Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Thomas Magnus Lloyd

Fleet and Scheduling Optimization for Offshore Floating Wind Installation under Impact of Weather

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2021

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Master Thesis in Marine Systems Design

Stud. techn. Thomas Magnus Lloyd

"Fleet and Scheduling Optimization for Offshore Floating Wind Installation under impact of weather"

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Background

The rapid deployment of low-carbon technologies for replacing conventional fossil fuel generation and uses has led to large cost reductions and technology improvement in available renewable power generation technologies such as, wind power, both onshore and offshore, concentrating solar power (CSP) and solar PV. In the last decade, onshore wind has shown significantly large cost reductions while improvement in technology has resulted in larger hub heights and rotor diameter. Offshore wind is also experiencing cost reductions with larger turbines and higher hub heights as wind farms are moving into greater water depths. Having wind turbines offshore has greater potential as there is larger amount of wind energy, less visual disturbances compared with turbines on land and larger available areas that increases investment possibilities. The world energy demand is increasing rapidly and so is offshore wind technology. Several wind parks projects have been completed the last decade and several more under development.

An offshore wind park is much more costly compared with having a wind park on land. Some of the major reasons are the cost of installations of turbines and foundations. The installation work is challenging due to operational handling at sea and strict weather requirements on vessel operation. Floating wind concepts provide the possibility of installation that can be largely pre-assembled in port and then towed out fully assembled to the operation site. However, the key for cost reduction for future offshore wind parks, is industrialization of floating wind technology. By investigating key cost drivers such as fabrication, assembly, standardization, installation, operation and maintenance floating wind technology can become more cost competitive.

Overall aim and focus

The overall aim of this thesis is to develop an optimization model for determining the installation fleet and schedule for a specific offshore floating wind farm located in the North Sea where weather is considered. As weather is difficult to predict in a planning phase, different weather categories based on historical data will be set and will be implemented in the optimization model. The work done will evaluate and present different optimal fleet configurations and schedules.

For developing the optimization model, a literature review of similar research from the last decade will be conducted and used as the basis for the work done in the master thesis. Different conceptual floating wind concepts will be investigated and evaluated in an economic and technological point of view. There are several different installation strategies for installing a floating offshore wind farm depending on the floating wind turbine concept. Equinor's installation strategy for Hywind Tampen is chosen as the basis for the work conducted in the master thesis. The model should be designed as a strategic problem to find the optimal installation fleet and schedule that minimizes the total costs of the installation phase.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide a short overview of the current status and important development trends related to offshore floating wind farms and present important factors in the main installation steps of Hywind Tampen.*

2. *Develop an installation concept for a floating wind farm where all the main impacts and requirements that are needed for the installation of floating wind are defined. Information from offshore floating wind will be presented where different potential vessels and fleet configurations are investigated.*

3. *Based on chosen installation concept, develop two different optimization models that includes vessel selection and fleet schedules decisions considering different weather approaches.*

4. *Perform a case study and with the result obtained from the optimization models, evaluate vessel strategies for the installation process with impact from weather.*

5. *Discuss and conclude*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the MSc Project work.

The thesis shall be submitted June 2021.

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Stein Ove Erikstad
Professor/Responsible Advisor

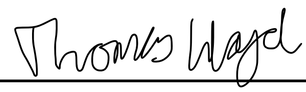
Preface

This master thesis has been written during the spring semester of 2021 and the final delivery of two years studying at the Department of Marine Technology at the Norwegian University of Science and Technology(NTNU) in Trondheim, Norway. The master thesis has been written within the specialization field of Marine Systems Design and counts for a workload corresponding to 30 ECTS.

The main focus of the master thesis has been to study fleet size and mix problems of the installation logistics of floating wind turbines with the impact of weather. Using two different optimization models with two different approaches to include the impact of weather, valuable insight has been achieved to see how the logistics of the installation process can be optimized. The master thesis is an expansion of the Project Thesis that was written in fall 2020 with a corresponding workload of 7.5 ETC. Several of the chapters has been included in master thesis where they have been edited and expanded. At the start of semester 2021 I have done alot of research on optimizing as I don't have any optimization courses. A lot of time have been used early in the semester to learn Python and Gurobi of how to develop the optimization models.

I would like to thank my supervisor of my master's thesis, Stein Ove Erikstad. With weekly meetings, he has provided professional support and constructive discussions throughout the semester. He has also helped alot with formulating my optimization models mathematically and implementing the models in Python.

Trondheim, June 10, 2021



Thomas Magnus Lloyd

Abstract

Electricity generation from renewables is growing rapidly as the world transitions from fossil fuel to meeting the 2 °C climate target. A severe transformation from fossil fuel-based energy generation to low-carbon technologies for the global energy market is necessary. Both wind and solar PV installation costs have dropped significantly over the last decade due to improvements in technology, more competitive supply chains, and internationally active project developers. The majority of the offshore wind turbines in operation today are installed near shore. The installation of floating wind structures is, however, expected to grow in the coming years. By eliminating the depth constraint that the bottom fixed concepts have, the floating wind concept will enable access to areas where the wind resources are more robust and consistent. Also, floating wind concepts allow a more straightforward turbine set-up that can offer a lower-cost alternative to bottom-fixed concepts. The main costs of an offshore wind farm are turbines(including tower), foundations (fixed or floating), the electrical interconnection between the wind farm and the grid onshore and construction and installation costs. Cost reduction can then be achieved by more efficient utilization of each vessel in the installation fleet. Even a small improvement will have a significant impact on the total installed costs.

The objective of this master thesis is to provide insight into the logistic installation chain and create two optimization models for the installation of FOWTs with impact of weather. The DOFS model includes decisions on vessel selection whereas the CFSS model includes decisions on scheduling and vessel selection. Weather conditions and vessel limitations are factors that will influence the start time of the different installation operations. The optimal fleet will be determined by which vessel to use, the charter period of each vessel, and when to perform the different operations. Hywind Scotland is the world's first fully commercialized installed floating offshore wind farm (FOWF), and the Hywind Tampen project is already on its way to being installed. When Hywind Tampen is fully commercialized and in operation, this will be the largest FOWF. The project's installation processes will be used as a basis for the optimization model in the thesis. This is because the installation process in the Hywind Tampen project is an excellent example of how to install FOWT. The chosen vessels are based on the Hywind Tampen project and the vessel types that can be chosen in the model are OSV, ATHS, CLV, and SOV.

The DOFS model showed that installing one turbine with no weather impact, the total installation time was 25 days, and installing ten turbines took 84 days. However, when Hs was increased to 2.5 meters, the installation time for ten turbines took 126 days, an increase of 33 %. The

installation cost of ten turbines when Hs = 2.5m showed an increase of 36 % from a turbine cost of 1 164 000 £ to 1 843 000 £. The results from the CFSS model showed a lower installation time for one turbine without weather of 20 days, however, the installation time for ten turbines took 120 days. When implementing the waiting days for Hs equal to 2.5 meters, the installation time increased significantly for ten turbines resulting in 165 days. The cost per turbine for ten turbines without weather was 1 305 400 £ whereas the turbine cost was 2 435 500 £ when installing ten turbines when Hs was equal to 2.5 meters, an increase of 47 %. When comparing the two models, there is no significant difference in the results for when the weather impact is not included. However, when the weather was implemented, the difference between the results from each model are much more significant. Nevertheless, it should be kept in mind that two different approaches were used when considering the weather in the models.

The CFSS model is shown to be a useful tool for planning the installation phase for floating offshore wind farms to get information on fleet sizes and schedules for different weather conditions. It shows that the model provided results that was considered sufficient enough to answer the scope of the master's thesis.

Sammendrag

Elektrisitet som er produsert fra fornybare kilder vokser raskt ettersom verden må gå vekk fra fossile energi ressurser for å oppnå klima målet på 2 grader. For å oppnå klima målet, må det skje en kraftig overgang fra energi som er produsert fra fossil energikilder til lavkarbonteknologi. Det siste tiåret har installasjonskostnader for både vind og solcelle sunket betydelig grunnet forbedringer i teknologi, mer konkurransedyktige logistikk og internasjonal produktutvikling. De fleste offshore vindturbiner er av bunnfaste konsepter. Imidlertid forventes installasjon av flytende vindturbiner å øke de neste årene. Med flytende vind elimineres vanndyp begrensinger som bunnfast turbiner har og muliggjør tilgang til områder der vindressurser er sterkere og konsist. Flytende vind har i tillegg en mer enkel måte å montere turbiner på som kan tilby et billigere alternativ enn bunnfaste konsepter. Hovedkostnadene for en vindturbinpark er turbiner (inkl. tårn), fundamenter (bunnfast eller flytende), elektrisk sammenkobling mellom vindpark og nettet på land, konstruksjon og installasjon. En mulig kostreduksjon er ved å bedre utnytte de ulike fartøyene som inngår i installasjonsflåten. Selv med en liten forbedring kan ha en betydelig innvirkning på den totale installasjonskostnad.

Målet med denne master er å gi en innsikt i installasjons logistikken og lage to ulike optimaliserings modeller for installasjon av flytende vind turbiner under påvirkning av været. DOFS modellen inkluderer valg av ulike fartøy imens CFSS modellen inkluderer både valg av tidsplaner og valg av ulike fartøy. Vær kategorier og fartøy begrensninger er faktorer som vil påvirke når de ulike operasjonene kan starte. Den optimale vil bestemme hvilke fartøys som skal brukes, leie perioden av hvert enkelt fartøy, og når de ulike fartøyene skal utføre de ulike operasjonene. Hywind Scotland er verdens første kommersielle installert flytende vindpark, og Hywind Tampen prosjektet er allerede på vei til å bli installert. Når Hywind Tampen blir ferdigstilt vil den være verdens største flytende vindpark. Dette prosjektet vil bli brukt som et utgangspunkt for optimaliseringsmodellene i masteren. Grunnen for dette er at installasjonsprosessen i Hywind Tampen er godt eksempel på hvordan flytende vindturbiner kan installeres. Fartøyene som er brukt i modellene er tatt utgangspunkt i Hywind Tampen og de følgende fartøy typene er OSV, AHTS, CLV og SOV.

DOFS modellen viste å installere en turbin uten påvirkning av vær, gav en installasjonstid på 25 dager, og installasjon av ti turbiner tok 84 dager. Men, når Hs økte til 2.5 meter, tok installasjonstiden for ti turbiner 126 dager, en økning på 33%. Installasjonskostnaden for ti turbiner når Hs var 2.5 meter gav en økning på 3% fra en turbin kostnad på 1 164 000 £ til

1 843 000 £. Resultatene fra CFSS modellen viste en lavere installasjonstid for en turbin uten påvirkning av vær på 20 dager, men installasjonstiden for ti turbiner tok 120 dager. Når vente dager ble implementert for Hs lik 2.5meter, økte installasjonstiden for ti turbiner til 165 dager. Kostnaden per turbin uten påvirkning av vær var 1 305 000£ imens kostnaden var 2 435 000 £ for installasjon av ti turbiner når Hs var lik 2.5 meter, en økning på 47 %. Når en sammenligner de to modellene, er det ingen store forskjeller mellom resultatene når været ikke er inkludert. Men når vær er inkludert, er forskjellen mellom resultatene mye større. Uansett så burde en huske på at det er brukt to forskjellige fremgangsmåter for å ta hensyn til været i modellene.

CFSS modellen har vist seg til å være et brukbart hjelpemiddel for å planlegge installasjonsfasen for flytene vindparker ved å anskaffe informasjon om ulike flåtestørrelser og tidsplaner ved ulike tilstander av været. Det viser at modellen kan gi resultater som var vurdert gode nok til å svare på målet ved denne masteroppgaven.

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Abbreviations

AHT Anchor Handling Tug.

AHTS Anchor Handling Tug and Supply.

CLV Cable Laying Vessel.

CP Compromise Programming.

CSP Concentrating Solar Power.

DEA Drag Embedment Anchor.

DSM Design Structure Matrix.

FWT Floating Wind Turbine.

GWEC Global Wind Energy Council.

HVAC High-Voltage-Alternating-Current.

HVDC High-Voltage-Direct-Current.

ILP Integer Linear Program.

IP Integer Programming.

LCOE Levelized Cost of Energy.

MFSMP Maritime Fleet Size and Mix Problems.

MILP Mixed Integer Linear Programming.

MIP Mixed Integer Programming.

OCV Offshore Construction Vessels.

OSV Offshore Support Vessels.

OWT Offshore Wind Turbine.

PSV Platform Supply Vessel.

ROV Remote Operated Vehicle.

SA Simulated Annealing.

SOV Service Operation Vessels.

SP Stochastic Programming.

TLP Tension Leg Platform.

VNS Variable Neighborhood Search.

VRP Vehicle Routing Problem.

WTIV Wind Turbine Installation Vessel.

Chapter 1

Introduction

The global energy demand has been growing exponentially due to industrial activity, population growth, and advancement in developing and developed countries. As a result, access to electricity for the world's population has steadily increased over the last few decades, where approximately 71% of the world population in 1971 had access to electricity and in 2016 it had risen to 87 % (Ritchie, 2019). 2018 was a great year where the global energy demand increased by 2.3 %, the most significant annual increase of the last decade. Since more households worldwide are gaining access to the electricity grid due to urbanization, global electricity demand and consumption will continue to increase rapidly in the years to come. Electricity demand is forecasted to grow each year with 2.1 % resulting in 2040 with more than 36 000 terawatt-hours, whereas in 2018, the electricity demand was 23 000 terawatt-hours. Today's primary energy source for meeting the world energy demand is still fossil fuel-based, such as coal, natural gas, and oil. However, the consequences of the COVID-19 pandemic have shown a drop in energy demand from fossil fuel sources. Renewables are the only source of energy that has demonstrated a demand growth during the pandemic (IEA, 2020). According to (IEA, 2019) states that solar PV and wind in the global electricity generation will increase from 7 % in 2018 to between 29-45 % by the year 2050.

Electricity generation from renewables is growing rapidly as the world transitions from fossil fuel to meeting the 2 °C climate target. A severe transformation from fossil fuel-based energy generation to low-carbon technologies for the global energy market is necessary. Energy-related emissions need to be reduced by 3.5 % each year until 2050 and continue after to be able to meet the aim of the Paris Agreement (IRENA, 2019), where decarbonization of the world's energy system could be done by scaling up electricity generation from renewable sources. The most promising renewables sources for generating electricity are wind and solar energy. According to (IRENA, 2019), wind energy alone could supply one-third of the total electricity demand by 2050, and therefore scaling up the wind power generation is of great importance as it is becoming a prominent generation source. Both wind and solar PV installation costs have dropped significantly over the last decade due to improvements in technology, more competitive supply chains, and internationally active project developers.

Despite the COVID-19 pandemic, the wind industry delivered a record year in 2020 with an increase of 93GW. For offshore wind installation in 2020, the year was the nest best in the history with 6.1GW installed, giving complete installations offshore to 35.3GW (BVGassociates, 2019). Global Wind Energy Council (GWEC) expects that the growth in the offshore wind market will quadruple by 2025, with 70GW installed between 2021-2025. Offshore wind is becoming more cost-competitive with other renewable energy technologies with larger turbines and higher turbine ratings. IRENA anticipates a 55% cost reduction in offshore wind in 2030 compared with 2018 (IRENA, 2020). However, to achieve the cost reduction, the cost drivers for installing and operating an offshore wind farm need to be reduced. According to *BVGassociates* (BVGassociates, 2019) the installation cost accounts for up to 19.2% of the total of an offshore wind farm. By reducing the cost of the installation, phase is one way to achieve total lifetime cost reduction.

Most of the wind turbines that are installed offshore is near shore with bottom-fixed concepts. However, the installation of floating wind structures is expected to grow in the coming years. By eliminating the depth constraint that the bottom fixed concepts have, the floating wind would enable access to areas where the wind resources are more robust and consistent. Also, floating wind concepts allow a more straightforward turbine set-up that can offer a lower-cost alternative to bottom-fixed concepts (IRENA, 2019). The time it takes to install a wind turbine depends on how many offshore operations to execute, weather limitations, and the complexity of the installation process. By reducing the need for operational handling at sea, the installation time, the primary key cost driver of the installation phase can be reduced. The main costs of an offshore wind farm are turbines(including tower), foundations (fixed or floating), the electrical interconnection between the wind farm and the grid onshore and construction and installation costs. The two latter are the costs with the most significant opportunity for cost reduction. They account for up to 19 % of the total installed cost and include the required time of installing each megawatt capacity of an offshore wind farm, where charter rates of installation vessels are the largest contributor (IRENA, 2016). Cost reduction can then be achieved by more efficient utilization of each vessel in the installation fleet. Even a small improvement will have a significant impact on the total installed costs.

The overall aim of the installation fleet is to install an offshore wind farm most cost-effectively while minimizing the total installation time. One way of achieving this is by determining which vessel to charter, when to charter the vessels, and what activity each vessel is to execute. Floating wind concepts have the advantage that assembling of wind turbine structure can be done in port and then towed fully assembled directly to its final location. Planning and scheduling the installation phase is crucial to achieving the optimal schedule and selection of vessels for offshore wind installations. Installation projects are planned a year or months in advance and are hard to complete due to the high uncertainty of weather as this directly impacts the vessel operation. Developing optimization models that minimize the total installation cost by selecting the optimal fleet and schedule for installation can then be used as a decision support tool for wind farm owners.

1.1 Motivation

The rapid deployment of low-carbon technologies for replacing fossil fuel for electricity generation has led to significant cost reductions and technology improvement in available renewable power generation technologies such as wind power, both onshore and offshore, Concentrating Solar Power (CSP) and solar PV. In the last decade, onshore wind investment has significantly reduced cost reductions, while improved technologies have resulted in larger rotor diameter giving higher capacities. Offshore wind is also experiencing cost reductions enabling more larger turbines and higher hub heights as wind farms move into greater water depths. Having wind turbines located offshore gives access to a higher amount of wind energy. Less visual disturbances compared with turbines on land and with larger available areas offer increased investment possibilities. The world energy demand is growing rapidly, and so is offshore wind technology. Several offshore wind farm projects have been completed during the last decade, and many more are under development.

An offshore wind farm project is much more costly compared with having the wind farm on land. Some of the primary reasons are the cost of installing the turbines and the foundations, as installation work is challenging due to operational handling at sea and strict weather requirements on vessel operation. Floating wind concepts allow for large pre-assembly of the turbines in port, and these can then be towed out to offshore sites. The key to cost reduction for future offshore wind farms in the industrialization of floating wind technology. By investigating key cost drivers such as fabrication, assembly, standardization, installation, operation, and maintenance, there are clear opportunities for floating wind technology to become more cost-competitive.

In this master thesis, a detailed investigation of the installation of floating wind farms will be performed. Starting with background information of offshore wind farms, including the primary components necessary for producing electricity, followed by different concepts covering wind farms already and those under development. Then a thorough analysis of the installation methods used for the Hywind projects will be done. The information gathered from the research will then be used to develop two optimization models for the installation phase of floating wind with impact of weather. The models can then be used to support fleet compositions and schedules to install floating wind farms.

1.2 Objectives

The main activities in the master thesis include the following main points:

- Provide a short overview of the current status and important development trends related to offshore floating wind farms and present important factors in the main installation steps of Hywind Tampen .

- Develop an installation concept for a floating wind farm where all the major impacts and requirements needed for the installation of floating wind are defined. Information from offshore floating wind will be presented where different potential vessels and fleet configurations are investigated.
- Based on chosen installation concept, develop two different optimization models that includes vessel selection and fleet schedule decisions considering different weather approaches.
- Perform a case study and with the results obtained from the optimization models, evaluate vessel strategies for the installation process with impact from weather.
- Discuss and conclude.

1.3 Structure of the report

The master thesis is structured as follows:

- *Chapter 2*: The offshore wind industry is described, including components that are typically used for floating wind turbines. Then requirements for installation vessels are provided, followed by different vessels used in offshore wind installation. Lastly, installation methods are introduced where restrictions and weather impacts need to be considered during planning.
- *Chapter 3*: The problem description for the thesis is specified where the objective is explained thoroughly.
- *Chapter 4*: Presents literature review of previous work done within maritime fleet size and mix, optimization of fleet selection, and schedules of offshore wind installations.
- *Chapter 5*: Explains methodology used in the thesis.
- *Chapter 6*: Presents a discrete optimization model of fleet selection where the weather is taken into account. All the sets, parameters, and variables in the mathematical formulation are explained in detail.
- *Chapter 7*: An expansion of the first model is described where the improved model is formulated with an arc-flow formulation where the time is continuous, and the nodes are defined as the installation activities. The weather may impact the performance of the installation, so a robust solution is suggested to capture the increased service time to perform the various installation activities.
- *Chapter 8*: The results from the optimization models are presented.
- *Chapter 9 and Chapter 10*: The results are discussed in chapter 9, where concluding remarks and further work are presented in chapter 10.

Chapter 2

Background

This chapter presents the relevant background of the offshore wind industry and offshore wind farm installation. Firstly a brief outline of the different components of floating wind turbines is described. Then the logistics of the installation phase are described, including vessels, different installation activities depending on chosen wind turbine concept to be installed. Lastly, the weather impacts related to offshore wind installation and some of the challenges with offshore wind are described.

2.1 Components of an offshore wind turbine

A wind farm, either onshore or offshore, consists of several wind turbines. At an offshore wind farm, the wind turbine is located not far from the coastline, where the mean wind speed is favorable. Wind turbine technology has grown rapidly since the first 22kW wind turbine model in the 1980s to today's technology, where over 10MW offshore wind turbines are commercially available (IRENA, 2019). The wind turbine is composed of three main components; the tower, nacelle, and the rotor. The common design of a wind turbine is a horizontal design where the rotor rotates about a horizontal shaft that drives a generator through a gearbox. A foundation is attached to the wind turbine as it cannot stand directly on the water (or on the ground if they are onshore).

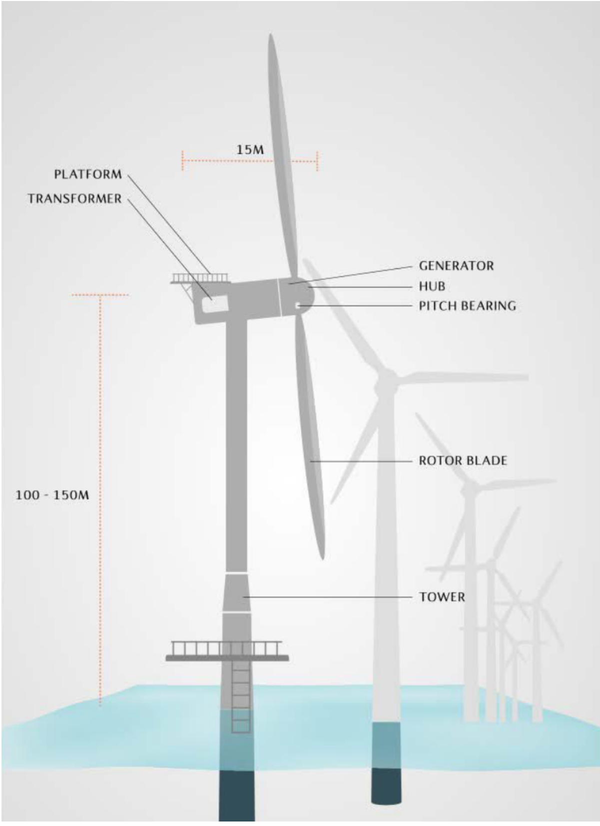


Figure 2.1: Components of an offshore wind turbine (Equinor, 2020)

An onshore turbine structure needs a solid concrete slab foundation that is heavy enough to withstand bending moments and movements induced from wind acting on the turbine. For an Offshore Wind Turbine (OWT), four additional factors must be considered when designing the foundation for the wind turbine; water depth, soil condition, wave load, and frequency induced by the turbine.

Tower

Large sections of steel plates that are cut, rolled and welded together form the cylindrical tower structure. The tower can either be assembled section by section at the installation site or pre-assembled at the port. It provides support to the wind turbine configuration and balance of plant components such as the transformer, yaw motor, communication, and power cables. The tower height is determined by clearance above the water level and rotor blade diameter size. Today, the total height, including the hub, is approximately 90 meters in addition to foundation height above the seawater level. The expected wind load and weight of the nacelle determine the strength and diameter of the tower. The turbine nacelle requires access, so a ladder or an elevating mechanism is provided within the tower (Manwell et al., 2009).

Rotor

The design purpose of the rotor is to extract power from wind and convert this to rotary motion. The rotor includes the hub, which is a steel cast structure, and blades which are airfoils made of composite or reinforced plastics. The primary function of the hub is to transmit and withstand all of the loads generated by the blades. It connects the blades to the main shaft and to the rest of the drive train. The blades are devices for converting the wind force into torque that is needed to generate useful power (Manwell et al., 2009). Over the last decade, the rotor diameter has steadily increased in size, resulting in the increased capacity of wind turbines.

Nacelle

The nacelle is a large and heavy unit that houses the shaft, gearbox, generator components, communication cables, environment maintenance, and monitoring equipment. The nacelle consist of the mainframe and a cover where a gearbox, generator, and brake are attached to the mainframe Manwell et al., 2009. The shaft rotates with a lower frequency which is then amplified in the gearbox to an appropriate level for the electricity generator. A mechanism called a yaw system is used to align the nacelle with the direction of the wind. The reaction loads and rotor loads are transmitted from the generator and break to the tower.

Foundations

The foundation of an OWT structure is an important component regarding stability. The foundations are subjected to axial forces from the turbine support structure and cycle loads from extreme wave loads. When designing a foundation, it needs to resist hydrodynamic loading cycles that vary with direction, amplitude, and frequency. Offshore wind production is much more complicated than onshore regarding the design of wind turbine systems and operation sites. Today, several innovative foundation designs have been constructed for the offshore wind industry, both bottom-fixed foundations and floating structures, some of which are shown in figure 2.2. Bottom-fixed foundations are typically used for a wind farm where the water depth is not greater than 50m. The interest for floating structure solutions has increased due to several coastal countries such as USA, Japan, and western European countries having limited coastal areas with water depth less than 50m (Wu et al., 2019). Foundation designs typically used for bottom-fixed wind turbine structures are gravity-based, tripod, monopile, and jacket. For floating wind turbines, mooring systems which are anchored to the seabed are necessary.

Figure 2.2: Foundations used in offshore wind industry (Equinor, 2020)

Floating wind turbine concepts

When the water depth increases, floating structures with a mooring system are a better option. The floating structure needs to have sufficient buoyancy to support the weight of the wind turbine. In addition, pitch, roll, and heave motions have to be within acceptable limits. There are three main concepts for floating wind substructures: ballast stabilized, mooring line stabilized, and buoyancy stabilized. Stability is achieved with a ballast stabilized concept through righting moments caused by ballast below the center of buoyancy. With a mooring line stabilized concept, the stability is achieved by excess buoyancy for providing tension in the mooring lines. Stability is achieved with a buoyancy stabilized concept by optimal positioning of buoyancy elements in the substructure (Bjerkseter and Ågotnes, 2013). Inspired by floating structures from the oil and gas industry, wind turbines are installed on floating structures such as semi-submersible, Tension Leg Platform (TLP), and spars, as shown in figure 2.3.

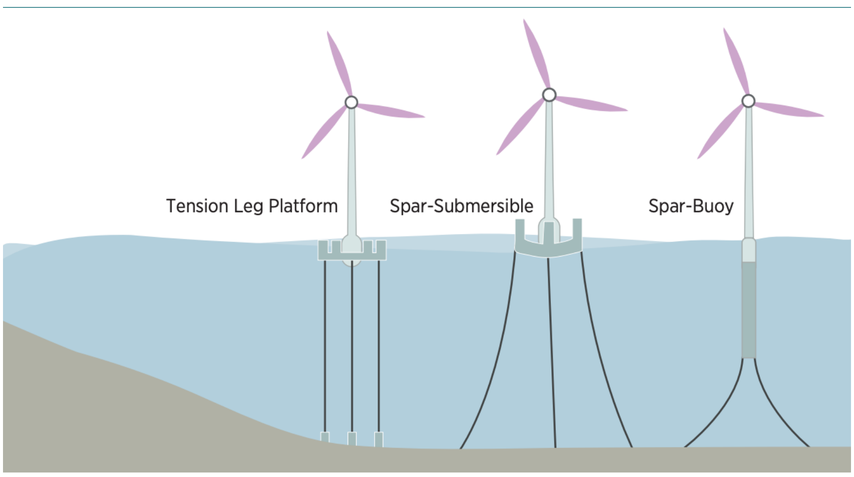


Figure 2.3: Floating offshore wind foundation concepts (IRENA, 2019)

The floating offshore structures are tethered through mooring systems which are anchored to the seabed. Wind energy utilization at deep water is steadily increasing due to improved technology development of having wind turbines installed on floating structures with mooring systems based on different anchorage types. A description of the most commonly used floating concepts are listed below:

- **Tension leg platform**: The TLP is a semi-submersible floating wind structure that is connected to the seabed with vertical tethers that are anchored using suction anchors or suction caissons. It has three columns that are connected with horizontal pontoons to a center column for supporting the turbine. The mooring lines provide a stable structure that enables damping of the vertical movements (Suzuki et al., 2011).
- **Semi-submersible**: A semi-submersible wind foundation has the main structure partly below the water surface to reduce the impact of wave loads and global motion. It is stabilized by the waterplane area of large and heavy columns connected by braces where the turbine is located either on one side column or center column if there are 4 columns. It is fastened to the seabed with a conventional mooring system with components of chain and polyester connected to anchors (Liu et al., 2016).
- **Spar**: A cylindrical structure of either concrete or steel with ballast where the center of gravity is below the center of buoyancy ensures stability. The Spar is connected to anchors on the seabed with a 3-line catenary mooring system of steel cables and/or synthetic fiber ropes (Tomasicchio et al., 2018).

Anchors

The type of anchors most used for floating structures is drag embedment anchors, vertically loaded anchors, and suction anchors. Drag embedment anchors are one of the most popular anchors and use the resistance in front of the anchor to stay in place. They are designed to withstand large horizontal loads but not large vertical force components. The vertical loaded anchor is installed in the same way as the Drag Embedment Anchor (DEA) but is designed to penetrate much deeper into the seabed. This anchor type can withstand vertical and horizontal forces and is often used when the entire mooring lines are lifted from the sea bottom. The suction anchor has a cylindrical shape attached with a close top and a pump. When the suction anchor is lowered to the seabed, the water inside the anchor is pumped out and creates low pressure inside the cylinder. The anchor will sink into the seabed and is suited to withstand both vertical and horizontal loads (Vryhof, 2005). In the selection and design of which anchors to use for mooring, there are two primary design considerations (Ma et al., 2019) that needs to be investigated:

Structural design- Anchor design needs to be evaluated under the following loads:

- Maximum loads that are imposed by the anchor line
- Maximum loads imposed during both transportation and installation
- The fatigue damage experienced over the lifetime

Geotechnical design- Anchor design needs to be evaluated under the following analyses:

- Soil condition should be analyzed to determine soil reactions acting on anchor. Before the engineering and installation phase of the floating wind project, it is necessary with a site investigation. The investigation can provide essential information such as subsea terrain, topography, soil properties. With the gathered information, the anchor location and anchor size can be determined. Soil strength is expressed in terms of shear strength parameters of the soil, where undrained shear strength is a key parameter for anchor design.
- Geotechnical holding capacity needs to be analyzed to determine the required anchor size and embedment depth of anchor to achieve the desired capacity.
- Ability check of anchor to achieve required embedment and ease of removal.

