foundations.

2.3.2 Top-Structure

For the installation of the top-structure, the strategy can bo chosen from several configurations. These all depend on the degree of pre-assembly of the different parts before they are transported to site for installation. Normally, all components for one turbine will be transported together, so that one turbine can be finished before moving on to the next. The tower is often divided into several parts to enable easier transportation, and assembled on site. This is done to reduce transit- and positioning time at each turbine. Additionally, it is also possible to begin installation of all towers, then return to the first turbine again and start installing the nacelle, hub and blades. When deciding installation strategy, one must also consider the transit time to port for loading if not a feeder vessel is being used. This will depend on the capacity of the installation

(a) Fred. Olsen Brave Tern lifts a rotor and blade assembly for installation (Fred. Olsen Windcarrier, 2016a)

(b) Fred. Olsen Bold Tern lifts with configurations on deck for carrying nacelles, towers and blades (Fred. Olsen Windcarrier, 2016a)

Figure 5: Fred. Olsen Windcarrier jack-up installation vessels

vessel. Pre-assembly of parts will reduce installation time at site, and is therefore a strategy less sensitive to weather changes because the time to complete activities is reduced. However, this configuration is more exposed to weather because of the increased size of the object to lift, and requires higher lifting capacity. The turbine blades are in particular very sensitive to wind loads, as blades are designed to catch the wind and will start moving even at small wind loads. With increasing wind strength, the sensitivity of the operation when installing the assembled hub and blades is further increased. Figure 5a shows how the Fred. Olsen vessel Brave Tern lifts the rotor assembly for installation on the nacelle.

2.4 Installation Vessels

The installation vessels are some of the most prominent parts of the operation, and also introduce a large cost driver in the system. The EU program LEANWIND (Cradden et al., 2013) have outlined the main operational requirements that needs to be considered for the installation of both sub- and top-structures. This is illustrated in table 1. Water depth is important when installing bottom-fixed foundations and top-structures, as the vessels needs stability. The crane capacity and height needs to be sufficient in order to lift the heavy parts, though it should be mentioned that usually the installation of foundations require higher lifting capacity, and installation of the top-structure will require higher crane height. Deck space is depending on the installation strategy, and the reason why installation of sub-structure require less deck space than top-structure is because of the homogeneity of the components, while the top-structures consists of several different parts. However, this can be solved by using feeder-vessels for transportation. The variable load is most prominent when lifting at heights, such as the nacelle and blades.

It is important to also consider the mobilization of the installation vessel. Before each job, the

Table 1: Operational requirements for the installation phase. The letter Y means that he criteria required consideration (Cradden et al., 2013)

Component	Depth	Crane Capacity	Crane Height	Deck Space	Variable Load
Sub-structure	Y	Y	Y	N	N
Top-structure	Y	Y	Y	Y	Y

vessel must have the correct configurations on deck in order to carry and store the components that are required for the activities. This includes welding of support structures on deck, which again is depending on the prior decision of how to configure of the installation (Barlow et al., 2015). If the vessel is to install all blades separately, without any pre-assembly, a structure for easy storage and access must be installed on the vessel. An example of this is seen on figure 5b, where the Fred. Olsen Bold Tern is seen stocked with both nacelles, towers and blades.

An important property of vessels is the ability for station keeping when installing. For vessels that use dynamic positioning, it is crucial that operation comply with criteria for vessels, so that the vessel is not forced out of position. A collision between vessel and turbine structure can cause great damage. For jack-up vessels, critical phases includes jacking up and down. There are strict criteria for this phase, as vessel must extract legs at the correct location on sea-bed, and so especially wave height is limiting this operation. Different strategies requires specific properties for vessels, which must be investigated in the beginning of the project.

2.4.1 Vessel Types

Complex offshore operations have been performed for many years, and therefore solutions exist in this area. The difference between previous operations and operations related to offshore wind farms is that one sees a demand for more task-related vessels that can perform operations in the wind industry with higher operability at the lowest possible cost level.

Vessels most commonly used for installation of wind turbines today include jack-ups, lifting vessels and feeder vessels such as barges or supply vessels. (Cradden et al., 2013). The barges are mainly used for the transportation of larger parts, and tugs are needed when the barges are not self-propelled. Jack-ups can also be either self-propelled or platforms, and the self-propelled installation vessel (SPIV) are very common to use as they can both transport and install parts. These are also called turbine installation vessels (TIV). Heavy-lift vessels (HLV) are needed to perform lifts when the installation vessel has limited carrying capacity, and are usually used during installation of foundations an transition pieces. In addition, crew transfer vessels (CTV) are smaller vessels that are used to transport crew and technicians to the site. Table 2 explains the properties of the four different vessel types.

2.4.2 Current Solutions

To improve the understanding of how installation vessels are used, some examples from existing solutions are further explained. This is to give insight in how an offshore wind farm installation

Table 2: Vessel properties for SPIV, HLV and barges (Cradden et al., 2013)

Vessel type	Role in phase
SPIV	Installation of top-structures
HLV	Installation of sub-structures
Feeder	Transportation of components
CTV	Transportation of crew and technicians

phase is performed.

