Master's thesis

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Optimizing the Logistics of Floating Offshore Wind during Installation

Master's thesis in Marine Technology
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Master Thesis in Marine Systems Design

Stud. techn. Sebastian Erik Løken Rindvoll

"Optimizing the Logistics of Floating Offshore Wind during Installation"

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Background

The installation process of offshore wind turbines is a costly and complex operation which requires vessels with specific functions and capacities. Today offshore wind farms tend to be installed further offshore to obtain more reliable and higher wind speeds. However, the depths further offshore are too deep for conventional bottom-fixed foundations to be installed and the weather conditions are heavier. This has caused a demand for floating sub-structures and even more complex marine operations making the installation costs much higher than for bottom-fixed turbines. There are no specialized vessels for floating offshore wind turbine installation today and thus a heterogeneous vessel fleet is needed to satisfy all the required operations. Floating offshore wind today is not profitable. To reduce the costs of installation there is a need for more cost-efficient logistics and operations.

Overall aim and focus

The objective of this project is to provide insight into how logistics can be optimized for the installation process of floating offshore wind turbines.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide an overview of the current status and important development trends related to installation of floating offshore wind*
2. *Develop examples of how the installation process for floating offshore wind can be done.*
3. *Perform a case study based on a given fleet to optimize the fleet size and mix for the installation process of floating offshore wind.*
4. *Make a linear programming problem optimizing the fleet size and mix for the installation process and validate the results in Simulink simulating the installation process of floating offshore wind farms with the optimal fleet composition.*
5. *Discuss, conclude and propose further work.*

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

Stein Ove Erikstad
Professor

Preface

This Master Thesis is completed during Spring 2020 and is the final delivery after five years of studying at the Department of Marine Technology, at the Norwegian University of Science and Technology (NTNU). The thesis is written within the field Marine Systems Design and it counts as 30 credits. Approval of the Master Thesis results in achieving the title Master of Science in Marine Technology.

The overall focus of the thesis is to study the fleet size and mix problem for the installation process of floating offshore wind farms. By using optimization methods and simulations in Simulink the aim of the project is to provide insight into how the logistics of the installation process can be optimized. The report builds on the insight gained from the Project Thesis written during Fall 2019. Several of the chapters build on the Project Thesis, but they have been expanded and edited in this Master Thesis. During this spring a lot of time has been spent learning how to program an optimization model in Python and I have taken the course *TMR4225 - Marine Operations* to expand my knowledge within this field and utilize this in the Master Thesis.

I would like to thank my supervisor, Professor Stein Ove Erikstad, for great guidance and constructive discussions. I would like to thank PhD Candidate, Hans Tobias Slette, for help related to the simulation model. I would also like to express my gratitude to Vegard Nedrevåg and Odd Tore Skytterholm at Equinor for providing me with detailed answers to my questions about Hywind Scotland and Hywind Tampen. At last, I would like to thank Kjetil Fagerholt for great discussions about the optimization model.

This version was audited 19.07.2020. Smaller grammar errors and figure 8.1 have been corrected. The python code for the optimization, the flowchart of the operations, and the simulation model are all attached in the appendix. Also, the structure of the report has been improved.

Trondheim, July 19, 2020

Sebastian Erik Løken Rindvoll

Summary

Floating offshore wind is an emerging industry with high potential. The technology used for floating wind turbines creates opportunities for the extraction of renewable energy sources in much larger areas than the conventional bottom-fixed wind turbines. According to Equinor 80 % of the ocean's wind resource potential is in deep waters. The main downside is that it is currently not profitable to produce floating offshore wind with the costs related to the installation and operation. Also, the floating offshore wind projects tend to move further offshore. This means even worse weather conditions which again makes it difficult to execute complex marine operations. To make floating offshore wind competitive, more cost-effective logistic solutions must be developed for the installation process.

The objective of this report is to optimize the fleet size and mix for the installation process of floating offshore wind to minimize the total installation cost. The knowledge from investigating the floating offshore wind market, important components, and operations of the installation process has been used to create a mixed-integer linear programming optimization model and a stochastic simulation model. The optimization model solves the fleet size and mix problem, while the stochastic simulation model validates how this fleet composition would perform in different weather conditions.

A floating offshore wind turbine consist of a top- and a substructure. Top-structures consists of the tower, nacelle rotor, and blades, while the sub-structures consists of a foundation and a transition piece. The substructure is attached to the seabed through anchors and chains, and cables are connected to export the power produced. For floating offshore wind turbines the top-structures are pretty much the same as for bottom-fixed wind turbines. The part that separates them is the substructure. The floating substructures can be manufactured in a standardized shape and do not have to be fixed to the seabed. Mooring systems with anchors fixed to the seabed makes it possible to install these turbines almost anywhere in the world's oceans.

The installation process today mainly consists of transport of components to the installation port, ballasting, mating of top- and substructure, towing to the site, installation of anchors and chains, hook-up to the mooring system, and cable-laying of power cables.

For these operations, the vessels used are barges, tugs, stone-dumping vessels, heavy lift vessels, anchor handling tug supply vessels, and cable-laying vessels. The weather conditions impact marine operations during the installation process. The weather data used in the simulation model is based on historical data from the location of Hywind Tampen and Gulen Industrihamn. The historical data was run in a Markov chain script in Matlab to create a vector of the stochastic weather conditions.

The optimization model was developed to solve the fleet size and mix problem by minimizing the total costs of chartering these vessels. This analysis shows that this model is most suited for smaller size wind farms as it gets more difficult to solve the time-dependent multiple vehicle routing problems for larger instances. The results show that there is a fine balance between choosing vessels and the total time of the installation process. The optimal fleet for the installation of Hywind Tampen ended up consisting of seven tugs, ten anchor handling tug supply vessels, two heavy lift vessels, and one cable-laying vessel, and the total installation time was calculated to be close to one month.

To validate the optimal fleet found in the optimization model 100 iterations were run for a random seed of weather conditions. The simulation model was used to analyze the installation time and related cost for the optimal fleet size and mix given from the optimization model. The analysis shows that the weather mainly impacts the installation process during the anchoring and chain installation. It also showed that the anchor handling tug supply vessel chartering appears to be the main vessel driving costs up, but heavy lift vessels are also a heavy cost driver. It seems like a smart decision to eliminate this process by renting an onshore crane instead of the mating operation as Equinor will do for Hywind Tampen.

Sammendrag

Flytende havvind er en fremvoksende industri med stort potensiale. Teknologien som brukes på flytende vindturbiner skaper muligheter for utvinning av fornybare energikilder i mye større områder enn de konvensjonelle bunnfaste vindturbinene. I følge Equinor ligger 80 % av verdens havressurspotensiale på områder med dypt vann. Den største ulempen er at det foreløpig ikke er lønnsomt å produsere flytende havvind med kostnadene knyttet til installasjon og drift. I tillegg blir flytende havvind installert lenger offshore. Dette betyr enda dårligere værforhold som igjen gjør det vanskelig å utføre kompliserte marine operasjoner. For å gjøre flytende havvind konkurransedyktig, må mer kostnadseffektive logistikkløsninger utvikles for installasjonsprosessen.

Målet med denne rapporten er å optimalisere flåtestørrelsen og blandingen av de ulike skipene for installasjonsprosessen av flytende havvind for å minimere de totale installasjonskostnadene. Kunnskapen som er tilegnet gjennom å undersøke det flytende offshore vindmarkedet, viktige komponenter og operasjoner relatert til installasjonsprosessen har blitt brukt for å lage en blandet lineær heltallsprogrammeringsmodell og en stokastisk simuleringsmodell. Optimeringsmodellen løser problemet for flåtestørrelse og blandingen av skip, mens den stokastiske simuleringsmodellen validerer hvordan denne flåtesammensetningen vil fungere under forskjellige værforhold.

En flytende havvindmølle består av en topp- og en bunnstruktur. Toppstrukturer består av tårnet, nacellerotoren og bladene, mens bunnstrukturen består av et fundament og et overgangsstykke. Bunnstrukturen er festet til havbunnen gjennom forankringer og kjetting, og kabler er koblet til for å eksportere den produserte kraften fra vindturbinene. For flytende havvindmøller er toppkonstruksjonene stort sett de samme som for bunnfaste vindturbiner. Delen som skiller dem er bunnstrukturen. De flytende bunnstrukturene kan produseres i en standardisert form og trenger ikke å festes til havbunnen. Fortøyningssystemer med ankre festet til havbunnen gjør det mulig å installere disse turbinene nesten hvor som helst på alle verdens hav.

Installasjonsprosessen består i dag hovedsakelig av transport av komponenter til installasjonshavnen, ballastering, sammensetning av topp- og bunnstruktur, sleping til stedet, installasjon av forankringer og kjettinger, tilkobling til fortøyningssystemet og legging av

strømkabler. For disse operasjonene er fartøyene som brukes lektere, slepebåter, steindumpingskip, tunge løfteskip, ankerhåndteringsskip og kabelleggingsfartøy. Værforholdene påvirker de marine operasjonene under installasjonsprosessen. Værdataene som brukes i simuleringsmodellen er basert på historiske dataene fra Hywind Tampen og Gulen Industrihamns beliggenhet. De historiske dataene ble kjørt i et Markov-kjedeskript i Matlab for å lage en vektor av de stokastiske værforholdene.

Optimeringsmodellen ble utviklet for å løse flåtestørrelsen og blandingsproblemet ved å minimere de totale kostnadene for befraktning av disse skipene. Denne analysen viser at denne modellen for det meste er egnet for vindmølleparker av mindre størrelse, da det blir vanskeligere å løse det tidsavhengige ruteplanleggingsproblemet i større tilfeller. Resultatene viser at det er en fin balanse mellom valg av fartøy og total tid for installasjonsprosessen. Den optimale flåten for installasjon av Hywind Tampen endte opp med å bestå av syv slepebåter, ti ankerhåndteringsskip, to tunge løfteskip og ett kabelleggingsfartøy, og den totale installasjonstiden ble beregnet til å være nær en måned.

For å validere den optimale flåten som ble funnet i optimaliseringsmodellen, ble 100 iterasjoner kjørt for een tilfeldig sekvens av værforhold. Simuleringsmodellen ble brukt til å analysere installasjonstiden og tilhørende kostnader med den optimale flåten fra optimeringsmodellen. Analysen viser at været hovedsakelig påvirker installasjonsprosessen under forankring og kjettinginstallasjon. Den viste også at leie av ankerhåndteringskip ser ut til å være fartøyet som driver kostnadene opp, men tunge løftefartøy er også en stor kostnadsdriver. Det virker som en smart beslutning å eliminere denne prosessen ved å leie en kran på land i stedet for sammensetningen av topp- og bunnstruktur slik Equinor vil gjøre for Hywind Tampen.

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Abbreviations

AHTS	Anchor Handling Tug Supply
BFOW	Bottom-Fixed Offshore Wind
CLV	Cable-Laying Vessel
CPU	Central Processing Unit
DP	Dynamic Positioning
DSV	Dive Support Vessel
FIFO	First In First Out
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
FOWF	Floating Offshore Wind Farm
HLV	Heavy Lift Vessel
IDE	Integrated Development Environment
ISV	Installation Support Vessel
LCOE	Levelised Cost of Energy
MILP	Mixed Integer Linear Programming
NCS	Norwegian Continental Shelf
OCV	Offshore Construction Vessel
OSV	Offshore Supply Vessel
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine

O&M Operations and Maintenance

ROV Remotely Operated Vehicle

TLP Tension Leg Platform

WTIV Wind Turbine Installation Vessel

Chapter 1

Introduction

The increasing demand for energy in the world and the rising focus on the earth's climate change creates opportunities for growth in renewable energy industries. The fast-growing offshore wind sector has made it possible for projects to be developed on the Norwegian continental shelf. With an average depth of about 2,000 meters and the increasing demand for energy from renewable resources, the potential for floating offshore wind farms (FOWF) on the Norwegian continental shelf is increasing accordingly. The world's first commercial wind farm using floating wind turbines, Hywind Scotland, is also the only floating wind farm existing today, but future projects like Hywind Tampen have already been planned. However, the installation process of floating wind is not yet profitable and much more expensive than bottom fixed wind today, hence cost-effective solutions should be sought for.

Background

During the last three decades, the development of the offshore wind industry has rapidly improved. It all started in 1991 with the first offshore wind farm at Vindeby which was completed 2.5 kilometers off the Danish coast. The wind farm consisted of 11 turbines with a capacity of 450 kW each, making a total of 4.95 MW. In 2022 another wind farm consisting of 11 turbines will be ready to produce power. Only this time, the wind farm is floating and the capacity of each wind turbine is 8 MW, which makes a total of 88 MW for the whole wind farm. The wind farm is known as Hywind Tampen, and it is supposed to provide 35 % of the total power need for the oil & gas platforms at Snorre and Gullfaks, of the Norwegian West Coast. This will reduce the emissions of carbon dioxide (CO_2) by 500 000 tonnes and nitrogen oxides (NO_x) by 1 000 tonnes annually (Norwegian Petroleum Directorate, 2020).

The development tends to move the wind farms further away from shore in order to obtain more reliable wind currents and higher wind speeds. However, with the increase in the distance comes higher costs. There are higher installation costs related to longer installation time, more complex marine operations, and the need to install longer cables to transport the energy from site to shore. There are also heavier weather conditions further offshore, which requires more frequent maintenance and thus increases the operations and maintenance cost. With steeply-shelved coastlines in large areas of the world, the demand for floating offshore wind (FOW) is increasing.

Today, Equinor's Hywind concept is the most viable floating wind turbine design. The concept was used for Hywind Scotland, the world's first commercial FOWF, and is also going to be used for the planned Hywind Tampen outside the west coast of Norway. However, the concept is not suitable for projects using ports with shallow drafts due to the large draft of the spar buoy on the Hywind turbines. This makes the importance of project planning even more important.

Scope

Cost-effective solutions for the installation process of FOW are highly correlated with the duration of the process. The efficiency of the marine operations required will often depend on the weather conditions. Bad weather may cause delays which again will lead to high costs for expensive specialized vessels hired or loss of revenue from the power that could have been produced and sold. In this report, the objective has been to optimize the fleet size and mix for the installation process which minimizes the total installation costs.

Limitations

The scope of this report is limited to the operations of the installation process starting at the installation port, through to the final hook-up and cable-laying offshore. These operations are assumed to be the main cost drivers regarding the marine operations of the installation process. In addition, the turbine components are assumed to be ready for mating at the port. The models also assume that the capacity in port for storing components or fully assembled turbines after mating, will not be an issue.

There are many environmental weather conditions that could affect a marine operation.

For the simulation model made in this Master Thesis, the significant wave height and wind speeds are the only implemented weather conditions. This is due to the complexity of adding conditions like currents or tides. Also, the restrictions stated by the representatives from Equinor emphasized waves and wind.

Motivation

The work performed in this report is assumed to be useful for people working on developing logistics for the installation process of FOW. The optimization model is made generic and can be applied to projects with different locations and different installation processes. It can be used to figure out which fleet compositions that are most cost-effective for future projects. The simulation model is quite general too and can be used for different fleet sizes and mix as well as different numbers of turbines to validate how the fleet will perform for different weather conditions and wind farm sizes.

Structure

The report has been structured to give the reader an introduction to FOW before the problem description and method are presented. In the second chapter of the report, an introduction to the FOW market outlook is given. The third chapter is about the installation process of offshore wind. Here the aim is to provide the reader with basic knowledge about the components important for the installation process and some concepts existing today for floating sub-structures. The chapter ends with a review of the installation process for floating wind turbines. In chapter 4 the problem description is specified and the objective of the report is thoroughly explained. Chapter 5 is presenting a review of what has been done within research related to cost-effective solutions for offshore wind operations and reduction of the time of installation. Chapter 6 describes the case study for this project and chapter 7 explains the methodology used in this Master Thesis. Chapter 8 presents a generic mathematical model for the fleet size and mix problem and explains the parameters and constraints of the model. In chapter 9 the results from the optimization model can be found. The stochastic simulation model created is described in chapter 10 along with the parameters used. The results of the simulation are presented in chapter 11. These along with the results from chapter 9 will be discussed in chapter 12 followed by the conclusion and proposals for further work in chapter 13.