(a) Drag embedment anchor (Ma et al., 2019)
(b) Vertical loaded anchor (Ma et al., 2019)
(c) Suction piles (Ma et al., 2019)

Figure 2.4: Most used anchor designs for floating structures

Interarray cables

Once the wind turbine structure is installed, the power cables are used for interconnecting the turbines and the wind farm to the electrical grid onshore. Depending on the type of wind farm installed, both inter-array cables and export cables are required. An inter-array cable voltage ranges between 30-36kV and is used to connect the offshore wind turbines to an offshore substation. Depending on rotor diameter and requirements for minimum spacing between two turbines, the length of the cable between wind turbines is usually less than 1500m. For those turbines connected directly to an offshore substation, the length of the cable can possibly is longer, up to 3000m. As mentioned, the standard operating voltage is 33kV for offshore wind distribution, but 66kV cables are being investigated for future usage (Srinil, 2016a).

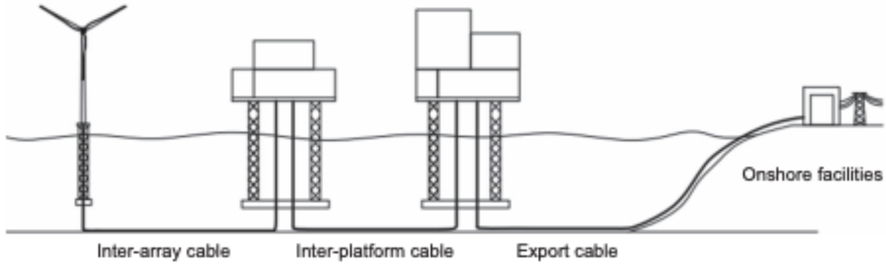


Figure 2.5: Cable for floating turbine, substation and converter (Srinil, 2016a)

Export cables

The primary function of the export cable is to transmit the generated electrical power to the onshore transmission system at the landfall point. The export cable is buried down in the seabed, and it can operate with High-Voltage-Direct-Current (HVDC) or High-Voltage-Alternating-Current (HVAC) technology. If the export cable is operating with HVDC, an AC/DC offshore converter and DC/AC onshore converters station are required. HVDC has the greater advantage when it comes to transmitting a large amount of power over long distances due to reduced power losses compared to an HVAC transmission system. Factors that determine the cable route for the export cable are water depth, soil condition, existing infrastructure on the seabed, and coastline type (Srinil, 2016a).

Dynamic cables

As floating wind turbines are not fixed to the seabed, dynamic, robust power cables are needed to resist motion. These require a high degree of flexibility, compliance with the motion of the Floating Wind Turbine (FWT), and fatigue resistance to the dynamic environment. Critical aspects of a dynamic cable design being connected to the FWT are the combination of waves and current effects, seabed touchdown interactions, and motion from a top-end floater. Cable configuration concepts that are in use for floating wind are similar to the same configuration of offshore risers for transporting oil from the seabed in the oil and gas industry. The W-type cable concept shown in figure 2.6 can be used to connect two wind turbines or floating substations and floating turbine (Srinil, 2016a). The lazy wave concept is more preferred for inter-array, interplatform, and export cable configuration as shown in figure 2.7. The latter concept has been used in the Hywind project of Equinor.

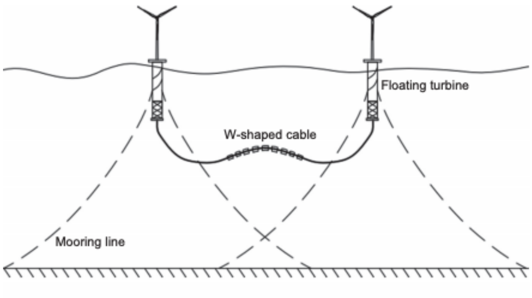


Figure 2.6: W-type shape cable configuration (Srinil, 2016a)

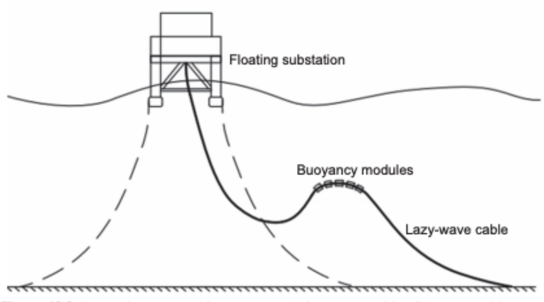


Figure 2.7: Lazy wave shape cable configuration (Srinil, 2016a)

Substation

Windpower offshore substation is a key for submarine electric power transmission systems. It receives the generated power from the wind turbines and exports it to the grid on land. In some cases, wind farms have the substation installed onshore, but the majority of the wind farms today have the substation(s) installed offshore. The operating wind farms today usually have only one substation, but it is expected that for the future, larger wind farms will require several substations if the expected energy output greater than 500MW (Anaya-Lara, 2016). Offshore substation structure can be divided into two main structures; (1) support structure and (2) topside. The support structure includes the foundation structure and substructure, where the purpose is to transfer loads from the topside and support structure to the seabed. The topside contains electrical equipment such as transformers, high-voltage (HV) and medium-voltage (MV) switchgear, backup diesel generator and tank, accommodation facilities, j-tubes, and medium- and high-voltage cables (Srinil, 2016a).

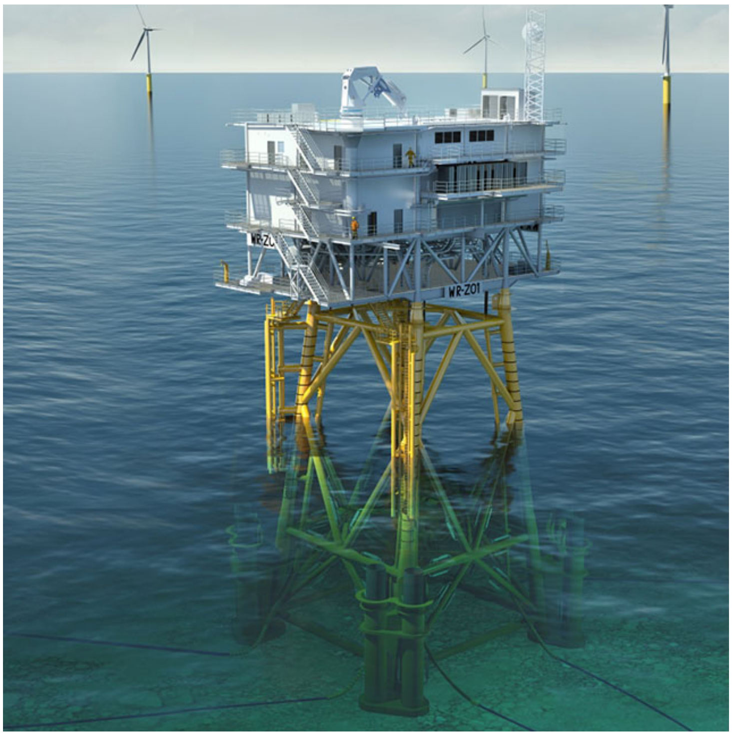


Figure 2.8: Offshore substation (Ramboll, 2016)

2.2 Offshore wind life cycle cost analysis

The life cycle cost analysis of offshore wind helps decide between fixed and operating costs to minimize the total life cycle cost, where one should consider minimizing the costs per energy unit produced (Bjerkseter and Ågotnes, 2013). In different wind farm concepts, the total life cycle cost can be divided into five life cycle phases: (1) Development and consenting, (2) Production and acquisition, (3) installation and commissioning, (4) operation and maintenance, and the final phase (5) decommissioning. To realize the benefits of floating wind, one should investigate the installation and commissioning phase. In order to make the Levelized Cost of Energy (LCOE) of floating wind more competitive to bottom-fixed, the CAPEX needs to be reduced by half. This is possible to be realized through improved installation methods. Figure 2.9 shows the CAPEX breakdown of floating wind foundations where installation accounts for approximately 13 %.

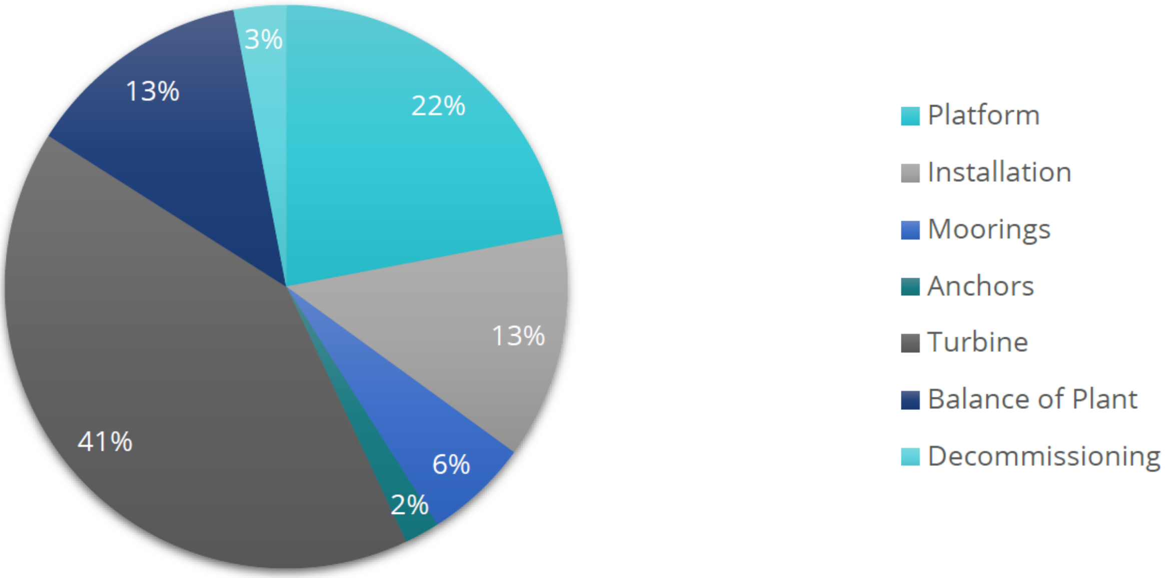


Figure 2.9: CAPEX breakdown of floating wind foundations (Harrison et al., 2020a)

Vessels are the largest cost contributors of the installation followed by labor and duration as shown in figure 2.10. By achieving simpler and faster installation methods, the cost contributors can be reduced. Improvements can be achieved by factors such as larger weather windows, cheaper installation vessels, and reducing the total installation time. These factors will be the primary focus for suggested cost-effective solutions in the master thesis.

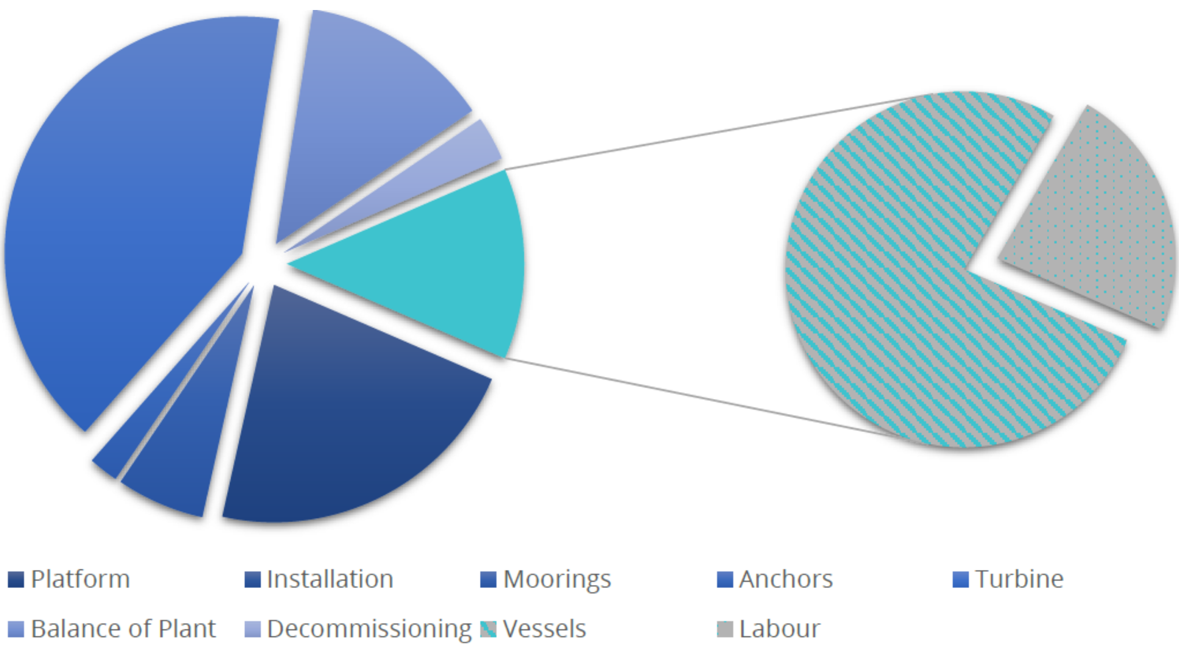


Figure 2.10: CAPEX breakdown of floating wind installation(Harrison et al., 2020a)

2.3 Vessel requirements for offshore wind installation

When planning and developing an offshore wind farm, there are several requirements for vessel selection that need to be taken into account. For selecting a vessel to execute a specific task or operation, the vessel performance characteristics need to be considered. The typical factors that may be required in the development of a wind farm may be as follows:

- Port selection
- Transport
- Lifting and installation of several and different structures/components.
- Laying of cables (inter-array cable and export cable)

For the above installation and operations tasks, the selection of what type of vessel to choose depends on the following criteria:

- Get a good and structured overview of what is to be installed.
- Environmental conditions; the water depth at the installation site. Floating or bottom-fixed turbines?
- What are the vessel requirements to be met?
- Costs or budget

From the above criteria, vessel requirements are the most crucial and can be divided into two main categories; (1) basic requirements of the vessel to ensure safety and performance and (2) what functional requirements the vessel needs for carrying out the intended installation task. In the following sections, both requirements are described in further detail.

2.3.1 Basic requirements

When choosing a vessel to carry out offshore operations at offshore wind farms, performance and strength are the basic prerequisites (Bai and Bai, 2010). The vessel performance during offshore installation are as follows:

- ***Stability***: Here, stability means that the vessel can return to its original position once forces or moments applied on it have been removed. The stability can be divided into two main classifications; (1) stability with a small inclination angle less than or equal to 10 ° and (2) large inclination angle. The initial stability shows a linear relationship between the up-righting moment and the inclination angle.
- ***Buoyancy***: Under a specific loaded condition, the vessel shall be buoyant. In practice, the vessel can experience four types of buoyancy conditions; trim, heel, upright, or a combination of these.

- ***Sea-keeping***: Sea-keeping means that the vessel can remain safe during operation and maintain its position while exposed to strong forces and moments induced by waves, wind, and ocean current.
- ***Manoeuvrability***: With maneuverability, it means the capability of the vessel to hold a constant direction or change of direction determined by the pilot.
- ***Insubmersibility***: Insubmersibility means that if one or several spaces are flooded, the vessel can remain buoyant and stable. The vessel in all stages of the marine operation shall have sufficient stability and adequate reserve buoyancy.

How resistant the vessel is to failure can be measured by its strength. Strength failures, stability failures, and fatigue failures are the three types of failures the vessel structure can experience. These failures are explained in further detail below:

- Strength failure: This is when the stresses of the vessel are larger than its specified minimum yield strength.
- Stability failure: Occurs when structure experiences large displacements due to the comprehensive stress being larger than the critical stability stress (Euler stress).
- Fatigue failure: Occurs when vessel structure experiences continuous stress circulations, which can result in cracks or fracturing. During vessel activities such as load-out, lifting, and transportation, the strength needs to remain intact.

2.3.2 Functional requirements

As mentioned, vessels are classified based on their functional requirements. A surface vessel can be described as a stable platform that sustains certain equipment that is necessary for performing specific ocean activities. Before the vessel starts its operation, the specific equipment is mobilized on board at the port and demobilized once the operation is completed. Mobilization and demobilization are both time-consuming and costly, so specialized purpose-built vessels are used in order to reduce both time and cost. Types of specialized vessels can be a Wind Turbine Installation Vessel (WTIV), anchor handling vessel, cable lay vessel etc. The main differences in functional requirements between an installation vessel and a Cable Laying Vessel (CLV) are the requirements for the specific equipment. In the following sections, critical features for both vessel types are discussed (Bai and Bai, 2010).

Function requirements for an installation vessel

The structure components used for assembling a wind turbine are usually installed using an installation or construction vessel with sufficient crane capacity, winch rope, and with or without heave compensator. A typical vessel for installation can be a WTIV, heavy lift vessel, or a jack-up vessel. For offshore installation, vessels need to have critical features such as:

- Crane capacity

- Deck space for equipment
- Deck load
- Vessel response amplitude operators (RAOs)
- ROV requirements, working-class ROV or survey RAO
- Accommodation
- Transit speed as wind farm site is often far from shore
- Positioning, i.e., DP systems. Offshore installation operations should be executed in an accurate, timely, and safe manner by considering all the limitations such as weather conditions, visibility, or other constraints (mooring systems, subsea installations etc.).

Vessel for wind turbine cable laying

A CLV needs to include the following additional requirements for some specific equipment/devices compared with an installation vessel:

- Winch abandonment and recovery: Required at the end of cable lay operation and if an emergency situation arises.
- The capacity of davits: Often required during offshore connection of cables when davit activities are necessary.
- Capacity of tensioner: Required based on buoyancy, water depth, and unit weight of the cable.
- Product storage capacity: This is required if the cable cannot be transferred from a feeder or storage barge to a cable lay vessel due to bad weather conditions.

The method used for installing cables in deep water is the J-lay method, where the cable is installed in a J-shaped configuration. It enters the water at a certain angle that is governed by the water depth, the submerged weight of the cable, and applied horizontal tension. It is important that the cable lay vessel maintains its position during installation to avoid bottom tension decreasing to minimum or compression forces that can damage the cable at touch down (TD). Waves and current can push the vessel from its position, and once the cable is being paid out, it will pull on the vessel. Therefore accurate DP systems are needed during cable lay installations, and the CLV often has multiple powerful thrusters to keep the required position at all times (Våben and Gudmestad, 2018). Figure 2.11 shows an overview of the cable laying process.

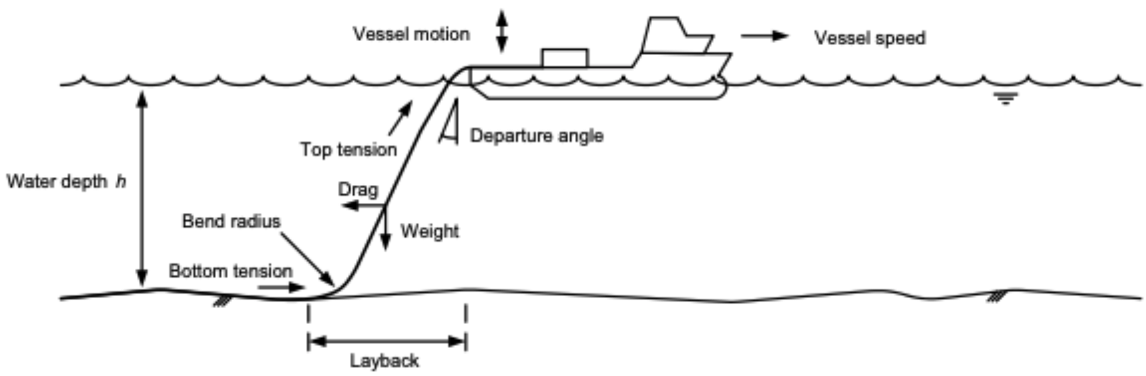


Figure 2.11: Cable laying process (DNV, 2016a)

2.3.3 Installation method of floating wind turbine

The installation and operation of an offshore wind farm can be divided into three phases; site investigation, installation, and commissioning, operation, and maintenance (Baldock et al., 2014). The installation phase is a complex phase to carry out that can involve many specialized vessels. Today there is a large variety of different concepts that have been developed and are being developed. For a wind turbine, the main components are the tower, the nacelle, and the blades. The wind turbine then needs to have a structure to be fixed onto, either a fixed-bottom foundation or a floating structure. A floating wind turbine can be assembled as a whole unit in port and then towed directly to the installation site (Bjerkseter and Ågotnes, 2013). Another alternative is to tow out the floating substructure and then use a heavy lift vessel to assemble the nacelle and rotor at the installation site. However, the floating wind turbine needs to be ballasted for maintaining operational depth and stability for both alternatives. When the floating wind turbine is in the correct position, a specialized vessel such as Anchor Handling Tug and Supply (AHTS) connects the wind turbine to the mooring system. The final phase is to connect the installed power cable to the wind turbine, which is done by a cable laying vessel (Camilla Knudsen Tveiten ; Eirik Albrechtsen, 2011). Installing a floating wind turbine such as TLP FTWs, semi-submersible, and spar requires less specialized vessels as used for bottom-fixed wind turbines. This is one reason why floating wind farm projects are becoming larger and larger as they can be more cost-competitive than the bottom-fixed turbines. The advantages and disadvantages of the different floating offshore wind concepts can be summarized in table 2.1.

Floating wind concept	Spar	Semisubmersible	TLP
Advantages	- Excellent design. - Design and fabrication are simple. - Towing of turbine in vertical position.	- Assembly onshore. - Good for a range of water depths. - Disconnect and towing for maintenance is easy.	- Excellent heave motion. - Assembly onshore. - Hull size is compact. - Small environmental foot print.
Disadvantages	- Heavy lifting vessel when installed offshore. - Deep draft requirements.	- Relative large motions. - Requires large amount of ballast, results in large displacement.	- Possibility of no stability upon tether failure. - Disconnecting is hard. - Suction anchors or driven piles are required.

Table 2.1: Floating wind concepts summarized

Installation of mooring systems

There are several different mooring systems used for floating wind turbines. The most traditional mooring lines are catenary lines and compiled of chain and steel wire. The catenary lines are installed in a hanging slope from the floating wind turbine down to the anchors. Another option is taut mooring, where the mooring lines are fastened with a tension that holds the line in a linear shape between the floating structure and anchors. The taut mooring configuration depends on elasticity, where the use of synthetic ropes provides the elasticity. Catenary lines have been used as moorings lines for the Hywind Scotland project, and the same mooring system will be used for Hywind Tampen. The mooring system consists of three clusters with one line per cluster. The mooring lines can consist of either steel wire ropes, chains, synthetic fiber ropes, or a combination of these. The mooring lines for Hywind Scotland consist of chains, while the mooring lines in Hywind Tampen will consist of steel wire ropes. Each turbine in both Hywind Scotland and Hywind Tampen is connected to three suction anchors (Jiang, 2021).

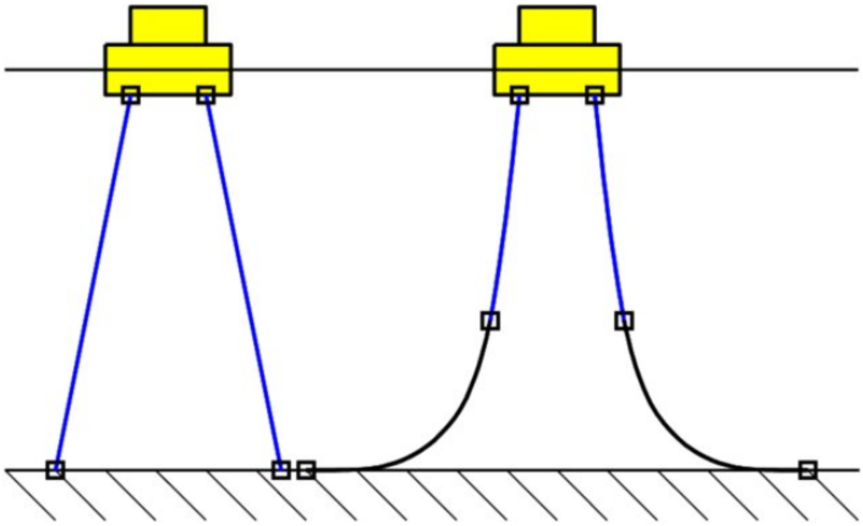


Figure 2.12: Configuration of taut mooring system and catenary mooring system (Weller et al., 2013)

Installation method for TLP

The TLP floating wind turbines are less commercialized than spar and semi-submersibles floating wind turbines due to the complexity in anchor systems and installation (Jiang, 2021). The tethers that are connected to the TLP are usually pre-installed. The tethers are dry towed out to the site with a barge, and a crane vessel will then lift and upend the tethers into place. Then a fully assembled wind turbine is towed out to the site from onshore with the use of tugboats. On-site, the TLP will be ballasted until it is connected to the tethers. Then the tethers are pre-tensioned by removing ballast water from the wind turbine. More cost-effective and less time-consuming installation methods must be developed to accomplish a full commercializing of TLP floating wind turbines. Several different installation methods have been suggested for reducing complexity, such as a tension device to complement the time-consuming process of de-ballasting the TLP during tether tensioning. Another suggestion is to tow out the TLP on a floating slab where the floating slab is ballasted on-site, submerging the TLP to its final draft.

Installation method for Semi-submersible

One of the features of semi-submersibles floating wind turbines is the superior tow ability. A good example is the Windfloat design, where the assembly of the turbine took place onshore in a dry dock. When it was fully assembled, the turbine was then towed to the site and tied to a pre-installed mooring system. The towing operation only required three tug vessels, where an AHTS assisted in the hook-up operation. With this installation process where assembling is carried out in a dry dock, maintenance and repair could also be carried out in a dry dock. Another semi-submersible design has been developed, and all of the design has the same installation superiority (Jiang, 2021).

Installation method for Spar

Two different method alternatives for the installation of floating wind turbines are shown in figure 2.13 and figure 2.14. The first alternative is to assemble the wind turbine to substructure at the port with either an onshore crane or a heavy lift vessel. The wind turbine is then towed with tugs or AHTS vessel to the site, hooked up to the mooring system, and connected to the cable power. The other alternative is to tow out the substructure horizontally and transport the wind turbine with a transport vessel. A heavy-lift vessel will assemble the wind turbine to the substructure at the site (Jiang, 2021).

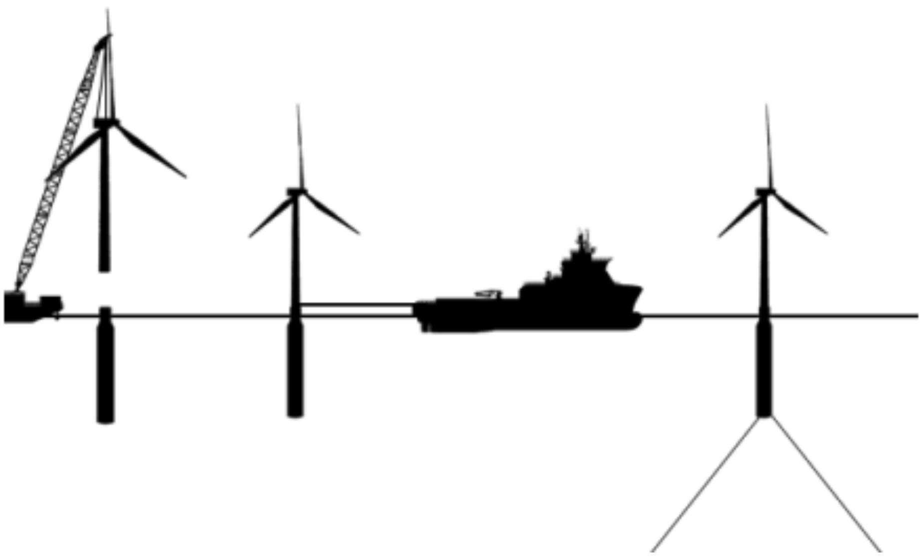


Figure 2.13: Towing complete assembled turbine from port to site (Bjerkseter and Ågotnes, 2013)

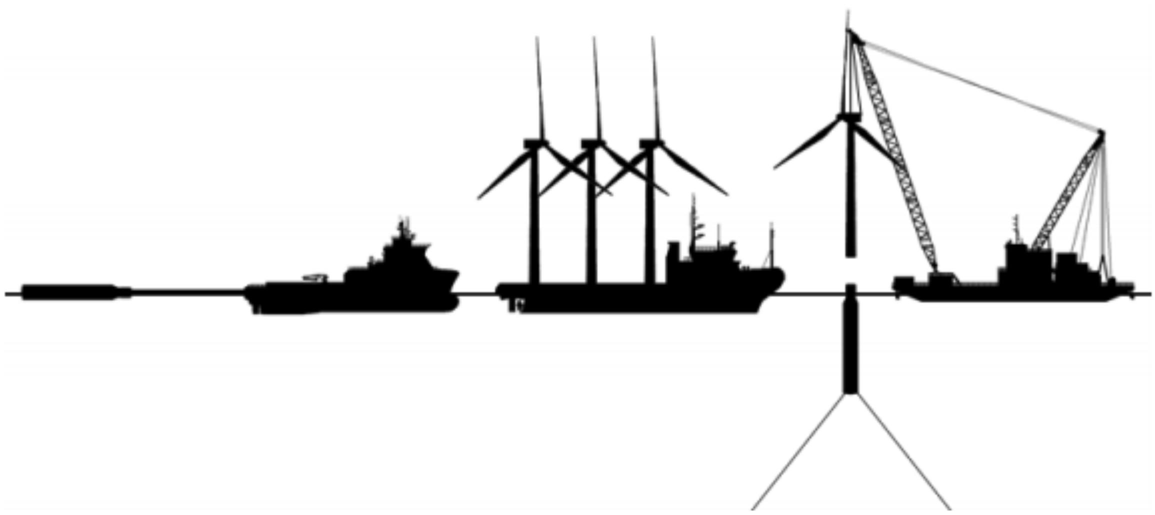


Figure 2.14: Towing of floater and wind turbine installed at site (Bjerkseter and Ågotnes, 2013)

Vessel selection for floating wind turbine

Selection of which type of vessel to be used in the fleet for different operations in installation for an FWT is made through the planning phase. This can be divided into four main phases developed by Pahl and Beitz. The phases are planning and task clarification, conceptual design, embodiment design, and detail design (Pahl et al., 2007). With these phases, vessels can be selected based on requirements and their functions. Table 2.2 shows different types of vessels that can perform different installation tasks based on requirements and vessel capabilities.

Operation task	Functions	Requirements	Vessel type
Transport of substructure	- Lifting - Transport	- Crane capacity - Deck space - Speed - Accomodation	- Transport vessel - Tug vessel - OSV
Assembly of turbine	- Lifting - Sea-keeping	- Crane capacity - DP system	- Heavy lift vessel
Anchor- transportation and installation	- Transport - Lifting - Monitoring	- Deck space - Crane capacity - ROV - DP system	- AHTS - OSV
Tow out	- Transport - Bollard pull	- Speed - Accomodation - Power	- Tug vessel - AHTS - OSV
Hook-up	- Positioning - Lifting - Monitoring	- DP system - Crane capacity - ROV	- AHTS - OSV
Cable installation	- Cable laying - Sea-keeping - Monitoring - Lifting	- Cable lay equipment - DP system - ROV - Crane capacity	- Cable laying vessel
Final commissioning	- Quality control - Sea-keeping	- DP system - ROV - Gangway	- SOV

Table 2.2: Operations requirements and vessel capabilities

2.3.4 Installation vessels for floating wind

There are several specialized vessels involved in the installation phase of OWT due to complex marine operations. The vessels involved are selected based on market availability, budget plan for installation tasks, and wind turbine technology. Over the last decade, where the offshore wind industry has experienced growth in the number of wind farms and larger wind turbine capacity, specialized vessels have been built. WTIV is one of the main specialized vessels that have been built for the installation of bottom-fixed foundations. However, as the wind industry is moving into deeper water depth, the demand for floating structures is increasing. Floating structures allow fewer offshore operations and reducing the requirement for expensive specialized vessels. The most commonly used vessels used for the installation of FOWT are presented in the following sections.