The HLV Oleg Strashnov, which is equipped with DP3 and capable of lifting up to 5000 metric tonnes (Mt), was used for the installation of foundations and transition pieces for both Sheringham Shoal and Dudgeon. For the installation of sub-structures at Dudgeon, the vessel carried three foundations and transition pieces in each leg, meaning that three sub-structures were completed before returning to port to reload, according to Olsen (2016).

During the construction of the Block Island Wind Farm on the East-Coast of the US, the Jack-Up vessel Brave Tern was used for construction of the five top-structures (Røset, 2016). The vessel transported the nacelles over the Atlantic Ocean, and the construction phase was supported by two self-propelled jack-up vessels, L/B Caitlin and L/B Paul. These transported tower sections and blades to the offshore site, where Brave Tern performed installation. This means that Brave Tern first had to lift the tower pieces for each turbine from the feeder vessel, and then install the tower, before they could install the nacelle situated on its own deck. Then the blades had to be lifted from the deck of the feeder vessel, in order to install all three blades. Figure 5a shows the Brave Tern installing a pre-assembly of hub and blades, to the already installed nacelle.

A list of commonly used vessels for installation is included in the Appendix B. Barges and feeder vessels are excluded as these are not as specific to wind farm development as HLV's and SPIV's.

2.5 Operational Criteria

The main limitation in the installation phase is the uncertainty of the weather. Even though one can predict a nicer weather during the summer season, the weather offshore may be rough and one may have to perform installation (and of course also operations and maintenance) outside the preferred season. Weather constraints include both currents, wind, waves and temperature. For analyses of installation activities it can be considered sufficient to limit the weather impact to include wind speed and significant wave height. The wind will affect all lifting operations, and also create accelerations in towers, while waves will impact the movements of the vessel and also floating foundations. Ship operability and sea keeping will also be affected by the wave height, and vessels have transit restrictions for wave heights. When the waves are too high, it might be too uncomfortable for crew, and especially technicians that are not seafarers, to be on board.

Operators usually follow their own operation guidelines, based on vessel operability and experience. Fred. Olsen Windcarrier (2016b) gives the following guidelines for the operation of a jack-up vessel during installation of top-structures, shown in tables 3 and 4. The weather window describes the assumed duration of activity, including a factor to account for uncertainties related to the activity.

Table 3: Example of weather limitations concerning the lifting operation of components (Fred. Olsen Windcarrier, 2016b) (Wind limitations are at a period of 60 s)

Location	**Lifting activity**	**Weather window** [h]	**Wind limitation** 80 m height [m/s]	**Wind limitation** 10 m height [m/s]
Inshore	Tower	2	12	8.6
	Nacelle	3	12	8.6
	Blade (1)	1	12	8.6
Offshore	Tower	3	13.7	9.4
	Nacelle	3	13.7	9.4
	Blade (1)	3	12	8.2

Table 4: Example of weather limitations concerning operations offshore (Fred. Olsen Windcarrier, 2016b) (Wind limitations are at a period of 60 s)

Activity	**Weather window** [h]	**Hs** [m]	**Wind limitation at 10 m height** [m/s]
Transit	7.5	3.5	25
Jack-up inshore	3.5	1.8	14
Jack-down inshore	3.5	1.8	14
Jack-up offshore	6.5	1.8	14
Jack-down offshore	5.5	1.8	14
Elevated condition	50 years	storm	storm

For the wind limitations shown in tables 3 and 4, a wind conversion has been performed in order to find the mean wind speed. The equation is found in DNV GL (2010), and is shown in equation 1.

$$U(T, z) = U_{10}(1 + 0.137 ln\frac{z}{H} - 0.047 ln\frac{T}{T_{10}}) \tag{1}$$

T = average period,

z = height above sea level,

H = 10m,

T_{10} = 10 minutes,

U_{10} = 10 minute mean wind speed at height H,

In Ursavas (2016), several operational criteria are stated that were used during the installation of the offshore wind farms *Bard 1* and *Borkum West* in the North Sea. There existed different wind criteria during activity at these farms, and the wind criteria for installation of sub-structures are shown in table 5.

Another actor in the industry, Statoil, has provided information about installation criteria during installation of sub-structures during operations with vessels using dynamic positioning (DP).

Table 5: Wind criteria for operations at wind farm sites Bard 1 and Bolkum West (Ursavas, 2016)

Wind site	Wind criteria foundation [m/s]
Bard 1	16
Borkum West	12

Related to this information, the criteria for installing sub-structures have been set to a H_s equal to 2 m (Olsen, 2016).

2.6 Rules and Regulations

In addition to the industry actors own criteria for operation, which usually are based on vessel performance and experience, operations must also comply with both national and international regulations. Vessel flag will impact vessel safety regulations, and location of operation implies that operation must follow national regulations for the country. The following sections will present different standards that are relevant to offshore wind farm installation, in addition to a guidance standard for national practice in the UK.