Chapter 2

Market Outlook

The Paris Agreement's long-term temperature goal is to keep the increase in the global average temperature to well below 2 °C. At the same time the European Commission has set a target of at least 32.5 % energy efficiency by 2030 and a long-term goal for the EU to become climate-neutral by 2050. To achieve these goals the development within the production of renewable energy must increase rapidly. The development of power production from wind has seen a great increase over the last decades, and especially within the offshore wind segment. FOW is an emerging technology making the above-mentioned goals more reachable. This technology makes it possible to extract wind energy from much larger areas far offshore.

In regions like the Norwegian West-Coast, U.S. West-Coast, the Mediterranean, Japan, and South Korea, the depth from the coastline increases rapidly. This makes large areas of the world unsuitable for conventional bottom-fixed wind farms, but it makes the outlook for FOW even better. According to WindEurope (formerly EWEA), an association promoting the wind power industry, bottom-fixed offshore wind (BFOW) will not be economically attractive with depths greater than 60 meters (WindEurope, 2018). In figure 2.1 the bathymetry of European oceans is depicted. From this map, the large areas suitable for floating offshore wind farms are clearly visible.

The first pilot floating offshore wind turbine (FOWT) was deployed outside of Karmøy in Norway in 2009. This was the start of the Hywind concept developed by Equinor (formerly Statoil). This pilot was tested for several years and was the foundation for what became Hywind Scotland in 2017. The world's first commercial wind farm using floating

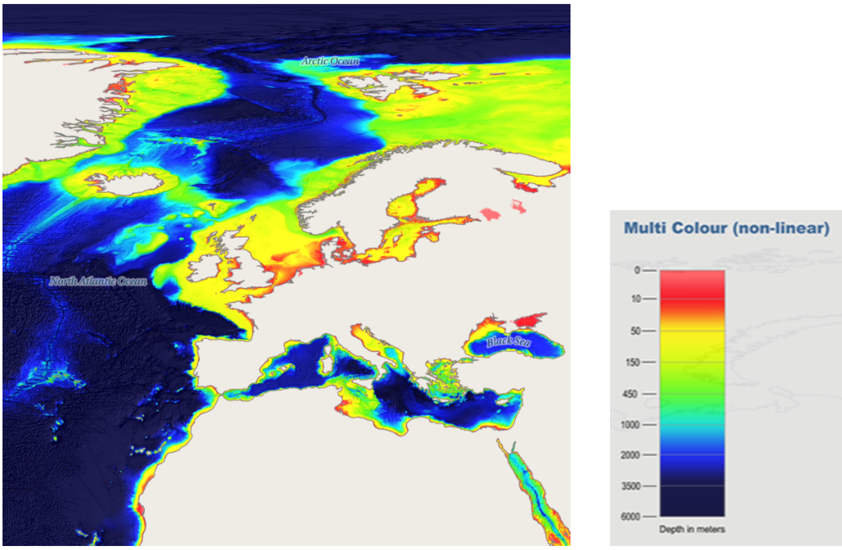

Figure 2.1: Bathymetry of European oceans (EMODnet, 2020)

wind turbines. The owner, Hywind (Scotland) Limited, is a joint venture of Equinor (75 %) and Masdar (25%). Over the first two years of operation, the wind farm has survived severe storms and it has delivered an average capacity factor of 56 % (ORE Catapult, 2019). Given the 30 MWs installed this gives an average of 16.8 MW power generated per hour during this period. Compared to the average capacity factor for all offshore wind in Europe in 2019 (38 %), this implies that the FOW is a step in the right direction for the future (WindEurope, 2020b). Below follows two figures showing the capacity factor of Hywind Scotland. In figure 2.2 the monthly capacity factor for Hywind Scotland compared to other offshore wind farms (OWF) in 2018 is plotted. In figure 2.3 the load duration curve for Hywind Scotland is compared to all other UK offshore windfarms. This curve shows that the floating Hywind Scotland windfarm delivers a higher capacity factor than the average of all the UK offshore wind farms.

Although the Hywind concept has proven to be a well-functioning concept outside Scotland, it is not necessarily the best concept for all FOW projects. According to Simen Moxnes in Equinor, the Hywind concept with its large draft is suitable for the North Sea due to the deep fjords and port sites in Norway (Presentation SFI Workshop 26.05.2020). Since the design of the substructure is simple and cheaper than a semi-sub foundation to manufacture it is the preferred choice for projects using a port along the Norwegian West

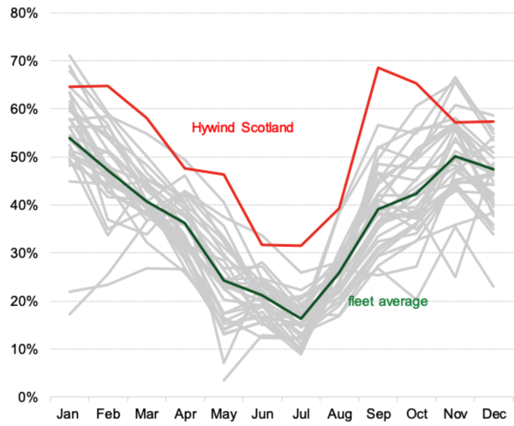

Figure 2.2: Source: BloombergNEF, Ofgem: Individual lines show the capacity factors for separate assets in 2018., Nedrevåg (Mail 09.03.2020)

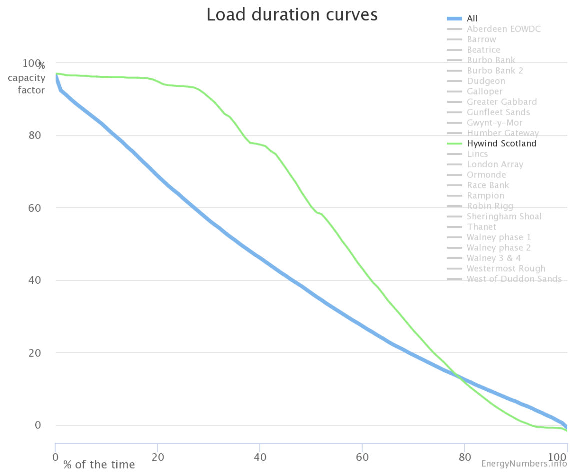

Figure 2.3: Load duration curve for Hywind Scotland, (Smith, 2020)

Coast. (Taboada, 2015). However, Moxnes states that Equinor is not concept agnostic and they are going to use the best concept for every project even though Hywind is their own developed concept. He also believes that a three-legged semi-sub is more suited for all projects using ports with shallow depths.

In 2018 WindEurope estimated the levelised cost of energy (LCOE) for pre-commercial projects to be in the order of 180 to 200 euro per megawatt-hour to become profitable. They expected that commercial-scale projects would reach an LCOE of 40-60 euro per megawatt-hour. In a presentation made by the renewable energy developer EOLFI in 2019, a graph for the average LCOE for FOW compared to BFOW by 2030 was provided. This graph is based on estimations made by experts within the industry. The graph is depicted in figure 2.4.

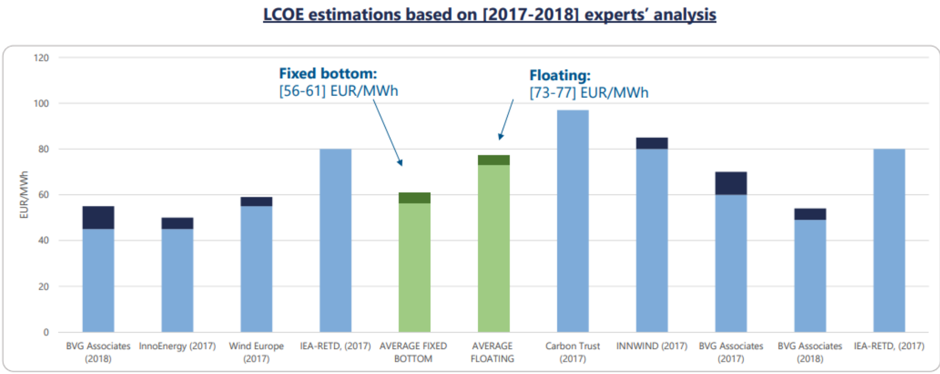

Figure 2.4: LCOE estimations (EOLFI, 2019)

According to the experts' estimations, FOW will need a wholesale baseload electricity price of about 73-77 euros per megawatt-hour by 2030. The average wholesale baseload electricity price for Europe in the last quarter of 2019 was 43.9 euros per megawatt-hour. Compared to today's electricity prices the FOW projects will not be profitable by 2030, but they are closing in.

In figure 2.5 Equinors market outlook for FOW is given. According to a report made by WindEurope (2007) developing less than 5 % of the North Sea surface area with offshore wind would make it possible to supply about 25 % of the EU's electricity needs in 2004 (180 GW).

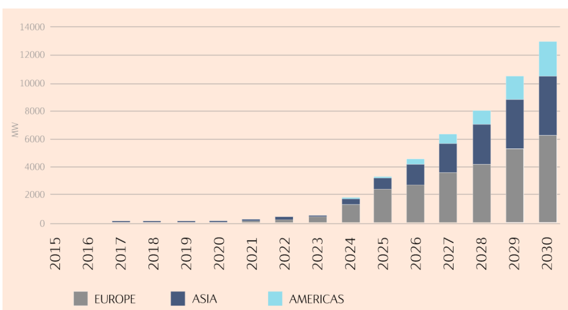

Figure 2.5: The FOW market outlook, (Equinor, 2019c)

Today, conventional BFOW is way cheaper than FOW. There are several reasons for this, but one of the most obvious is the costs of installation. Even though it requires fewer operations taking place at sea, the marine operations are more complex and time-consuming. In addition, costs will be high due to the fact that this is such a new and rapidly developing technology. An example can be seen in figure 2.6. There are currently no specialized vessels for the installation of FOW, but within the next decade, FOWFs will be much more standardized and industrialized. Odd Tore Skytterholm who was the Business Manager at Hywind Scotland estimated the costs of offshore operations to be around 7 % of the total costs (Mail 15.11.2019). According to Equinor, close to 80 % of the ocean's resource potential for offshore wind is in deep waters. Bottom-fixed sub-structures will always vary in design depending on the bathymetry and soil. While floating substructures can be standardized and identical from wind farm to wind farm, as they are connected to the seabed through mooring systems (Landbo, 2017). With industrialization and standardization, it will be easier to install larger projects, which again will lead to economies of scale. Adding up all of these benefits with FOW there might be a possibility that this technology can outperform the bottom-fixed offshore wind and become the most cost-effective solution.

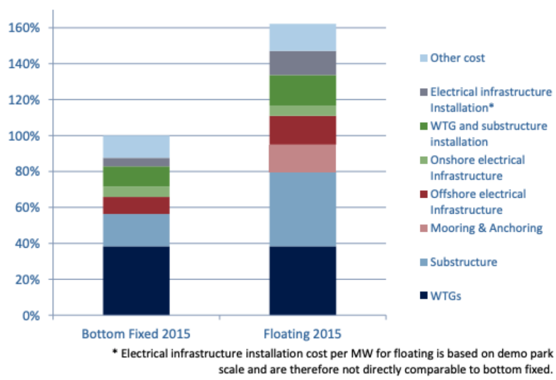

Figure 2.6: Cost comparison between bottom-fixed and FOWFs of 800 MW installed capacity, (DNV GL, 2015)

There has been a lot of research and development on how to cut costs within the manufacturing of the wind turbine components, logistics of the installation process, operations, and maintenance (O&M) as well as how to cut cost and loss of power through the cables into shore. A proposed solution for the last problem has been to store the energy. Either in the form of batteries or as hydrogen. The hydrogen can either be pressurized and stored in tanks on-site or be transported in pipelines to shore. At shore, it can be stored in tanks or in salt caverns under the ground. Equinor (2019a) is already looking at this with its H21 project in northern England.

The increasing global investment and collaboration between different scientists and companies within the maritime industry will create synergies for the whole industry. This will be in terms of knowledge and new technological solutions which will continue to drive down costs. In figure 2.7 the annual offshore wind installations by the countries in Europe are calculated. This figure shows how the European countries have increased their investments in all types of offshore wind over the last decade. According to table 2.1 based on QFWEs report *Global floating wind energy market & forecast*, there are 14 FOW projects either planned, under development or possible for the future. With this trend continuing into the next decade and with Equinor's market outlook for the FOW in figure 2.5, this industry might be the leading producer of renewable energy in the years to come.

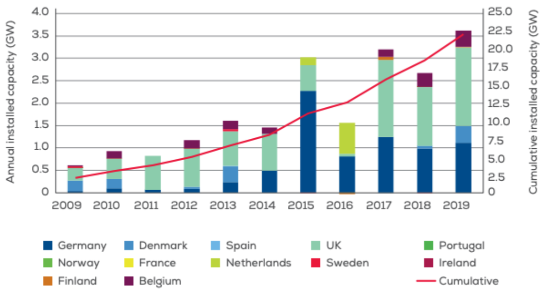

Figure 2.7: Annual offshore wind installations by country and cumulative capacity (MW), (Wind Europe, 2020a)

Table 2.1: Northern Europe FOW projects (Based on table from FWE, 2019)

ProjectName	Country	Online Year	DevType	Total Units	Total MW	Install-ation	CapexEst mUSD	Developer
Bretagne Sud	France	2025	Commercial	20	240	$51	$861	EOLFI
EoLink	France	2021	Demonstrator	1	6	$2	$21	Eolink
Groix & Belle-île	France	2021	Pre-Commercial	4	24	$13	$160	EOLFI
Gicon SOF	Germany	2021	Demonstrator	1	2	$2	$20	Gicon
Gicon SOF 5-6 MW	Germany	2025	Pre-Commercial	6	36	$12	$166	Gicon
Aker/BP Noaka	Norway	2027	Commercial	11	110	$20	$500	Aker/BP
Hywind Tampen	Norway	2021	Commercial	11	88	$28	$586	Equinor
SeaTwirl S2	Norway	2020	Demonstrator	1	1	$1	$8	Seatwirl, ColruytGroup, Norsea Group
TetraSpar Demo	Norway	2020	Demonstrator	1	4	$2	$20	Shell, Innogy, Stiesdahl
AFLOWT Hexafloat	UK	2022	Demonstrator	1	2	$3	$32	EMEC
Atlantis / Ideol	UK	2026	Commercial	10	100	$34	$463	Atlantis Ideol
Dounreay Tri	UK	2022	Demonstrator	1	10	$3	$52	Highland Floating Wind Ltd.
Kinkardine Tranche 2	UK	2020	Commercial	5	48	$17	$424	KOWL
TLPWind UK	UK	2021	Demonstrator	2	10	$3	$55	Iberdrola
Total				**75**	**680**	**$190**	**$3,369**	

Chapter 3

System Description

The FOW industry is moving in one direction at the moment with increasing sizes and capacity of the projects. At the same time, the LCOE of the projects decrease and the world focuses more than ever on the production of greener energy. Still, the industry needs subsidies to develop commercial projects. This is mainly due to the high costs related to the development of wind farms. They demand new technology, more complex marine operations, and operations in more exposed areas than before. A large part of the costs are related to the installation phase of the project and according to Skytterholm (Mail 15.11.19), 5-7 % of the total costs are related to the offshore work during this phase. The need for more cost-effective solutions should be sought for and in this Master Thesis the installation process will be thoroughly studied, especially concerning the fleet size and mix utilized for the marine operations.

3.1 Floating offshore wind farms

3.1.1 Components of a floating wind turbine

The OWT consists of foundation, transition piece, tower, nacelle and rotor blades. In addition, the turbines are moored to the seabed to keep them placed in the right position, and power cables are attached to transport the generated power to where it is needed. All of these parts can be seen in figure 3.1. The assembly of these parts is often divided into two structures. The sub-structure which is the foundation and the transition piece, and the top-structure consisting of the tower, nacelle and rotor blades.