Heavy lifting vessel

A heavy lifting vessel (HLV) is defined as a large crane vessel with lifting capacities of up to one thousand tonnes. When large structures such as subsea templates are installed offshore, HLV is often required. In the offshore wind industry, HLV is often used for installing and removing substations, turbines, or foundations (Bai and Bai, 2010). Compared with a typical construction vessel with a lifting capacity below 250 tonnes, the lifting capacity range of most HLV is between 500 to 1000 tonnes. Essential characteristics of HLV are stability and sea-keeping abilities. They can generally be categorized into two groups: (1) non-propelled heavy crane barges and (2) self-propelled heavy crane vessels.

Figure 2.15: Heavy lifting vessel Ulstein(ULSTEIN, 2018)

Tug

Tugs are a specialized working vessel that performs operations or tasks such as pushing, towing, supporting dive operations, transporting personnel and equipment, surveying, and similar operations. Tugs are capable of towing structures with weight up to 5-10 times their own weight due to the powerful engines. The factors that contribute to the power produced by the tug are engine size, engine type, propeller size, shape, and size of the tug. Tugs typically have a transit speed between 8-12 knots and have this speed when towing barges in the open sea. All tugs are equipped with powerful fire-fighting equipment. The three major tug categories based on the operation purpose are ocean-going tugs, harbor tugs, and river tugs. Ocean-going tugs are the tugs that are used for transporting and installation in the offshore wind farm industry. Harbour and river tugs have engines that can produce 500-2500Kw output power (680-3400 horsepower), and ocean-going tugs have much larger engines that produce up to 20 000Kw output power (27 200 horsepower). Most of the tugs that are in operation today have 2-stroke engines since these have a higher power-to-weight ratio compared to 4 stroke engines (Douglas-Westwood, 2013).

Figure 2.16: Offshore tug (KoTug, 2018)

Offshore support vessel

Offshore Support Vessels (OSV)s, as shown in figure 2.17, are often needed in various stages of offshore wind operations such as installation, maintenance, decommissioning. Several different types of OSV are typically used in the offshore wind industry, such as Ocean Going tug, Platform Supply Vessel (PSV), AHTS and Offshore Construction Vessels (OCV) (Erikstad and Levander, 2012). In general, towing operations in the offshore industry require powerful machinery and strong bollard pull to tow large offshore constructions. Both the ocean-going tug and AHTS vessels are typically used for towing operations as they are designed for the needed requirements. The AHTS vessel and ocean-going tugs can maintain high speed and are suitable for rough conditions. However, the ocean goings tugs often have much lower bollard pull than ATHS vessels, as they are often used as support in towing operations (Kopits and Losz, 2013). For towing FWTs it is often used a combination of ocean-going tugs and AHTS vessels. When selecting these vessels for an operation, the parameters that influence is bollard pull, deck area, maneuverability, and total power.

Figure 2.17: Offshore support vessel (BOSKALIS, 2013)

Anchor handling supply and tug vessel

Floating wind structures are moored with mooring lines anchored to the seabed. Choosing an anchor concept is based on mooring configuration, seabed conditions, and the required holding capacity. For installing the anchors in offshore industries, either Anchor Handling Tug (AHT) or AHTS vessels are used. The AHT is designed for transporting/installing anchors or towing drilling vessels, or similar vessels. The AHTS is a combination vessel of supply and anchor handling services and can also tow offshore platforms, barges, and production modules/vessels (Chen, 2013). These vessels are designed for operating in harsh environments and have equipment for anchor handling services. When the FWT is assembled, the AHTS will connect the mooring system to the installed anchors holding the turbine in its operating position.

Figure 2.18: AHTS (“M/S «SKANDI ICEMAN» - Skipsrevyen.no”, 2014)

Cable laying vessel

A CLV is a specialized vessel that is used for laying and repairing cables at sea. The CLV has a turntable with 6000–7000 tonnes cable capacity or a carousel for loading, transporting, and installing cables as seen in figure 2.19. When laying cables, it is crucial that the vessel can maintain its position when the cable is paid out. Large tensions are acting from the cable onto the vessel, so most CLVs rely on a dynamic position system. Regardless of storage, the cable must always be held in tension to stay in place, and disorder is prevented. A pull-in team, together with the installation team, will guide the cable into the turbine using a Remote Operated Vehicle (ROV) assistance and/or sonar to monitor the operation ((OWPB), 2018).

Figure 2.19: Cable laying vessel (Management, 2017)

Service operation vessel

Service Operation Vessels (SOV) in the offshore wind industry is often referred to as Walk-to-Work vessels. They have been installed with motion-compensated gangways and are usually employed for cable installation and wind turbine commissioning phase. However, SOVs have been increasingly more involved in scheduled maintenance of wind turbines and substations. SOVs are designed for both installation and maintenance operations to have come to the offshore wind market since 2015. The motion-compensated gangways onboard the SOVs make transferring technicians and cargo easier and safer. One of the advantages of the SOVs is that technicians often have to work on a rotation of two weeks, so the SOVs follow the same work pattern. Since they can stay at sea for up to two weeks before reloading cargo and bunkering, technicians will increase their adequate work time on turbines. A positive effect of the performance of technicians is that SOVs have a good sea-keeping behavior that results in less motion-induced fatigue on the technicians (Hu et al., 2019).

Figure 2.20: Service operation vessel for offshore wind farms (ULSTEIN, 2017)

2.4 Floating wind concepts

Countries with shallow water depths have dominated the wind market so far due to the rapid development and possibilities of wind farms with fixed-bottom wind turbines. Offshore wind farms are also increasing in size. The average size of a commercial wind farm in 2010 was 313 MW, in 2019, this had increased to 612MW. The average water depth of offshore wind farms in 2019 was 33m. The development of offshore wind farms, however are heading further offshore and into larger water depths (James and Ros, 2015). Fixed-bottom foundations such as jackets or monopile have a water depth restriction of approximately 60m and are not economically beneficial at greater water depth than this. Floating wind technology makes it possible to exploit great wind potential further from shore and in deeper water areas, leading the way for growth in the offshore wind market. There were 9 floating wind farm installations operational in the world by the end of 2018, where the first commercial floating wind farm was Equinor's Hywind Scotland in 2017 (IRENA, 2019). In the following sections, several promising concepts of floating wind, both in operation and planned, will be presented and compared to fixed bottom concepts. Table 2.3 shows a quick overview of the different concepts.

Operational and planned floating wind concepts					
Concept name	***Floatgen***	***WindFloat Atlantic***	***Hywind Tampen***	***AFLOWT Hexafloat***	***GICON-SOF***
Classification	Caisson/ barge	Semi-sub	Spar	Semi-sub	TLP
MW	2	25	88	6	2.3
Depth range	33m	100m	100-500m	100m	37m
Moorings	3 catenary	3 catenary	3 catenary	3-6 catenary	4-leg taut
Turbine axis	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal
Developtment type	Demonstrator	Commercial	Commercial	Demonstrator	Demonstrator
Commercial Operation Date (COD)	2018	2020	2022	2022	2022

Table 2.3: Existing and future floating wind concept.

2.5 Weather

The weather has a significant influence on offshore operations where bad weather can result in long waiting-on-weather (WoW) windows where planned activities need to either wait or be rescheduled (Halvorsen-Weare and Fagerholt, 2016). The consequence of planning schedules without considering weather impacts the chances of delays and cancellations, resulting in higher costs. The forces that come from high wind speed and wave height are enormous and affect the safety of the crew and the performance of the operations. By awareness of weather impacts on the installation process, the undesired consequences can thus be minimized. Offshore installations are typically planned during the summer period when its more days of good weather than the winter period. The downside, however, is that charter rates typically increase and there is less availability of the necessary installation vessels.

Therefor, it is important to investigate the environmental conditions when planning and performing offshore operations, where the environmental conditions should be described in terms of characteristic parameters. The environmental conditions can be described using statistical data, realistic or statistical models, or mathematical models for representing the variations of environmental conditions (DNV, 2016b). For predicting how the environmental phenomena shall be considered, probabilistic methods for short-term, long-term, and extreme values should be used to establish statistical significance measures. The majority of installations studies use simple met-ocean parameters (wind speed, significant wave height, wave peak period) to determine the weather windows (Gintautas and Sørensen, 2017). Operations are assumed to be safe to execute when the met-ocean parameters are below predefined limits and not safe if one of the limits is exceeded. When predicting weather windows, weather forecast uncertainties must be taken into considerations.

The alpha factor method is used to address the weather uncertainties. Weather restriction may be reduced and making them more conservative with the alpha-factor. Weather restriction for a given operation and weather forecast is defined by equation 2.1:

$$OP_{LIM,WF} = \alpha_{OP_{LIM}} * OP_{LIM} \tag{2.1}$$

Where $OP_{LIM,WF}$ is forecasted operation limit criteria, $\alpha_{OP_{LIM}}$ is the alpha factor accounting for weather forecast uncertainties, and OP_{LIM} is the operational environmental limit criteria. The alpha-factor can be found in standards such as *DNV-OS-H101* (DNV, 2011).

Chapter 3

Problem description

In this chapter, the installation steps for FOWTs will be described in detail. The different steps of the installation process include, i.e., turbine assembly at the port, transport to offshore site, and connection of turbine to mooring system before traveling back to port. As there is no specialized vessel for FOWT installation, potential vessels will be investigated for the described operations. Based on the review of several papers on the installation of an offshore wind farm, the installation phase is a complex and challenging operation that requires a high-performance heterogeneous vessel fleet. As stated in chapter 2, offshore wind is not profitable today. One way to make offshore wind more attractive and profitable is that the costs need to be reduced. A way of accomplishing a reduction in cost is by developing a cost-efficient logistic strategy. The objective of this master thesis is to provide insight into the logistic installation chain and create two optimization models for the installation of FOWTs. The optimization models include decisions on scheduling and vessel selection. Regardless of the chosen FOWT concept, a floating wind turbine consists of a foundation structure, transition piece, tower, turbine, and rotor assembled in a predefined sequence. When the assembly stage is completed, the turbine will be towed to the site, connect to the mooring system and electrical cables. This process will be repeated until all the turbines at the wind farm are installed. Weather conditions and vessel limitations are factors that will influence the start time of the different installation operations. The optimal fleet will be determined by which vessel to use, the charter period of each vessel, and when to perform the different operations.

Hywind Scotland is the world's first fully commercialized installed floating offshore wind farm (FOWF), and the Hywind Tampen project is already on its way to being installed. When Hywind Tampen is fully commercialized and in operation, this will be the largest FOWF. The project's installation processes will be used as a basis for the optimization model in the thesis. This is because the installation process in the Hywind Tampen project is an excellent example of how to install FOWT. One of the major benefits of floating offshore wind is accessing deepwater sites further from shore. However, deep water sites are usually very far out from the shore and have rough environmental conditions. For floating wind the industry, there are still strict limitations of weather windows large enough for marine operations such as towing, mooring, and cable installation (Harrison et al., 2020b). Hywind Tampen wind park will be located 140km off the

Norwegian coast at a depth ranging between 260-300m. Their design of the spar turbines and installation strategy makes Hywind Tampen project an excellent example to use.

3.1 Installation strategies

The installation process of an offshore floating wind turbine can be divided into several operations. What operations need to be done depends on the chosen sub-structure for the offshore wind turbine. With a bottom-fixed concept, the assembly operations will be on-site while requiring more advanced and costly installation vessels. With floating concepts, the assembling of the turbines can be completed at port or in a fjord where the weather is favorable. No matter the chosen concept, the installation process is weather-dependent and takes place in the summer period. This is due to better weather conditions and fewer days of waiting on weather typically. In the decision process for installing offshore wind turbines, it is important to find a fleet composition that can perform all operations involved most cost-effectively. In this thesis, all the operations in the Hywind Tampen project are explained in detail, as it will be used as a basis for the optimization models. The following operations that are included in the project are as follows:

- Transportation of components
- Ballast of sub-structures
- Assembly of components
- Anchor transportation & installation
- Tow-out of wind turbines
- Hook-up
- Cable-laying
- Final commissioning

Before the installation process can start, several things have to be in place. This type of project requires a lot of logistical planning as several of the components are manufactured in different places in Europe. It is vital that port selection used for assembly and installation fulfill several requirements with a spar-buoy concept. The tasks that need to be carried out at the port have to happen safely, quickly, and cost-effectively. Both size and weight of wind turbines are large in the Hywind Tampen project, and therefore the port must be large enough to have suitable handling equipment. It is also desired to reduce traveling distance as much as possible, so ports close to the wind farm to save both costs and time. Finally, the size and depth of the port have to meet the requirements for the spar-buoy and the vessels involved. The essential port characteristics are summarized as the port's depth, distance to the wind farm, quay length, quay loadbearing capacity, component handling equipment, and seabed suitability.

3.1.1 Transportation of components

Most floating wind cases have the benefit of allowing more operations to be conducted onshore or port-side. However, onshore assembling requires that all necessary wind turbine components are located at the installation port. Depending on the offshore wind project, components can either be manufactured at the installation port or delivered by several different actors located at different ports. For example, for the Hywind Tampen project, only the sub-structures are manufactured locally, and several actors around Europe deliver the rest. This means that components have to be transported by vessels to the installation port where the turbines will be assembled. Since the components are often are large and heavy, the selection of transportation vessels are influenced by the following factors:

- ***Turbine class:*** Reflects on available deck space for a vessel. The required size of transportation vessels often increases with higher energy output as the wind turbines often increase in size (Sarker and Faiz, 2017).
- ***Pre-assembly method***: Decides the assembly method of structure to be transported. A higher level of pre-assembly of the wind turbine often increases the required number of vessel trips (Sarker and Faiz, 2017).
- ***Number of turbines:*** The number of either turbines or turbine components that are transported per cycle is important to the required size of the transportation vessel.

3.1.2 Ballast of sub-structures

When the steel or concrete sub-structures have arrived at the installation port, they will be unloaded of seawater and anchored in place at the port before the ballasting operation can start. The ballast of the spar-buoy is necessary to keep the center of mass low in the structure. The type of ballast that is typically used is either water or solid ballast. The ballasting operation consists of one phase or two phases, depending on the chosen concept of the spar sub-structure. The sub-structures in the Hywind Scotland project were made of steel material, resulting in two phases. The sub-structures were first pumped with water to make them vertical and achieved the required draft. Then the water ballast was replaced with solid ballast MagnaDense using a stone dumping vessel with DP (Lien, 2016). For the Hywind Tampen project, the sub-structures are made of concrete and can therefore be directly ballasted with 10 000ton solid ballast of Olivin at port (Equinor, 2019).

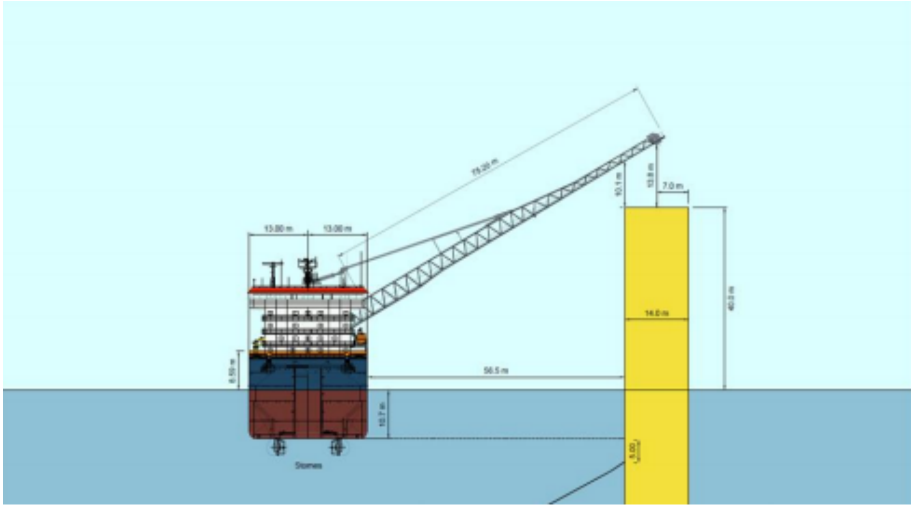


Figure 3.1: An illustration of ballast operation (Lien, 2016).

3.1.3 Assembly of components

When all the wind turbine components have arrived at the installation port, the assembly can start. A wind turbine usually consists of several individual components such as a nacelle, at least two tower sections, rotor blades, and a hub. The number of required lifts is dependent on the number of components the wind turbine consists of. There are different methods of assembling, and one way is components will be assembled together before final lift onto the sub-structure. When the top structure is ready to be attached to the sub-structure, a heavy lift vessel is needed. The installation port that was used in the Hywind Scotland project was not a deepwater port, so the heavy lift vessel Saipem 7000 was used for top-structure and sub-structure mating. Another method is to assemble the top-structure component by component directly onto the sub-structure like the illustration video (Kvaernervideo, 2019) of Hywind Tampen project. The sub-structure is connected to a barge at the quayside, and the onshore crane lifts transition piece in place, followed by tower sections, nacelle, and rotor blades.

Heavy lifting operations are weather-sensitive operations. This means to able to execute lifting operations, both wind and wave conditions as to be favorable. A wind turbine is designed to obtain as much wind as possible, so low wind speed during a lift is required. There will be a difference in wind speed between the top structure and ground, resulting in a probability that the rotor blades will experience higher wind speed. The same applies to the wave conditions. With the use of a heavy-lift vessel, the lift operation will be done from a floating structure to another floating structure. This will result in different movements that make the operation riskier and require a favorable weather forecast. As there will be an onshore crane in the Hywind Tampen project and the sub-structure is attached to a barge, wave restriction can be higher or event not relevant.

3.1.4 Anchor transportation & installation

Usually, the mooring installation takes place simultaneously as the onshore assembly operation is taking place. In the industry, a three-phase installation approach is the most preferred method where the following phases are: 1) Anchor installation, 2) mooring line pre-lay, and the final phase 3) hook-up to floating wind turbine. The three-phase mooring installation has the advantage of making the overall project more flexible. It also has the advantage of reducing costs in the third phase as a less expensive vessel can pick up and connect the pre-laid mooring lines. The complexity in the hook-up phase is reduced as most of the line segment connections were already made in the pre-lay phase. Suction anchor will be used in the explanation of the following phases as these anchors are used in the Hywind projects.

1) Installation phase

Before the installation can occur, the suction anchors need to be transported to the site by one large AHTS. If the deck space to accommodate the suction anchors is not large enough of the chartered AHTS, the suction anchors can be transported by a support vessel. If a support vessel is used, the AHTS needs to stay alongside the support vessel and pick up the anchors with a crane. The AHTS will lower the suction anchors down to the seabed with its crane and stop a few meters above the seabed. An ROV is used throughout the lowering operation to monitor and make sure that the suction anchors land in their position. When the suction anchor is in the correct position, the crane controls the lowering action to allow self-penetration into the seabed. An ROV pump is installed on top of the suction anchor when the self-penetration is complete. All evacuation valves are closed, and seawater is pumped out to create suction. When the required penetration depth is achieved, the suction pump is disconnected, and the butterfly valve is shut. This process is repeated for all the suction anchors that are needed for the wind farm project (Ma et al., 2019).

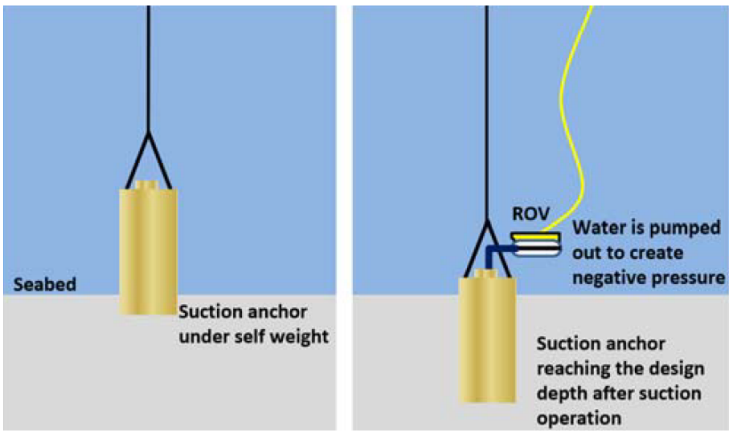
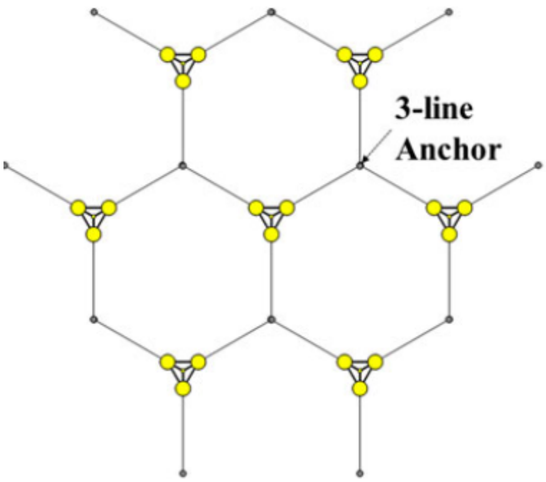


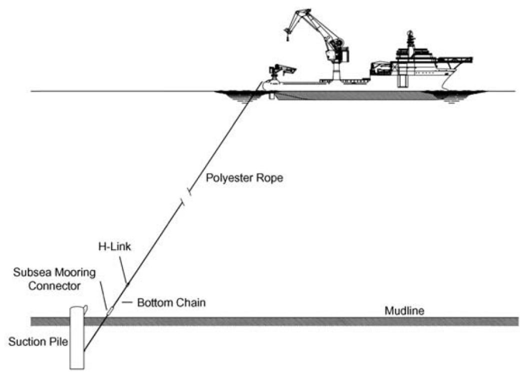
Figure 3.2: Mechanism of suction anchor (Ma et al., 2019)

2) Mooring line pre-lay

An ROV is used to survey the planned mooring lines routes to search for obstacles that may interfere. The seafloor survey makes sure that the mooring lines between the suction anchor and the turbine are free from obstacles. How many mooring lines are needed for a wind farm depends on the number of anchors and the anchor configurations. An efficient configuration will maximize the number of FOWTs connected to each anchor and minimize the number of anchors used to moor the FOWTs (Fontana et al., 2018). The anchor configuration in the Hywind project is the use of 3 mooring lines and anchors per FOWT as seen in figure 3.3a. The mooring line is then deployed from the AHTS, and an ROV connects the mooring line to the suction anchor. When the connection is completed, the mooring line can be slowly paid out and laid down on the mooring line route. This procedure will be repeated until all the mooring lines are pre-laid. The mooring lines will then be wet-parked, held by marker-buoys, and wait on the seabed until the hook-up operation (Ma et al., 2019).



(a) Wind farm configuration with 3-line Anchor (Fontana et al., 2018).



(b) AHTS ready to pre-lay the mooring lines (Ma et al., 2019).

Figure 3.3: Mooring line pre-lay operation

3.1.5 Tow-out of wind turbines

When the assembly operation is complete, the towing operation can start. The towing configuration of Hywind Tampen will consist of three towing vessels. One of the vessels, normally an AHTS, will be used for towing due to the high bollard pull, and the two other vessels are used to control the FOWT. For a more efficient and cost-effective towing strategy, each floating wind turbine will be installed one at a time – not in clusters (Backman, 2020). However, towing operation is a non-routine operation of limited, defined duration. The towing operaton shall be designed to bring the wind turbine from one defined safe condition to another safe condition (K. Larsen, 2020). Towing operation is usually defined either as weather restricted or unrestricted. If the planned towing operation is defined as weather restricted, the duration of the operation should be less than 72 hours. For weather restricted marine operation, the weather forecast must be within certain limits of the duration of the planned time period. This is referred to as reference time T_R and is defined as:

$$T_R = T_{POP} + T_C \tag{3.1}$$

where T_{POP} is defined as the planned operation period based on a detailed, planned schedule for the operation. T_C is the contingency time that includes general uncertainty in T_{POP} and possible contingency situations that will require additional time for completing the operation. The towing operation can not start until the weather forecast is below the operational criteria for the whole length of the weather window. The towing operation, seen in figure 3.4, in Hywind Scotland took four days meaning that the towing operation was classified as weather unrestricted (Lien, 2016).

Figure 3.4: Towing operation in Hywind Scotland project (Lien, 2016).

Hook-up

The pre-laid mooring system may have to sit on the seabed for a while, from a couple of months to a year, until the wind turbine is towed to the site. Once the wind turbine is towed to the site and weather conditions within the operational limits, the hook-up operation of mooring lines can commence. A vessel with high pulling capacity (AHTS) keeps the FWT in place, ready for hook-up to the mooring lines. The pre-laid mooring lines will first be picked up by the AHTS as shown in the first phase in figure 3.5. Then the wind turbine chain will be connected on the deck of the ATHS to the mooring line. Work wires are used to pick up the mooring line from the seabed onto the AHTS. Then the AHTS will slowly move away from the FWT while lowering and realizing the mooring line. Then lastly, a final pull-in and tensioning of the mooring line and the working wire is disconnected. This procedure needs to be repeated until all the FWTs are connected to the mooring lines. As a way to save cost in the Hywind Tampen project, some of the turbines will share the same anchor, resulting in 19 anchors instead of 33 (Equinor, 2019).

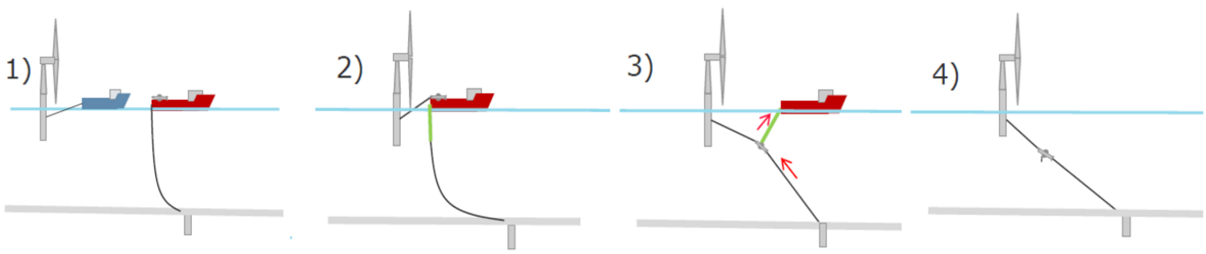


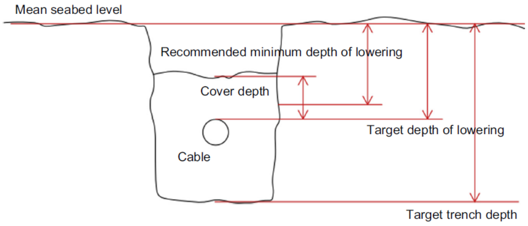
Figure 3.5: A illustration of hook-up operation (Haslum, 2019).

3.1.6 Cable-laying

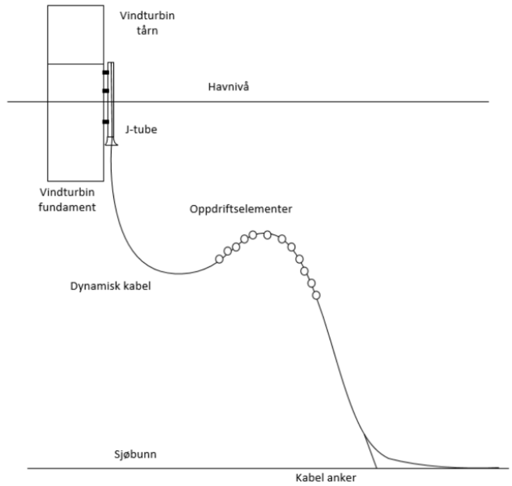
Cable-laying installation can start when the hook-up operation of the FTWs is completed. Before starting on the installation, the export power cable needs to be loaded onto the vessels. There are two different methods of cable loading, either direct or indirect (YE et al., 2018). With direct cable loading, the cable-laying vessel loads directly from the cable manufacture. With indirect loading, the cable is stored in storage tanks or drums and transported to the installation site. The most common loading method is direct loading due to larger cable lengths compared to the indirect method. Cable loading is often a very time-consuming task in the installation plan and can take between days and weeks. Loading, therefore, requires detailed planning, ensuring loading equipment, cable dimensions, and the layer carousel capacity. When cable-loading is complete, the cable-laying installation can start.

The cable-laying vessels pay out the cable over the planned route of for the FOWF. The cable is guided from a carousel through a drum where a brake system controls the pay-out rate. To ensure the correct tension on the seabed, the lay speed is generally between 0.25 and 3 knots. The lay speed can be influenced by weather conditions such as wave height, wind speed, and current. The weather can result in large vertical forces and too small a bending radius of the cable across the vessel stern. It is also essential to take into account mooring line and anchor arrangement in the planned route. Cables for FTWs consist of static and dynamic parts. The static part lays on the seabed while the dynamic part is connected to the FTW as seen in figure 3.6b. The static cable is pre-laid, while the dynamic cables can be installed and connected after FTW is in place or pre-laid and connected when FTW arrives.

The static cable then needs protection, which is done by trenching and cable burial. Trenching task is to make a trench with suitable depth in the seabed where the cable will be buried down. Where it is not possible to trench, the cable will be protected with rock. The cable installation method used in Hywind Tampen for the export cable will be buried in the seabed with a high-pressure water jet. The export cable will be buried 1-1,5 meters down in the seabed and use rocks to cover the cable where it's not possible to bury (Equinor, 2019). The pull-in operation and electrical connection are performed by use of an ROV.



(a) Trenching parameters (Srinil, 2016b)



(b) Cable configuration of Hywind Tampen (Equinor, 2019).

Figure 3.6: Cable overview of FOWT

Final commissioning

The final operation to complete before the wind farm can start producing stable power is final commissioning. In this phase, all the wind turbine components are tested and made sure they work properly. A specialized vessel with the ability to access the floating turbines is required so necessary personnel can finalize the project. The following test (P. E. Larsen et al., 2009) should be done in the final commissioning phase:

- **Site Acceptance Tests:** Make sure of communication between the FTWs and the electrical infrastructure.
- **Commissioning Tests:** Make sure that all wind turbine components are safe and operate. These tests include a run test of the generator, vibration level, proper cooling, yaw drives, cable voltage etc.
- **Completion Tests:** This test can be divided into two different tests:
  - Completion test on each individual wind turbine of continuous operation time of several days where parts of the run time include the generator that produces power to the grid.
  - Completion test on wind farm where all turbines are in continuous operation for several days. The same generator run test applies to the test of all the turbines at once.
- **Performance Test:** Test on different performance guarantees in the contract during a warranty period(5 years typically). These performance guarantees include that the wind farm is producing power and functions as stated in the contract. These tests are availability tests, power curves, electrical systems, and acoustic noise.

3.2 The relation between vessels and installation activities selection

The installation for a floating wind farm consists of several activities required to be executed within a time period and correctly. Figure 3.7 presents all the installation activities and different suitable vessels to perform each activity. This master thesis there will focus on marine operations, so the transport and assembly phase is not included in the optimization model.