2.6.1 GL Noble Denton Guidelines for Offshore Wind

The *Guidelines for Offshore Wind Farm Infrastructure Installation (0035/ND)* is a Technical Standard that can be applied in the installation phase of various types of offshore wind farms (GL Noble Denton, 2016). It provides guidelines for the installation of foundations, turbines, offshore substations and array and export cables. The guideline has recommendations for coordination of the installation, regarding several aspects of operation. Considerations should be made with regard to vessels, how their operation can affect cables on the seabed and possible collision when working alongside offshore structures. Moorings can also impact cables. All these factors provides basis for planning activities throughout the operational period.

GL Noble Denton (2016) states that the phase of selecting resources for installation is a consideration based on the economic trade-off. Vessels with high operating limits cause less delays in bad weather, but will normally come at a higher cost. Before the execution of operation, vulnerable items must be identified, and all parties included in the operational period should be notified in order to avoid accident, and reasonable risk assessment should be provided beforehand. Typical vulnerable items include cable connections, changes in seabed due to interaction with jack-up vessels with legs extracted, moorings and diving operations.

2.6.2 DNV GL Marine Operations, General

The document *Marine Operations, General (DNV-OS-H101)* is a standard covering marine operations, provided to ensure safe operations. In section A200 of the document, environmental loads are listed. These are divided into conditions that are of general importance and phenomena that might be of importance and should be investigated. Of the former category, wind, waves, current and tide is of significance. Regarding the latter, especially soil conditions, temperature, fog and visibility, tide variations and local swell or wave conditions are elements that are essential during installation of offshore wind turbines. For installation in shallow waters many of these factors must be thoroughly reviewed, due to the effect of shallow water operation.

Wind is calculated as mean wind, which is the average wind velocity over a period of time. Equation 1 shows how to calculate mean wind velocity profile in open sea.

Design wind conditions are calculated either by a deterministic or stochastic method. Deterministic waves represents regular, periodic waves, while stochastic waves have design sea states that are represented with a wave energy spectra. Wave height is normally described by significant wave height, which is the mean value of the highest one third of waves measured.

Table 6: Weather restricted and unrestricted operations

Operation	Duration	Explanation
Weather restricted operations	< 72 hrs	Weather forecast considered reliable
Weather unrestricted operations	> 72 hrs	Weather forecast not considered accurate

Criteria for operation should be selected while considering safety during the whole planned operation and special conditions at site. For weather restricted operations, uncertainties in forecasts must also be considered. For unrestricted operations, wave conditions shall be based on long term statistical data. The difference between these is explained in table 6. The characteristic significant wave height, $H_{s,c}$, can in this case be calculated according to equation 2. α and β are Weibull parameters for the probability function of the observed significant wave heights.

$$H_{s,c} = \alpha(\frac{2}{2+\beta} f_1)^{(1/\beta)} \tag{2}$$

Regarding swell, it is important that for operations sensitive to long period waves, swell types must be considered and critical swell periods should be be identified. In addition, the local tides are important to consider, such as during operation with jack-up vessels. Astronomical tidal range is the difference between the highest and lowest astronomical tides, respectively HAT and LAT, whereas the characteristic water levels also include storm surge effects.

For marine operations, the DNV GL Standard states that operations should only be executed knowing that all assumptions made prior to operations are fulfilled, in order to ensure safe operation. It is important to schedule both the planned operation period and a contingency time. The contingency time is accounting for uncertainties in operational time, and possible situations that may impact operation and require additional time to complete operation.

A limiting operational environmental criteria shall be established previous to all operations, OP_{lim}. The criteria must not be chosen greater that the limiting criteria for all equipment and activities in the planned operation, and not greater than the environmental design criteria. An α-factor is introduced to ensure that the probability of exceeding the OP_{lim} over 50% is smaller than 10^{-4}. DNV GL has provided tables with appropriate α-factors for use in the North Sea and

Norwegian Sea. These are found in the DNV GL (2011), section 705-710 for wave calculations and section 712 for wind. The α-factor is read from the tables based on the planned operational period and the design wave height (H_s).

2.6.3 RenewableUK Offshore Wind and Marine Energy

RenewableUK is a leading trade association for renewable energy in the UK, and is a non-profit association working to provide information to its members where current information is considered absent or incomplete (RenewableUK, 2014). The *Offshore Wind and Marine Energy Health and Safety Guideline* is created with considerations to existing good practice in the UK sector, in order to enable the expanding of the UK renewable energy sectors in a safe way, free of injuries, fatalities and work-accidents. The guideline emphasis the importance of offshore health and safety management, considering the role of leaders, the establishment of health and safety cultures, regulatory framework, and offshore specific techniques for managing emergency situations. It is a tool used to ensure safe operations and the minimization of accidents related to offshore wind activities on UK sector.