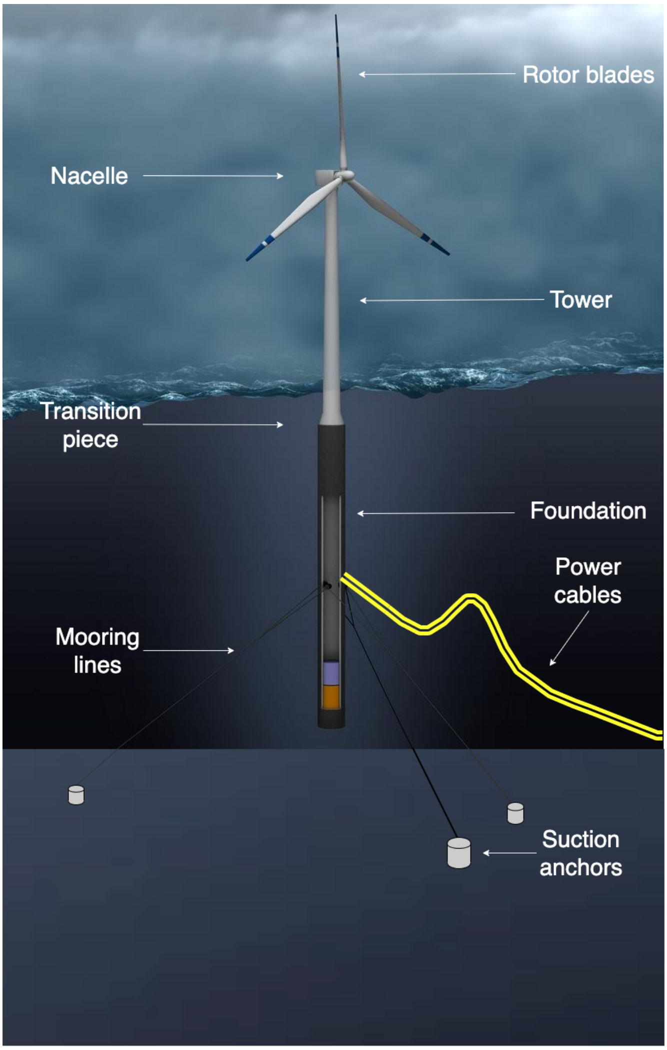

Figure 3.1: Parts of a Wind Turbine

Anchor and mooring systems

According to *Handbook of Offshore Engineering* (Chakrabarti, 2005) there are two types of anchors. An anchor either relies on self-weight or suction forces. Anchors used for FOWT concepts known today are drag embedment anchors and suction anchors. Drag embedment anchors are designed to penetrate the seabed partly or fully. As the name implies, the anchors are installed by dragging it when it is located on the seabed. These types of anchors are self-weight dependent and are more suitable for large horizontal loads rather than large vertical loads. This type of anchor was used on Principle Power's WindFloat concept (Principle Power, 2020). Suction anchors are long steel cylinders, enclosed only at one end. Once the anchor reaches the seabed it sinks a little bit into the seabed due to its heavy weight. Further, the hatches on the top are closed and the pressure inside the cylinder is lowered through valves. This makes a vacuum inside the cylinder which together with the weight of the anchor and the water column above it helps the anchor to get sucked into the seabed. This anchor withstands both vertical and horizontal loads. Suction anchors were used on the Hywind Scotland wind farm (OffshoreWind.biz, 2017). These will also be used on Hywind Tampen according to von der Fehr from DOF Subsea (Mail 26.05.20). Both types of anchors are depicted in figure 3.2a and 3.2b below.

(a) Drag embedment anchor (Vryhof Anchors, 2020)

(b) Suction Anchor (Acteon, 2020)

Figure 3.2: Anchors

The FOWT needs a permanent mooring to keep it at the required position. Mooring lines used to connect the FOWTs to the anchors could consist of chain, wire, or rope or a combination of these. There are two types of chain constructions used for mooring, stud-link and studless chains, see figure 3.3. The stud-link chain is metal bars formed in an oval shape with a link across the middle which adds weight, but strengthens the chains and prevents deformation. Studless chains formed in the same way as the stud-link, but without the link in the middle. This makes this type of chain much lighter and increases the chain's fatigue life (Chakrabarti, 2005). For Hywind Tampen the preliminary choice of chain is studless (Mail von der Fehr 26.05.20).

Steel wire ropes used for mooring are wires wound in a helical pattern known as a "strand". The flexibility and axial stiffness of the strand are determined by the pitch of the helix (ibid.). In figure 3.4 different wire rope constructions are depicted. For Hywind Tampen the preliminary choice of steel wire will be spiral strand wires (Mail von der Fehr 26.05.20).

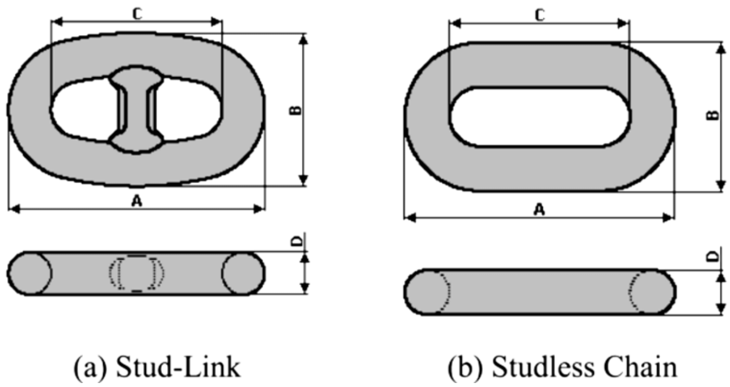

Figure 3.3: Stud-link and studless chain, (Chakrabarti, 2005)

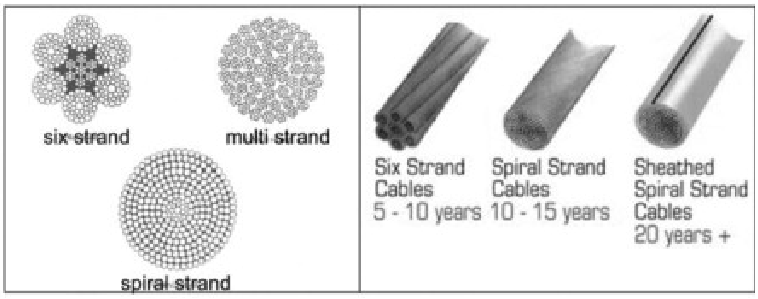

Figure 3.4: Steel wire rope construction, (Chakrabarti, 2005)

Power cables

To export the power generated from the turbines power cables or umbilical's are used. The power cable is pulled into the middle of the turbine through a service pipe. Here it is protected from the splash zone. The wind turbine generators are connected through inter-array cables before they are fed into export cables carrying the energy to its destination (Cruz and Atcheson, 2016). Below a figure of a high-voltage direct current (HVDC) submarine power cable is depicted, figure 3.5

The cables are installed both static and dynamic as the cables close to the turbine must be able to move with the structure. For Hywind Tampen there will be 11 inter-array cables and two export cables transferring power to the oil & gas platforms Snorre A and Gullfaks A, provided by the British company JDR Cable Systems (OffshoreWind.biz, 2019). An illustration of how the infrastructure of inter-array and export cables for Hywind Tampen will be, see figure 3.6.

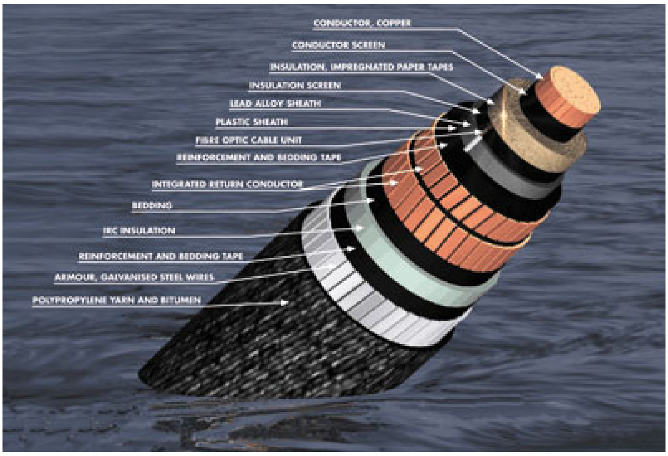

Figure 3.5: HVDC submarine power cable, (European Subsea Cables Association, 2020)

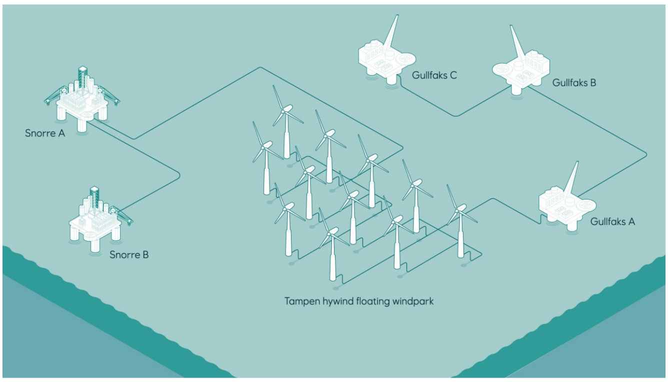

Figure 3.6: Illustration of inter-array and export cables at Hywind Tampen, (Equinor, 2020)

Rotor blades

The rotor blades are shaped in an aerodynamic way to extract as much energy from the wind as possible. They are also made in a lightweight and robust material to resist the forces on the blades. The cross-sections and shape of a rotor blade can be seen in figure 3.7.

Nacelle

The nacelle contains the generator and the gearbox. It has sensors on the top to detect the wind speed and direction, to turn the rotor and blades in the position that maximizes the energy output. The cross-section of the nacelle can be seen in figure 3.8

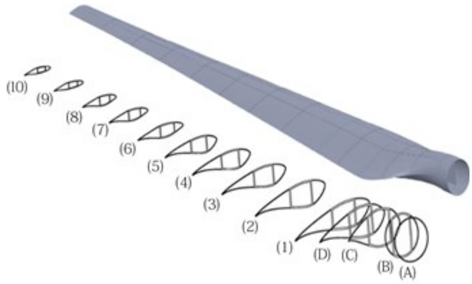

Figure 3.7: Cross-sections and shape of a rotor blade, (Sheibani and Akbari, 2015)

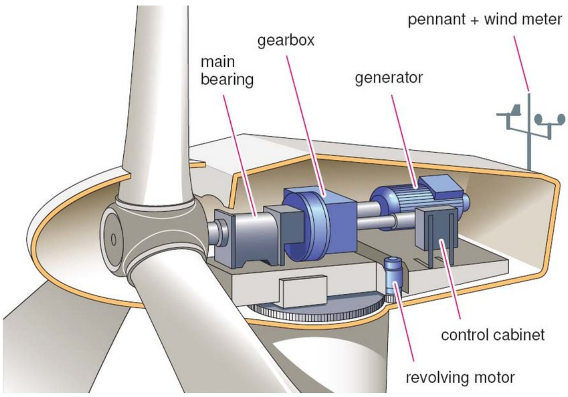

Figure 3.8: Cross-section of a nacelle, (Al-Ahmar et al., 2008)

Tower

This is a steel structure made to withstand the forces from the wind towards the blades and to keep the clearance between the water and the rotor blades within the maritime safety regulations. Offshore wind shear is lower than onshore, which makes it more cost-effective to build the towers as low as possible, (BVG Associates, 2019). This is also better for the stability of floating OWTs due to the increase in the center of gravity for higher towers.

Transition piece

The transition piece connects the tower to the foundation. This piece could either be an integrated upper part of the foundation or a separate part that is bolted or grouted. The transition piece gives the personnel access to the turbine via a platform.

Figure 3.9: Transition piece, (Smulders, 2017)

Foundation

There are several sorts of foundations for OWTs which can be seen in figure 3.10. Bottom-fixed OWTs can be grouped into two different types; bottom-fixed and floating. Bottom-fixed substructures have foundations mounted to the seabed and can be installed in water depths up to 50 m. Floating substructures have ballasted floating foundations which are moored to the seabed.

Bottom-fixed structures

Which bottom-fixed sub-structures to choose are depending on the typical environment, bathymetry, and soil of the seabed at the site where the wind turbine is going to operate. Today the most common offshore wind turbines are bottom-fixed, and the most used foundation structure is the monopile, as seen in figure 3.11. These foundations are very simple to design and produce as it is only one large steel cylinder. They are also inexpensive to manufacture, easy to store, and simple to install and maintain, (Thomsen, 2014). Monopiles are suited for depths up to 30 m, as monopiles in deeper waters will be more flexible and might require guy wires to stabilize the structure.

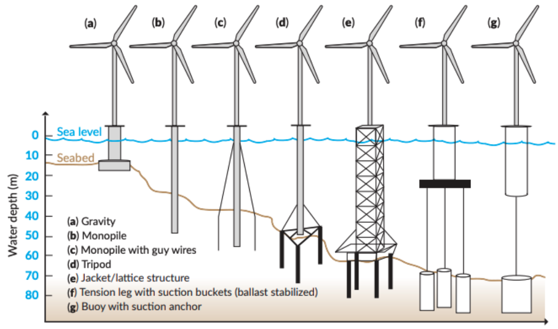

Figure 3.10: Illustration of bottom-fixed offshore wind foundation types, (O'Kelly and Arshad, 2016)

The second most used substructure for bottom-fixed structures is the jacket foundation. This foundation is a four-legged steel lattice structure which has a better global load transmission compared to monopiles. It is also a more economical alternative for greater depths, as they are more robust to heavier weather conditions because of the additional stiffness from the lattice structure. The tripod structure is constructed from steel pipes. There is one central shaft with three steel legs mounted into the seabed. Together with the tripod, the jacket structure is more suitable to degradation in the seabed than monopile structures as they are mounted to the seabed with either gravity base, suction buckets, or piles.

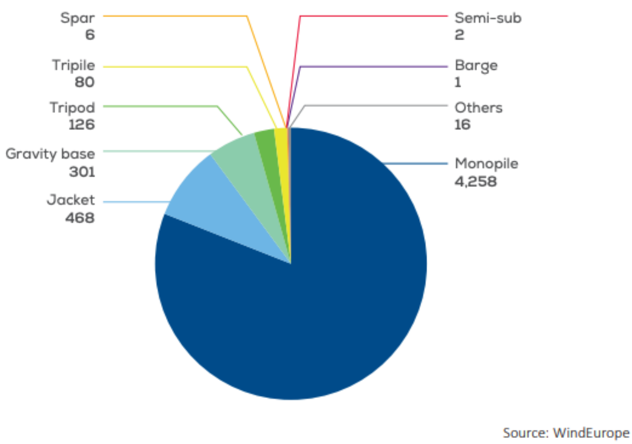

Figure 3.11: Share of substructure types for grid-connected wind turbines at the end of 2019, (WindEurope, 2020b)

Floating structures

The offshore floating wind foundations are inspired by the history of the offshore oil and gas industry. Which sub-structures to use is also depending on the environment where the wind turbine is to operate. The most commonly used floating foundations in Europe today are the spar buoy (ballast stabilized), semi-submersible (buoyancy/ballast stabilized), and barge (buoyancy stabilized). Another concept that could be used for floating structures is the tension leg platform (mooring line stabilized).

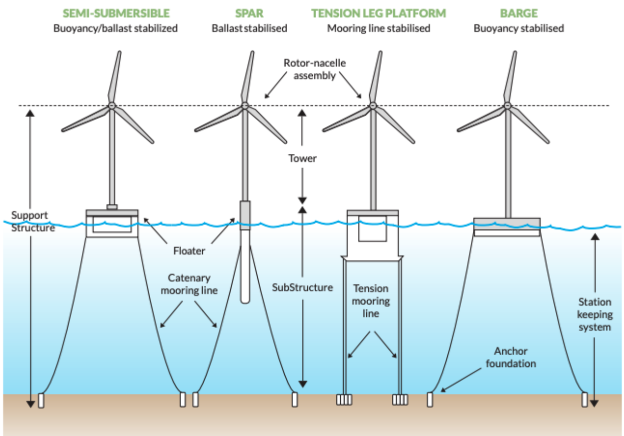

Figure 3.12: Different types of floating foundations for OWTs, (DNV GL, 2018)

The spar buoy, typically made in steel or concrete, is a single cylindrical vertical foundation with a low waterplane area, (Hopstad et al., 2013). It is ballasted with water or solid ballast to make the construction float upright with high stability. The heavy ballasting also results in a large draft. The structure is moored to the seabed with cables or chains to keep the turbine at a specific position. The Hywind concept, developed by Equinor, is a wind turbine floating on a spar buoy. The Hywind prototype was deployed with a 2.3 MW wind turbine outside the west coast of Norway in 2009. This concept was also used for the project Hywind Tampen, which was the first FOWF.