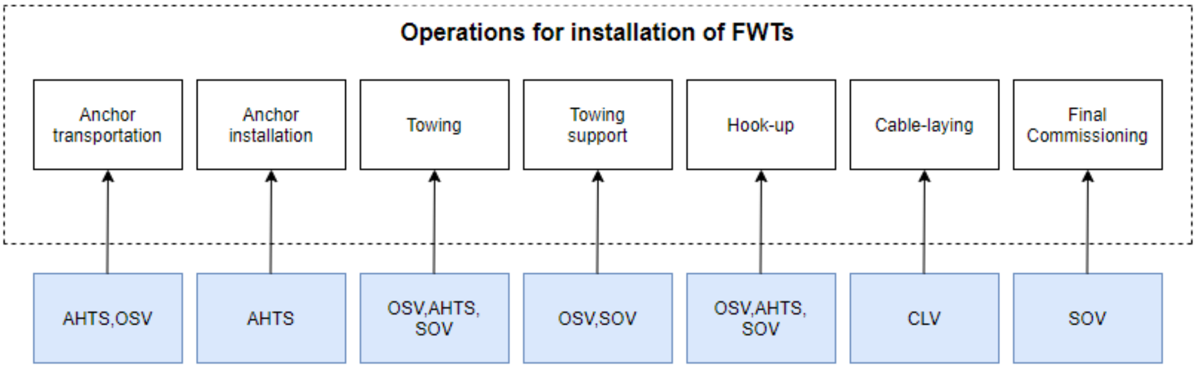


Figure 3.7: Relationship between installation activities and vessels

The anchor transportation activity requires sufficient deck space measured in m^2 and significant carrying capabilities, which is measured in metric tons MT to transport the suction anchors to the site. The vessels that have the requirements are AHTS and OSV. However, with the use of OSV for transporting the suction anchor, a vessel with sufficient crane capacity needs to lift them off the OSV. Only the AHTS have the requirements to install the suction anchors, as they have the necessary equipment.

Towing of an FWT is a weather-sensitive operation that requires a vessel with powerful machinery and high bollard pull. Both the AHTS and OSV can maintain the towing speed and suitable for rough conditions. In a towing operation, there are usually several vessels involved, depending on the floating structure. In this thesis, it is assumed that towing operation is supported by a second vessel. As the second vessel is used to control the turbine and not to tow, this operation does not require as much bollard pull, resulting in a less expensive vessel. The hook-up activity requires vessels that can pick up the pre-laid mooring lines on the seabed. Typically AHTS vessels are used for in hook-phase of the floating structure and mooring lines, and however, if the OSV is equipped with a crane, they can also be used.

The cable-laying vessel has the necessary load capacity to transport and install the cables to the wind farm. CLVs are equipped with dynamic positioning (DP) systems for keeping the vessel in position when laying cables. Cable installation requires several different types of equipment such as turntables or carousel to store the cables, cableways, rollers, pick up arms, and laying wheels. With the use of an ROV, the installation team can monitor the cable-laying operation. Some of the CLVs in use today have cable laying equipment and trenching equipment, making cable-laying and trenching simultaneously possible.

The final operation, final commissioning, requires vessels that have gangways. SOVs designed for offshore wind have a gangway to ensure safe passage for installation- or maintenance crew and cargo. When working offshore close to the floating turbines, the vessel will experience motion from waves, wind, and current. Thus the SOV used for final commissioning must have good enough seakeeping behavior to ensure safe and effective work under the influence of the weather.

3.3 Fleet composition

In this section, a summarized fleet composition will be presented. All the vessel types that are included in the model with their vessel characteristics are shown in table 3.1. The vessels that are included in the fleet composition are used in the oil and gas industry, the offshore wind industry, or both. Not all vessel owners share all information about the vessels, so assumptions were made where information is missing. The SOV all have a gangway to access the floating wind farms, and all of the vessels are equipped with a crane of varying sizes. Only the AHTS has the required equipment for anchor installation, and the CLV is the only vessel that can perform cable installation.

Vessel type	**BHP**	**Bollard pull [tonnes]**	**Speed [kn]**	**Deck space [m^2]**	**Cable lay equipment**	**Anchor handling equipment**
OSV	12.000- 20.000	100-200	12-16	300-1500	No	No
AHTS	12.000- 20.000	200-400	9-14	800-1200	No	Yes
CLV	5.000- 10.000	-	8-12	-	Yes	No
SOV	6.000 - 14.000	-	10-14	100-500	No	No

Table 3.1: Vessel characteristics in the fleet for optimization

Chapter 4

Literature Review

In the following chapter, a discussion of the literature on the logistics during the installation phase of an offshore wind farm will be presented. There is limited research that has been done on the installation phase of floating wind, so the literature will be used to support choices made in the thesis.

4.1 Maritime fleet size and mix

The most important and complex decision for ship owners is to find the optimal fleet size and mix for future needs. Ship companies operate in changeable environments and markets with high uncertainty. Strategic planning for designing the optimal fleet of vessels is therefore crucial. In short, a Maritime Fleet Size and Mix Problems (MFSMP) is the problem of deciding how many ships of each type to operate for handling the demand. The object is typically to minimize the costs of operating a fleet, and the problem often includes decision support on vessel routing and scheduling. In the paper *A survey on maritime fleet size and mix problems* (Pantuso et al., 2014), two different MFSMP are reviewed, the single-period MFSMP and multi-periods MSFMPs. The single-period MFSMP focuses on the design of a fleet of vessel transportation systems with long-lasting characteristics. The multi-period MFSMPs focuses on dynamic adjustment of the fleet where it is possible to add or remove vessels depending on changes in demand. The paper also presents studies on MFSMPS as a strategic problem of which vessels should be purchased or chartered, while the actual demand is unknown, resulting in uncertainty in schedules and routes. Furthermore, the paper also presents tactical problems where typical problems on this level are fleet deployment, ship routing, and scheduling. Having the possibility of chartering in or out vessels or lay-up vessels in order to meet the demands will deal with these problems.

In the paper *Model Integrating Fleet Design and Ship Routing Problems for Coal Shipping* (Zeng and Yang, 2007), an integrated optimization model is developed to improve the efficiency of coal shipping. The background for the paper was developing a new ocean shipping system for the larges coal supply company in China. The objective was to determine the types of ships, the number of each type of ship, and to optimize the ship routing. To solve the model, an algorithm was designed and was based on a two-phase tabu search. The results showed that the proposed method reduced the unit shipping cost and ship delay and improved the reliability of the coal shipping system. This was extended in the paper *Robust Fleet Sizing and Deployment for Industrial and Independent Bulk Ocean Shipping Companies* (Alvarez et al., 2011) to include uncertainty in demand and multi-period fleet sizing. The proposed Mixed Integer Programming (MIP) model could be used to assist shipping companies with varying degrees of risk tolerance in the decision of sale, purchase, chartering, lay-up, scrapping of ships, as well as deployment of active ships to contracts and geographic markets. They tested their model on a realistic case study based on an independent dry bulk transportation company.

The paper *Optimal policies for maintaining a supply service in the Norwegian Sea* (Fagerholt, 2000) evaluates the effect on the total supply cost of having all or some offshore installation closed for service during the night and determine the optimal routes. The optimization model that was developed is a short-term MFSMP to supply different offshore installations. Six different scenarios were developed with varying opening hours and weekly demand. The problem to investigate was to select which vessel to operate among a pool of vessels and then find the optimal routes and schedules. The solution approach was made in two phases by first generate a number of feasible candidate schedules and then solve an Integer Programming (IP) to find which vessel to operate and weekly schedules.

Proper planning of offshore activities is important to reduce time and risk. Extension of the MFSMP model in the previous paper was done in the paper *Optimiziation in offshore supply vessel planning* (Halvorsen-Weare and Fagerholt, 2016) by including the uncertainty for the OSV planning. A model was developed to determine an optimal fleet size and mix of OSVs and weekly routes and schedules for oil and gas installations. To models are presented in the paper, an arc-flow model and a voyage-based model to solve the OSV planning problem. The voyage-based method generates all possible voyages are generated and then solves them to find the optimal fleet and schedules. They also consider rough environmental conditions where wave limits may cause reduced sailing speed and time to perform operations. Robust approaches are proposed to better withstand delays due to weather. The solutions obtained showed more robust and lower expected costs.

The paper *Optimizing vessel fleet size and mix to support maintenance operations at offshore wind farms* (Stålhane et al., 2019) propose a two-stage Stochastic Programming (SP) to determine the optimal fleet to support O&M at offshore wind farms. The first stage is to find what vessels to charter, and the second stage how to support the maintenance operation with the chartered vessels. Weather uncertainty and failure occurrence are implemented in the second stage. The results achieved from the computational study showed that the model could be used for decision support for determining an optimal fleet for maintenance campaigns for different offshore wind farms. It is also suggested for further work to incorporate condition-based maintenance tasks in the model.

4.2 Offshore wind farm installation

There are several challenges with the installation operation of offshore wind farms, as large components are installed with expensive specialized vessels, often in a harsh environment. Bad weather may delay the installation operation for an extended period, leading to high costs as day rates for chartering vessels for these types of operations are expensive. High costs and unwanted consequences can be minimized with good logistical planning, considering the type of vessels, installing the turbines (assembled at operation site or pre-assemble at port), and port selection. In the offshore wind market, there are limited, exact solution methods for optimizing the installation phase of offshore wind farms. In the following section, papers exploring and researching methods for optimizing the installation phase for offshore wind farms are presented.

For logistical planning for offshore wind, a Mixed Integer Linear Programming (MILP) model has been developed in the paper *Strategic Optimisation of Offshore Wind Farm Installation* (Backe and Haugland, 2017). The purpose of the model is to analyze cost-effective port and vessel strategies for the installation operation of wind farms. The authors argue that the logistical planning of installation crucial decisions need to include selecting the most cost-effective vessels, arranging how the components should be loaded and installed, and selecting a port that minimizes expenses and delays. The operations considered in the framework are weather restricted and have to be performed during a time window. Several numerical test instances inspired by realistic data have been performed with the developed model, where the purpose was to test how large instances the model could handle. As uncertainty is not considered in the model, it is recommended that more instances should be implemented to somehow deal with uncertainty. For the solver to solve large instances in a reasonable time frame, drastic simplifications of the framework in the model are needed. Developing heuristic methods to solve instances may be an alternative, but it still might be challenging to prove optimality.

The authors in the paper *Bi-objective optimization model for installation scheduling in offshore wind farms* (Irawan et al., 2015) propose a bi-objective optimization model for installation scheduling of an offshore wind farm. The model involves two objectives, minimizing total installation cost and completion time. The mathematical model is formulated as an Integer Linear Program (ILP) restricted to weather conditions and vessels' availability. As there are a large number of parameters, developing a mathematical model for the problem is complex. The authors propose an approach for reducing the complexity by pre-generating a new set of all feasible slots where a vessel can execute a given installation activity. The problem is treated as a combinatorial optimization problem. The problem is solved to find the best slot configuration of feasible time slots to minimize total installation cost or total completion period. Despite reducing the complexity, there are still many periods and vessels included in the model, which makes it difficult to solve the ILP using exact methods. The authors suggest then using Compromise Programming (CP) with two metaheuristics methods, Variable Neighborhood Search (VNS) and Simulated Annealing (SA) as an approach for solving the large problem. Optimality was attained for all data sets in the results with CP using the exact method (using CPLEX). The metaheuristics methods gave good results, and computational time was much faster than the exact method, where CP with VNS outperforms SA.

A mathematical model calculating optimal installation schedules for offshore wind farms using MILP is presented in the paper *A MILP for installation scheduling of offshore wind farms* (Scholz-Reiter et al., 2010). The objective of the model is to reduce vessel operation time as this is proportional to installation costs. Installation vessels are the bottleneck in the wind farm installation process. The utilization of the installation fleet should therefore be effective and used most efficiently. The installation scheduling of offshore wind farms depends on weather conditions, so three types of weather conditions are modeled considering good weather, medium weather, and bad weather. The mathematical model identifies the optimal installation schedule for exactly one vessel for short time periods based on up-to-date weather forecasts. When a vessel returns to port and needs to be loaded, the model is solved, and a new optimal installation schedule based on updated weather forecasts is calculated. The paper's authors concluded that the developed mathematical model was only applicable for short time periods, the mathematical model is NP-hard.

For solving the limitations of the mathematical model in the previous paragraph, a heuristic method is presented in the paper *Towards a Heuristic for Scheduling Offshore Installation Processes* (Scholz-Reiter et al., 2011) written by the same authors who proposed the mathematical model. The heuristic method can solve larger problems and consider several vessels, longer time horizons, and a larger range of weather conditions. An optimal installation schedule for a more extended planning period and a larger fleet was achieved using the heuristic method. The results are not optimal, but the solution is a good enough approximation so it can be used as support for a decision-maker.

The authors in the paper *Simulation-based aggregate Installation Planning of Offshore Wind Farms* (Alla et al., 2013) suggest a MILP model generates an aggregated installation schedule taking into account weather conditions and vessel availability. The model's objective is to minimize the total installation costs, consisting of vessel utilization costs and fixed wind farm project costs during runtime. The model is solved for a medium planning horizon (2-18 months) and returns an optimal schedule for the number of components needed to be installed by each available vessel over the planned time horizon for meeting the weather forecast. Different scenarios can be studied and analyzed with the mathematical model, making the model a good decision tool for medium-term planning of offshore wind parks. In another paper, *Assessment approaches to logistics for offshore wind energy installation* (Vis and Ursavas, 2016), the authors assess different approaches to offshore wind farm installation planning by analyzing different logistical solutions. Considering different logistical methods for installing wind farms, both the installation time and installation costs can decrease. The installation phase is definitely an inevitable bottleneck in the supply chain due to weather dependency. Uncertainty and weather interruptions make only short-term planning possible, so logistical methods need to be chosen with efficiency in mind. Therefore a simulation-based decision-support tool was developed for supporting decision-makers in assessing various logistical methods within the installation phase. With the decision support tool, schedule and budget estimates can be developed by comparing alternatives and estimating the total duration of an operation.

Chapter 5

Methodology

In this chapter, the methodologies that are used for solving the optimization models are presented. To create a realistic representation of the weather, a Markov Chain script in *MATLAB* is used to simulate weather of the planned time horizon for the installation process. A detailed explanation of how Markov Chain simulation works and how the weather is simulated. The optimization models are implemented in Python programming language, and Gurobi is used for commercial optimization solving. How Gurobi works will be explained in this section in detail. The weather simulation and the optimization analysis are conducted on a computer with an AMD Ryzen 7 4800H 2.90GHz processor, 16GB RAM, and a 64-bit operating system.

5.1 Markov chain

The Markov Chain is a stochastic process describing a sequence of possible events based on probabilities. The probability distribution of the next state depends only on the current state. The definition of Markov chain is that it does not matter which previous events the process has been to, all possible future events are fixed. Equation 5.1 states that time step X_n is dependent on the former time step value X_{n-1}.

$$X_{n-1} \rightarrow X_n \tag{5.1}$$

Further, the probability of changing from one state to another state is represented by the probabilistic value $P_{i,j}$. This means that if the process is in state i, there is a fixed probability $P_{i,j}$, see equation 5.2, for transition into state j (Ross, 2007).

$$(P_n)_{i,j} = \mathbb{P}\left(X_{n+1} = j \mid X_n = i\right) \tag{5.2}$$

The Markov Chain can be implemented for simulating weather. The stochastic weather data used for creating a Markov Chain means that state-change probabilities need to be calculated. A transition from a weather state with a low value to a weather state with a high value has a low probability of occurrence. When performing Markov Chain simulation, absorbing states could appear, and these states need to be investigated. An absorbing state is a condition when going from one state to another, the probability in the transition matrix is zero. The simulation will then end up in an infinite loop, and by removing these absorbing states, good results are achieved.

5.1.1 Weather simulation

The fleet schedule for the installation phase should represent a schedule that can be realistically executed. For creating a Markov Chain of the weather, historical weather data of the summer period from the last 4 years are used from an area 100 km west of Bergen. This area will be used for the different cases in the optimization models. The data include measurements every third hour, and the significant wave height is a combination of wind waves and swell. The Markov Chain script that is used for weather simulation is a *MATLAB* script, which was provided in the course *Ocean System Simulation*. To ensure that the correct simulation of the case area, the script is slightly altered to make the historical weather data more applicable for the simulation. By dividing the number of sea states into a set, the range of each sea state can be set, and each sea state can be calculated. The occurrence of the simulated waves can set the operational limit of the installation process. Figure 5.1 illustration the occurrence of the significant wave height in the summer period over the last 4 years.

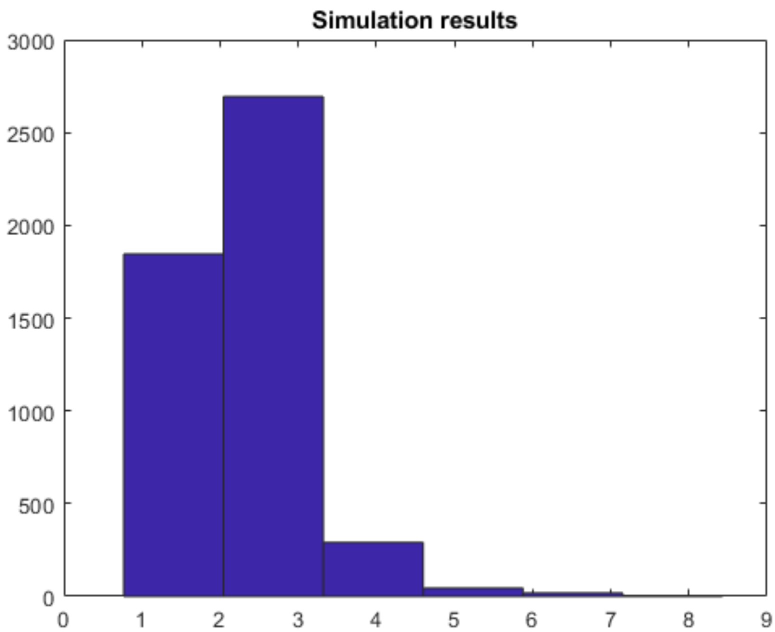


Figure 5.1: Significant wave height occurrence in summer period from year 2017-2020

A weather representation is generated with the results from Markov Chain simulation. A floating wind farm installation needs a weather window where the waves are under the operational limit. If the wave limits are over the operational limit, the planned installation needs to wait until a favorable weather forecast. Predicting what the actual weather be like in the head of time is difficult to achieve. However, with a simulated weather forecast, it is possible to plan for several installation strategies based on what the weather will be on the installation day. Figure 5.2 shows a timeline of a potential summer period and will be used to set different operational requirements in the optimization models. With weather forecast taken into account, it is possible to achieve more robust planning.

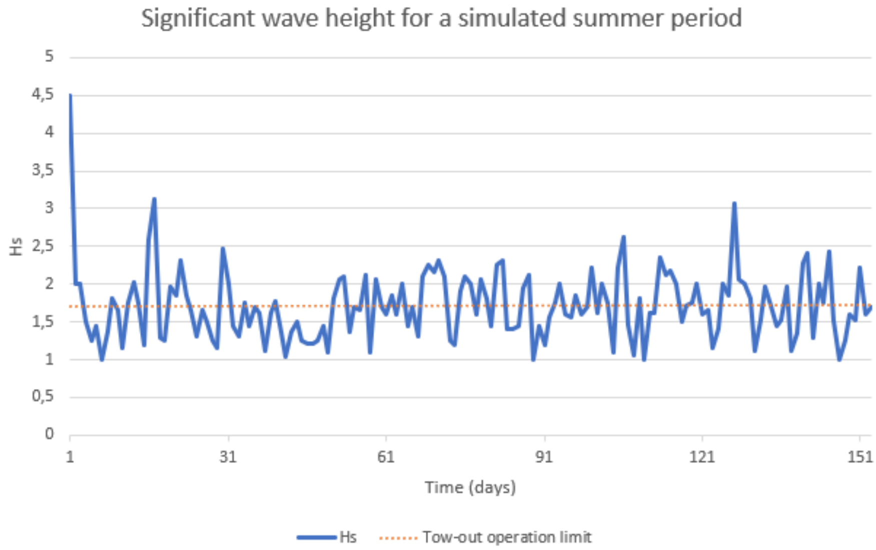


Figure 5.2: Significant wave height in a simulated summer period based on historical data

5.2 Gurobi

A model with no quadratic features is referred to as MILP. The MILP in Gurobi har often solved by using a linear-programming-based branch-and-bound algorithm. The problem is solved directly by the basic LP-based branch-and-bound. All the integrality restrictions are removed, and the result is an LP called linear-programming relaxation of the original MIP. The LP can now be solved. An optimal solution of the MIP is achieved when the result of the LP satisfies all of the integrality restrictions. If there is no satisfaction, the model picks up a variable that is restricted to being integer but has a fractional value in the LP relaxation. The value can then be excluded by implementing restrictions $\geq$ the next value above or $\leq$ the first value below. The new variable is called a branching variable. This procedure is done for more MILPs where more branching variables are selected, and this results in a search three as seen in figure 5.3. The nodes in the three are the generated MIPs from the search procedure, and the leaves in the search three are nodes that have not been branched yet. The original MIP is solved when a point is reached that is solvable or all the leaf nodes are disposed of (GUROBI, 2021b). The best feasible integer solution found in the search is defined as an incumbent solution. For a minimizing problem such as this master thesis, the objective value for the incumbent solution will be the upper bound in the search. An integer solution with a higher value will never be accepted. At the same time, there will always be a valid lower bound during the branch-and-bound search. The lower bound is found by taking the minimum of all the current leaf node's optimal objective values. The difference between the upper and lower bound is called the gap, and when the gap is zero, optimality is proven.

Figure 5.3: Branch-and-bound method (GUROBI, 2021b)

5.2.1 MIP Gap

The MIP Gap in Gurobi is a measurement to identify the difference between the lower and upper bound in the objective function. The best integer solution found by the solver at any point in the optimization run is called the incumbent solution (primal objective value). By defining z_p as the primal objective value and dual objective bond as z_D, then MIP Gap is defined as:

$$gap = |z_P - z_D| \, / \, |z_P| \tag{5.3}$$

z_p and z_D typically have the same sign throughout in most optimization problems with a monotonically decreasing; however, if the signs are opposite to each other, the relative gap may increase. The MIP Gap is used to indicate how far away the solver is from finding an optimal solution. If the gap in the solution is zero, the incumbent solution is optimal. However, the solver cannot determine if the incumbent solution is optimal with a large gap, so the branch-and-bound search continues. The MIP Gap will return a solution that is infinity if the solver cannot find an incumbent solution, if there is no available objective bound or if the current incumbent objective is 0 (GUROBI, 2021a).

Chapter 6

Discrete Optimization Model

6.1 Model explanation

The optimization model will determine an optimal fleet for a predefined schedule of offshore floating wind installation. The model's mathematical formulation is referred to as a discrete optimization model of fleet selection (DOFS). The model will take into account operation requirements when selecting vessels for the different operations. The model is based on the installation activities described in section 3.1 with assumptions to make the model as realistic as possible. The model will explore the potential benefits of optimizing fleet selection for floating wind installations where the weather is taken into account. There are several ways to consider the weather in optimizing, and one way is proposed in the model to make the solutions more robust. Furthermore, the model is used as a basis for an expanded and improved model presented in the next section. It is important to keep the model simple enough to make them applicable for installing FWTs.

6.2 Model input

In the following section, all the parameters used for both optimization models are described. The parameters are based on research from the offshore market, and assumptions are made where values are missing. Time periods are only defined for the first model as the model aims to find the optimal fleet and not schedule.

Activities

The transportation routes in the model are defined as activities step which requires a specific set of vessels. Transport and assembly activities that are described in section 3.1 will not be included in optimization models due to a longer planning horizon. The anchors and cables are transported to the same installation port, where the wind is assembled for simplicity. It is assumed that all the vessels can start from the same location and end in the same location. Furthermore, towing and sea-keeping activities are included as two activities in the models, not as one activity as in a realistic scenario. The reason for splitting the towing activity into two activities is to capture the vessels needed for towing a wind turbine. The following installation activities that are included in the models are:

- **Anchor transportation:** installation process starts with anchors are transported to the site.
- **Anchor installation:** When the anchors arrive at the site, the installation of the anchors can start. This includes both anchors and the mooring lines between the floating turbines and anchors.
- **Tow-support:** When the anchors and mooring system activities are complete, the first stage of towing can start. Several support vessels are needed to maneuver the turbine from the port to the open sea in a realistic case.
- **Towing:** Towing of the fully assembled to site after the first stage of towing is complete.
- **Hook up:** Connecting the wind turbine to the mooring lines at the site.
- **Cable laying:** The export cables from the onshore electricity grid to the offshore wind farm are installed. Furthermore, the inter-array cables are installed for interconnecting the wind turbines.
- **Final commissioning:** Final operation to complete before the wind can start producing power, necessary tests on wind turbine components to check that everything works as planned.

An illustration of the installation process for the models is shown in figure 6.1. All the different operations that are included are shown with different types of vessels.

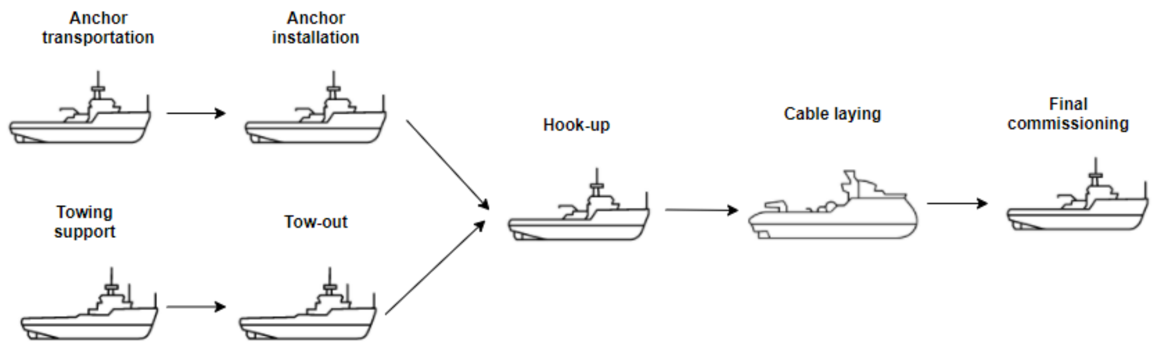


Figure 6.1: An illustration of the installation process

6.2.1 Time periods

The time period in the DOFS model is defined according to a predefined schedule of the installation process. The time periods are set to last for one week each, and the activities are assigned to a time period. The activities need to be completed within the time interval of the time period. The schedule for each turbine is divided into four different time stages of the installation.

- **Anchor transportation and installation (Period 0):** The first time period includes the anchor transportation to the site and installing the anchors and mooring line.
- **Towing (Period 1):** The next time period is towing the fully assembled wind turbine to the site. This time period includes both stages of towing, ensuring the involvement of support vessels. This stage is very weather sensitive and will set the limit for the installation process.
- **Hook-up and cable installation (Period 2):** This time period involves the hook-up and cable installation stage of the wind turbine.
- **Final commissioning (Period 3):** In the final time period, the wind turbine is finalized before production can start.

6.2.2 Weather conditions

The weather conditions affect whether it is possible to execute an installation activity or not. Vessels that are included in the fleet have different weather limitations for executing the installation operations. Weather data from the wind farm site will therefore influence the choice of vessel selection. The weather for the planning horizon is assumed known and based on historical data. Different weather categories are given as a number representing four weather states, where state 1 represents good weather and state 4 is bad weather. The weather state will only consider significant wave height as this is a critical factor. Table 6.1 classifies four different weather categories based on the Markov Chain simulation and also shows a reduction in sailing speed if the wave height increases.

Weather condition	**Weather category**	**Wave height [m]**	**Sailing time increase**
Excelente	1	≤ 1.0	0
Good	2	≤ 2.0	10 %
Medium	3	≤ 3.0	20 %
Bad	4	≥ 4.0	WOW

Table 6.1: Weather categorizations

For the discrete optimization model, each weather state will is assumed for a given time period. The weather in each time period will be given a number from 1 to 4. These numbers will then be compared in each time period and determine if a vessel can be selected for the activity to be performed. A vessel can then operate if the weather limitations for the vessel are lower than the weather state in the time period. The vessel weather limitations can be shown in table 6.2, and for simplicity, all types of vessels will have the same range limitations.

Vessel type	Weather requirements (Hs)
OSV	1.5m-3.5m
AHTS	1.5m-3.5m
CLV	1.5m-3.5m
SOV	1.5m-3.5m

Table 6.2: Vessel weather limitations

6.2.3 Fleet

The vessel types that can be chosen in the model are OSV, ATHS, CLV, and SOV, as mentioned in section 3.2. Each vessel type consists of 5 vessels with different capabilities, and this is done so that the model can choose between each type. The chosen vessels are based on the Hywind Tampen project as the assembly operation will happen onshore, excluding the need for heavy-lift vessels. The ballasting operation is also done onshore, whereas in the Hywind Scotland project, a stone dumping vessel where required. The operations mentioned in a realistic wind farm project often require several support vessels to execute the operation. Towing, anchor activities and hook-up are operations that often require multiple vessels. The model will only optimize the main vessel for each operation. In the model, the use of a support vessel is included to capture the use of multiple vessels in a towing operation. Typically a towing operation requires several support vessels to maintain control and maneuverability of the turbine.

- **Offshore support vessel**: The vessels have powerful engines will that makes them able to perform an operation such as towing. In the model, they can also be used for the transport of anchors and hook-up.
- **AHTS**: They are used for the anchor installation. They are the only vessel type in the pool of vessels that can do the operation. They can also be used for anchor transportation, tow-out, and hook-up.
- **Cable laying vessel**: Specialized vessel that is designed specifically lay underwater cables for the offshore industry.
- **Service operation vessel**: For the final commissioning phase, the service operation vessels have the capabilities to transfer crew personnel safely and effectively onboard the floating wind turbines with a motion-compensated gangway.

6.2.4 Costs

In the following section, a description of the costs included in the model is described. Several factors impact the charter cost of a vessel, and the mobilization cost depends on the charter cost. The waiting cost is the penalty for prolonging an operation and will only be included in the second model.

Mobilization cost

The mobilization needs to be included when a vessel is a move between operation regions. It shall cover all activities and the associated costs for transportation of contractor's personnel, operating supplies to the site, and other necessary general facilities needed for the contractor's operations at the site. If the operation company reviews the asset as a permanent relocation, the cost of transportation can be ignored. Drilling rig and supply vessel market long distances movements are often considered as investment decision rather than billing the mobilization cost to a single project (Kaiser and Snyder, 2012).

Mobilization costs can be calculated by the distance, charter cost of the vessel, the size of vessels, and how the vessel is transported. There is three transportation method that is typically used, and they are self-propel, semisubmersible heavy-lift or towing. For the offshore wind industry, the vessels typically included in the installation process are self-propelled or towing. The formula for self-propelled is used for the thesis when calculating mobilization costs for the pool of available vessels.

Self-propelled vessels are capable to mobilize without use of support vessel, the cost can then be calculated by travel time multiplied by dayrate plus the fuel cost:

$$(\frac{x}{24V_i})(I + (1.2P_i)G) \tag{6.1}$$

where X is the traveling distance in miles, V_i is the transit speed of vessel in knots, I is the day rate (\$/day), P_i is the installed power(hp) and G is the cost of fuel per gallon (\$/day). Equation 6.1 will be used for estimating the mobilization cost of each vessel.

Time charter cost

Time charter cost for offshore vessels depends on several factors such as market situation, contract length, vessel characteristics, size, and age. A time charter is the specific time period a vessel is hired. The duration of a contract length can be either spot, short-term charter, or long-term charter. The charterer pays for vessel fuel, port chargers, and a daily cost of hire to the vessel owner (Vskills, 2013). Charter costs are in most cases concealed from the public; however, litterateur gives an indication of typical charter rates for the vessels used in the thesis. Table 6.3 shows different ranges of charters rates of typical vessels used in the offshore wind industry. The typical day rate for tugs will be used for the OSV, and the day rate for the DP vessel will be used as input for the SOV in models.

Vessel type	Typical daily charter rate
Tug	£ 20 000 - £ 50 000
AHTS	£ 20 000 - £ 50 000
CLV	£ 70 000 - £ 110 000
Barge	£ 80 000 - £ 180 000
DP vessel	£ 50 000 - £ 200 000
Bespoke vessel	£ 200 000
Other	Vessel dependent

Table 6.3: Daily charter rates of different vessels used in the offshore wind industry (Harrison et al., 2020a)

6.3 Mathematical formulation

The discrete optimization model is described in the following sections, including the sets, parameters, and variables in the mathematical formulation, followed by a detailed explanation of every constraint. Variables and indices are represented by lower-case letters, and parameters and sets are represented by capital letters. The code of the mathematical formulation can be found in appendix B.1.