The semi-submersible foundation is a free-surface structure with a much lower draft than the spar buoy. This is a heavy weighted, but flexible structure due to the high amount of steel used and the low draft. The structure has a high manufacturing complexity due to the welding of many different parts. Principle Power's WindFloat concept is based on a semi-submersible foundation and results have shown that it provides sufficiently low pitch performance due to the static and dynamic stability, (Principle Power, 2020). The

WindFloat prototype was installed outside of Portugal in 2011.

The tension leg platform (TLP) is a lightweight structure with a relatively shallow draft. This structure is stabilized with tight tendons, or tension legs, which also keeps the foundation moored to the seabed. There are no deployed TLPs for FOW today, but the PelaStar TLP is a concept developed by Glosten.

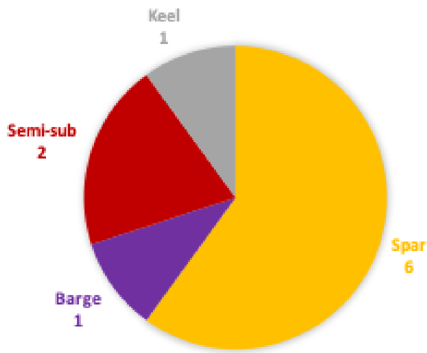

Figure 3.13: Share of floating substructure types in Europe at the end of 2019 (WindEurope, 2020b)

In the diagram above the six spar floating substructures are the Hywind Demo and the Hywind Scotland Pilot Park. The two semi-submersible floating substructures are WindFloat Atlantic Phase 1 and Kincardine Pilot. The floating barge is FloatGen and SeaTwirl S1 has the floating keel concept.

3.2 Marine operations

To install all of the above-mentioned components into one fully functional FOWT there is a need for several operations, and some of these operations take place in the marine environment. These operations are known as marine operations. A marine operation is defined as a *"Non-routine operation of a limited defined duration related to the handling of object(s) and/or vessel(s) in the marine environment during temporary phases."*, according to DNV GL (2011). The marine environment is in this context either at the surface of the sea or below.

All marine operations shall be planned and designed in such a manner that an object is brought from one safe condition to another. A *safe condition* is defined as a condition where the object being handled is exposed to normal risk for damage or loss. To ensure that the marine operations are performed within the safety levels defined there is a set of requirements to vessels undertaking the marine operations, known as the ”VMO Standard”. This standard is followed in the DNV GL offshore standards covering marine operations *“DNV-OS-H101: Marine Operations, General”* where the requirements and recommendations for planning and execution of marine operations are described.

Marine operations can be divided into two categories according to Larsen (2020), subsea- or surface marine operations. Subsea marine operations include installation of subsea hardware, underwater inspection and cable- and pipelaying. Surface marine operations include transport, lifting, towing, station keeping, and mooring.

The type of operation should be defined early in the planning process as an unrestricted or restricted operation may have a great impact on the level of safety and cost of the operation. To define the sub-operations as either unrestricted or restricted the environmental loads one could experience during the operation shall be assessed. Environmental conditions are described in Section 3, A 200 of DNV GL’s standards, as a *”natural phenomena which contribute to structural stress and strain, impose operational limitations/restrictions or navigational considerations”*. The phenomena of general importance are:

- Wind
- Waves/Swell
- Currents
- Tide

Other phenomena that may be of importance to a FOWT are ice conditions and seismic activity. This is information that is critical to the design of the structure.

When planning a marine operation it is recommended to follow a sequence for the planning and design process,(DNV GL, 2011). First, the rules as well as standards have to be determined, before one could identify the physical limitations for the operation. Then the overall planning of the operation like evaluating operational concepts, determine available vessels, and perform a risk assessment must be done. After this one needs to establish a design basis and briefs like environmental conditions and physical limitations related to the operation. In the following step, the engineering and design verification is done through analyses. At last, one should prepare and develop operational procedures. The sequence is presented in figure 3.14.

The operation reference period, T_R, defines the duration of a marine operation and is calculated:

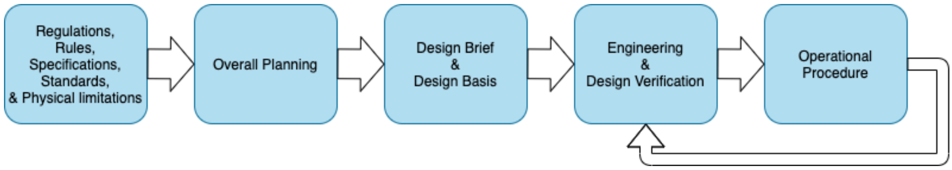

Figure 3.14: Planning sequence for Marine Operations (DNV GL, 2011)

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

Here T_{POP} is the planned operation period, and this parameter should be based on a detailed schedule for the operation. The estimated time for each of the tasks during an operation should be based on experience from operations with similar tasks. If a task typically experiences time delays this should be included in T_{POP}. T_C is the contingency time and should cover uncertainties related to T_{POP} or possible contingency situations. To execute the operation as safe and cost-effective as possible every contingency situation shall be identified. Contingency plans and actions like considering redundancy, preventive measures, or back-up equipment should be made to avoid any hazards or unnecessary time spent. T_C smaller than six hours is normally not accepted. If there are great knowledge and experience with similar operations one could normally apply a T_C of 50 % of T_{POP}. For operations with little knowledge about uncertainties and required time T_R should be at least twice the time of T_{POP}, i.e. $T_R \geq 2 \cdot T_{POP}$.

The weather window is a sufficient period of time that is acceptable to safely carry out a marine operation. During all of this period, the weather forecasted environmental conditions shall be below the operational criterion (OP_{WF}. As seen in figure 3.15 below the weather window is the same as the reference period, T_R. The figure also illustrate the relationship between T_R, T_{POP} and T_C.

The operational criterion is given as OP_{WF}, and this is the maximum weather condition for the execution of the marine operation. OP_{LIM} is the design criterion which is the weather condition used to calculate the design load effects. The relation between OP_{WF} and OP_{LIM} is given the ALPHA factor, α. This is shown in the equation below.

$$OP_{WF} = \alpha \cdot OP_{LIM} \tag{3.2}$$

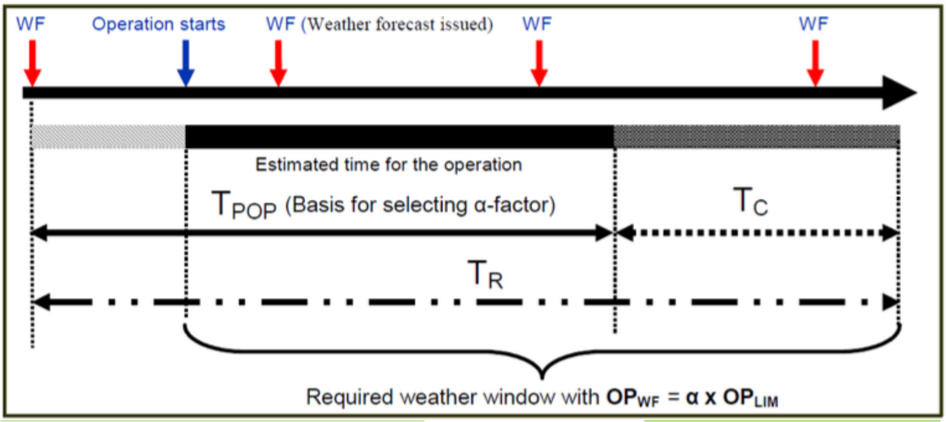

Figure 3.15: Weather window (DNV GL, 2011)

3.2.1 Weather restricted marine operations

If T_R is less than 96 hours and T_{POP} is less than 72 hours the marine operation can normally be defined as weather restricted. Still, if it is unlikely to get a realistic weather forecast for the period and the area of the operation a shorter limit of T_R shall be applied.

3.2.2 Weather unrestricted marine operations

A weather unrestricted operation is an operation that has a T_{POP} normally longer than 72 hours. If this is the case the marine operation shall be planned and executed in a way that it can take place safely in any weather condition which may be experienced during the season. For this one should use the statistical extremes for the area and the season of the operation into consideration when setting the design criterion, OP_{LIM}. A typical environmental condition used for planning marine operations is the significant wave height, H_S. This parameter is calculated as *"Four times the standard deviation of the surface elevation in a short term wave condition (close to the average of the one third highest waves)."* according to DNV GL (DNV GL, 2011). In table 3.1 below the minimum acceptable return periods, T_d, for H_S is given.

3.3 Installation vessels

Due to complex marine operations involved during the installation process, there is a demand for highly specialized vessels. Today, there are only a few wind turbine installation

Table 3.1: Acceptable return periods for the significant wave height, H_S

Reference Period, T_R	**Return Period, T_d**
$T_R \leq 3$ days	$T_d \geq 1$ month
3 days $< T_R \leq 7$ days	$T_d \geq 3$ months
7 days $< T_R \leq 30$ days	$T_d \geq 1$ year
30 days $< T_R \leq 180$ days	$T_d \geq 10$ years
$T_R > 180$ days	$T_d \geq 100$ years

vessels (WTIV). However, with the rapid development within the offshore wind industry, the size of the wind turbines and the need for floating substructures are continuously increasing. An illustration of how large the wind turbines have become compared to well-known monuments is seen in figure 3.16. This makes the shipowners hesitant to build new vessels until they know what size the vessels need to be according to Bloomberg (2019). It is also common to use vessels originally built for the oil and gas industry, bridge building, and near-shore construction according to BVG Associates (BVG Associates, 2019).

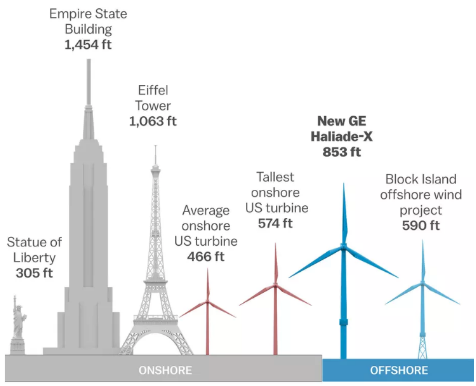

Figure 3.16: Wind turbine heights compared to known monuments (GE, Vox research, 2018)

3.3.1 Wind turbine installation vessel (WTIV)

The main vessel used during the installation of bottom-fixed wind turbines is the WTIV. This is a jack-up vessel and it is specifically built to install OWFs. The vessel may be self-propelled or towed by tugs. These vessels can carry all the components for the top-structure, and some might even carry the foundations as well, before installing them on-site. They are equipped with legs to self-elevate the vessel above the sea level. This makes it a stable platform when performing lifting operations from the vessel to the bottom-fixed structures. In figure 3.22a and 3.22b, Fred. Olsen Windcarrier's "Brave Tern" and "Bold Tern" is pictured during installation.

(a) Fred. Olsen Windcarrier's "Brave Tern" installing a wind turbine at the Albatros wind farm in the German North Sea (Renews Ltd, 2019)

(b) Fred. Olsen Windcarrier's "Bold Tern" installing a wind turbine at the Butendiek wind farm in the German North Sea (Fred. Olsen Windcarrier, 2015)

Figure 3.17: Fred. Olsen Windcarrier's WTIVs

3.3.2 Stone dumping vessel

When the substructure has arrived at the port and is ready for upending a stone dumping vessel is chartered. The stone dumping vessel has been loaded with the solid ballast in port and with the help from an excavator and a crane it can fill up the substructure with the solid ballast required. In figure 3.18 an illustration from the video of the preliminary project description of Hywind Scotland is depicted.

Figure 3.18: Stone dumping vessel (*Technip Hywind Demo* 2020)

3.3.3 Heavy-lift vessel (HLV)

An HLV is needed when the lifting capacity of the WTIV is exceeded. These vessels are usually used during lifting operations of the foundations and transition pieces in the installation and decommissioning phases. The advantage of using an HLV instead of a jack-up vessel for foundation installation is that the process is not very sensitive to weather conditions and a jack-up vessel will use several hours on the jacking process. HLVs are also often used for the installation of the substation weighing 2,000 tonnes and above. The largest disadvantage of using an HLV is the high charter rates because of the low availability of HLVs with a crane capacity of 1,000 tonnes or greater. In figure 3.19 below, the vessel Saipem with a maximum crane capacity of 5,000 tonnes is pictured.

Figure 3.19: Saipem 7000 (Saipem, 2019)

3.3.4 Cable-laying vessel (CLV)

The energy produced by the OWFs is transported in underwater cables installed by a CLV. The CLV can perform a wide range of tasks. On-site, the CLV installs the inter-array cables enabling the connection between the wind turbines and the offshore substation. From the offshore substation, the CLV installs export cables enabling the connection to the onshore substation. The CLV might have installed a plow to create a trench that the cable falls into before it is buried.

Figure 3.20: Van Oord's CLV "Nexus" (Van Oord, 2020)

3.3.5 Remotely Operated Vehicle (ROV)

The ROV is generally used for visual inspections of subsea structures, but they are also used to assist the laying and pull-in of cables. For great depths requiring special equipment and long decompression time for the divers, it is often more cost-effective to use an ROV. There are also trenching ROVs which use a cutter to form a trench in which the cable is buried.

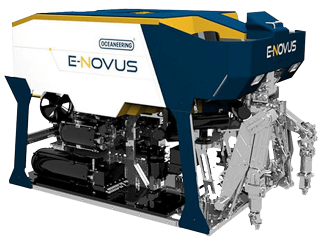

Figure 3.21: Oceaneering's ROV "eNovus" (Oceaneering, 2019)

3.3.6 Feeder vessel

The feeder vessels support the installation process and might be barges, anchor handling tug supply (AHTS), dive support vessel (DSV), offshore construction vessel (OCV), or tugs. The barges can carry large and heavy components. They are often not self-propelled and require vessels with the towing capacity to be moved. Supply vessels like tugs can carry or tow components or equipment to the WTIV on-site. The AHTS and DSV can tow turbines and/or install anchors and chains. Feeder vessels can move between the site and the installation port to reload components, making the utilization of the WTIV higher than it would have been if the WTIV had to sail back every time it had finished a turbine.

(a) DOF Subsea's "Skandi Acergy" (DOF Subsea, 2019)

(b) Buksér & Berging's "BB Worker" (Buksér & Berging, 2019)

Figure 3.22: Feeder vessels

3.3.7 Installation Support Vessel (ISV)

For the commissioning operation, it is useful to have an ISV. These vessels are often equipped with active motion-compensated gangways to secure safe and fast access for personnel from the vessel to the foundations or wind turbines. They are also equipped with a 3D motion compensated crane to transfer goods from the vessel over to foundations.

Figure 3.23: Siems ISV "Siem Moxie" operating on a foundation (Seaway7, n.d.)

3.4 Installation process

When developing the logistics for the installation of offshore wind turbines (OWT) there are several parameters involved. The location of the wind farm, estimated energy demand nearby, fleet composition, and costs related will all play a part in this decision process. Knowing the location one can determine the depth, typical weather conditions, distance from shore and the ports to be involved in the process. This will also be helpful when choosing which concept and substructure to install the wind turbines on. The energy demand will indicate how many turbines to install. The fleet composition needs to be determined to handle logistics in the most cost-effective way.

The installation process of an OWF can be divided into different operations, and the operations will be performed differently depending on the sub-structure used. Most bottom-fixed wind turbines will be assembled and installed on-site, while floating wind turbines have until now been assembled in fjords or port, before being towed to the site. Usually, the installation process will take place in the summer half of the year. This is mainly due to better weather conditions and fewer days waiting for weather. This thesis will thoroughly explain how FOWTs have been installed for the Hywind concept.

The main operations during installation of OWTs can be divided into the following:

- Manufacturing of the components
- Transportation of components to the installation port
- Ballasting of sub-structures
- Assembly of the components
- Pre-installed infrastructure
- Installation on-site

Before the installation process is started project planners have to design a system taking all the parts of the installation process into account. The components of the wind turbines are manufactured in many different countries. Thus, it is essential for project planners to organize the transport of the different components to the assembly site or the installation port. The installation port chosen must satisfy several requirements. For the location of the installation port, it is important to look at the distance between the wind farm site and the port. The port needs to have the infrastructure required for both onshore and offshore logistics. The size and the depth in the port must satisfy the dimensions and the draft of the vessels and the turbines involved. If needed, the port should also be in a sheltered area where it is easy to assemble the different components of the wind turbine. The equipment required for the different operations in the port should be available and there should be storage opportunities for the wind turbine components to minimize the time between each assembly.

Installation of floating wind turbines

The installation process of a FOWF in this report is based on the installation process of Hywind Scotland, what is known for the installation process of Hywind Tampen (Kværner, 2019), mail correspondence with DOF Subsea representative Project Manager, Fredrik Johan von der Fehr and mail correspondence with the Equinor representatives Principal Engineer Marine Operations, Vegard Nedrevåg and Business Manager at Hywind Scotland, Odd Tore Skytterholm.

Unlike the installation process of bottom-fixed wind turbines, which can be both offshore or in an installation port, floating wind turbines have by now only been assembled in an installation port. Thus, all the different parts of the wind turbine must be transported to the installation port.

Ballasting

When the sub-structures (foundation and transition piece) have arrived at the installation port they have to be unloaded and anchored before the ballasting operation can be executed. It is important to mention that during the installation process of Hywind Scotland, this operation was very time-consuming and costly. To receive and prepare the sub-structures which were transported from Spain took a lot more time than expected according to Skytterholm (Mail 10.12.2019).

The ballasting operation consists of two phases. First, the sub-structures are pumped with water to upend them into the required draft is achieved. Secondly, the sub-structures are anchored to a floating quay where the ballasted water is replaced by a solid ballast like MagnaDense. This is a product manufactured from the mineral magnetite and was used in the Hywind Scotland foundations (LKAB Minerals, 2018). The solid ballast comes from a fallipe/stone dumping vessel with DP. The whole ballasting operation takes a few days depending on how much ballast the sub-structure needs. According to Nedrevåg (Mail 09.12.2019), a fallpipe vessel from Boskalis managed to fill about 200 tonnes per hour. Since every sub-structure needed a total of 5,100 tonnes, the sub-structure was filled in 25 hours. However, Nedrevåg says that it should be possible to halve this time. As this operation is done with a semi-submerged structure inshore it will not be very much affected by the weather.

Figure 3.24: Upending operation of sub-structure for Hywind Scotland (Equinor, 2017)

Assembly

The assembly operation of all the components in the top structure can be started as soon as the parts are available at the installation port. For Hywind Scotland this operation took several weeks according to Nedrevåg (Mail 13.12.2019). This was due to the installation of cables and equipment inside the turbine. The top-structures were assembled in about four to five days. Starting with the rotor and the rotor blades. Then the nacelle was lifted onto the tower before the rotor with blades was lifted onto the nacelle. When the top-structure and sub-structure are ready for mating a heavy lift vessel is needed for the lifting operation. This was done by the heavy-lift vessel Saipem 7000 for Hywind Scotland and the mating of the last turbine took 3 hours. A picture from the mating of one of the turbines can be seen in figure 3.25

To reduce both time and costs for Hywind Tampen they have planned to do all the heavy lifts of the mating operation from the quay. This will be done by an onshore crane supplied by Mammoet Norge. Due to the large draft of the wind turbines and the depth of the port, the need for a large crane with a lifting capacity of 500 tonnes at an outreach of about 142 m is required according to Mammoet Norge (Phonecall 25.03.2020). This will reduce the costs of the assembly operation significantly as the crane will cost about 3-4 million euros to mobilize and demobilize and have a monthly rate of about 500 000 euros. In comparison, a heavy lift vessel like Saipem 7000 will have a day rate of about 3-400 000 euro per day depending on period/scope, etc. according to Analyst Jesper Skjong in

Figure 3.25: Heavy lift during mating operation by Saipem7000 (Equinor, 2020)

Fearnleys (Mail 04.05.20). Still, this operation can also be done in several ways, because the top structure can either be pre-assembled or it may be mated part by part like in the illustration video by Kværner. In this video, the foundation is attached to the barge at the quayside. Then the transition piece is lifted onto the foundation, followed by the tower pieces, nacelle, rotor, and blades.

This operation is very dependant on the wind and wave conditions. Especially during the heavy-lift when mating the top- and bottom structure. The winds need to be low because of the blade on the top-structure, which is designed to obtain as much air as possible. The lift will happen in a height greater than 100 m and thus the blades will probably experience higher wind speeds than on the ground. Waves need to be very low, because for a lift from a heavy lift vessel will be performed from a floating structure to another floating structure. This will make the sub-structure and top-structure have different heave movements, which again will make the operation riskier and more time-consuming. According to Nedrevåg (Mail 13.11.2019), the wind speed during the mating lift could not be greater than 15 m/s at Gulen Industrihan according to von der Fehr (Mail 08.06.20), and the significant wave height had to be less than 0.5 m for the lift of the Hywind Scotland turbines (Mail Skytterholm 15.11.19).

Towing

Towing of the turbines can start as soon as a turbine is fully assembled. However, the towing of turbines in the Hywind Scotland project did not start before all the turbines were assembled. The towing operation requires two tugs and one AHTS with a DP system. The first part of the towing is from the quayside and through the fjords. Once the towing exit the fjords there is only needed for one AHTS and one tug.

With today's technology, it is most cost-effective to tow one turbine in each tow. This is because a tow with several turbines would require an extra vessel to control the movement of the extra turbines during the connection of the other turbines on-site. It would also be riskier with regard to weather conditions (Mail Nedrevåg 13.11.19). Another possibility would be to use a larger vessel fleet to tow several turbines at a time. This would reduce the installation time, but it would increase the fixed and variable costs related to the chartering of vessels.

Figure 3.26: Towing of a turbine for Hywind Scotland (National Geographic, 2017)

The tow of each wind turbine is very long and according to DNV GL's *Marine Operations, General* (2011), a tow that exceeds 72 hours is not weather restricted. The towing speed of the Hywind Scotland turbines was about three knots. With a distance of about 270 nautical miles between the installation port in Stord and Peterhead in Scotland, this operation took about 90 hours or 4-5 days. According to Nedrevåg (Mail 13.12.2019), the planning before the towing operation had to document an unrestricted tow, and that they would not have started a tow on a bad forecast.

Pre-installation

At the same time as the installation process inshore is taking place, the suction anchors and chains can be pre-installed on-site. The chain laying could have been done a long time in advance, but according to Nedrevåg (Mail 13.12.2019), it was the most cost-effective to do this immediately before the turbines arrived. Then it was possible to use the same vessel to install the chain and do the hook-up. The suction anchors are embedded into the seabed by either pushing or creating a negative pressure inside of the suction anchor. For the suction anchors, a DSV is used and for the chain installation, an AHTS is used. Each suction anchor takes a bit less than one day to install, while the chains take one day each.

Figure 3.27: Installation of suction anchors at Hywind Scotland, done by TechnipFMC with the DSV "Deep Explorer" (FFU, 2018)

The weather restrictions for the suction anchor installation was restricted to less than 2 m significant wave height. This is due to the forces in the crane and the suction structure during deployment in the splash zone crossing of the lift. TechnipFMC retrofitted the crane on the vessel "Deep Explorer" with a Splash Zone Mode for the installation of the suction anchors for Hywind Scotland. This was mainly an upgrade of the control system, which ended up saving about 11 days waiting for the weather.

If there is a need for a substation this installation is done in a heavy lift operation due to the weight of the substation (over 2,000 tonnes). The foundation of the substation is installed in the same way as the foundation for the wind turbines. The inter-array cables are connected between the wind turbines and the sub-station. They can be installed in a series between the wind turbines to the substation. The export cables are laid as the vessel sails, in as long sections as possible, to prevent too many expensive subsea joints.

Hook-up

When the first turbine arrives the site of the wind farm the hook up to the anchors starts immediately. As previously mentioned, the hook up can be done by the same AHTS that installed the chains for the anchors. Every turbine is hooked up to three anchors each, but on Hywind Tampen they have planned to hook-up some turbines to the same anchor to save cost. Instead of 33 anchors for the 11 turbines, there will be 19 anchors in total according to Equinor representative Moxnes (Presentation SFI Workshop 26.05.2020). The anchors prevent the wind turbines from moving. For the hook up the operations are typically restricted by the AHTS being able to work. According to Nedrevåg (Mail 13.12.2019), one could assume that the significant wave height has to be below somewhere between 2-5 m.

Cable-laying

When the hook-up is done the CLV can start the process of laying the inter-array cables. With the help of an ROV and a winch installed on the turbine, the pull-in of the cables into the turbines is done. Following this comes the laying of the export cables between the substation and shore. Hywind Scotland was connected to the SSE Peterhead Grange substation (Equinor, 2017). Hywind Tampen does not need any substation as it is going to supply the platforms at the Snorre and Gullfaks fields directly with about 35 % of the total power need. The laying of inter-array cables takes about two days to finish. Most of this time goes to the mounting of floating parts (Mail Skytterholm 06.12.19 and 01.04.20). The export cables take about one day per end part, while the static part takes about two days for Hywind Tampen which will be from the turbines to the five platforms at the oil & gas fields Gullfaks and Snorre. The weather restrictions for the cable installation can be assumed to be a significant wave height about 2-3 m as it affects the fatigue of the cables as well as the stability of the CLV while laying the cables. This operation could also have been done independently of the other operations, but this would have increased the cost of the operation as one would have to coil the cable back up to install the buoyancy elements, hold-back anchors, and pull-in equipment. It would also increase the risk of damage to the cable (Mail Skytterholm 29.05.20).

Commissioning

After all the turbines have arrived the commissioning operation can start. Now all the wind turbines components are tested to make sure that they work properly and that the wind farm can produce stable power. According to NordZeeWind (2008) and Larsen et al. (2009) the following tests should be done after final installation is done:

- Site acceptance tests: Communication between the wind turbines and the electrical infrastructure of the wind farm.
- Commissioning tests: Test the generators, vibration, yaw, pitch, voltage in cables, transformer cooling, proper grounding, etc.
- Completion tests: Continuous operation testing one grid-connected turbine at a time for several days to detect faults and make sure that they do not exceed a maximum number. Then the availability of the whole wind farm is tested while all turbines produce power.
- Performance tests: During the warranty period (typically 5-years) the operator of the wind farm can perform performance tests to make sure that the wind farm is producing power and functioning as stated in the contract terms. Then availability tests, power curve tests, electrical system tests, and acoustic noise tests.

Figure 3.28: "Siem Moxie" during the commissioning of Hywind Scotland (Seaway7, 2017)

In table 3.2 the summary of the operations, time consumed, weather restrictions, and the functions required for the Hywind Scotland project is presented. In table 3.3 the vessel fleet for the Hywind Scotland project is presented.

Table 3.2: Summary of the installation process for Hywind Scotland

Operation	Time	Weather restrictions	Functions
Transport of components	Distance dependant	-	Transport to site
Ballasting	1.75 days	-	Tow sub-structure to ballast operation. Filling and pumping of water. Solid ballasting.
Assembly	Top structure: 4-5 days Mating operation: 3 hours	Wind speed $\leq$ 12 m/s Hs $\leq$ 0.5 m	Heavy lift
Towing	Hywind Scotland: 4-5 days	The tow was unrestricted.	Transport of turbine Bollard pull above AHTS: 200 tonnes Tugs: 100 tonnes
Pre-installation	Suction anchor: 1 day each Chain: 1 day each	Suction anchor: Hs $\leq$ 2 m	Anchor handling Chain handling capabilities Chain lockers Bollard pull above AHTS: 300 tonnes
Final installation	Inter-array cables: 2 days Export cables: 1 day each end 2 days static part	Hook up: Hs $\leq$ 2-5 m Cable laying: Hs $\leq$ 2-3 m	Hook up of wind turbine. Cable-laying Commissioning

Table 3.3: The fleet utilized at the Hywind Scotland project, Nedrevåg (Mail 13.12.2019)

Vessel	Vesseltype	Function	Speed [kts]	Lifting capacity [t]	Bollard pull [t]	Operation
Saipem 7000	HLV	Heavy Lift	9.5	14,000		Mating
BB Coaster	Tug	Port Tug	13			Towing in fjord
BB Worker	Tug	Port Tug	15			Towing in fjord
Manta	AHTS	Assisting Tug	17	8.6	206	Towing Offshore
Union Lynx	AHTS	Assisting Tug	15	5	187	Towing Offshore
Normand Ferking	AHTS	Main Tug	12	14.5	239	Towing offshore
Normand Drott	AHTS	Main Tug	12	10	344	Towing offshore
Deep Explorer	DSV	Anchoring	14	400		Suction anchors
Normand Prosper	AHTS	Anchoring	12	8	338	Chains & Hook up
Skandi Acergy	OCV	Cables	15	500		Cable installation
Siem Moxie	ISV	Commissioning	14	5		Commissioning

Chapter 4

Problem description

The installation process of OWTs is a costly and complex operation which requires vessels with specific functions and capacities. Today OWFs tend to be installed further offshore to obtain more reliable and higher wind speeds. However, the depths further offshore are too deep for conventional bottom-fixed foundations to be installed and the weather conditions are heavier. This has caused a demand for floating substructures and even more complex marine operations making the installation costs much higher than for bottom-fixed turbines. There are no specialized vessels for FOWT installation today and thus a heterogeneous vessel fleet is needed to satisfy all the required operations. As stated in chapter 2 FOW today is not profitable. To reduce the costs of installation there is a need for more cost-efficient logistics and operations. The objective of this project is to provide insight into how logistics can be optimized for the installation process of FOWTs and minimize the total cost of the fleet size and mix used. To do this an optimization model and a simulation model of the installation process are developed. The results from the optimization model are validated with the stochastic simulation model. Both models will be developed on the basis of the OWT components and different operations of the installation presented in this project.

The installation process of the first commercially installed FOWF, Hywind Scotland, and the planned FOWF, Hywind Tampen, will be the basis of this project. This is because Hywind Tampen is a great example of how FOW can be installed in the future. With the installation of 11 turbines of 8 MW, it will be the largest FOWF in the world, both in the number of turbines and capacity. As the industry strives to install FOW further offshore the need for towing over large distances and rougher environmental conditions will be experienced. Hywind Tampen is supposed to be installed about 140 km from shore and the installation port is already known to be Gulen Industrihamn (167 km from Tampen or 90 nautical miles). This makes the location of Hywind Tampen great as an example of a large towing distance and with environmental conditions that represent an area with rougher weather conditions than closer to the shore. This means that the weather window will be important for the model. The move further offshore also means larger depths and at Hywind Tampen the depths vary between 260-300 m. With this information, it is possible to make a realistic simulation model of the installation process. The parameters mentioned in this chapter are given in table 4.1.

Table 4.1: Parameters of the FOWF Hywind Tampen (Equinor, 2019b)

Parameter	**Value**
Amount of turbines	11
Turbine capacity	8 MW
Distance	90 nm
Depth	260 - 300 m

Chapter 5

Literature Review

In this section, literature from research and development related to logistics during the installation of offshore floating wind will be presented. Fleet size and mix problems, analyses of improvements of installation time, and ideas for new concepts will be covered.

5.1 Optimization of fleet size and mix

(Elin E. Halvorsen-Weare et al., 2013) In the publication *Vessel fleet analysis for maintenance operations at offshore wind farms*, a deterministic vessel fleet optimization model for O&M is presented. The model only focuses on the weather parameters wind speed and wave height, and all uncertain parameters are treated as known to simplify the real-world problem. Wind speed and wave height for the period of each planning horizon is based on the historical data from the Ekofisk field in the North Sea. The model can be used for decision support and analysis when facing decisions regards to the vessel fleet composition and infrastructure.