Sets

There are three sets in this model to describe the pool of elements involved in the decision process. The sets include vessels, the different needed activities, and time periods that represent a predefined scheduled time horizon.

V Set of vessels, indexed by v

N Set of activities, indexed by i

T Set of time periods indexed by t

Parameters

Two parameters are introduced regarding the cost of installation. The first cost parameter is daily charter cost C_v^{TC} of a vessel, and the second cost parameter is mobilization cost of a vessel C_v^{M} . Next following input parameters are each vessel $v \in V$ has two associated non-negative duration time parameters which are operation time T_{vi}^{D} and sailing time T_{vi}^{S}. The last two following parameters that are included in the model are equipment requirement Q_{vi}, execution timing T_{ti}^{W} .

C_v^{TC} Charter cost of vessel $v \in V$

C_v^{M} Mobilization cost of a vessel $v \in V$

T_{vi}^{D} Duration of vessel $v \in V$ executing activity i

T^S_{vi} Sailing time of vessel $v \in V$ to activity i

Q_{vi} 1 if vessel v can execute activity i, 0 otherwise

T^W_{ti} 1 if activity i is done in time period t, 0 otherwise

Decision variables

Two following binary variables are used to describe the installation problem. x_{vti} equal to 1 if vessel $v \in V$ executes operation $i \in N$ in time period $t \in T$ and is 0 otherwise. z_{vi} is equal to 1 if vessel $v \in V$ is used for activity $i \in N$ and is 0 otherwise.

Objective function

The overall aim of the model is to minimize the total cost related to the fleet used for the installation of a floating wind farm. The main cost contributors in this model for chartering a vessel are the mobilization cost and time charter cost. The first part of the objective function is the mobilization cost for a vessel that is included in the fleet. The second part is the time charter cost that is multiplied by the vessel duration for the activities. Waiting time is not included, so the model's reasonable assumption is that mobilization costs are only imposed once.

$$min \sum_{v \in V} \sum_{i \in N} C^M_v z_{vi} + \sum_{v \in V} \sum_{t \in T} \sum_{i \in N} C^{TC}_v (T^D_{vi} + T^S_{vi}) x_{vti} \tag{6.2}$$

Constraints

The constraints defining the discrete optimization model for fleet selection are listed below:

Operation constraint

A vessel can only execute one activity in each time period:

$$\sum_{i \in N} x_{vti} \leq 1, \quad v \in V, t \in T \tag{6.3}$$

Flow-conservation

If a vessel is assigned to an activity, the mobilization costs follow. The decision variable z_{vti} is therefore forced to be equal to 1 if a vessel is used sometime during the planning horizion.

$$\sum_{t \in T} x_{vti} \leq M z_{vi}, \quad v \in V, i \in N \tag{6.4}$$

Time

Each of the activities is assigned a specific time slot, where a vessel is assigned to execute activity i if its scheduled to time period t.

$$\sum_{i \in N} x_{vti} = MT_{vi}, \quad t \in T, v \in V \tag{6.5}$$

Weather

A vessel can operate if the limitations for the vessel is lower than the weather state in the time period.

$$\sum_{t \in T} x_{vti}(W^R_{vi} - W_{ti}) \geq 0, \quad v \in V, i \in N \tag{6.6}$$

Requirement

Each activity has specific requirements, and the vessel used shall have the capabilities for performing the activity.

$$\sum_{t \in T} x_{vti} \leq MQ_{vi}, \quad v \in V, i \in N \tag{6.7}$$

Variable domains

The domains of each of the variables used for in the aforementioned constraints and objective function are listed below. x_{vti} is equal to 1 if vessel $v \in V$ executes operation $i \in N$ in time period $t \in T$, 0 otherwise. z_{vi} is equal to 1 if vessel $v \in V$ is used for activity $i \in N$, 0 otherwise.

$$z_{vi} \in \{0, 1\} \quad v \in V, i \in N \tag{6.8}$$

$$x_{vti} \in \{0, 1\} \quad v \in V, t \in T, i \in N \tag{6.9}$$

6.4 Case example

For testing the function and benefits of the model, a case example is performed. Several scenarios will be analyzed where the results will be compared to check how the weather impacts the different installation strategies. The case will be tested for Hs = 0m, Hs = 2.0m and Hs = 2.5m. It is assumed that the turbines to be installed are located approximately 90 miles west of Bergen in the North Sea. All the vessels included in the fleet will start from the same port in Gulen, Sogn og Fjordane, the same port where turbines in the Hywind Tampen project are towed out.

Scenario 1

In this scenario, a fleet for installing one turbine is investigated. Figure 6.2 shows a visualization of the pre-defined schedule of when all the activities with start day and the duration. Anchor transportation will start at day 0 as this activity must be completed before anchor installation and tow-out. Hook-up is dependent on several activities, meaning that tow-out and anchor installation needs to be completed before hook-up can start.

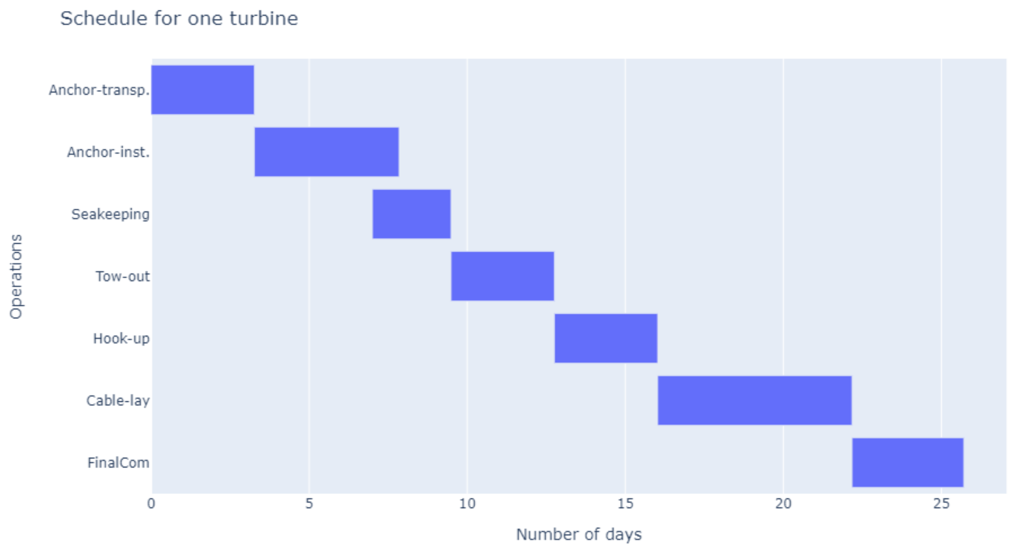


Figure 6.2: Schedule for installation of one turbine with no weather impact

Scenario 2

This scenario will investigate how the weather makes an impact on the selection of the fleet. The input of the significant wave height (Hs) will be set to 2m. This means that each vessel duration needs to increase as vessel speed will reduce by 10 %, as shown in table 6.1. Figure 6.3 show a similar schedule as in scenario 1 but with an increase in the duration.

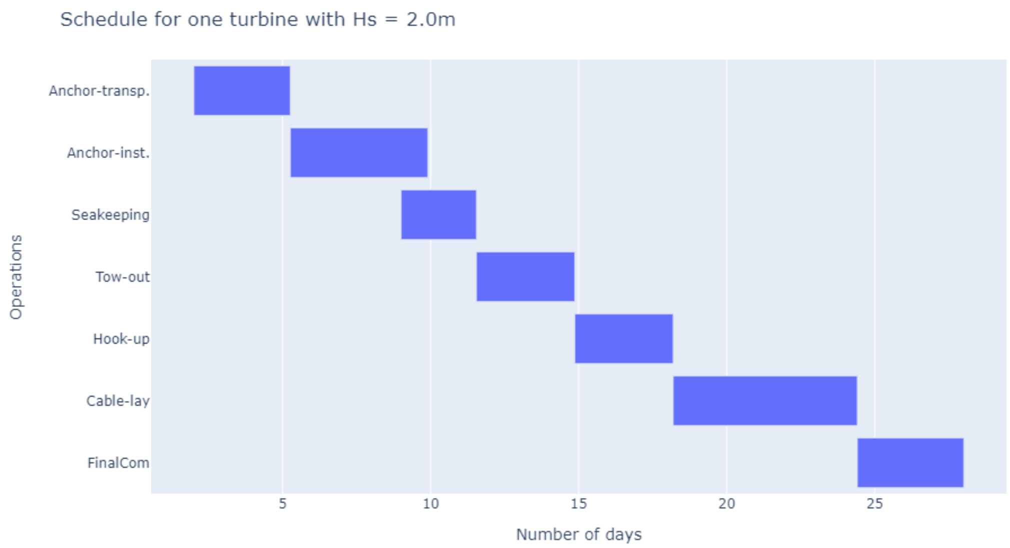


Figure 6.3: Schedule for installation of one turbine with impact of Hs = 2.0m

Scenario 3

For this scenario, one turbine will be investigated under the impact of 2.5m significant wave height. As a result, the vessel speed will be reduced by 20 %, which will result in increased duration and is shown in figure 6.4.

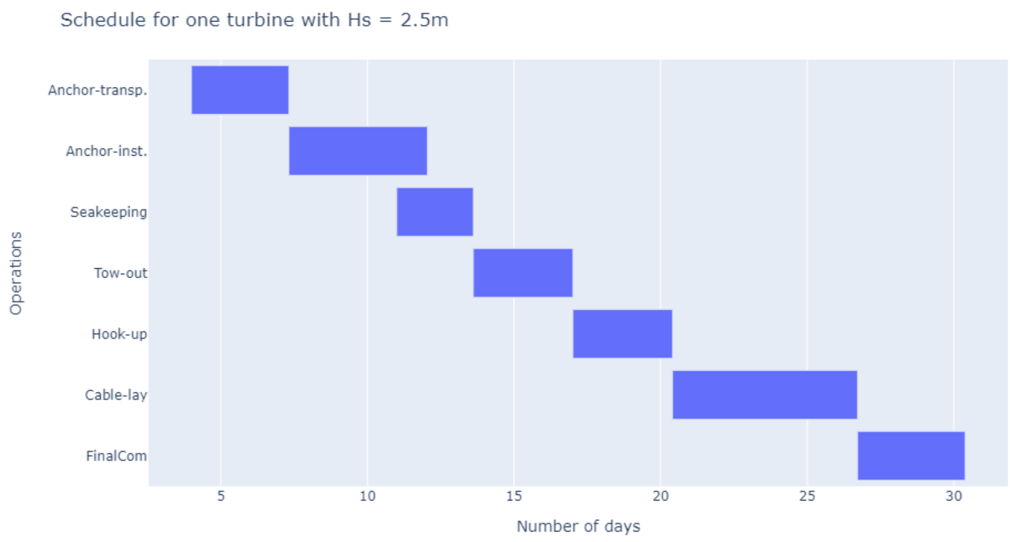


Figure 6.4: Schedule for installation of one turbine with impact of Hs = 2.5m

Scenario 4

The fleet for the installation of two turbines is investigated without weather impact. When a vessel has completed an operation, it will return to port and wait for five days before the vessel can perform a similar operation for the next wind turbine. The schedule for two turbines is shown in figure 6.5.

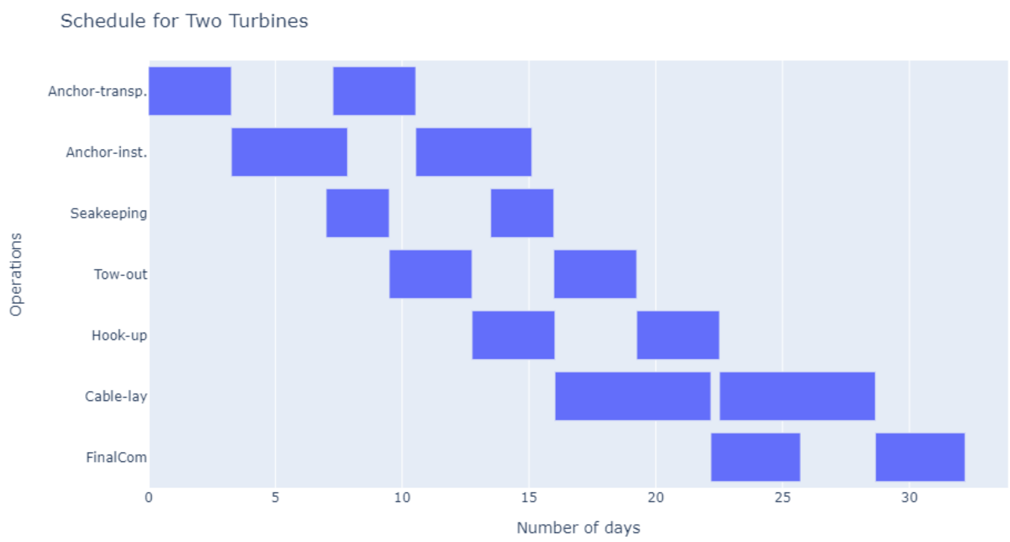


Figure 6.5: Schedule for installation of two turbines

Scenario 5

The schedule for two turbines when Hs is equal to 2.0 meters.

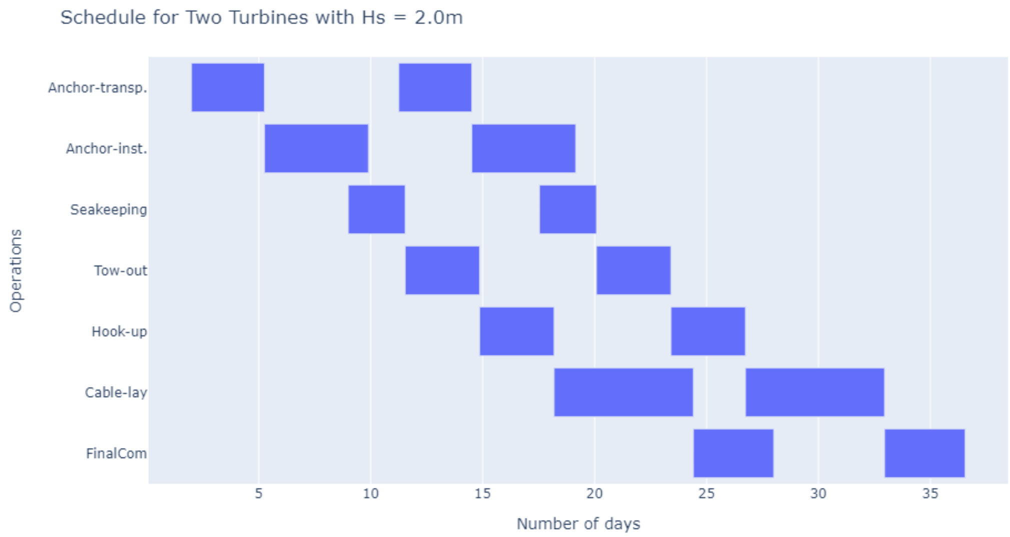


Figure 6.6: Schedule for installation of two turbines with weather impact of Hs = 2.0m

Scenario 6

The last schedule shown in figure 6.7 is for two turbines under the impact of 2.5m significant wave height. Compared with no weather impact for two turbines, the duration has increased by one day.

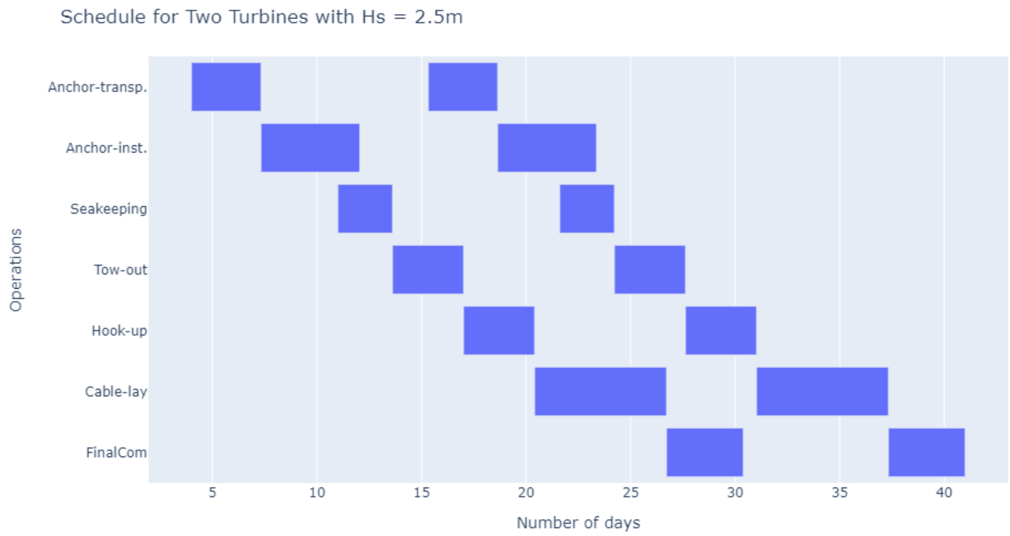


Figure 6.7: Schedule for installation of two turbines with weather impact of Hs = 2.5m

6.4.1 Results from case

The main objective of the DOFS problem is to determine the optimal fleet for installing floating wind turbines under the impact of weather. The optimal fleet for the different scenarios has been found with corresponding cost and time utility. Each installation operation is assigned in the model to a specific time period where a vessel is charted to operate. Having assigned the operations results in a constant total installation time. Thus, a more efficient fleet regarding installation time will not be possible to achieve with this model.

The objective function in the model captures the essential cost contributors related to chartering offshore installation vessels. However, the model optimizes the installation cost based on the duration each vessel uses to sail and operate. In the model, the vessels may only be used partly in each time period, which will result in low utilization of the installation fleet. Therefore, it would be interesting to investigate the time utilization of the fleet with and without the impact of weather. Time utilization is defined as the duration, including execution and sailing time, over the total scheduled time for the operation.

Results for One Turbine

The results of the first scenario for installation of one turbine show that the fleet has an average utilization time utility of 59 %. Furthermore, the third time period has the largest utility time, and this is due to less waiting time for the vessels operating in that time period. Figure 6.8 also shows a linear increase in time utilization from the first time period to the third time period.

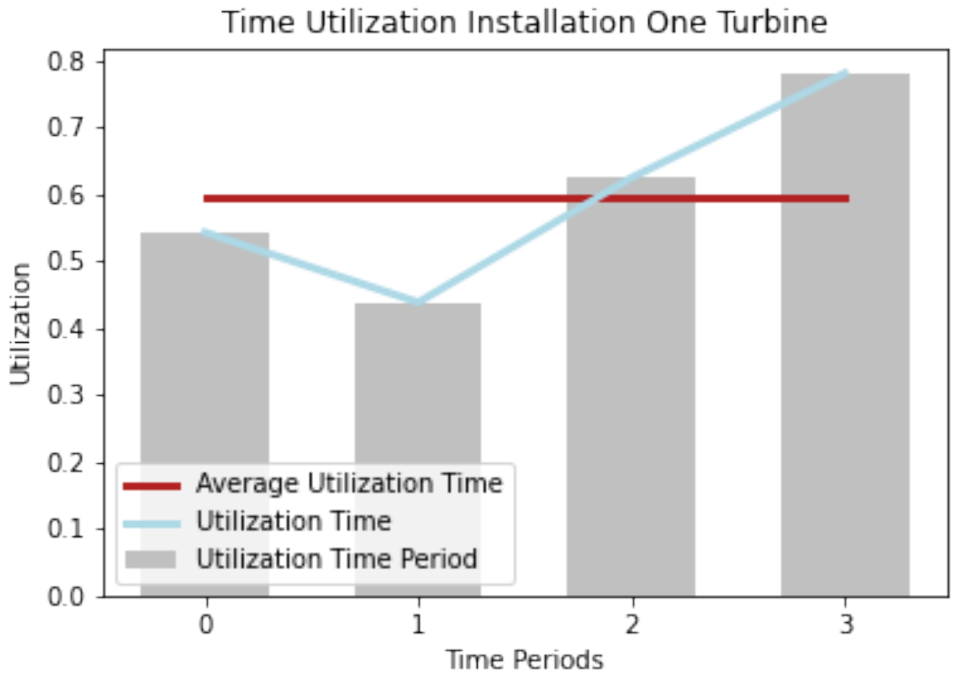


Figure 6.8: Time utilization of the fleet for one turbine

The selected fleet for the operations is shown in table 6.4 with a total cost of 2 690 000 £ and the total duration of installation is 25 days.

Operations	***Anchor transp.***	***Anchor Inst.***	***Sea-keeping***	***Towing***	***Hook-up***	***Cable laying***	***Final commi-ssioning***
Vessel selected	OSV 0	AHTS 9	OSV 2	OSV 1	AHTS 5	CLV 14	SOV 19

Table 6.4: Optimal fleet for installation of one turbine

Results for One Turbine with impact of Hs = 2.0m

The average time utilization of the fleet with the impact of 2.0m significant wave height shows a reduction compared with no weather impact from scenario 1. The average time utilization of the fleet is 53%. The reduction of time utility can be shown in the three first time periods in figure 7.1. The reduction can be a result of the increase of waiting on weather and reduced sailing speed.

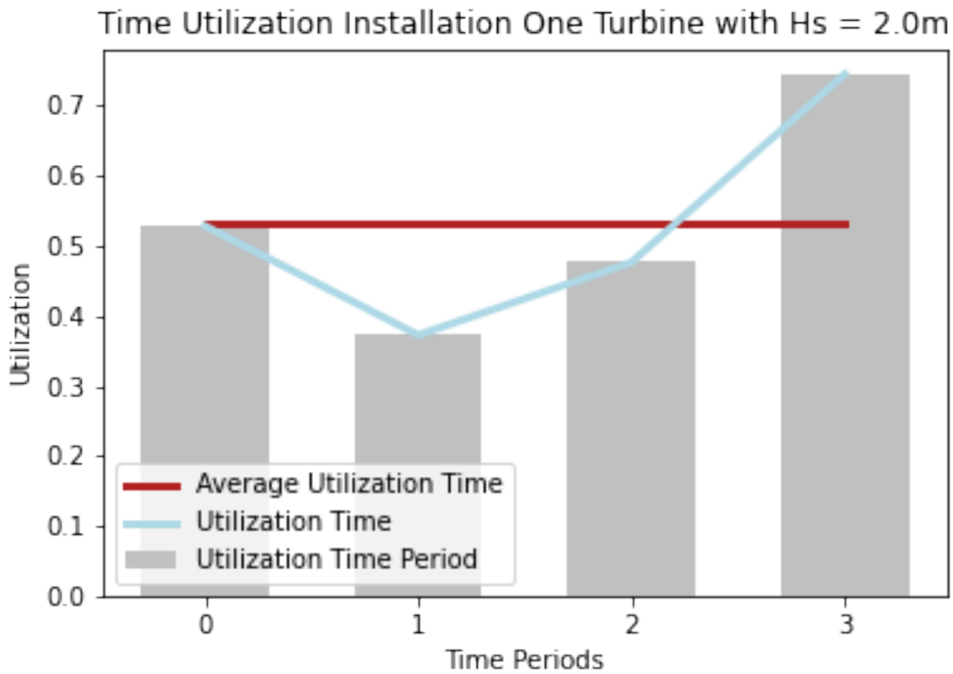


Figure 6.9: Time utilization of the fleet for one turbine under the impact of Hs = 2.0m

The optimal fleet for installation of one turbine with the impact of Hs = 2.0m is shown in table 6.5 with a total cost of 2 988 000 £. The total installation time has increased compared to the first scenario, which is expected due to the reduction of sailing speed and waiting on weather.

Operations	***Anchor transp.***	***Anchor Inst.***	***Sea-keeping***	***Towing***	***Hook-up***	***Cable laying***	***Final commi-ssioning***
Vessel selected	OSV 0	AHTS 8	OSV 2	OSV 0	AHTS 5	CLV 13	SOV 19

Table 6.5: Optimal fleet for installation of one turbine with the impact of Hs = 2.0m

Results for One Turbine with impact of Hs = 2.5m

For the third scenario with the installation of one turbine, the significant wave height is set to 2.5m. This results in average time utilization of the fleet of 47 %. With a larger Hs, the sailing speed and waiting on weather results in one more time period. The third time period is still the time period with larger time utilization of the fleet.

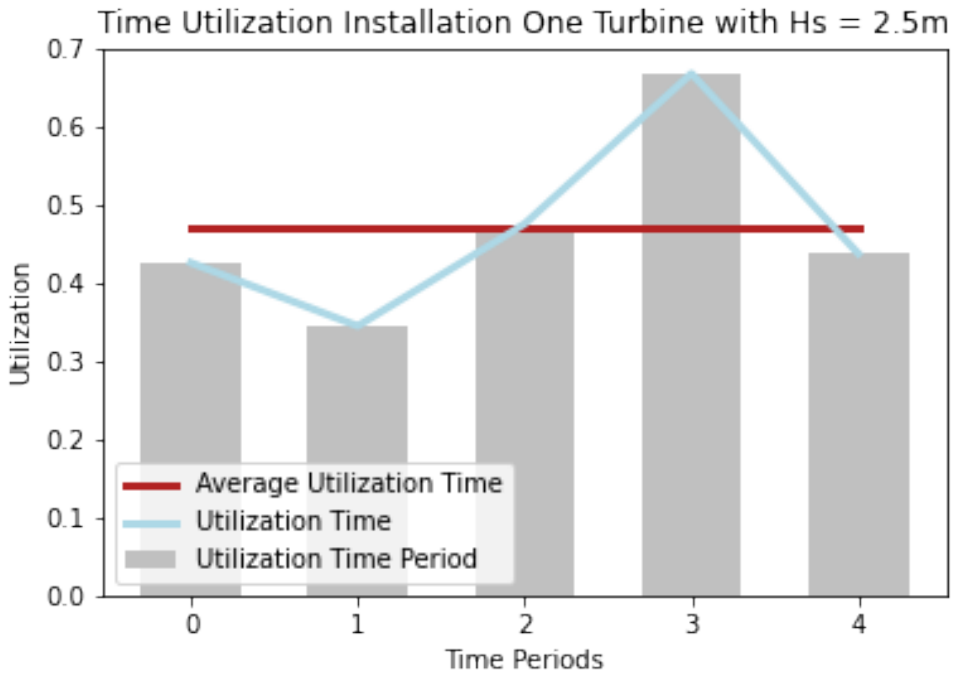


Figure 6.10: Time utilization of the fleet for one turbine under the impact of Hs = 2.5m

The impact of Hs = 2.5m results in a total cost of 3 327 000 £ for the optimal fleet, which is an increase of approximately 600 000 £ compared to the optimal fleet with no weather impact. The results for the optimal fleet are shown in table 6.6 where the total installation time is 30 days.

Operations	***Anchor transp.***	***Anchor Inst.***	***Sea-keeping***	***Towing***	***Hook-up***	***Cable laying***	***Final commi-ssioning***
Vessel selected	OSV 0	AHTS 7	OSV 2	OSV 1	AHTS 5	CLV 12	SOV 15

Table 6.6: Optimal fleet for installation of one turbine with the impact of Hs = 2.5m

Results for Two Turbines

For scenario 4, where two turbines are installed, the average time utilization of the fleet is found to be is 55 %. This is a small reduction compared to the installation of one turbine with no weather impact. Furthermore, figure 6.11 shows three of the time periods have equal utilization time. Similar to the installation of one turbine, the last time period has the largest time utilization of the fleet.

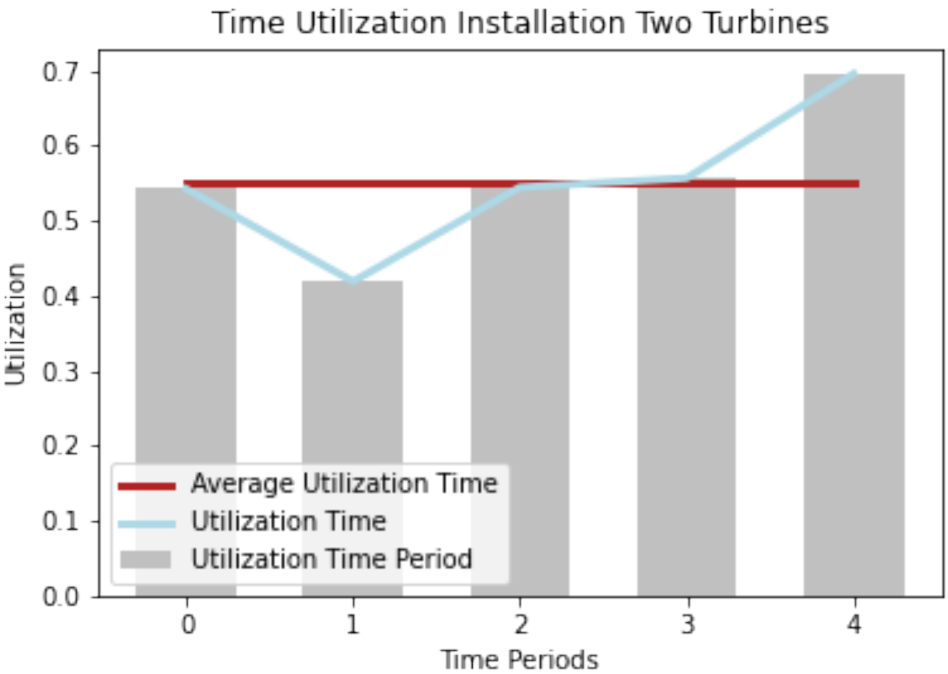


Figure 6.11: Time utilization of the fleet for two turbines

With the installation of two turbines, the total cost of the fleet is 3 921 000 £ and the total installation time is 32 days. The optimal fleet is similar to the fleet for one turbine except for the final commissioning operation, where the model selects vessel type SOV 15.

Operations	***Anchor transp.***	***Anchor Inst.***	***Sea-keeping***	***Towing***	***Hook-up***	***Cable laying***	***Final commi-ssioning***
Vessel selected	OSV 0	AHTS 9	OSV 2	OSV 1	AHTS 5	CLV 14	SOV 15

Table 6.7: Optimal fleet for installation of two turbines

Results for Two Turbines with impact of Hs = 2.0m

The average time utilization of the fleet is 52 % which is a decrease from the average time utilization in scenario 4. Figure 6.12 shows a reduction in time period 1, 2 and 3, whereas time period 0 and 4 is the same as the results from installing two turbines with no weather impact.