(Pantuso et al., 2014) *A survey on maritime fleet size and mix problems* is a paper presenting a literature survey on the fleet size and mix problem in maritime transportation. Pantuso et al. state that this problem "*consists of deciding how many ships of each type to use in order to meet the demand.*". The paper also concludes that the uncertain market behavior and the various number of alternative ways to renew a fleet should be taken into account in future research.

(Gundegjerde et al., 2015) *A stochastic fleet size and mix model for maintenance opera-*

tions at offshore wind farms is a publication studying the vessel fleet size and mix problem for O&M at offshore wind farms. In this publication, a stochastic three-stage programming model is proposed. This model considers uncertainties in vessel spot rates, weather conditions, electricity prices, and failures to the system. Adjustment to the vessel fleet can be made at stage 1 and 2, while stage 3 executes the maintenance operations by available vessels in the fleet. The authors claim that the solution approach in this publication is one of the first attempts to include important uncertainty aspects.

(Siljan and Hansen, 2017) In the Master Thesis *Optimizing the Vessel Fleet Used to Install an Offshore Wind Farm*, two mathematical formulations, one original model, and one reformulated pattern-based model, are proposed. The model optimizes the fleet size and mix of the installation phase of offshore wind by minimizing cost. The two models suggest a fleet composition, charter period, and the vessels' respective installation schedules, based on a given set of weather data.

(Backe and Haugland, 2017) The paper *Strategic Optimization of Offshore Wind Farm Installation* presents a MILP model minimizing the total cost of analyzing the weather conditions, ports, and vessel fleet size and mix. They conclude that the model is more reliable if large offshore wind farms (OWFs) are considered in fractionated parts and that further work should be done on developing heuristics for the model.

(Stålhane et al., 2019) In the paper, *Optimizing vessel fleet size and mix to support maintenance operations at offshore wind farms* a two-stage stochastic programming model of the problem of determining the optimal vessel fleet for the maintenance operations at OWFs. The decisions of the first stage are what vessels to charter, while the decisions of the second stage are how to support the maintenance tasks with the vessel fleet determined from the first stage. In the conclusion of this paper, it is stated that the model can provide decision support and that further work should incorporate condition-based maintenance tasks into the model.

5.1.1 Improvements of time schedules and installation time

(Scholz-Reiter et al., 2011) The paper *A MILP for Installation Scheduling of Offshore Wind Farms* introduces a planning and control concept for the installation of offshore wind. They also developed a mathematical model using integer linear programming (MILP). This model calculates the optimal installation schedule by observing weather conditions. This MILP can be used for simulation runs that consider stochastic weather conditions. Another paper from Scholz-Reiter et al. (2011), *Towards a Heuristic for*

Scheduling Offshore Installation Processes, has implemented a heuristic which can consider longer time horizons, multiple vessels and a broader variety of weather conditions.

(Stålhane, Hvattum, et al., 2015) In the publication *Optimization of routing and scheduling of vessels to perform maintenance at offshore wind farms* Stålhane et al. presents two mathematical models for the routing and scheduling of vessels performing maintenance tasks at offshore wind farms. One is based on arc-flow and the other is based on path-flow. The paper concludes that the path-flow model together with a heuristic labeling algorithm solves the problem with a significantly smaller computational time than the arc-flow model.

(E. E. Halvorsen-Weare and Fagerholt, 2017) In the paper *Optimization in offshore supply vessel planning* the weather impact on the execution of a schedule is analyzed. An arc-flow model and a voyage-based model is made to obtain an optimal fleet size and mix of OSVs, weekly routes, and schedules for servicing offshore oil and gas installations. For further work, the paper suggests developing column generation schemes or heuristic methods to make it more applicable to larger problems.

(Lacal-Arántegui et al., 2018) The paper *Offshore wind installation: Analysing the evidence behind improvements in installation time*, analyze the evidence behind cost reduction for the installation of foundations and turbines. The study is based on the time of installation for 87 wind farms installed from 2000 to 2017. The results in this paper show that installation time has been reduced with 70% during this time period. They claim that this reduction is related to the larger size of the OWTs, not because of any improvements in the installation process.

5.2 Simulation

(Barlow et al., 2014) In the paper *An Assessment of Vessel Characteristics for the Installation of Offshore Wind Farms*, a simulation tool combining a model of the installation of an OWF with a weather model is presented. The simulation model provides realistic installation durations and costs associated. The simulation model allows a project planner to compare different vessel fleet compositions and make decisions based on this.

(Vartdal, 2016) In the Project Thesis *A Simulation Approach to the Installation Phase for Offshore Wind*, a description of the installation process for bottom fixed offshore wind is provided. She also presented a simulation model that calculates the time of the installation based on vessel parameters and stochastic weather conditions. In conclusion, she suggests that further work should include simulations over different types of weather series and that the model should be more applicable for combinations of several configurations of the turbine assembly.

5.3 Studies of different concepts

(Walther et al., 2013) In the paper *How to evaluate installation vessel concepts for offshore wind farms* an evaluation tool for the decision making when choosing the installation vessel fleet, is presented. This tool is based on simulation and returns a schedule for when the vessels should operate, installation cost, and time. By running the model multiple times only changing the vessel input data. The different outputs are compared and the most cost-effective concept can be determined.

(Ahn et al., 2016) *Comparative evaluation of different offshore wind turbine installation vessels for Korean west-south wind farm* is a paper evaluating different vessels to find the lowest installation cost of a Korean west-south OWF. The cost of an OWT and the duration of transportation for each vessel are analyzed.

(Hatledal et al., 2017) In the paper *Numerical Study for a Catamaran Gripper-Monopile Mechanism of a Novel Offshore Wind Turbine Assembly Installation Procedure* a novel wind turbine installation process is presented. This process is supposed to reduce installation and maintenance costs. The paper presents a new catamaran vessel carrying pre-assembled top-structures. Installed on the vessel is a set of deck grippers with active heave compensation function, which can make the heavy lift operation to mate the turbines top-structure together with the sub-structure. It is also installed a set of grippers to hold the sub-structure during the heavy lift, making the two structures have the same heave period.

Chapter 6

Case study

In this Master Thesis, a case study is prepared to explore what fleet size and mix that will be optimal for the installation process of a FOWF. As previously mentioned this process can be executed in several ways depending on what type of floating sub-structure to use and the location of the wind farm. The case in this project thesis will take the location of Hywind Tampen as a base case and use the knowledge from Hywind Scotland to create the vessel type opportunities and logistics for the installation process. The focus will be on marine operations during the installation process.

6.1 Method

By developing a mathematical model as a linear programming problem the optimal fleet for the installation process is found. The results from this model will then be validated in a simulation model developed to represent the installation process with stochastic weather conditions. The methodology is presented in detail in chapter 7.

6.1.1 Logistics for the installation process

Creating the logistics for the installation process is a process of making all the operations and functions the system requires as efficient as possible. The marine operations required for the Hywind Tampen installation were mainly transport of components, ballasting, mating, towing, anchoring & chains, hook-up, cable-laying, and commissioning. Each of these operations has either one or more functions that need to be fulfilled.

For the case in this Master Thesis, the operation of transport is neglected as this is often done by subcontractors. Commissioning is also neglected because this operation demands a lot of testing of the communication and performance of the wind turbine. All the time spent on commissioning does not necessarily need marine operations to be executed. This means that the functions of ballasting, mating, towing, anchoring & chains, hook-up, and cable-laying needs to be defined. For the ballasting operation, the functions needed are the transport of the sub-structure to the site of ballasting, anchoring to a floating quay, filling of water to upend the structure, and changing water with solid ballast. The next operation is the mating operation and for this operation, the only functions needed are transport and anchoring of sub-structure at the mating site and the heavy lift of the top-structure on to the bottom-structure. After the mating, the turbines are ready for towing out to the site of the wind farm. For this operation, the function required is the required amount of bollard pull on the vessels which tows the turbine. For the anchoring & chain operation there is a need for a crane with the required lifting capacity for the suction anchors and bollard pull for the tension test of the chains (Mail von der Fehr 26.05.20). When the turbine has arrived at the wind farm location the functions needed for hook-up are an AHTS with an ROV having the ability to hook the AHTS's work chain to the mooring lines. It is also needed at least one tug for station keeping of the wind turbine. For the cable-laying operation, it is important that the vessel used can carry as much cable in the carousel as possible and enough deck-space to equipment and about 1000 floating elements (Mail Skytterholm 02.04.20).

The illustration of the installation process with the different operations are presented in figure 6.1 below. A full-scale figure of the illustration is presented in appendix C.

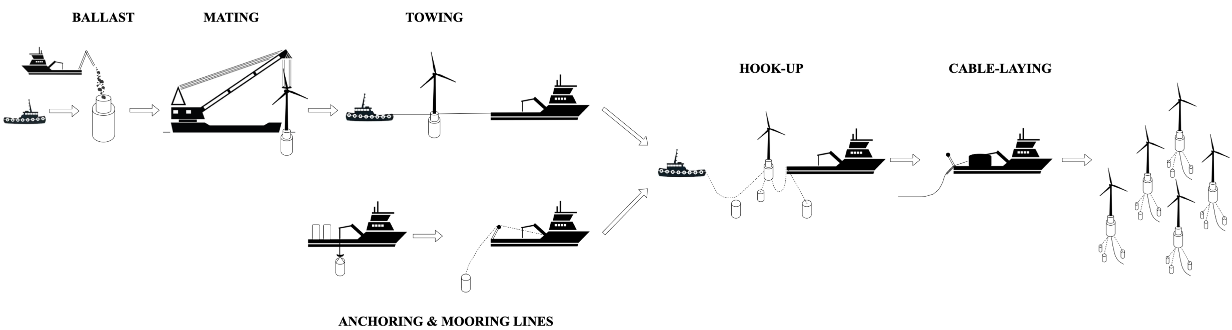

Figure 6.1: Illustration of the installation process used in the optimization model

Chapter 7

Methodology

7.1 MILP Problem

To optimize the fleet size and mix for the installation process of a FOWF a mathematical model for a mixed-integer linear programming (MILP) problem has been made. This model will take the vessels functions into account when designating the vessels to different tasks. The objective function is minimizing the total cost of the installation process and is based on the total time chartered per vessel as well as the total time of the whole installation process. For programming and calculation of the model python and a commercial solver will be used. The mathematical model and parameters used are described in detail in chapter 8.2.

7.1.1 Mathematical programming

For mathematical programming, the programming language Python has been used in an integrated development environment (IDE) known as PyCharm. The LP problem has been modeled using the LP modeler PuLP and calls for the commercial optimization solver Gurobi. The python file named *MasterThesis.py* can be found in appendix A.

Gurobi

The Gurobi solver uses a linear-programming based branch-and-bound algorithm to solve MILP problems. The LP-based branch-and-bound starts by solving the problem directly. All integrality restrictions are removed and the resulting LP is known as a linear-programming relaxation of the original MILP. Now the LP can be solved. If the result satisfies all of the original integrality restrictions it is an optimal solution and process stops. If not, the model picks a variable that is restricted to be an integer, but in the LP relaxation has a fractional value. Then this value can be excluded by implementing restrictions less than or equal to ($\leq$) the first integer below and greater than or equal to ($\geq$) the first integer above. This new variable is called a branching variable. This procedure is then done for more MILPs and more branching variables are selected which results in what is called a search tree. All MILPs generated are called nodes and all the nodes that have not yet been branched are known as leaves. If all leaf nodes can be solved or disposed, the original MILP is solved (Gurobi, 2020). Below is an illustration of how a search tree can be visualized, figure 7.1.

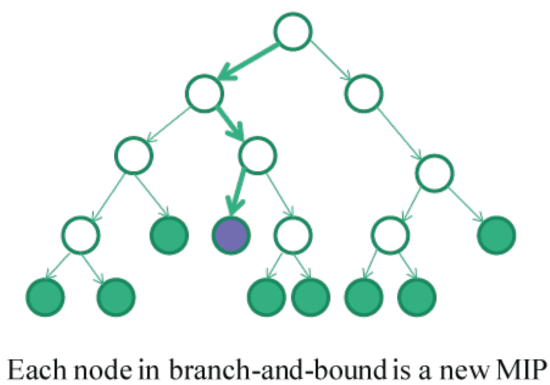

Figure 7.1: Branch-and-bound search tree (Gurobi, 2020)

If the search finds a feasible solution it denotes this as the incumbent solution. This is the best feasible solution so far in the search. For a minimization problem like the case in this Master Thesis, the incumbent solution will be the upper bound of the search. Any solution with a higher value than this will never be accepted. At the same time as the search goes on, there is always a valid lower bound during the branch-and-bound search. This bound is found by taking the minimum of all the current leaf nodes' optimal objective values. The difference between the upper and the lower bound is known as the current MIP gap. When this gap is equal to zero the optimality is proven.

7.2 Stochastic programming and simulation

To validate the results from the MILP problem a simulation model has been developed in Matlab. The method used for simulating the installation of a FOWF is based on the operational profile of the system. This system will consist of different operations within the installation process. An operation will depend on how it is executed and what restrictions the system has. The next paragraphs will explain how a realistic system can be made based on the information and methods available. The simulation model is described in chapter 10.

When analyzing a system like the installation process of FOWFs the system will depend on stochastic variables such as weather conditions. Stochastic programming is a method used to model problems that involve uncertainty. The goal is to represent a problem as realistic as possible. To do this stochastic programming models benefit from the fact that the probability distributions governing the data used are either known or can be estimated.

7.2.1 Implementation of stochastic weather data

The weather data in this project thesis is downloaded from the Copernicus Climate Data Store (Copernicus, 2019). The data is collected from 61°N, 2°E (Tampen), and 61°N, 5°E (Gulen Industrihamn), which are the two places used for the main operations of this installation process. Both significant wave height and the wind speed in the horizontal plane (u- and v-direction) at 100 m height are downloaded. These are the most important weather data for the simulation model.

7.2.2 Simulating a Markov Chain

A Markov chain is a stochastic process experiencing transitions from one state to another based on probabilities. The definition of a Markov chain is that it does not matter which states the process has been to, all the possible future states are fixed. It can be explained mathematically like in equation 7.1 and 7.2.

$$X_{n-1} \longrightarrow X_n \tag{7.1}$$

If X_{n-1} is the value of the previous state *i* and X_n is the value of the present state *j*. Then the probability of going from state *i* to state *j* is represented by P_{ij}.

This gives the transition matrix for the Markov Chain, containing the probability of transitioning between states.

$$(P_n)_{i,j} = \mathbb{P}\left(X_{n+1} = j | X_n = i\right) \tag{7.2}$$

The Markov chain can be implemented for simulating stochastic data like the weather. To create a Markov chain for the weather data downloaded for Copernicus Climate Data Store the probabilities from going from one state to another have to be calculated. Absorbing states also have to be investigated to prevent the model from ending up in an infinite loop going to the same state for each time step. This is because the probability of going to the same state is zero. This will happen if all the weather data gathered will go to state 2 from state 1 every time state 2 occurs. The Markov chain Matlab script was provided in last falls course *Ocean System Simulation* at NTNU and has been slightly adjusted to make it applicable for the data downloaded for this model.

After running the scripts two other scripts named *SeaDataMatrixGulen.m* and *SeaDataMatrixTampen.m* are run to store the stochastic weather data into vectors with the length of the size of the downloaded data. These data are further imported into the simulation model explained in chapter 10.

For this model, the significant wave heights from Gulen Industrihamn and Tampen are stochastic while the wind data is historical. This is because the wind change states more random than significant wave height. The probability of going directly from 1 m/s to 5 m/s is much higher than going from a significant wave height of 1 m to 5 m, without going through state 2,3 or 4. This can be explained due to wind gusts.

7.2.3 Matlab SimEvents

To simulate the model the simulation tool used is MATLAB SimEvents. This is a tool that can be used to run discrete event simulations. The problem is modeled by generating entities that move through a system with several SimEvents blocks like entity generators, queues, servers, gates, terminators, etc. The blocks used in this model can be seen in the figures in chapter 10.

Chapter 8

Optimization model

The fleet size and mix problem of the installation process of FOWFs has been studied in this thesis. To solve this problem a deterministic MILP model has been made and is presented later in this chapter. The model strives to find the optimal fleet size and mix which minimize the total cost of the installation process of a FOWF. To do this the time each vessel is chartered has been implemented in the model, due to the significance of this factor for the total cost.