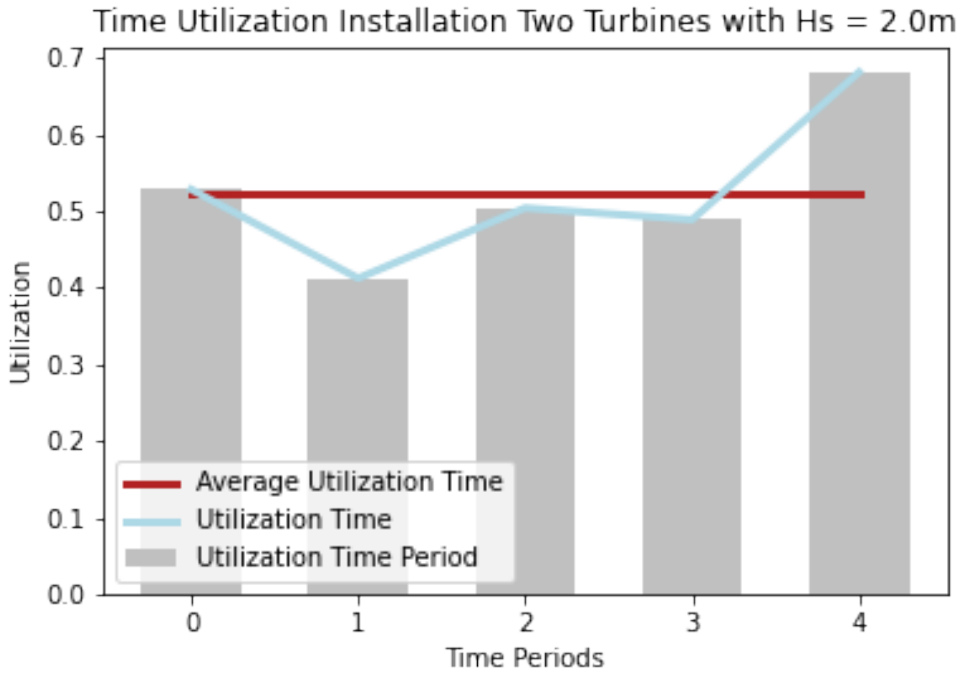


Figure 6.12: Time utilization of the fleet for two turbines under the impact of Hs = 2.0m

The total installation time is 36,5 days with a total cost of 4 190 000 £ for the fleet. The selected fleet is very similar to the optimal fleet for one turbine with Hs=2.0m. The difference is the vessel chosen for the final commissioning operation, where SOV 15 is preferred.

Operations	***Anchor transp.***	***Anchor Inst.***	***Sea-keeping***	***Towing***	***Hook-up***	***Cable laying***	***Final commi-ssioning***
Vessel selected	OSV 0	AHTS 8	OSV 2	OSV 1	AHTS 5	CLV 13	SOV 15

Table 6.8: Optimal fleet for installation of two turbines with the impact of Hs = 2.0m

Results for Two Turbines with impact of Hs = 2.5m

The result of installing two turbines with the impact of Hs = 2.5m shows a reduction in the average time utilization. The average time utilization is 44 % which is very different from two turbines with no weather impact. Similar to one turbine with Hs = 2,5m, an increase in waiting time and reduction in sailing speed results in one more time period. Time period 0 has very low time utilization, and this may be caused by longer waiting time for performing the operations.

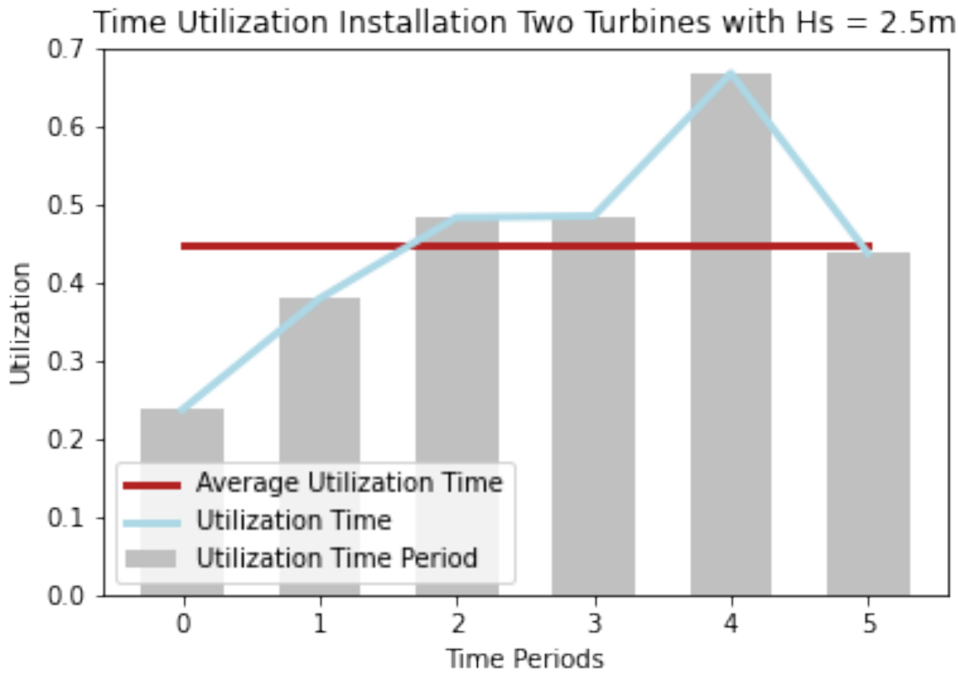


Figure 6.13: Time utilization of the fleet for two turbines under the impact of Hs = 2.5m

The total cost of the fleet is 4 718 000 £, an increase of 800 000 £ compared with installing two turbines with no impact of weather. This is a larger increase of weather comparison for the installation of one turbine. The total installation time is 41 days, 9 more days than the total installation time for two turbines with no weather impact.

Operations	*Anchor transp.*	*Anchor Inst.*	*Sea-keeping*	*Towing*	*Hook-up*	*Cable laying*	*Final commi-ssioning*
Vessel selected	OSV 0	AHTS 7	OSV 2	OSV 1	AHTS 5	CLV 12	SOV 15

Table 6.9: Optimal fleet for installation of two turbines with the impact of Hs = 2.5m

6.5 Comparisons of weather impact

Several more test instances are analyzed to see if there is a trend in reduction of cost per installed turbine where the results are shown in table 6.10. Going from installing one turbine to ten turbines without the impact of weather results in a cost reduction of 56 %. The cost reduction with Hs = 2.5 is lower with a 44 % reduction. Furthermore, the gap between the installed cost of no weather and Hs = 2.5m increases with the number of turbines. The difference in no weather and weather impact for one turbine is 637 000 £, and the difference for ten turbines is 685 000 £.

Turbines	Hs	Obj.function	Cost per turbine
1	0	2 690 000 £	2 690 000 £
1	2,5	3 327 000 £	3 327 000 £
2	0	3 921 000 £	1 960 000 £
2	2,5	4 718 000 £	2 359 000 £
3	0	4 318 000 £	1 439 000 £
3	2,5	6 485 000 £	2 161 000 £
5	0	6 437 000 £	1 287 000 £
5	2,5	9 920 000 £	1 984 000 £
10	0	11 649 000 £	1 164 000 £
10	2,5	18 492 000 £	1 849 000 £

Table 6.10: Cost per installed turbine

Figure 6.14 shows the trend of the number of installed costs per turbine with no weather involved and the effect of weather when Hs = 2.5m. There is a significant decrease in cost for the first number of installed turbines, and cost reduction converges with the number of installed turbines.

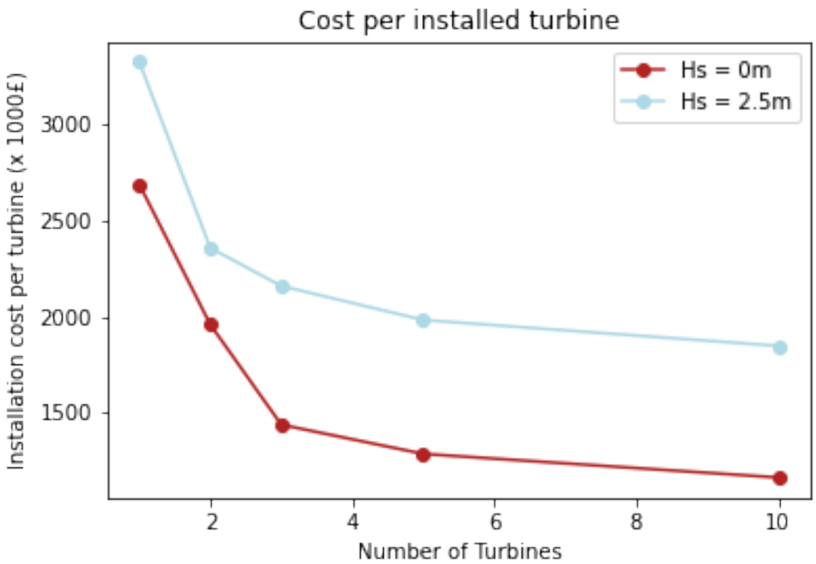


Figure 6.14: Installation cost comparison of weather impact

In this chapter, an optimization model was developed to find the optimal fleet for a predefined installation schedule of floating wind turbines. It was suggested solutions to capture the impact of weather where the set of vessels had different weather limitations and sailing speed dependent on significant wave height. The results showed a large difference between the cost per installed turbine when the weather was included. The reason for the difference is that waiting time increases and sailing time reduces. However, in both cases, the cost per turbine decreases with the number of installed turbines. This is due to the model only impose the mobilization costs once. This constraint might be questioned due to the mobilization cost in reality, which might occur more than once if the waiting time between operations is too long.

Chapter 7

Fleet selection and scheduling optimization model

The model is formulated as a continuous optimization problem for fleet selection and scheduling (CFSS) for an installation. First, the mathematical formulation of the improved optimization model will be presented and explained. The same parameters used in the case study in the first model will be used for analyzing the improved optimization model. Furthermore, the effect of weather impact and wind farm size will be analyzed and discussed.

7.1 Model expansion

Reformulating the model from the previous chapter gives an alternative for fleet selection and scheduling optimization. The floating wind farm planning can be treated as a vehicle routing problem where the "routes" are assigned installation activities that need to be performed by installation vessels. The scheduling term in the installation includes the time of the various activities along the vessel route. The activities in the installation process are weather-dependent, meaning that the activities need to be performed within a time window. The weather may impact the performance of the installation, so a robust solution is suggested to capture the increased service time to perform the various activities.

The new, improved model has similarities to the MILP model developed in the paper *Planning of an Offshore Well Plugging Campaign: A Vehicle Routing Approach* (Bakker et al., 2017). The MILP model is defined as a Vehicle Routing Problem (VRP) where precedence and non-concurrence are included when planning a plugging campaign. In the planning problem for the installation of floating wind, the same set of vessels as the previous model will be used to create routes to execute all the activities. The model is formulated with an arc-flow formulation where the time is continuous, and the nodes are defined as the installation activities. In addition, the weather is implemented to achieves a more robust solution, where waiting on weather is added when wave height exceeds the operation limit. Weather is included the same way as the approach of weather impact *Optimization in offshore supply vessel planning* (Halvorsen-Weare and Fagerholt, 2016). The Markov Chain simulates the occurrences of wave height and is used to calculate the operational limit in the planning of floating wind installation.

7.2 Penalty cost

To capture the weather impact in the model, a penalty cost term is introduced. Suppose the installation process needs to wait for a better window and thus completes after the original deadline. In that case, this then results in loss of electricity production, which leads to loss of revenue. The penalty cost is defined as lost revenues by not producing electricity. The penalty cost term can be found by multiplying each turbine's capacity factor times turbine rating, the electricity price, and how many turbines in the wind farm. The penalty cost is defined as a waiting cost of each vessel in this thesis and is given as:

$$C_v^W = \text{ Price }^{el} \times \text{ Capacity factor } \times \text{ Capacity in MW} \times \text{ Number of turbines} \tag{7.1}$$

The capacity factor used for calculating the penalty cost is 0.57, the same capacity factor of Hywind Scotland wind farm (Equinor, 2017) and turbine capacity of each turbine rating is set to 8 MW. The energy price is an average of European wholesale baseload electricity price of 2020. This results in a penalty cost of 4300 £ every day the installation is delayed. Furthermore, the day rates need to be taken into account while waiting. It is assumed that the charterer doesn't pay for fuel while the vessels wait for weather. The total waiting cost in the model is then 40-45% of the day rate and the penalty cost.

7.3 Mathematical formulation

In this section, the mathematical formulation for the MILP Model, in other words, the CFSS formulation, is described and presented. All the sets, indices, parameters, and variables will be explained, followed by all constraints and the objective function. The code of the mathematical formulation of the CFSS model can be found in appendix B.2.

7.3.1 Sets

Several operations need to be executed in the installation. The operations can be defined as set $N = \{1, 2.., 6\}$, which consists of all the activities that need to be executed on all the turbines. The next set is defined as $V = \{v_1, v_2, ..., v_{20}\}$ and consist of all heterogeneous vessels that are available to perform the activities. For every vessel $v \in V$, define $N_v \subseteq N$ to be set operations compatible with vessel v. Two artificial nodes which represent the vessel origin and destination $o(v)$ and $d(v)$, where the vessels start and end of the planning horizon. Routing options are defines as arcs and activities as vertices. $A_v = \{(i, j) : i, j \in N_v\}$ represents the arc set in the network that can be traversed by vessel v. Some of the activities are dependent on each other so by defining precedence set P, consisting of pair (i,j) with $i, j \in N$, meaning that activity i should precede activity j. Furthermore, Given vertex i, $\delta_v^+(i)$ is defined as a set of possible vertices j

that vessel v kan visit after visiting vertex i, where the set is a subset $(i, j) \in A_v$. Given vertex i, $\delta_v^-(i)$ is defined as a set of possible vertices j that vessel v may have visited before visiting vertex i, where the set is a subset $(j, i) \in A_v$. The sets are summarized below:

V Set of vessels, index by v

N Set of activities represented as vertices, indexed by i

N_v Set of operations compatible with vessel v, including two artificial nodes which represents vessel origin and destination, $o(v)$ and $d(v)$

A_v Set of arcs in the network that can be traversed by vessel v, where $A_v = \{(i, j) : i, j \in N_v\}$

P Precedence set consisting of pairs (i,j) where $i, j \in N$, meaning that operation i should precede operation j

7.3.2 Parameters

Two parameters are introduced regarding the cost of installation. The first cost parameter is daily charter cost C_v^{TC} of a vessel, and the second cost parameter is mobilization cost of a vessel C_v^M. The third cost parameter C_v^W in the objective function is the waiting cost parameter and is included if vessels need to wait for the weather. The next following input parameters are non-negative duration T_{iv}^{ET}, T_{iv}^{ST}, T_i^S and T_i^E representing execution time, sailing time, start and end time restrictions. The time parameters capture the time characteristics involved in the installation. Lastly, parameter, T_i^{WHS} represents the waiting time of the corresponding activity in vertex i if significant wave height from the site is higher than the vessel restrictions.

C_v^{TC} Charter cost of vessel $v \in V$

C_v^M Mobilization cost for chartering vessel $v \in V$

C_v^W Waiting cost of each vessel $v \in V$

T_{iv}^{ET} Execution time of activity i with vessel $v \in V$

T_{iv}^{ST} Sailing time of activity i with vessel $v \in V$

T_i^S Earliest start time of activity i

T_i^E Latest completion time of activity i

T_i^{WHS} Waiting time for starting on activity i

7.3.3 Decision variables

The model is presented using an arc-flow formulation. The first variable is a binary flow variable x_{ijv} and defines arcs between vertices for a specific vessel. For keeping track of the time aspect of the installation activities, a continuous-time variable, t_{iv} is defined. Variable t_v is introduced when vessel $v \in V$ needs to wait if the weather forecast is over the vessel restrictions.

x_{ijv} 1 if activity $i \in N_v$ is completed before activity $j \in N_v$ with vessel $v \in V$

t_{iv} Start time of operation $i \in N_v$ with vessel $v \in V$

t_v Waiting time for vessel $v \in V$

7.3.4 Objective function

The overall aim of the model is to minimize the total cost related to the fleet that is used for installation of a floating wind farm. This can be done by minimizing the charter cost of each vessel that is included in the fleet. A vessel is hired from start on its assigned operation until the end of its last operation. When a vessel is hired the mobilization cost for that vessel is included in the objective function. The last part of the objective function, a waiting cost in multiplied with the waiting time of each vessel $v \in V$ if included in the fleet. The objective function will minimize the complete installation time (CIT) and given as:

$$\min \sum_{v \in V} \sum_{j \in N} C_v^M x_{o(v)jv} + \sum_{v \in V} \sum_{i \in N_v} \sum_{j \in N_v} C_v^{TC} \left(T_{iv}^{ET} + T_{iv}^{ST} \right) x_{ijv} + \sum_{v \in V} C_v^W t_v^W \tag{7.2}$$

7.3.5 Constraints

Operation

All operations needs to be executed in the installation of the floating wind farm, this is ensured by:

$$\sum_{v \in V} \sum_{j c \delta_v^+(i)} x_{ijv} = 1, \quad i \in N \tag{7.3}$$

Waiting time

If the weather on site is larger than vessel restrictions, waiting time of installation start needs to be included and is taken care of with constraint:

$$t_v^W = \sum_{(i,j) \in N_v} T_i^{WHS} x_{ijv}, \quad v \in V \tag{7.4}$$

Routing

A vessel needs to start at its origin and can only perform one route:

$$\sum_{j \in \delta_v^+(o(v))} x_{o(v)v} = 1, \quad v \in V \tag{7.5}$$

The arc between origin and end destination with zero cost gives the option of not hire a vessel. With this, each vessel is assured to end its route in its destination:

$$\sum_{i \in \delta_v^-(d(v))} x_{id(v)v} = 1, \quad v \in V \tag{7.6}$$

Finally a flow balance ensures feasible routing. If a vessel is used in an operation, it needs to move to another operation or to the destination.

$$\sum_{i \in \delta_v^-(j)} x_{ijv} - \sum_{i \in \delta_w^+(j)} x_{jiv} = 0, \quad v \in v, j \in N_v \tag{7.7}$$

Timing

The following time constraints ensure schedule feasibility regarding time schedules to the operations involved. This implies that a vessel can only execute one operation at a time. If a vessel executes an activity or enters its destination, it must have completed the previous activity or left its origin:

$$x_{ijv}\left(t_{iv} + T_{iv}^{ET} + T_{iv}^{ST} - t_{jv}\right) \leqslant 0, \quad (i,j) \in A_v, v \in V \tag{7.8}$$

The equation can be linearized as:

$$t_{iv} + T_{iv}^{ET} + T_{iv}^{ST} - t_{jv} - M\left(1 - x_{ijv}\right) \leqslant 0, \quad (i,j) \in A_v, v \epsilon V \tag{7.9}$$

The activities that are to be executed have to be completed within a time window. The activities often require limited weather windows, and the vessel involved are usually available for limited time periods. Time windows for operations can be defined as:

$$T_i^S \sum_{j \in \delta_v^+(i)} x_{ijv} \leqslant t_{iv} \leqslant \left(T_i^E - T_{iv}^{ET}\right) \sum_{j \in \delta_i^+(i)} x_{ijv}, \quad v \in V, i \in N \tag{7.10}$$

These constraints force the time variable to zero if a vessel does not execute a certain activity. Furthermore, weather window for the origin and end destination vertices are imposed:

$$T_i^S \leqslant t_{iv} \leqslant T_i^E, \quad v \in V, i \in \{o(v), d(v)\} \tag{7.11}$$

Precedence

For the wind turbine installation there exists a strict ordering in the sequence of the which activities to execute. The correct ordering is guaranteed by following constraint:

$$\sum_{v\in v} t_{iv} + \sum_{v\in V} \sum_{k\in\delta_v^+(i)} (T_{iv}^{ET} + T_{iv}^{ST})x_{ijv} - \sum_{v\in v} t_{jv} \leqslant 0 \quad (i,j) \in P \tag{7.12}$$

Vessel requirement

Each activity to be performed has certain requirements, and the vessel used for the specific activity shall have the capabilities for performing the activity. So for forcing the correct type of vessel to execute each activity is ensured by constraint:

$$\sum_{j\in N_v} x_{ijv} \leqslant MQ_{iv}, \quad i \in N, v \in V \tag{7.13}$$

Domains

The domains of each of the variables used for the model need to be enforced with constraints. The following constraints ensure the binary domain of the arc-flow variable and non-negative, continuous values.

$$x_{ijv} \in \{0,1\}, \quad (i,j) \in N_v, v \in V \tag{7.14}$$

$$t_{iv} \in \mathbb{R}_0^+, \quad v \in V, i \in N_v \tag{7.15}$$

$$t_v \in \mathbb{R}_0^+, \quad v \in V \tag{7.16}$$

7.4 Case study CFSS

Delay in a project schedule may lead to a significant financial loss, so implementing more robust solutions to capture weather and increase the probability for feasible solutions can be used in the case of delay. The case study from the DOFS model will be used for the CFSS model with a different approach to capturing weather impact. It would be interesting to see if the approach capturing weather is different or not with the results from the DOFS model.

As there is no predefined schedule in the CFSS model, the schedule is generated based on vessel properties and precedence of the different operations. For the development of a floating wind farm, the operations to install the turbines need to be performed logically. The operations can be implemented in a Design Structure Matrix (DSM) to show the relationship between different operations needed to install a wind turbine.

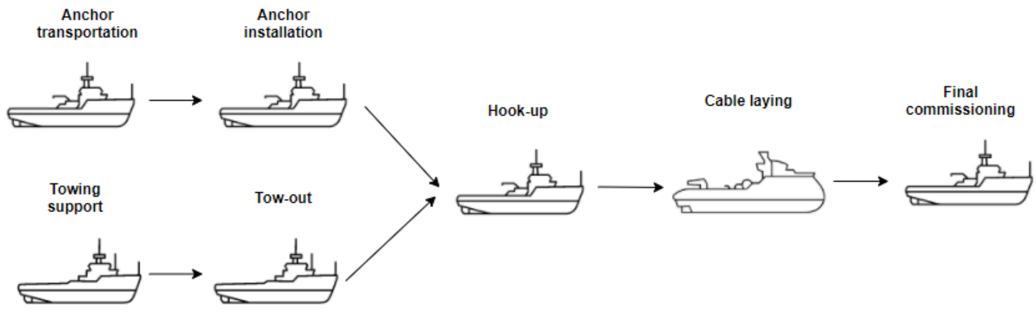


Figure 7.1: The installation process in the model, showing the sequence of the operations

Precedence between the operations in table 7.1. The precedence of an operation has a value of 1 if the operation needs to be completed before the next operation can start. An example shown in the DSM is that sea-keeping, defined in the model as the first stage of towing operation, needs to be completed before towing to the site. Furthermore, both towing and anchor installation need to be completed before hook-up can start.

Operations	Anchor.Trans	Anchor.Inst	Sea-keeping	Towing	Hook-up	Cable-laying	Final. comm
Anchor.Trans	0	1	0	0	0	0	0
Anchor.Inst	0	0	0	0	1	0	0
Sea-keeping	0	0	0	1	0	0	0
Towing	0	0	0	0	1	0	0
Hook-up	0	0	0	0	0	1	0
Cable-laying	0	0	0	0	0	0	1
Final. comm	0	0	0	0	0	0	0

Table 7.1: DSM showing precedence between operations

Installation of One Turbine

Installation of one turbine results in a schedule, shown in figure 7.2, with a total installation time of 20 days and the optimal fleet cost is 1 756 000 £. The installation fleet consists of a total of five vessels with 2 vessel types of OSV, 1 AHTS, 1 CLV, and 1 SOV.

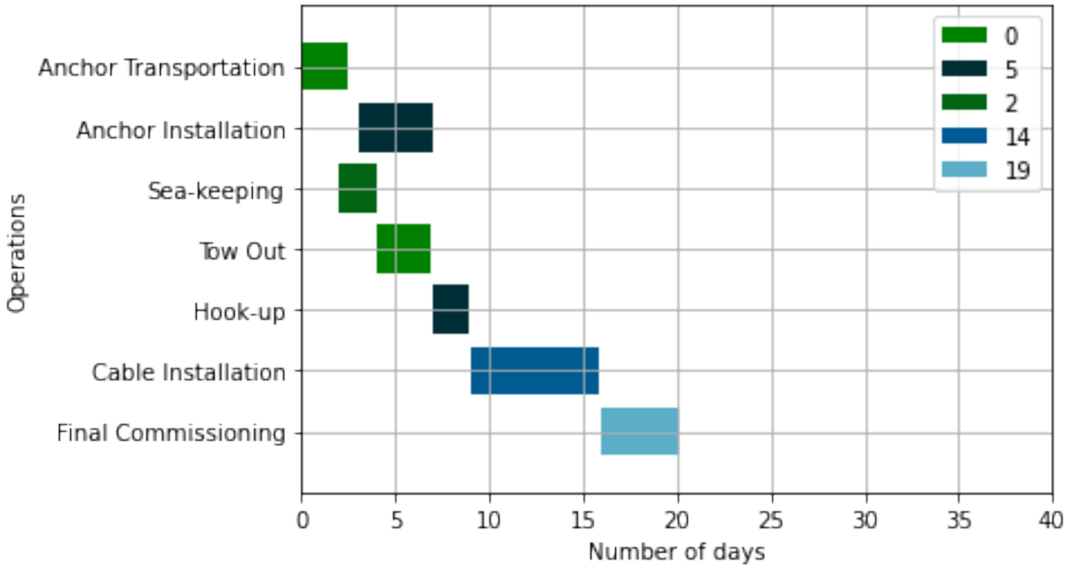


Figure 7.2: Schedule for installing one turbine

Installation of One Turbine with the impact of Hs = 2.0m

It was counted 32 days from the simulated weather with Hs larger than 2.0m resulting in a total installation time of 52 days. The impact of waiting results in a total cost of 27 425 000 £. The high cost is due to over a month of waiting on weather, meaning all the operations are delayed, resulting in a significant increase in total cost. The optimal installation fleet consists of six vessels, one more vessel than the fleet for installing one turbine. However, some of the operations have been assigned a different type of vessels, such as AHTS 8 for anchor installation, OSV 1 for towing, and SOV 17 for final commissioning, as shown in figure 7.3.

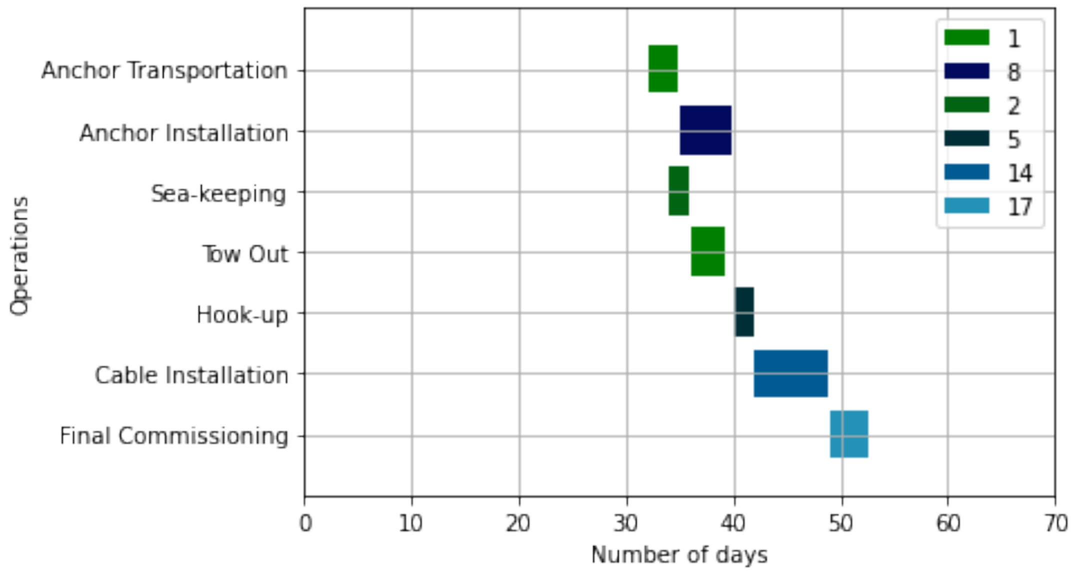


Figure 7.3: Schedule for installing one turbine with the impact of Hs = 2.0m

Installation of One Turbine with the impact of Hs = 2.5m

It was counted 5 days from the simulated weather with Hs larger than 2.5m resulting in a total installation time of 27 days. The optimal fleet has a total cost of 5 710 000 £ for five vessels. The fleet has similarities to the optimal fleet for the installation of one turbine with no weather impact. The difference between the fleets are for anchor transportation, OSV 1 is assigned, and for anchor installation, AHTS 8 is assigned as shown in figure 7.4.

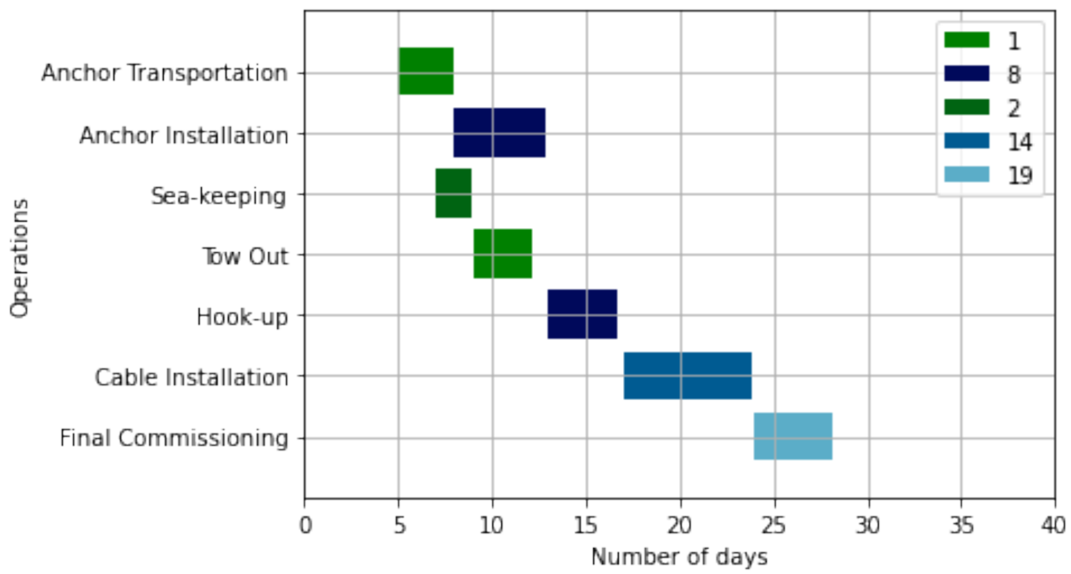


Figure 7.4: Schedule for installing one turbine with the impact of Hs = 2.5m

Installation of Two Turbines

The schedule for the installation of two turbines is shown in figure 7.5. The total installation time is 40 days, and the optimal fleet cost is 3 060 000 £. Thus, the fleet is similar to the optimal fleet installing one turbine except for the final commissioning operation where SOV 15 is chosen instead of SOV 19.

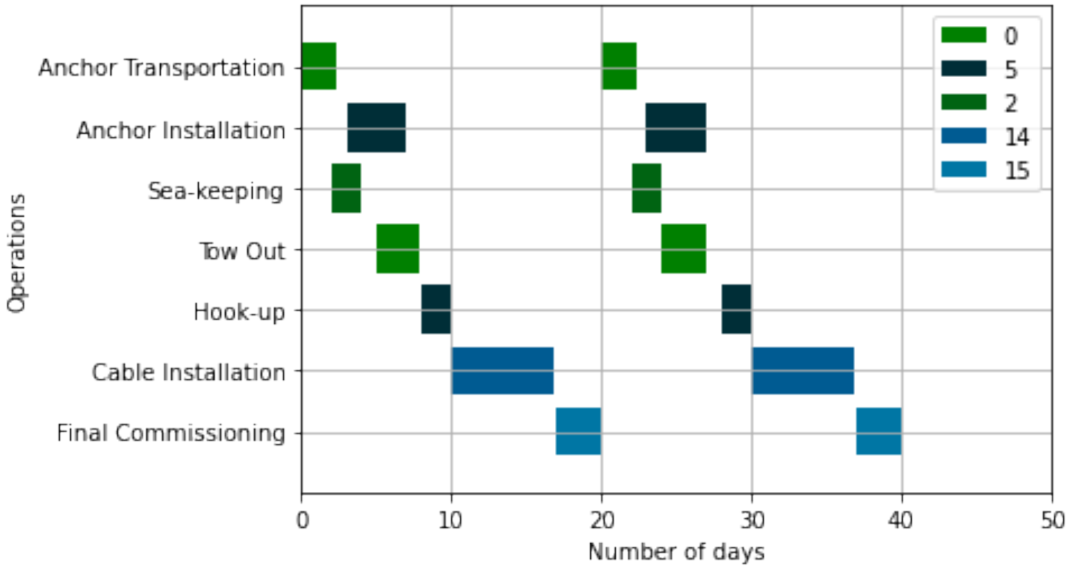


Figure 7.5: Schedule for installing two turbines

Installation of Two Turbines with the impact of Hs = 2.0m

The total installation time is found to be 72 days with a cost of 33 797 000 £. The optimal fleet is very different compared with the optimal fleet for installing one turbine with the impact of Hs = 2.0m. As shown in figure 7.6 shows, the fleet consists of 9 vessels. Some of the operations for the second turbine installed have been assigned different vessels from the first turbine.