8.1 Assumptions

The assumptions made for the model presented in section 8.2 are outlined in this section. To make the model as realistic as possible it is important to use realistic parameters and make the execution of the installation process happen in a logical way. However, the availability of the data needed for this model is limited as a lot of the data is either hidden behind paywalls or not public due to confidentiality or non-disclosure agreements. Therefore, several assumptions have been made when the data cannot be retrieved. Assumptions are also made to keep the model simple enough to make it applicable to different installation projects of FOWFs.

8.1.1 Operations

Operations in the optimization model made for this Master Thesis are all marine operations that are supposed to be done from the installation port, Gulen Industrihamn. As mentioned in chapter 3 section 3.4 the different parts of the turbines are manufactured in different geographical places around the world and transported to the installation site. For this model, all the parts are assumed to be ready for assembly at the installation port. Although the ballast operation is going to be done at Dommersnes where the sub-structure is fabricated this model considers the operation to be done at Gulen Industrihamn for simplicity.

The operations are assumed to be executed in a pre-determined sequence. This sequence is based on correspondence with Nedrevåg and Skytterholm from Equinor, von der Fer from Dof Subsea, and the video of the installation process published by Kværner (2019).

Every operation is given in the input data set named *I*. This set is consists of several subsets giving the different operation types.

An example of the operations set is:

$$I = \{d, C, B, M, T, A, H\}$$

In this set the subsets are given as depot node or installation port *(d)*, cable-laying *(C)*, ballast of the substructures *(B)*, mating of the sub- and top-structure *(M)*, towing of the turbine to the site *(T)*, anchoring and mooring lines *(A)* and hook-up *(H)*.

8.1.2 Vessels

A vessel can only have one charter time period. This means that if a vessel has returned to the depot node the vessel cannot start on a new route. It is assumed that the vessels executing the towing operation can only tow one turbine at a time. The fuel costs are only based on sailing between the different operations.

8.2 Mathematical Model

To find the optimal fleet size and mix for the installation process of a FOWF a Time-Dependent Multiple Vehicle Routing Problem (TDMVRP) has been developed. The details of the model's mathematical formulation are presented in this section. First, the definitions of indices, sets, parameters, and variables are given. These are followed by the objective function and constraints with descriptions. Indices and decision variables are all presented with lower case letters, while the parameters and sets are represented by capital letters.

8.2.1 Indices

i, j	Operations for turbines
v	Types of vessels
k	Vesselnumber
f	Functions

8.2.2 Sets

I	Set of operations for each turbine indexed by *i* and *j* ($I = \{d,C,B,M,T,A,H\}$)
V	Set of types of vessels indexed by *v*
K	Set of vessels indexed by *k*
F	Set of functions indexed by *f*

8.2.3 Parameters

T_i^S	Service time at node *i*
C_v^F	Fixed charter cost of vessel type *v*
C_v^V	Variable cost per hour for vessel type *v*
C_v^{FUEL}	Fuel cost per nautical mile sailed for vessel type *v*
C^P	Penalty cost in EUR per hour
U_v	Speed in knots for vessel type *v*
L_{ij}^{DIST}	Sailing distance in nautical miles between node *i* and *j*
Q_{vf}^{FUNC}	Function *f* for each vessel type *v*
R_{if}^{REQ}	Function *f* required for operation *i*
D_{ij}^{DEP}	Dependency between operation *i* and operation *j*
N^{HLV}	Maximum amount of HLVs operating the mating operation
N^{TOW}	Minimum amount of vessels operating the towing operation
N^{AHTS}	Minimum amount of AHTSs needed for the towing operation
N^{HOOK}	Minimum amount of vessels operating the hook-up operation

8.2.4 Variables

Binary variables

y_{ivk} 1, if vessel *k* of type *v* is used for operation *i*

0, otherwise

z_{ijvk} 1, if vessel *k* of type *v* is sailing on the route from operation *i* to *j*

0, otherwise

Continous variables

s_{ivk} Start time of vessel *k* of type *v* for operation *i*

o_i Start time for operation *i*

t_{vk} Total time vessel *k* of type *v* is chartered

e End time for the whole installation process

8.2.5 Objective Function

$$min \quad Z = \sum_{v \in V} \sum_{k \in K} C_v^F \cdot z_{0jvk} + \sum_{v \in V} \sum_{k \in K} (C_v^V + C_v^{FUEL}) \cdot t_{vk} + e \cdot C^P$$

The aim of the objective function is to minimize the total cost of the fleet used for the installation of a FOWF. In the first part of the objective function, the fixed costs of utilizing vessels are summarized. In the second part variable costs and fuel costs of operating the vessels are multiplied with the time period, every vessel is utilized. This time period is calculated by the model. In the last part of the objective function, a penalty cost is multiplied with the total time of the whole installation process. This part ensures that the model takes the total project duration into consideration as it is beneficial to start power production as soon as possible.

8.2.6 Constraints

Flow constraints

$$\sum_{j \in J} z_{ijvk} \leq 1 \qquad \forall i \in I, \forall v \in V, \forall k \in K \quad (8.1)$$

$$\sum_{i \in I} z_{ijvk} \leq 1 \qquad \forall j \in J, \forall v \in V, \forall k \in K \quad (8.2)$$

$$\sum_{j \in J} \sum_{v \in V} \sum_{k \in K} z_{ijvk} \geq 1 \qquad \forall i \in I \quad (8.3)$$

$$\sum_{i \in I} \sum_{v \in V} \sum_{k \in K} z_{ijvk} \geq 1 \qquad \forall j \in J \quad (8.4)$$

$$z_{iivk} = 0 \qquad \forall i \in I, \forall v \in V, \forall k \in K \quad (8.5)$$

$$\sum_{j \in J} z_{ijvk} = \sum_{j \in J} z_{jivk} \qquad \forall i \in I, \forall v \in V, \forall k \in K \quad (8.6)$$

The flow constraints (8.1)-(8.6) ensures an optimal flow of vessels between the different operations. Constraint (8.1)-(8.2) makes sure that every vessel visit an operation only once. These constraints also make sure that a vessel leaves and arrive at the depot only once. Constraint (8.3)-(8.4) secures that all operations are executed. Constraint (8.5) ensures that a vessel cannot travel back to the same operation it just executed, which also eliminates this type of subtour. Flow conservation is established in constraint (8.6), making sure that every operation visited also must be left at some point.

Functional requirement constraints

$$\sum_{i \in I} \sum_{v \in V} \sum_{k \in K} z_{ijvk} \cdot Q_{vf}^{FUNC} \geq R_{jf}^{REQ} \qquad \forall j \in J, \forall f \in F \quad (8.7)$$

$$\sum_{i \in I} \sum_{v \in V} \sum_{k \in K} z_{ijvk} = N^{HLV} \qquad \forall j \in M \quad (8.8)$$

$$\sum_{i \in I} \sum_{v \in V} \sum_{k \in K} z_{ijvk} \geq N^{TOW} \qquad \forall j \in T \quad (8.9)$$

$$\sum_{i \in I} \sum_{k \in K} z_{ij1k} \geq N^{AHTS} \qquad \forall j \in T \quad (8.10)$$

$$\sum_{i \in I} \sum_{v \in V} \sum_{k \in K} z_{ijvk} \geq N^{HOOK} \qquad \forall j \in H \quad (8.11)$$

Every operation has some functional requirements. Constraint (8.7)-(8.11) are to make sure that the vessels used for an operation actually can execute that operation. Constraint (8.7) summarizes all the vessels attribute for every function and makes sure that the sum satisfies the functional requirement for every operation. There can only be one vessel operating on the heavy-lift during the mating of the different turbine parts. This is taken care of in constraint (8.8). As a tow of a FOWT is not only depending on the bollard pull of the vessels but the stability of the wind turbine too, constraint (8.9) has been made to ensure at least three vessels operating the towing operation. Constraint (8.10) makes sure that at least one AHTS operates on the tow. This secures the main tug for every towing operation. The last functional constraint (8.11) demands two vessels for every hook-up operation.

Constraints for vessels used

$$\sum_{i \in I} z_{ijvk} = y_{jvk} \qquad \forall j \in J, \forall v \in V, \forall k \in K \quad (8.12)$$

$$\sum_{v \in V} \sum_{k \in K} y_{ivk} \geq 1 \qquad \forall i \in I \quad (8.13)$$

What operation every vessel is operating is handled by constraint (8.12), while constraint (8.13) ensures that every operation is done at least once. These constraints are needed for the time constraints in the subsequent paragraph.

Time constraints

$$s_{0vk} + \frac{L_{0j}^{DIST}}{U_v} \cdot z_{0jvk} \leq s_{jvk} \qquad \forall j \in J \setminus \{0\}, \forall v \in V, \forall k \in K \quad (8.14)$$

$$s_{ivk} - (1 - y_{ivk}) \cdot M \leq o_i \qquad \forall i \in I \setminus \{0\}, \forall v \in V, \forall k \in K \quad (8.15)$$

$$o_i + T_i^S + \frac{L_{ij}^{DIST}}{U_v} - (1 - z_{ijvk}) \cdot M \leq o_j \qquad \forall i \in I \setminus \{0\}, \forall j \in J \setminus \{0\}, \quad (8.16)$$

$$\forall v \in V, \forall k \in K$$

$$(o_i + T_i^S) \cdot D_{ij}^{DEP} \leq o_j \qquad \forall i \in I \setminus \{0\}, \forall j \in J \setminus \{0\} \quad (8.17)$$

$$o_i + T_i^S = o_{i+2} \qquad \forall i \in T \quad (8.18)$$

$$s_{ivk} - (1 - y_{jvk}) \cdot M \leq o_i \qquad \forall i \in I \setminus \{0\}, \forall v \in V, \forall k \in K \quad (8.19)$$

$$s_{ivk} + (1 - y_{jvk}) \cdot M \geq o_i \qquad \forall i \in I \setminus \{0\}, \forall v \in V, \forall k \in K \quad (8.20)$$

$$\sum_{i \in I} \sum_{j \in J} (T_i^S + \frac{L_{ij}^{DIST}}{U_v}) \cdot z_{ijvk} \leq t_{vk} \qquad \forall v \in V, \forall k \in K \quad (8.21)$$

$$s_{ivk} + (T_i^S + \frac{L_{i0}^{DIST}}{U_v}) \cdot z_{i0vk} - s_{0vk} \leq t_{vk} \qquad \forall i \in I \setminus \{0\}, v \in V, \forall k \in K \quad (8.22)$$

$$s_{ivk} + T_i^S + \frac{L_{i0}^{DIST}}{U_v} \leq e \qquad \forall i \in I \setminus \{0\} \forall v \in V, \forall k \in K \quad (8.23)$$

All the time constraints (8.14)-(8.23) make sure that the operations are executed in the most optimal sequence as possible. First, the start time of the vessels leaving the depot must happen before any other operation. This is done by constraint (8.14). Constraint (8.15) is made to keep track of the start time of every operation. Here the big M method has been adopted. The value of big M is set to be large enough to make sure that the left-hand side of the constraint always will be less than the right-hand side if operation *i* is not handled by vessel *k* of type *v*. The time calculated in the previous constraint can then be used in constraint (8.16) to ensure that operation *i* must happen before operation *j* if a vessel travel from operation *i* to *j*.

Constraint (8.17) takes care of the operations depending on another and makes sure that they will happen in the correct order. Constraint (8.18 secures that hook-up must happen right after the turbines have arrived on site. If several vessels are operating on the same operation the start time of that operation for each of the vessels should be the same. This is handled by (8.19) and (8.20). Constraint (8.21) states that the total time a vessel is chartered must be greater than the sum of the duration of all the operations it executes in addition to the sum of the sailing times between these operations. To tighten the constraint, even more, constraint (8.22) makes sure that the total time a specific vessel is chartered must be larger than the sailing time of the last operation added to the duration and start time of that operation, and subtract the start time of the first operation for this vessel.

Binary constraints

$$z_{ijvk} \in \{0, 1\} \qquad \forall i \in I, \forall j \in J, \forall v \in V, \forall k \in K \quad (8.24)$$

$$y_{ivk} \in \{0, 1\} \qquad \forall i \in I, \forall v \in V, \forall k \in K \quad (8.25)$$

Non-negativity constraints

$$s_{ivk} \geq 0 \qquad \forall i \in I, \forall v \in V, \forall k \in K \quad (8.26)$$

$$t_{vk} \geq 0 \qquad \forall v \in V, \forall k \in K \quad (8.27)$$

$$e \geq 0 \qquad (8.28)$$

The binary constraints are handled by constraint (8.24)-(8.25), while the non-negativity constraints managed by constraint (8.26)-(8.28).

8.2.7 Symmetry breaking inequality

Since all the vessels, *K*, in every set of vessel types, *V*, are identical, symmetry is added to the model and this will make the model more difficult to solve. To cope with this problem a symmetry breaking inequality constraint (8.29) has been added. This constraint makes sure that a vessel of a lower ID number is chosen first. This is done by requiring a greater or equal time chartered for a vessel of a lower ID number. This constraint is inspired by the symmetry equality constraint given in the Master Thesis of Siljan & Hansen (2017).

$$t_{vk} \geq t_{v,k+1} \qquad \forall v \in V, \forall k \in K \quad (8.29)$$

8.3 Model Input

The parameters used in this model are based on data acquired from experts from different fields and assumptions. In this section, all the parameters used for the optimization model are described.

8.3.1 Vessels

The pool of vessel types the model can choose between is assumed to be tug, AHTS, HLV, and CLV as these are either crucial to execute an operation and because these were the most common vessel types used for the installation of Hywind Scotland. The pool for this case will consist of 10 vessels of each type. The stone dumping vessel is not a part of the ballast operation in this model. Instead smaller tugs are handling the substructures during transport at the assembly site.

The variable costs for all the vessels are based on the maximum of the day rates for each of those vessel types provided by Skjong from Fearnleys (Mail 04.05.20). The fixed mobilization costs are assumed to be half of a day rate, except for the CLV which is rounded up to the nearest 5 000 euro. This is because it is very difficult to acquire fixed mobilization costs as it depends on what equipment the different vessels need to execute an operation and how long time it will take to mobilize these vessels. Fuel costs are based on the oil price (assumed to be about 30 euro with the oil price by May 2020), and the fuel consumption each vessel types have. The fuel costs are only depending on the total amount of days sailed between the different operations. Below are the parameters used for C_v^F, C_v^V and C_v^{FUEL} in the model presented in table 8.1.

Table 8.1: Cost table

Vessels	**Fixed cost 1 000 [€]**	**Variable cost 1 000 [€/day]**	**Fuel cost [€/day]**
Tug	6	12	95
AHTS	20	40	167
HLV	200	400	239
CLV	35	65	119

The sailing speed of the different vessel types is based on specification datasheets. The tug's speed is based on BB Worker from Buksér & Berging (2019). The AHTS's speed is based on the transit speed for Normand Drott (Solstad Offshore, 2020). The HLV speed is given by the transit speed of Saipem 7000 (Saipem, 2020). The CLV speed is given by the Van Oord vessel Nexus (2020). The speed parameters, U_v, used for the model of the different vessels are presented in table 8.2 below.

Table 8.2: Speed

Vessels	**Speed [knots]**
Tug	15
AHTS	12
HLV	9.5
CLV	12

The functions of the different vessels are found on the specifications sheets mentioned above or provided from the email correspondence. The functions parameters, Q_{vf}^{FUNC}, of each vessel is presented in table 8.3.

Table 8.3: Functions

Vessels	Bollard pull [tonnes]	Lifting Capacity [tonnes]	Anchor handling equipment	Cable-laying equipment
Tug	100	0	No	No
AHTS	350	300	Yes	No
HLV	0	14 000	No	No
CLV	0	0	No	Yes

8.3.2 Operations

The duration of the operations has been provided in email correspondence by Nedrevåg and Skytterholm from Equinor. For the optimization model, a contingency time of 50% of every operation has been used to account for the waiting on weather or mobilization time that can affect the total time of an operation. Weather conditions have not been added to the model as this is assumed to be a part of the contingency time. The duration parameter, T_i^S, can be found in table 8.4 below.