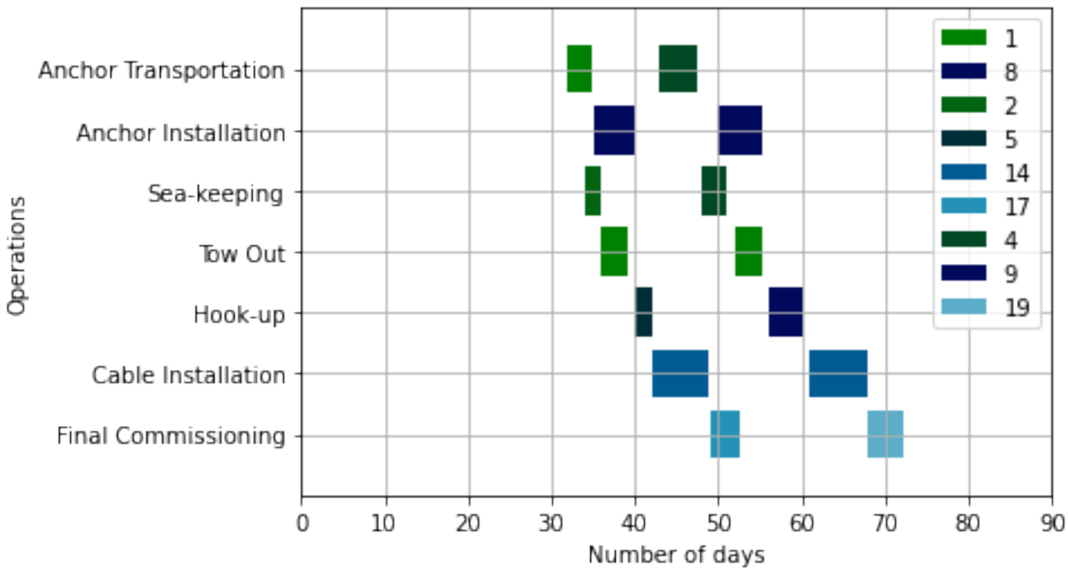


Figure 7.6: Schedule for installing two turbines with the impact of Hs = 2.0m

Installation of Two Turbines with impact of Hs = 2.5m

Installation of two turbines with an impact of Hs = 2.5m, the total installation time was found to take 48 days. The cost of the optimal fleet, which consists of five vessels, is 8 148 000 £. The schedule in figure 7.7 shows a similar fleet to the fleet for installing one turbine with the impact of Hs = 2.5m.

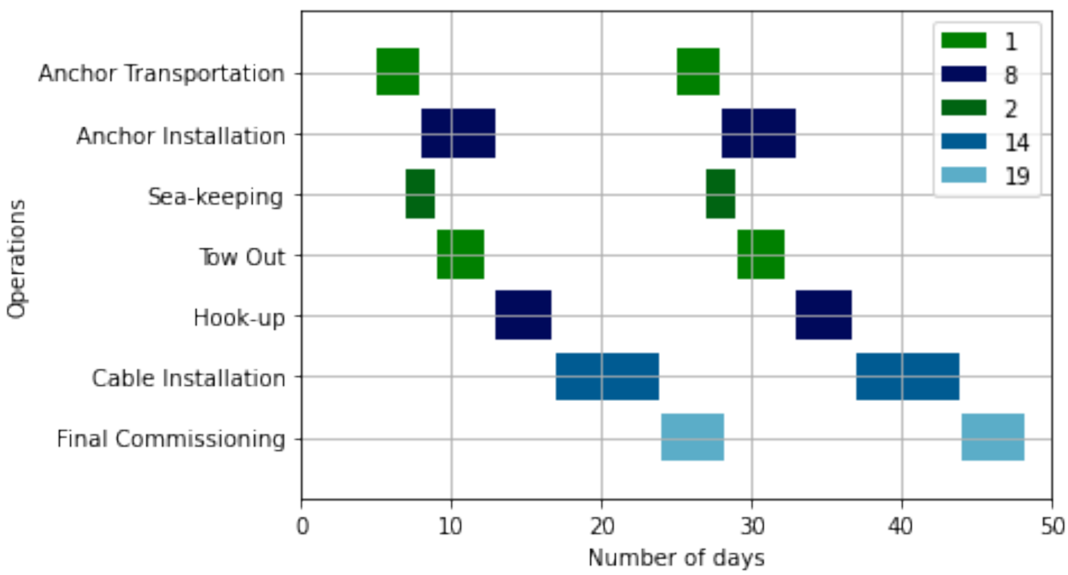


Figure 7.7: Schedule for installing two turbines with the impact of Hs = 2.5m

Comparison between Hs = 0m and Hs = 2.5m

There are some interesting results when comparing the cost of a turbine when increasing the number of installed turbines. Figure 7.8 shows the graphs for the number of installed turbines when Hs = 0m and Hs = 2.5m. The trend of the installation cost per turbine when Hs = 0m shows a reduction from 1 turbine installed to ten turbines. The same reduction trend is for the installation cost per turbine when Hs = 2.5m. There is a steep reduction in the graph from one to two turbines, and from two turbines, the graph flattens more out with an increasing number of turbines.

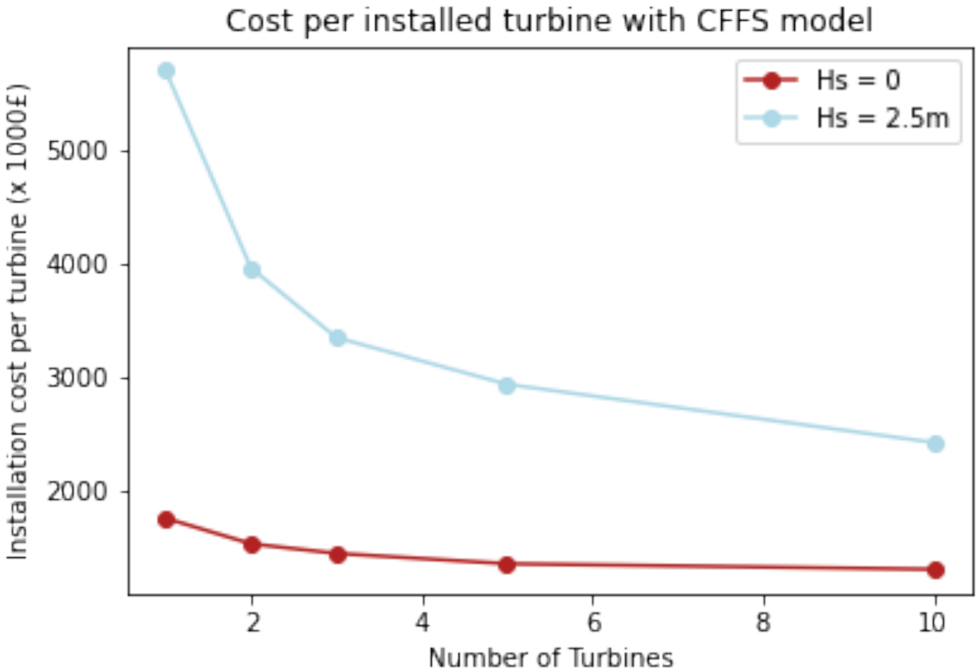


Figure 7.8: Cost comparison of weather impact from the CFSS model

Table 7.2 shows the results from running the model for 1 turbine to 10 turbines. The fleet cost when Hs = 0m has a steady increase from 1 turbine with a cost of 1 756 000 £ to ten turbines with a cost of 13 054 000 £. However, the results are interesting for Hs = 2.5m as cost increase between 1 turbine and 10 turbines are 84 %. The increase is lower than the increase between 1 turbine and 10 turbines when Hs = 0m of 76 %. Another interesting result to study is the increase in installation time of the turbines. The installation time between the turbines when comparing the impact weather shows an increase of 7-8 days except for ten turbines. The significant difference of 45 days is a result of more waiting on weather, which is consistent with the graph shown in figure 7.8 where the cost increases.

Number of Turbines	Hs	Number of OSV	Number of AHTS	Number of CLV	Number of SOV	Total cost of fleet	Total installation time
1	0	2	1	1	1	1 756 000 £	20 days
1	2,5	2	1	1	1	5 710 000 £	27 days
2	0	2	1	1	1	3 060 000 £	40 days
2	2,5	2	1	1	1	7 935 000 £	48 days
3	0	2	1	1	1	4 335 000 £	50 days
3	2,5	2	2	1	1	10 056 000 £	58 days
5	0	2	2	1	1	6 733 000 £	70 days
5	2,5	4	2	1	1	14 699 000 £	78 days
10	0	2	2	2	1	13 054 000 £	120 days
10	2,5	3	2	1	1	24 255 000 £	165 days

Table 7.2: Results from the CFSS model

The table shows an increase in fleet size after the installation of three turbines. The largest fleet from the results was for installing 5 turbines with Hs = 2.5m consisting of 8 different vessels. All the fleet configurations have only one SOV and one CLV except for the installation of ten turbines when Hs = 0m, where the fleet has 2 CLVs. The anchor transportation operation had a variation of what type of vessel was assigned. For the installation of 5 turbines and 10 turbines, AHTS was chosen along with OSV to perform the operations.

Chapter 8

Results

In this chapter, the results from both models will be presented and compared. Two different approaches have been suggested to capture the impact of weather, and it is interesting to see if there is a difference in the results and how large these differences are.

8.1 Installation cost

In this section, the installation cost from both models is presented. Figure 8.1 shows the results from the models when the weather is not included. It is observed that the DOFS model has a much higher installation cost for the installation of few turbines. Both models show that a wind farm size of three turbines has a similar installation cost. When the number of turbines increases, the CFSS model shows a slightly higher cost per turbine. However, the DOFS model is a simple model that can be used for achieving quick cost estimates for larger wind farms as it has low running time.

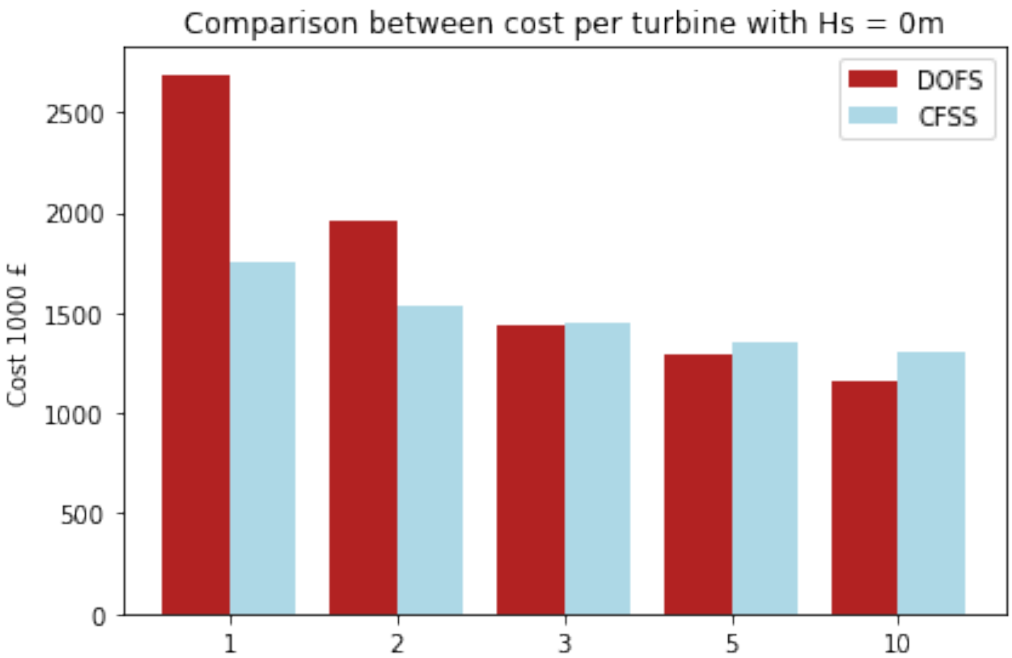


Figure 8.1: Cost comparison between the models with Hs = 0m

Figure 8.2 shows the result from the model when Hs = 2.5m is implemented. The models have a different approach to include the weather; however, it is interesting to see the results. It is observed that the CFSS formulation has a much higher installation cost independent of the number of turbines. The DFOS shows a slight reduction in the cost from two turbines to ten turbines. For the CFSS costs, there is much more difference in reduction when increasing the number of turbines. It is also worth noticing that there is less difference between DOFS and CFSS costs with the increasing number of turbines.

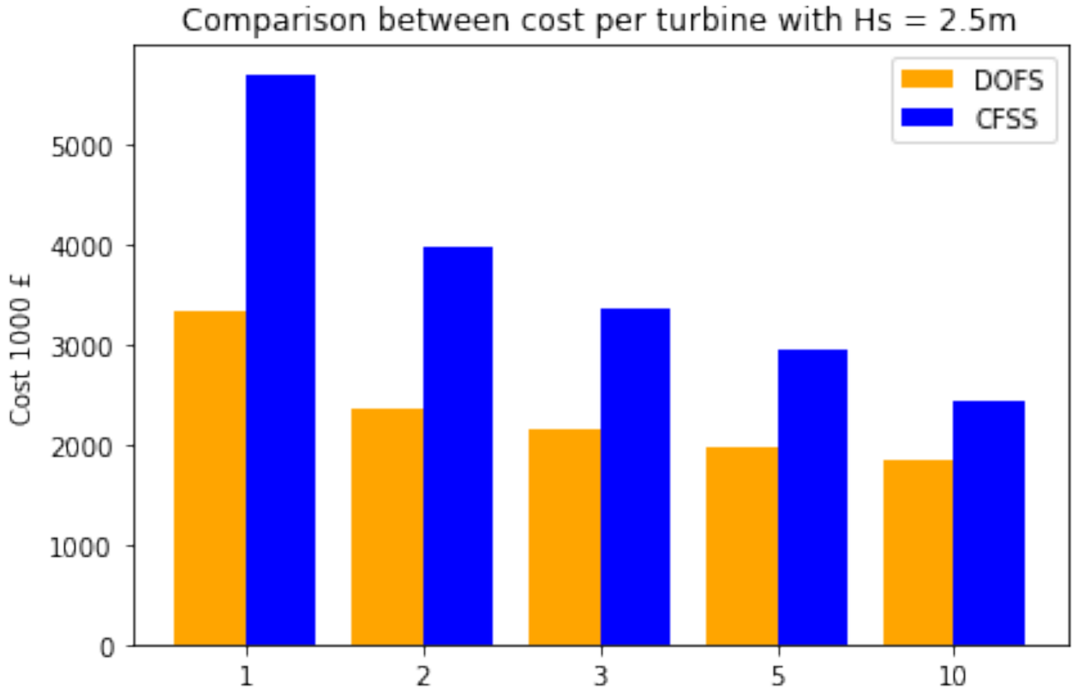


Figure 8.2: Cost comparison between the models with Hs = 2,5m

In the CFSS model, Hs = 2.0m has also been analyzed for the same number of turbines. From figure 8.3 it observed that when Hs = 2.0m, it results in a much higher cost per turbine compared to no weather or Hs = 2.5m. This can be explained by the number of days from the simulated weather where it found 32 days with Hs over 2.0m. It is also worth noticing the significant decrease between one and two turbines when Hs = 2.0m. This can be explained that the total cost of installing one turbine is much larger, with waiting 32 days compared to wait 32 days for installing two turbines. The DOFS and CFSS cost results show the same trend where turbine costs decrease with increasing the number of turbines. Also, it is interesting to see that both models yield results with minor differences for Hs = 0m and Hs = 2.5m.

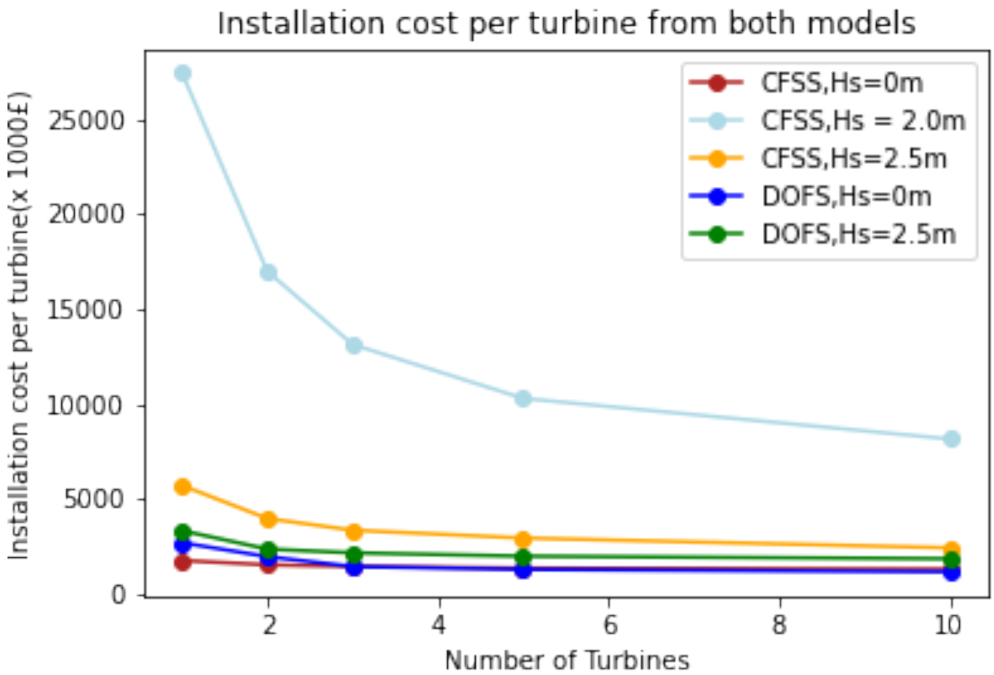


Figure 8.3: Cost comparison between the models

8.2 Schedules and fleet configuration

Schedules and choice of the fleet are also clear regarding the differences between the DOFS and CFSS. Figure 8.4 shows the duration of installations per turbine when Hs = 2.5m. The CFSS shows a lower duration of installation of one turbine; however, this is not the case when the number of turbines increases. The installation time can be explained by the that the DOFS model is based on a predefined schedule, whereas the schedule made from the CFSS model is based on precedence constraints. CFSS has waiting days included in the model, whereas the DOFS model has increased sailing time when Hs increases. However, the only significant difference in the results is for ten turbines where CFSS shows the most significant installation time. Despite longer installation time, there is not a substantial difference in installation costs for ten turbines between the models as shown in the previous figure 8.3

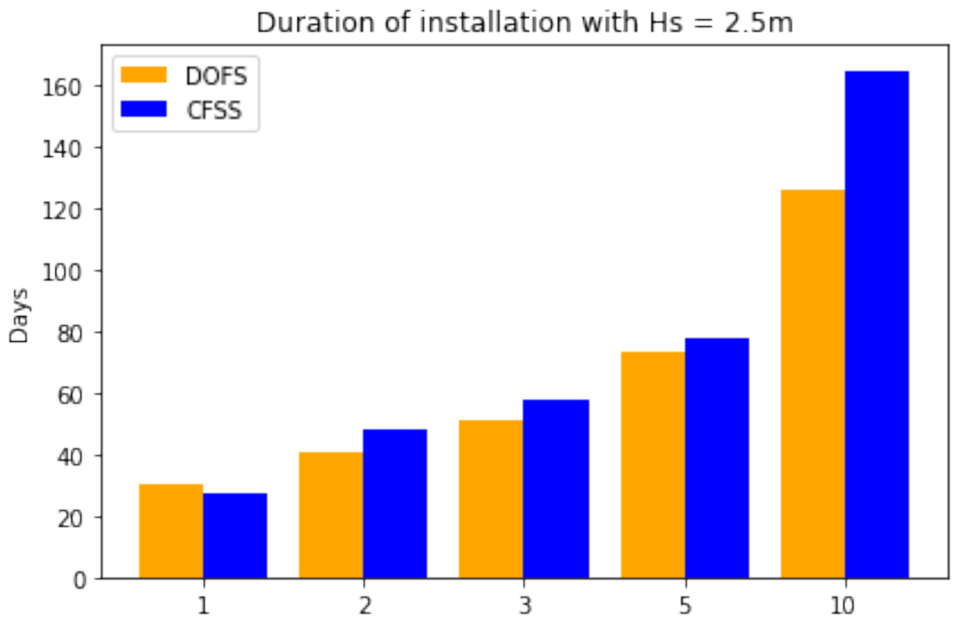
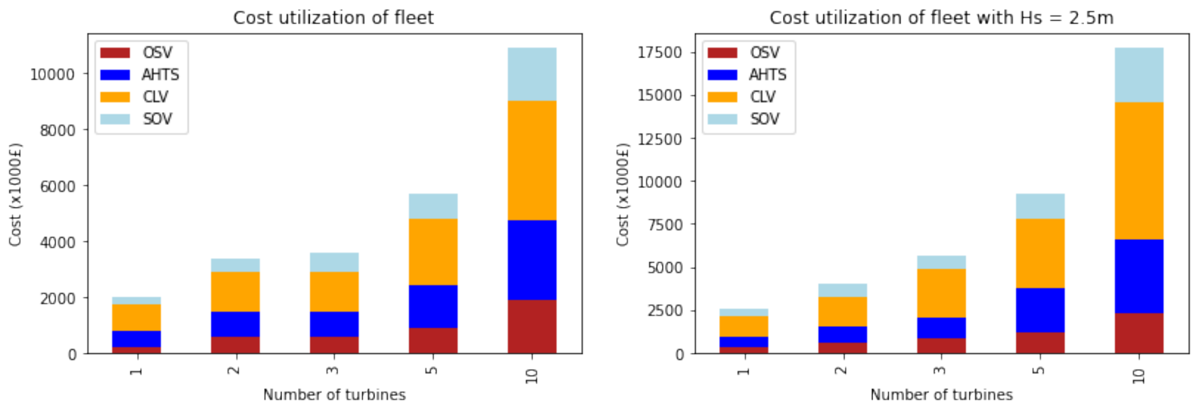


Figure 8.4: Total installation time results from the models

Figure 8.5a and figure 8.5b shows the fleet composition for the number of turbines with the DOFS model. Several observations can be made from the figures. First, when the weather is not included, the cost of the fleet for 2 and 3 turbines is very similar. Furthermore, there is a significant difference in the total fleet cost for ten turbines when Hs = 2.5m. This is a result of sailing time is much larger than sailing time without the impact of weather. Also, with operational limits for each vessel, the DOFS generates a much more expensive fleet when the weather is considered. Another observation from the figures is that the cost of CLVs in the fleet for installation of ten turbines with Hs = 2.5m compared with the fleet without weather.

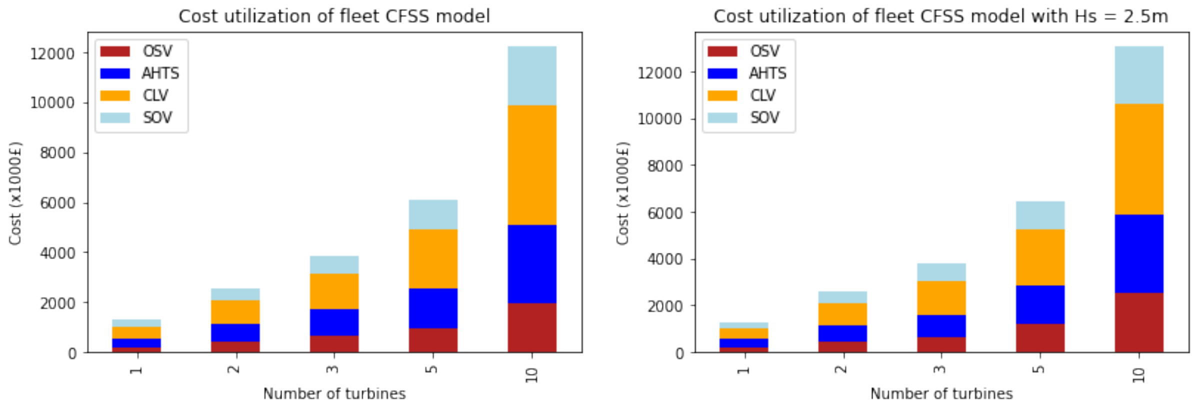


(a) Cost utilization of fleet **(b)** Cost utilization of fleet with Hs = 2.5m

Figure 8.5: Cost utilization of fleet per turbine with DOFS model

Similarly, figure 8.6a and figure 8.6b presents the results with Hs = 0m and Hs = 2.5m from the CFSS model. It can be observed that fleet sizes are similar to the increase in the number of installed turbines. For installation of ten turbines when Hs = 2.5m, the fleet size consists of more OSVs than the fleet for ten turbines without weather impact. This results in a higher fleet cost for ten turbines. The only clear difference is the cost difference for ten turbines. For turbine one to five turbines, there is no or little difference between the figures.

The results from the DOFS model for Hs = 2.5m and the CFSS model for Hs = 2.5m are interesting to study. When comparing the figures with each other, the DOFS cost of the different fleet sizes is much higher than the fleet sizes from the CFSS model. The main reason for the large differences is that the CFSS model maximizes the utility of each vessel that is mobilized. With the DOFS model, one vessel is assigned to one operation, resulting in a higher mobilization cost resulting in a higher fleet cost. This is not the case for the CFSS model, where one vessel is assigned for several operations. In section 7.4, where for example, the schedule for installation of turbine showed that vessel OSV 0 was used for both anchor transportation and tow-out.



(a) Cost utilization of fleet **(b)** Cost utilization of fleet with Hs = 2.5m

Figure 8.6: Cost utilization of fleet per turbine with CFSS model

Table 8.1 summarize findings from both models where the weather is considered for different farm sizes. It can be observed that the DOFS model shows the lowest cost for the installation of ten turbines. The highest cost is found from the CFSS model for installing one turbine when is Hs = 2.0m. The results from the CFSS model also have the most significant cost decrease with an increasing number of installed turbines. The cost decreases from one turbine to ten when Hs = 2.0m from the CFSS model is 70%.

CFSS had a lower fleet cost for ten turbines when Hs = 2.5m, however, the table shows that result for ten turbines from the DOFS model has the lowest cost. The CFSS model showed a lower cost because waiting cost was not considered, only the fleet cost. Adding the waiting cost to the fleet cost results in a turbine cost of 2 425 000 £ when installing ten turbines when Hs = 2.5m. The waiting cost caused by weather will be addressed in the next section for the results from the CFSS model.

	Number of Turbines	Hs	Number of OSV	Number of AHTS	Number of CLV	Number of SOV	Cost per turbine in million £	Cost decrease[%]
DOFS	1	2,5	3	2	1	1	3.327	0
	2	2,5	3	2	1	1	2.359	29
	3	2,5	3	2	1	1	2.161	35
	5	2,5	3	2	1	1	1.984	40
	10	2,5	3	2	1	1	1.849	44
CFSS	1	2	2	1	1	1	27.425	0
	2	2	2	1	1	2	16.898	38
	3	2	2	1	1	2	13.134	52
	5	2	2	2	1	2	10.294	62
	10	2	2	1	1	2	8.156	70
	1	2,5	2	2	1	1	5.710	0
	2	2,5	2	2	1	1	3.967	30
	3	2,5	2	2	1	1	3.352	41
	5	2,5	4	2	1	1	2.939	48
	10	2,5	3	2	1	1	2.425	57

Table 8.1: Results from both models where weather is included

8.3 Weather comparison

Figure 8.7 presents how much the total installation cost when the weather is included. The weather has a significant impact on marine operations. The occurrence of Hs larger than 2 meters resulted in 32 days of waiting. From the figure, it is evident that waiting cost is dominating the total fleet cost for installing the turbines. With only considering the fleet costs, the result from both Hs = 2.0m and Hs = 2.5m are close to similar.

The waiting cost dominates in the total installation cost when Hs = 2.5m for installing two and three turbines. For one and five turbines, the waiting cost and fleet cost are close to equal. The fleet cost only dominates in the total installation cost for ten turbines. However, in this master thesis, it has been assumed that the waiting days is equal to the number of occurrence of Hs = 2.0m or Hs = 2.5m. Hs larger than 2.5 meters occurred 5 times during the simulated weather of five months and 32 times for Hs larger than 2 meters. The results obtained have given suggestions for fleet compositions for two different significant wave heights that could support decision-makers.

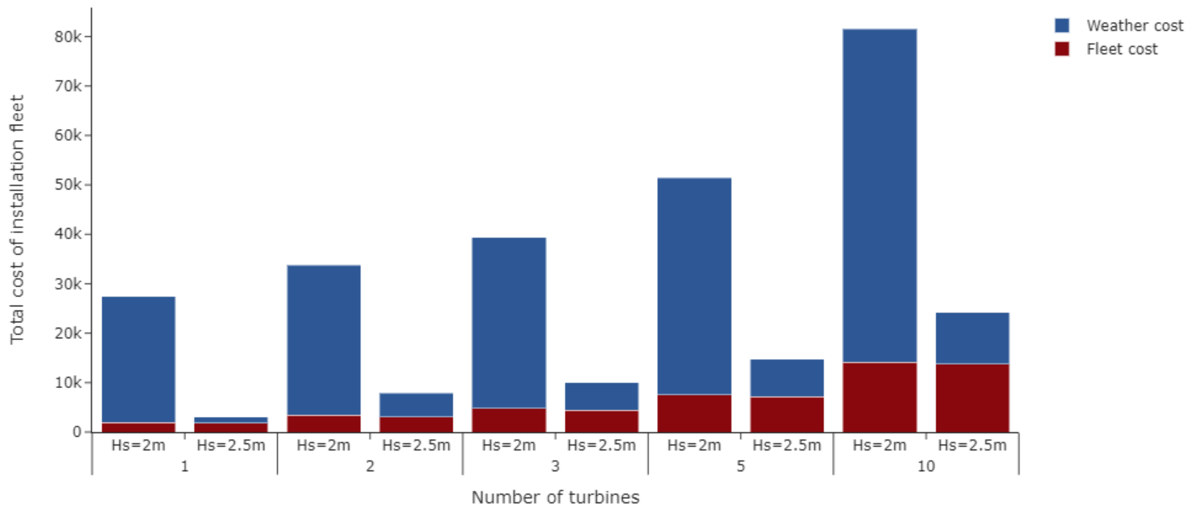


Figure 8.7: Fleet and weather cost results from CFSS model

Chapter 9

Discussion

In this chapter, a discussion of the work and results obtained from the optimization models will be presented. In the first two chapters, a thorough description of FOWFs and essential aspects of the installation process of FOWFs is described. A case study was performed based on the installation process presented in chapter 3 and a pool of 20 vessels with different costs and properties. The weather has been simulated based on a Markov Chain, and the results from the Markov Chain have been used for two different approaches to obtain optimal fleet size and mix and schedules. Necessary assumptions and simplifications have been made to achieve results which will be addressed more in the following discussion chapter.

9.1 Assumptions

The installation of FOWFs consists of several complex operations in series. For the optimization models, the focus has been on the operations after the assembly of the wind turbines. Therefore, transport of components from different locations manufacturers to the installation port has not been considered in the models. Also, other operations at the installation port, such as assembly and ballasting the turbines, have been neglected. There are two main reasons for neglecting some of the operations that are included in the installation process. The first reason is the aim of the master thesis was to capture how weather impact affects the installation process, so only the operations taken place at sea were considered. The second reason was to keep the model limited, not involving too many operations to avoid a too large and complex optimization model.

Some of the operations might require support vessels such as towing. The fleet configuration for the towing operation for Hywind Scotland consists of one AHTS vessel and at least two support tugs. In this master thesis, to capture the use of support vessels, the towing operation was split into two operations. The sea-keeping operation was defined as the first phase of towing, from port to open sea, where smaller OSV was assigned. Then, the main towing operation to the farm site, either an AHTS or a larger OSV, was assigned. However, in reality, the operations consist of several vessels, so an optimal model should consider capturing multiple vessels for each operation.

It has been assumed that the operations for the installation of the turbines are in series. The pre-determined sequence of the operations in the master thesis is not necessarily the correct order. Of course, some of the operations have to be completed before the next operation can start. For example, hook-up cannot start before anchor operations, and towing are completed. However, some of the operations could have been in parallel, such as cable laying. In the models, cable laying operation is defined in series and starts after hook-up is completed. An alternative is to assign the cable laying operation parallel with the anchor operations or start with cable laying.

The assumption of executing the operation in series should also be investigated, as the duration of some operations might vary depending on the number of turbines being installed. The anchor operations and cable laying operation could be done once for all turbines being installed. It is unnecessary to transport and install the anchors for one turbine and travel back to the port to transport the anchors for the next turbine. This could be done in one go, where all the anchors are installed for all the turbines installed. Like the cable installation, it is enough to install the export and inter-array cables only once.

9.2 Weather uncertainties

Most of the operations that are needed for the installation of FOWFs are highly weather-dependent. The weather has been included in both optimization models with different approaches. The weather has been simulated using Markov Chain and historical weather data for the same location where Hywind Tampen is planned to be. The wind has not been considered when simulating weather, only historical weather data for Hs for the summer periods over the last four years. To achieve a more accurate weather simulation, larger historical data sets and the wind speed could have been used for the Markov Chain. However, the results suggest several installation strategies based on what the weather will be on the installation day.

For the DOFS model, it has been assumed that the operation can happen regardless of wave height. However, if the wave height increases, the sailing time had to increase with a percentage depending on the table shown in section 6.2.2. Also, each vessel had its own weather limitations, meaning that some of the vessels could not be used with certain wave heights. This approach can be questioned. In reality, the operations have been designed to certain weather limitations where the operations have to wait if weather exceeds the limitations. However, the results with this approach give an insight into what vessel can be used, total installation cost, and installation time by increasing the weather limitations.

The approach in the CFSS model captures the waiting time when the significant wave height is too high. Two different Hs have been chosen to see the impact on the results from the optimization models. When Hs was equal to 2.5 meters, the model counted five waiting days. With setting Hs equal to 2.0 meters, the model assumed that the installation process had to wait 32 days before starting as the model counted 32 days with Hs large than 2.0 meters. This approach may be questioned as the 32 days are spread throughout the whole simulation period.

This is not captured in the model where the first operation starts after the waiting days. As it is spread throughout the summer period, it is possible to complete the operations, resulting in lower cost and installation time. However, the result can still be used as an insight for choosing installation strategies when there is over a month with bad weather during an installation period of several months.

9.3 Cost assumptions

The different costs used in the models are based on public information and research vessels typically used for offshore operations. In Norway, the day rates for the vessel selected in this master thesis are highly influenced by the market situation, especially the oil price. Supply and demand are also factors that influence the day rate cost of offshore vessels. The summer period is usually used for performing offshore operations as there are more days with good weather. When the market is good, the vessels needed for operations might be unavailable and expensive to hire. When the market is poor, the day rates may be low, and more available vessels in the market. However, the day rates in this master are based on a large range, resulting in a reasonable estimate when selected vessels for the optimal fleet.

The mobilization cost for each vessel has been calculated with the equation shown in chapter 6.2.4. The mobilization costs depend heavily on the distance, fuel cost, and day rate. The fuel cost used to calculate the mobilization costs is based on the average MGO prices for spring 2021. There are high variations in the fuel prices depending on the market. The MGO prices for 2020 are very different compared to 2021 due to the Covid pandemic. The mobilization cost will have been much lower if the MGO prices from 2020 had been used. Furthermore, the mobilization cost in the model is included when a vessel first operates. Costs that are assumed in the mobilization cost are relocation costs, crew mobilization costs, and the cost for preparing equipment. The models do not account for re-mobilization as there might be necessary to re-mobilize in between operations. For example, a vessel used for anchor transportation may need to reload equipment for handling the hook-up operation.

It was difficult to find any public information of cost related to weather, so it was assumed in the CFSS model that waiting cost is a sum of lost revenue and day rate cost. However, the day rate cost when waiting is assumed lower than the day rate when vessels are in operation. Reducing the day rate costs is that the vessels do not use fuel when they are at port. This assumption has been made to motivate the model to find a solution with the shortest installation time with the impact of weather.

9.4 Computational time

Several challenges have been encountered during the development and solving of the optimization models, especially the CFSS model regarding computational time. Gurobi was used as the optimization tool to solve the optimization models. The DOFS was solved with no problem regarding computational time, even with implementing weather. However, the DOFS model is a small and simple model that captures only the essentials of the installation of FOWFs. The CFSS model is a more complex and larger model that encountered a problem regarding the computational time when the number of turbines increased. With the first objective function shown in equation9.1, the solver runs for several days without finding any solutions. The reason for the long-running time is the large data sets input to a complex model. It was, therefore, necessary to change the objective function shown in chapter 7.3.4. With a less complex model, it was possible to achieve satisfactory results that answered the scope of the master's thesis.

$$\min \sum_{v \in V} \sum_{(j) e N} C_v^M x_{o(v)jv} + \sum_{v \in V} C_v^{TC} \left(t_{d(v)v} - t_{o(v)v} \right) + \sum_{v \in V} C_v^W t_v^W \tag{9.1}$$

By optimizing only one operation at a time, it is possible to achieve more realistic results for a complex problem. An alternative for reducing the complexity is to break down the model with decomposition techniques. This could also decrease both installation time and the total installation cost when the weather is included.

Chapter 10

Conclusion and further work

The rapid growth in the offshore wind industry of moving into deeper water depths, the rising need for more detailed investigation of how to reduce costs of FOWFs are crucial to becoming cost-competitive against other energy generating sources. The objective of this master's thesis has been to develop two optimization models for optimizing the fleet size and mix for the installation phase of floating offshore wind farms with the impact of weather. The goal was to minimize the cost related to the installation process of floating offshore wind by identifying the optimal fleet and schedules for different wind farm sizes. However, research on the optimization of the installation phase of floating wind farms is relatively limited. However, with the research of the floating wind industry and previous work to optimize the installation phase of bottom fixed turbines, it was possible to develop the optimization models. The case study performed is based on the installation of Hywind Scotland and Hywind Tampen with a pool of 20 vessels. The case study and the self-developed optimization models have provided the optimal schedule and optimal fleet size and mix to minimize the cost of the installation process.

The DOFS model is the first model that has been developed. The model is a simple model that captures the essential parts of the installation process with low computational time. The results were achieved very easily and can be used when there is a need to estimate costs for different farm sizes with weather included quickly. The CFSS model being an expansion of the DOFS model, achieved more realistic and better results. The weather was implemented as waiting days with a waiting cost for every day the installation had to wait. The approach captures a more realistic scenario as the weather often delays offshore operations. However, with increased complexity and larger data sets, the computational time increases significantly. To achieve the necessary results to answer the problem in the master's thesis, the objective function was simplified. When comparing the results included weather from both models, it was found that the results from the CFSS model had the most significant cost decrease per turbine from the installation of one turbine to ten turbines.

The DOFS model showed that installing one turbine with no weather, the total installation time was 25 days, and installing ten turbines took 84 days. However, when Hs was increased to 2.5 meters, the installation time for ten turbines took 126 days, an increase of 33 %. The installation cost of ten turbines when Hs = 2.5m showed an increase of 36 % from a turbine cost of 1 164 000 £ to 1 843 000 £. The results from the CFSS model showed a lower installation time for one turbine without weather of 20 days, however, the installation time for ten turbines took 120 days. When implementing the waiting days for Hs equal to 2.5 meters, the installation time increased significantly for ten turbines resulting in 165 days. The cost per turbine for ten turbines without weather was 1 305 400 £ whereas the turbine cost was 2 435 500 £ when installing ten turbines when Hs was equal to 2.5 meters, an increase of 47 %. When comparing the two models, there is no significant difference in the results for when the weather is not included. However, when the weather was implemented, the difference between results from the models are much more significant. Nevertheless, it should be kept in mind that two different approaches were used when considering the weather in the models.

The CFSS model is shown to be a useful tool for planning the installation phase for floating offshore wind farms to get information on fleet sizes and schedules for different weather conditions. It shows that the model provided results that was considered sufficient enough to answer the scope of the master's thesis. However, the CFSS model is based on the Hywind project, so it is recommended with further analyzes to make a more general model for different types of floating wind farms.

10.1 Further work

The major problem with the CFSS model was computational time, so investigating different methods to solve even more realistic cases and larger data sets should be considered. This could then improve the model also to include different types of floating wind farms. Alternative to using decomposition techniques to reduce the complexity of the model with, for example, optimizing one operation at a time.

Two different approaches have been implemented to address the problem with the weather. The approach in the CFSS model by adding the number of waiting days at the start of the schedule should be looked into. Adding the waiting days between the operations and not having the total number of waiting days at the start could reduce installation time and installation costs. Furthermore, another solution to address weather is to combine an optimization model and a simulation model. In the optimization model, only Hs have been considered, however it is possible to include wind speed. With a simulation model, more realistic results could be achieved by implementing historical weather data for a specific location.

As mentioned in the chapter 9, some of the operations could be done in parallel. In both models, it is assumed that the operations are in series, whereas in reality, some operations happen parallel to each other. Completing as many operations as possible before possible bad weather occurs can minimize both cost and time.

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Appendix A

Data input

A.1 Vessel parameters

Vessel type	*Day rate [£/day]*	*Mob. cost [£]*	*Penalty cost [£/day]*	*Wait cost [£/day]*	*Distance [miles]*	*HP*	*Fuel price*	*Daily fuel cons.*	*Speed [kn]*
OSV 0	30 000	78 520	4 300	19 300	175	20 000	5 929	11	16
OSV 1	28 000	75 870	4 300	17 600	175	18 000	5 929	11	15
OSV 2	26 000	72 830	4 300	16 000	175	16 000	5 929	11	14
OSV 3	24 000	69 330	4 300	14 500	175	14 000	5 929	11	13
OSV 4	22 000	65 250	4 300	13 100	175	12 000	5 929	11	12
AHTS 5	60 000	125 580	4 300	34 300	175	20 000	7 546	14	14
AHTS 6	55 000	132 460	4 300	30 430	175	18 000	7 546	14	13
AHTS 7	50 000	129 180	4 300	26 800	175	16 000	7 546	14	12
AHTS 8	45 000	125 250	4 300	23 430	175	14 000	7 546	14	11
AHTS 9	40 000	116 390	4 300	18 300	175	12 000	7 546	14	10
CLV 10	110 000	145 440	4 300	59 300	175	20 000	5 390	10	12
CLV 11	100 000	143 460	4 300	51 800	175	18 000	5 390	10	11
CLV 12	90 000	141 090	4 300	44 800	175	16 000	5 390	10	10
CLV 13	80 000	138 180	4 300	38 300	175	14 000	5 390	10	9
CLV 14	70 000	134 550	4 300	32 300	175	12 000	5 390	10	8
SOV 15	80 000	98 260	4 300	44 300	175	14 000	6 468	12	14
SOV 16	75 000	94 310	4 300	39 930	175	12 000	6 468	12	13
SOV 17	70 000	89 700	4 300	35 800	175	10 000	6 468	12	12
SOV 18	65 000	84 250	4 300	31 930	175	8 000	6 468	12	11
SOV 19	60 000	77 710	4 300	28 300	175	6 000	6 468	12	10

Table A.1: Vessel input values for the models

A.2 Vessel requirements

Vessel type	Anchor transp.	Anchor Inst.	Sea-keeping	Tow-out	Hook-up	Cable lay	Final commissioning
OSV 0	1	0	0	1	0	0	0
OSV 1	1	0	0	1	0	0	0
OSV 2	1	0	1	0	0	0	0
OSV 3	1	0	1	0	0	0	0
OSV 4	1	0	1	0	0	0	0
AHTS 5	1	1	0	1	1	0	0
AHTS 6	1	1	0	1	1	0	0
AHTS 7	1	1	0	1	1	0	0
AHTS 8	1	1	0	1	1	0	0
AHTS 9	1	1	0	1	1	0	0
CLV 10	0	0	0	0	0	1	0
CLV 11	0	0	0	0	0	1	0
CLV 12	0	0	0	0	0	1	0
CLV 13	0	0	0	0	0	1	0
CLV 14	0	0	0	0	0	1	0
SOV 15	1	0	0	1	0	0	1
SOV 16	1	0	0	1	0	0	1
SOV 17	1	0	0	1	0	0	1
SOV 18	1	0	0	1	0	0	1
SOV 19	1	0	0	1	0	0	1

Table A.2: Vessel requirements

Appendix B

Python Codes

B.1 FleetFinal.py

```
"""
Author: Thomas M. Lloyd
Master's thesis Spring 2021
"""

import pandas as pd
import gurobipy as gp
from gurobipy import *
import numpy as np
from gurobipy import GRB
import plotly.express as px
import matplotlib.pyplot as plt

#Dataframes
dfV = pd.read_excel("Vessel_Info1.xlsx", sheet_name='Vessels',
↪  index_col='Vessel_name')
dfT = pd.read_excel("Weather_Info.xlsx", sheet_name='Duration2')
dfVC = pd.read_excel("Vessel_Info1.xlsx", sheet_name='Act_req',
↪  index_col=0)
dfVN = pd.read_excel("Vessel_Info1.xlsx", sheet_name='Dur_Vessel',
↪  index_col=0)
dfST = pd.read_excel("Weather_Info.xlsx", sheet_name='Sail_vessel2',
↪  index_col=0)
dfWL = pd.read_excel("Vessel_Info1.xlsx", sheet_name='Weather_lim',
↪  index_col=0)
```

```
dfWh = pd.read_excel("Vessel_Info1.xlsx", sheet_name='Weather_Hs',
↪   index_col = 0)
data_time = pd.read_excel("Activity_Info.xlsx", sheet_name='Act_time2',
↪   index_col=0)

# Developing schedule

dfT['end'] = dfT['start'] + dfT['duration']
fig = px.timeline(dfT, x_start="start", x_end="end", y="Activity_id")
fig.update_yaxes(autorange="reversed")

fig.layout.xaxis.type = 'linear'
fig.update_layout(
    title="Schedule for one turbine with Hs = 2.5m",
    xaxis_title="Number of days",
    yaxis_title="Operations",
)
fig.data[0].x = dfT.duration.tolist()
f = fig.full_figure_for_development(warn=False)
fig.show()

##Sets##
activities = [0, 1, 2, 3, 4, 5, 6] # indexed by i
vessels = [v for v in range(dfV.shape[0])]
time_periods = np.arange(0,4,1)
noTurbines = 1
length_period = 7
bigM = 10000


##Parameters##
op_req = dfVC.values.tolist()
operation_requirement = np.asarray(op_req)
w_lim = dfWL.values.tolist()
Weather_lim = np.asarray(w_lim)
t_op = dfVN.values.tolist()
time_operation = np.asarray(t_op)
s_op = dfST.values.tolist()
Sail_vessel = np.asarray(s_op)
Vessel_Time = data_time.values.tolist()
```

```
Vessel_TimePeriod =np.asarray(Vessel_Time)

# Weather parameter
Hs = dfWh.values.tolist()
Weather_Hs = np.asarray(Hs)

a = []

for i in range(0,3):
    a.append(Weather_lim - Weather_Hs[:,i])
Period0 = a[0]
Period1 = a[1]
Period2 = a[2]

# Costs
cost_TC = dfV.Day_rate.tolist()
cost_mobilization = dfV.Mob_cost.tolist()

# ------ MODEL-----------------------
m = Model('vessel_configuration')

# Variables
 #------ VARIABLES --------------------
vessel_job = m.addVars(vessels, time_periods, activities,
↪   vtype=GRB.BINARY, name="vessel_job")
vessel_selected = m.addVars(vessels, activities, vtype=GRB.BINARY,
↪   name="vessel_selected")

# ------ OBJECTIVE FUNCTION -----------
m.setObjective(sum(vessel_selected[v, i] * cost_mobilization[v] for v in
↪   vessels for i in activities) +
               sum(vessel_job[v, t, i] * cost_TC[v] *
                ↪   (time_operation[v,i]+Sail_vessel[v,i])
                   for v in vessels for i in activities for t in
                    ↪   time_periods), GRB.MINIMIZE)



##Constraints##

# Operation constraint
```

```
for v in range(len(vessels)):
    for t in range(len(time_periods)):
        m.addConstr(
            (sum(vessel_job[v, t, i] for i in range(len(activities))) <=
            ↪ 1), "taskOne")

# Flow-conservation constraint
for v in vessels:
    for i in activities:
        m.addConstr(
            (sum(vessel_job[v, t, i] for t in time_periods) <= bigM *
            ↪ vessel_selected[v, i]), "selection_requirement")

# Time constraint
for t in time_periods:
    for i in activities:
        m.addConstr(
            (sum(vessel_job[v, t, i] for v in vessels) ==
            ↪ Vessel_TimePeriod[i, t]), "task_completion")

# Weather constraint
for v in range(len(vessels)):
    for i in range(len(activities)):
        m.addConstr(
            (sum(vessel_job[v, t, i] * Period2[v,i] for t in
            ↪ range(len(time_periods))) >= 0), "Weather")

# Requirement constraint
for v in range(len(vessels)):
    for i in range(len(activities)):
        m.addConstr(
            (sum(vessel_job[v, t, i] for t in range(len(time_periods))) <=
            ↪ bigM* operation_requirement[v,i]),
            ↪ "operation_requirement")


## SOLUTION###

# Compute optimal solution
m.optimize()
```

```
m.write("out.sol")
obj = m.getObjective()
best_objective = obj.getValue()
runtime = m.Runtime
MIPGap = m.MIPGap
print(MIPGap)
print(runtime)

# ------- SOLUTION PRINT ------------------
if m.status == GRB.Status.OPTIMAL:
    solution = m.getAttr('x', vessel_job)
    solution2 = m.getAttr('x', vessel_selected)
    A = {}
    B = {}
    C = {}
    for t in time_periods:
        for i in activities:
            for v in vessels:
                if solution[v, t, i] > 0:
                    time = (time_operation[v, i] + Sail_vessel[v,i])
                    cost_charter = cost_TC[v]
                    tot1_cost = cost_TC[v]*(time_operation[v, i] +
                    ↪  Sail_vessel[v,i])*solution[v,t,i]
                    print('\nOptimal vessel for task %s in time period %s
                    ↪  is: %s' % (i, t, v))
                    if t not in A.keys():
                        A.update({t: [i, v, time, cost_charter]})
                        B.update({t: [v]})
                        C.update({t: [tot1_cost]})
                    else:
                        A[t].append(i)
                        A[t].append(v)
                        A[t].append(time)
                        A[t].append(cost_charter)
                        B[t].append(v)
                        C[t].append(tot1_cost)

# Calculations Analysis
information = {}
utilization_cost = []
```

```
utilization_time = []
total_time = 0
total_cost = 0  # Total cost for a time period
actual_total_cost = 0  # Actual cost for time period
sum_cost = 0
time0 = 0
time3 = 0
no0 = 0
no3 = 0

for i in A:
    value = int(len(A[i])/4)
    for j in range(value):
        step = j*4
        if A[i][step] == 0:
            time0 = noTurbines*A[i][2+step]
            no0 = no0 + 1
        elif A[i][step] == 3:
            time3 = noTurbines*A[i][2+step]
            no3 = no3 + 1

timeAvg0 = time0/no0
timeAvg3 = time3/no3

for i in A:
    value = int(len(A[i])/4)
    for j in range(value):
        step = j*4
        if A[i][step] == 0:
            time = timeAvg0
        elif A[i][step] == 3:
            time = timeAvg3
        else:
            time = A[i][2+step]
        total_time = total_time + time
        vessel_cost = cost_TC[A[i][1+step]]
        total_cost = total_cost + vessel_cost*time
        actual_total_cost = actual_total_cost + vessel_cost*length_period
    sum_cost = sum_cost + total_cost
    utility_time = total_time/((len(A[i])/4)*length_period)
```

```
    utility_cost = total_cost/actual_total_cost
    information[i] = utility_time, utility_cost
    utilization_time.append(utility_time)
    utilization_cost.append(utility_cost)
    total_time = 0
    total_cost = 0
    actual_total_cost = 0


# Averages
avg_utilization_time = sum(utilization_time)/len(utilization_time)
avg_utilization_cost = sum(utilization_cost)/len(utilization_cost)

a = [avg_utilization_time]*len(time_periods)


# Average cost
avg_cost = m.objVal/noTurbines


# Plots the utility
fig = plt.figure()
ax = fig.add_subplot(111)
y_pos = time_periods
ax.bar(y_pos, utilization_time, color='silver', width=0.6, linewidth=3,
↪  label='Utilization Time Period')
ax.plot(y_pos, a, color='firebrick', linewidth=3, label='Average
↪  Utilization Time')
ax.plot(y_pos, utilization_time, color='lightblue', linewidth=3,
↪  label='Utilization Time')

values = np.arange(0, len(time_periods), 1)

# Add title and axis names
plt.title('Time Utilization Installation Two Turbines with Hs = 2.5m')
plt.xlabel('Time Periods')
plt.xticks(np.arange(min(time_periods), max(time_periods)+1, 1.0))
plt.ylabel('Utilization')
plt.legend(loc='lower left')
plt.xticks(values, ['%d' % val for val in values])
```

```
plt.savefig('Utility Installation Two Turbines with Hs = 2.5m.png')
plt.show()
```

B.2 ScheduleAndFleet.py

```
"""
Author: Thomas Magnus Lloyd
Master's thesis Spring 2021
"""

import numpy as np
from gurobipy import *
import pandas as pd
from pandas import ExcelWriter
from openpyxl import load_workbook
import xlrd as xl
import matplotlib.pyplot as plt
from matplotlib import cm
from matplotlib.colors import ListedColormap, LinearSegmentedColormap
from Functions import *
from itertools import repeat

# Dataframes
dfV = pd.read_excel("Vessel_Info.xlsx", sheet_name='Vessels')
dfVC = pd.read_excel("Vessel_Info.xlsx", sheet_name='Act_req',
↪  index_col=0)
dfVN = pd.read_excel("Vessel_Info.xlsx", sheet_name='Dur_Vessel',
↪  index_col=0)
dfST = pd.read_excel("Vessel_Info.xlsx", sheet_name='Sail_vessel',
↪  index_col=0)
data = pd.read_excel("Vessel_Info.xlsx", sheet_name='weather')

solutions = []
# Sets
for n_turbines in[2]:
    n_duplicates = 1
    n_operations = 7
    size_input = dfV.shape[0]
```

```
vessel_ids = np.arange(size_input)
vessels = np.arange(n_duplicates * size_input)
operations = np.arange(1, n_turbines * n_operations + 1)
nodes = np.arange(n_turbines * n_operations + 2)

# Vertices
vertices_to = []
to = []
vertices_been = []
been = []
for r in nodes:
    to = np.array(range(r + 1, len(nodes)))
    been = np.array(range(0, r))
    vertices_to.append(to)
    vertices_been.append(been)
    to = []
    been = []

# Creating arc set
Av = [(1, 2), (2, 5), (3, 4), (4, 5), (5, 6), (6, 7), (1, 8)]
for i in range(1, n_turbines):
    for j in range(n_operations):
        tuple = (Av[j][0] + (n_operations * i), Av[j][1] +
        ↪  (n_operations * i))
        Av.append(tuple)
Av = Av[:-1]

# ----------------- PARAMETERS -------------------------
# Start time and end time
time_increment_start = 10
time_increment_end = 10
slack = 40
start_time = [0, 0, 1, 2, 3, 4, 5, 6]
end_time = [time_increment_start * n_turbines + slack,
↪  6,8,10,12,16,18,20]

# Weather calculations
swh = ['sw2']
```

```
df = pd.read_excel("Vessel_Info1.xlsx", sheet_name='Markov')

df = df.dropna()
df = df.sw2.tolist()
k = 7
NrHs = sum(i > k for i in df)
time_increment_wait = 0
count=[]
count.extend(repeat(NrHs,8))

for i in df[:50]:
    if i >= k :
        start_time = [0, 5, 6, 7, 8, 9, 10, 11]
        count = count
        end_time = [time_increment_start * n_turbines + slack, 14, 16,
         ↪  18, 20, 24, 26, 28]
        time_increment_wait = 5
    else:
        start_time = start_time
        count = [0, 0, 0, 0, 0, 0, 0, 0]
        end_time = end_time
        time_increment_wait = time_increment_wait
for i in range(1, n_turbines):
    for j in range(n_operations):
        start_time.append(start_time[j + 1] + time_increment_start *
         ↪  n_turbines)
        count.append(count[j+1])
        end_time.append(end_time[j + 1] + time_increment_end *
         ↪  n_turbines)
start_time.append(time_increment_start * n_turbines)
count.append(time_increment_wait * n_turbines)
end_time.append(time_increment_end * n_turbines + slack)

# Cost for chartering, mobilization and waiting
cost_TC = dfV.Day_rate.tolist() * n_duplicates
cost_mobilization = dfV.Mob_cost.tolist() * n_duplicates
cost_W = dfV.Wait_cost.tolist() * n_duplicates
bigM = 100000

    # Operation requirements
```

```
requirement = np.asarray(dfVC)
operation_requirement = []
for j in vessel_ids:
    req = []
    if n_duplicates > 1:
        for n in range(n_duplicates):
            req = []
            for i in range(n_turbines):
                req.extend(requirement[j][1:-1])
            operation_requirement.append(req)
    else:
        for i in range(0, n_turbines):
            req.extend(requirement[j][1:-1])
        operation_requirement.append(req)

# Execution times
time = np.asarray(dfVN)
operation_time = []
for j in vessel_ids:
    t = []
    if n_duplicates > 1:
        for n in range(n_duplicates):
            t = []
            t.append(0)
            for i in range(n_turbines):
                t.extend(time[j][1:-1])
            t.append(0)
            operation_time.append(t)
    else:
        t.append(0)
        for n in range(n_turbines):
            t.extend(time[j][1:-1])
        t.append(0)
        operation_time.append(t)

# Sailing time
time1 = np.asarray(dfST)
sail_time = []
for j in vessel_ids:
    t = []
```

```
    if n_duplicates > 1:
        for n in range(n_duplicates):
            t = []
            t.append(0)
            for i in range(n_turbines):
                t.extend(time1[j][1:-1])
            t.append(0)
            sail_time.append(t)
    else:
        t.append(0)
        for n in range(n_turbines):
            t.extend(time1[j][1:-1])
        t.append(0)
        sail_time.append(t)

# ------------- MODEL CREATION -------------------
# Create optimization model
m = Model('schedule_optimization')

 # ------------- VARIABLES ------------------------
vessel_job = m.addVars(nodes, nodes, vessels, vtype=GRB.BINARY,
↪   name="vessel_job")
job_time = m.addVars(nodes, vessels, vtype=GRB.INTEGER,
↪   name="job_time")
wait_time = m.addVars(vessels, vtype= GRB.INTEGER, name
↪   ="waiting_time")

# --------------- OBJECTIVE FUNCTION ------------------
# Operation time minimization (OT)
m.setObjective(sum(cost_mobilization[v] * vessel_job[0, j, v] for v in
↪   vessels for j in nodes[:-1]) +
               sum(vessel_job[i, j, v] * cost_TC[v] *
               ↪   (operation_time[v][i] + sail_time[v][i]) for v in
               ↪   vessels
                   for i in nodes for j in nodes)  +
                   ↪   sum(cost_W[v]*wait_time[v] for v in vessels),
                   ↪   GRB.MINIMIZE)

# ------------- CONSTRAINTS --------------------------
for i in operations:
```

```
    m.addConstr(sum(vessel_job[i, j, v] for v in vessels for j in
    ↪  vertices_to[i]) == 1, "one_task2")

# Weather constraint
for v in vessels:
    m.addConstr(
    wait_time[v] == (sum(vessel_job[i, j, v] * count[i] for i in nodes
    ↪  for j in nodes)), "wait_time")

# Routing constraints
for v in vessels:
    m.addConstr(sum(vessel_job[0, j, v] for j in vertices_to[0]) == 1,
    ↪  "operation_start")


for v in vessels:
    m.addConstr(sum(vessel_job[i, nodes[-1], v] for i in
    ↪  vertices_been[nodes[-1]]) == 1, "operation_end")


for j in operations:
    for v in vessels:
        m.addConstr(sum(vessel_job[i, j, v] for i in vertices_been[j])
        ↪  -
                    sum(vessel_job[j, i, v] for i in vertices_to[j])
                    ↪  == 0, "routing constraint")

# Time Constraint
for i in nodes:
    for j in nodes:
        for v in vessels:
            m.addConstr(job_time[i, v] + operation_time[v][i] +
            ↪  sail_time[v][i] - job_time[j, v] -
                        bigM * (1 - vessel_job[i, j, v]) <= 0,
                        ↪  "time_constraint")

# Origin Time constraint
for v in vessels:
    m.addConstr(start_time[0] <= job_time[0, v],
    ↪  "origin_time_constraint")
```

```
        m.addConstr(job_time[0, v] <= end_time[0],
         ↪  "origin_time_constraint1")

    for v in vessels:
        for i in operations:
            m.addConstr(start_time[i] * sum(vessel_job[i, j, v] for j in
             ↪  vertices_to[i]) <= job_time[i, v],
                        "time_windows")
            m.addConstr(job_time[i, v] <=
                        (end_time[i] - operation_time[v][i]) *
                         ↪  sum(vessel_job[i, j, v] for j in
                         ↪  vertices_to[i]),
                        "time_windows1")

    # Precedence constraints
    for i, j in Av:
        m.addConstr(sum(job_time[i, v] for v in vessels) +
                    sum((operation_time[v][i]+ sail_time[v][i]) *
                     ↪  vessel_job[i, r, v] for r in vertices_to[i] for v
                     ↪  in vessels)
                    - sum(job_time[j, v] for v in vessels) <= 0,
                     ↪  "Precedence")

    # Equipment requirement constraint
    for v in vessels:
        for i in operations:
            m.addConstr(sum(vessel_job[i, j, v] for j in nodes) <= bigM *
             ↪  operation_requirement[v][i-1],
                        "Task_requirement")

    # Compute optimal solution
    m.optimize()
    obj = m.getObjective()
    best_objective = obj.getValue()
    runtime = m.Runtime
    MIPGap = m.MIPGap

# Create solution list
```

```
List, start_times, end_times, vessel_selected, wait_times, total_cost =
↪  create_solution_list(m, vessel_job, job_time, nodes, vessels,
↪  operation_time, sail_time, wait_time, cost_TC)


# Solutions of cost per turbine
solutions.append(best_objective / n_turbines)

# Creates a Gant chart
create_gant(List, vessels, n_turbines, n_operations=7,
↪  end_time=end_time[-1])
```

Thomas Magnus Lloyd

Fleet and Scheduling Optimization for Offshore Floating Wind Installation under Impact of Weather

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