Table 8.4: Duration of operations

Operations	Duration [h]
Cable-laying	144
Ballast	63
Mating	36
Towing	54
Anchor & Chains	216
Hook-up	36

The functions required for each operation has been acquired from a report made by the partnership between Kværner and DOF Subsea for Hywind Tampen (Mail von der Fehr 26.05.20). The requirement parameters, R_{if}^{REQ}, are shown in table 8.3 below.

Table 8.5: Requirement matrix

Operations	Bollard pull [tonnes]	Lifting Capacity [tonnes]	Anchor handling equipment	Cable-laying equipment
Cable-laying	0	0	0	1
Ballast	0	0	0	0
Mating	0	500	0	0
Towing	300	0	0	0
Anchor & Chains	300	100	1	0
Hook-up	0	15	1	0

The sailing distance, L_{ij}^{DIST} from a finished operation to the start of another is represented by table 8.6.

Table 8.6: Sailing distance between operations

Operations	Cable-laying	Ballast	Mating	Towing	Anchor & Chains	Hook-up
Cable-laying	0	90	90	90	90	0
Ballast	90	0	0	0	0	90
Mating	90	0	0	0	0	90
Towing	0	90	90	90	90	0
Anchor & Chains	0	90	90	90	90	0
Hook-up	0	90	90	90	90	0

The precedence matrix, D_{ij}^{DEP}, shows how the different operations depend on each other. In this matrix, binary variables show how the operation in the top row is dependent on the operations in the first column. An example is that mating can only happen if ballast has happened, but ballast does not necessarily need to have happened for mating to happen. The precedence matrix is given in table 8.7.

The parameters for maximum vessels operating the mating operation, N^{HLV}, the minimum value of vessels operating the towing operation, N^{TOW}, minimum value of AHTS vessels during towing, N^{AHTS}, and the minimum value of vessels during hook-up, N^{HOOK}, are all presented in table 8.8 below.

To make sure that the installation process is done as quickly as possible a penalty cost

Table 8.7: Precedence matrix

Operations	Cable-laying	Ballast	Mating	Towing	Anchor & Chains	Hook-up
Cable-laying	0	0	0	0	0	0
Ballast	1	0	1	1	0	1
Mating	1	0	0	1	0	1
Towing	1	0	0	0	0	1
Anchor & Chains	1	0	0	0	0	1
Hook-up	1	0	0	0	0	0

Table 8.8: Parameters for amount of vessels needed for the specific operations

Parameter	**Value**
N^{HLV}	1
N^{TOW}	3
N^{AHTS}	1
N^{HOOK}	2

is added for every day the installation is not finished. This penalty cost is based on the revenue the FOWF could have gained from the production of electricity. The cost is based on the average European wholesale baseload electricity pricy for 2019 and the capacity factor of the wind farm. For this model, the same capacity factor as Hywind Scotland is assumed.

The penalty cost, C^P, is found by multiplying the average cost of the wholesale baseload electricity price with the capacity factor and the number of turbines. This can be seen in equation 8.30.

$$C^P = \text{Price}^{el} \cdot \text{Capacity factor} \cdot \text{Capacity in MW} \cdot \text{Number of turbines} \tag{8.30}$$

This gives a penalty cost of about: 54 000 [€/day].

8.4 Model output

The optimization model gives the optimal fleet size and mix for the installation process for a FOWF. It also gives the start time and end time of every vessel chartered as well as the sequence the different operations are executed.

An example of the sequence for the installation of one wind turbine given from this model is depicted in figure 8.1.

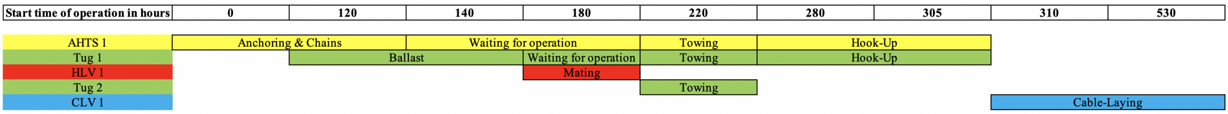

Figure 8.1: Sequence of execution

Chapter 9

Results optimization model

The results from the optimization model are presented in this section as these results are going to be validated in the simulation model in chapter 10. The results from running the MILP model can be found in table 9.1

The central processing unit (CPU) time for running the model with Gurobi was very little for small instances of the problem. The solver had no difficulties finding the optimal solution with a MIP Gap of 1 % for a wind farm with turbines up to 3 turbines, but above this, the solver had to use several hours to reach an optimal solution within a MIP Gap of 10 %. In the table, the CPU times are given for the different instances.

The reason for these high computational numbers is because this is a complex route planning problem which includes synchronizing restrictions according to Professor Kjetil Fagerholt. This is done by the constraints ensuring that several vessels have to do a task at the same time. As a result of this, the pool of 10 vessels was used for 1 to 9 turbines. For 10 turbines the model ran for several days without finding any feasible solutions. After this, the pool was increased to have 22 vessels of each vessel type. Still, there were no feasible solutions for 10 turbines found after several days of running time. However, the model found feasible solutions for 11 turbines, and after running the model for about one and a half day the process was stopped at a MIP Gap of 26 %. This gave a fleet of 7 tugs, 14 AHTSs, 2 HLVs, and 1 CLV.

It is also clear that the fleet compositions provided not necessarily increases linearly with the increase in the size of the wind farm. This can be seen from 4 turbines to 5 turbines where the number of tugs is respectively 10 and 4, while the number of AHTSs is 4 and

Table 9.1: Results from the optimization model

Number of turbines	Number of Tugs	Number of AHTSs	Number of HLVs	Number of CLVs	Total cost in million €	Total time chartered in days	MIP GAP in %	CPU time
1	2	1	1	1	2.1	23	0.94	0.9 s
2	3	3	1	1	3.5	23	1.00	37.6 s
3	7	3	1	1	4.8	23	0.97	1 h
4	10	4	1	1	6.2	23	0.98	25 h
5	4	6	1	1	7.8	28	4.88	18 h
6	7	6	1	1	9.4	29	7.37	1.5 h
7	6	7	1	1	10.6	28	4.81	15 h
8	7	8	1	1	12.7	36	9.92	9.5 h
9	7	6	2	1	14.5	40	12.52	1.5 h
11	7	14	2	1	20.8	33	26.11	35 h

6 respectively. The table also shows how the number of AHTSs increase quite steadily except for the 9 turbine wind farm. For the sequence of executions printed in PyCharm all the optimal results showed that there were two tugs and one AHTS for the towing operations. This also showed that the tug was chosen for the hook-up also, which had a constraint requiring at least two vessels for this operation.

Another result that is interesting to study is the costs of the vessels chartered for the different number of turbines as this is what the optimization model minimizes. These also increase quite steadily from 2.1 million euros for 1 turbine to 20.8 million euros for 11 turbines. The time chartered shows that the minimum time of the entire installation is 23 days. This charter period is the same for 1 to 4 turbines. Above this, the results jump to around 28 days before it exceeds 30 days.

Chapter 10

Simulation model

In this chapter, the assumptions made for the simulation model, the simulation model itself, and the parameters used will be described in detail.

10.1 Assumptions

Most of the assumptions made for the simulation model are the same as for the optimization model. However, there are some extra assumptions listed below.

- It is assumed that the installation port has the capacity to store all the turbines, even if it is very unlikely for large amounts of turbines.
- Tugs have to execute the ballast operation
- HLV has to execute the mating operation.
- The same tugs used for the ballast operation are executing the towing operation too.
- There are two tugs and one AHTS towing the whole way from the installation port to the wind farm site.
- A tug and an AHTS can only tow one turbine at a time.
- AHTS is assumed used for anchoring & chain operation.
- One AHTS and one tug are assumed used for the hook-up.
- Assume that the towing operation has a restriction for the significant wave height even though it is not weather restricted. This is because both Nedrevåg and Skytter-

holm said that they would never start a towing operation on a bad weather forecast.

- The fuel costs are not calculated in this model.
- The penalty cost is not a part of this model either, as this was implemented in the optimization model to motivate for a solution with a short installation time.
- Stochastic weather is a part of this model.
- All vessels costs except for the CLV starts running from the start.

10.2 Model input

10.2.1 Global variables and parameters

Global variables are the variables that are known to the whole program. For the simulation model presented in this chapter, the global variables are imported from the Matlab code *SimulationFSM.m*.

To create a simulation model of the installation process as realistic as possible it is important to have a set of input parameters that represents the real operation in a satisfying way. The input parameters that are important for this model are the weather data, amount of each vessel type, the towing distance, time of each operation if there is no delay due to waiting for an open weather window and the weather restrictions for significant wave height and wind speed for the respective operations. The parameters used are based on the results from the optimization model and mail correspondence with Nedrevåg, Skytterholm, and von der Fehr and are shown in table 10.1 below. Due to the large MIP Gap for the results for 11 turbines and that a pool with 10 vessels of each vessel type was set as a restriction for this case, it is assumed that the fleet used in the simulation model consists of 7 tugs, 10 AHTSs, 2 HLVs, and 1 CLV. The anchoring & chain operation consists of two sub-operations of 72 hours each, anchoring, and chain installation.

10.2.2 Weather states

The significant wave heights are as mentioned in chapter 7.2.1 and 7.2.2 downloaded, implemented into a Markov chain simulation, and stored in a vector. For the simulation of the 11 turbines at Hywind Tampen a random seed has been implemented in *SimulationFSM.m* to make the results more robust. The random seed makes the weather condition for every iteration unique. This introduces a stochastic element to the model which makes it more realistic. The vector gives the value of the state the significant wave height is

Table 10.1: Parameters used in the simulation model

Parameter	Amount	Maximum significant wave height	Maximum wind speed
Towing distance	90 nm		
Tug	7		
AHTS	10		
HLV	2		
CLV	1		
Ballast	42 h		
Mating	24 h	0.5 m	15 m/s
Towing	36 h	3.5 m	
Anchoring & Chains	144 h	3 m	
Hook-up	24 h	3 m	
Cable-laying	96 h	2.5 m	

in. Due to the restriction of 0.5 m significant wave height during the mating operation at Gulen the values were rounded to the nearest half. Then the states were set to be every half meter in *MarkovChainGulen.m*, so state 1 represented 0-0.5 m. For Gulen the number of states then had to be the highest rounded value times two. In *SeaDataMatrixGulen.m* the values in the list of states were halved to make the list represent the actual significant wave height. The values of the significant wave height at Tampen were rounded to the nearest integer and the number of states was set to be the highest value in the weather data. The state number and their corresponding actual values are given in table 10.2.

Table 10.2: The states and their corresponding actual values

States	Actual significant wave height Gulen [m]	States	Actual significant wave height Tampen [m]
1	0-1	0.5	0-0.5
2	1-2	1	0.5-1
3	2-3	1.5	1-1.5
4	3-4	2	1.5-2
5	4-5	2.5	2-2.5
6	5-6	3	2.5-3
7	6-7	3.5	3-3.5
8	7-8		
9	8-9		

10.3 Model structure

The simulation model was created in Matlab SimEvents and consists of six loops. Each representing an operation of the installation process; ballasting, mating, towing, anchoring & chains, hook-up, and cable-laying. The model is focused on the four vesseltypes; tug, AHTS, HLV, and CLV due to the high importance of these vessels for these operations. The model is shown in figure 10.1 and a full-scale figure of the model is presented in appendix B. A time step in the simulation corresponds to one hour in real-time. This is due to the fact that the wave and wind data are given hourly.

Ballasting operation

In the first loop tug, boats are created. An entity generator creates tugs before sending it through an entity input switch and into a first in first out (FIFO) queue. At the time the tug leaves the entity generator a fixed cost is added to a global variable named *FixedCostTugs* and a variable cost for tugs starts to run and is added to a global variable named *CostTugs* for every time step the tug is operating. This will happen for every tug generated. After the queue, the tug goes into a server that simulates the upending and ballasting operation of the substructure. When the tug leaves the server the simulation writes to a global

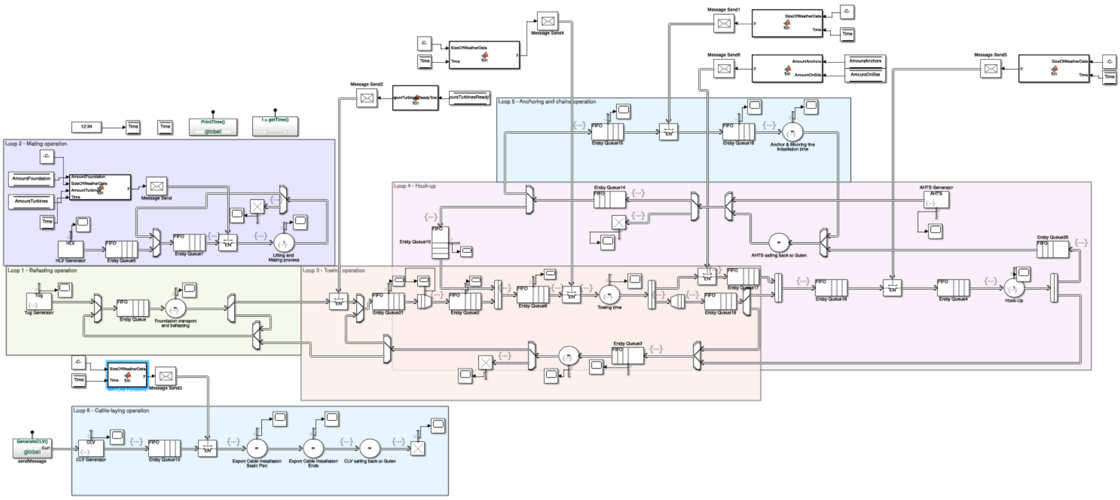

Figure 10.1: Simulation model created in SimEvents.

variable named *AmountFoundations* to add one substructure ready for mating. After the server, the tug will go into an entity output switch. This switch is triggered by an entity attribute. The entity output switch will send the tug into the towing operation in loop number three if there is a turbine ready for towing or if all the substructures have been ballasted. The attribute will make the tug go through the second port which sends it back into the queue and into the server again. This process will continue until the system has created the number of substructures needed. The first loop is depicted in figure 10.2 below.

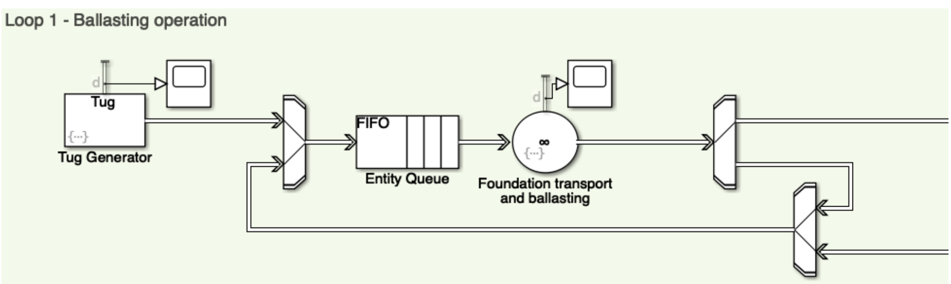

Figure 10.2: Loop 1 - Ballasting operation.

Mating operation

Loop number two creates HLVs in the entity generator. As in loop number one the HLVs fixed and variable costs are added to *FixedCostHLV* and *CostHLV* respectively. From here, the HLV is sent through an entity input switch followed by a FIFO queue and an entity gate. The entity gate will only let an HLV pass if specific criteria are met. These criteria are; a weather window for the mating operation meeting the weather restrictions and a substructure ready for mating. For the mating operation, the weather window must be of a size of at least 27 hours, as the operation itself takes about 24 hours, but can be delayed due to wind speeds during the lifting of the top-structure. After the HLV is let through the gate it enters a server simulating the mating operation. For the HLV the variable costs are running from the start of this operation. The time consumed in this server is depending on what the weather conditions are in the time step the HLV enters the server. For each meter per second of an increase in the wind speed, a factor is multiplied to the operation, increasing the time spent in this operation. Next, the HLV enters an entity output switch triggered by an entity attribute. This attribute will send the HLV back in the loop through port number one until the system has created all the turbines needed. Then the attribute will send the HLV through port number two sending the HLV into an entity terminator. When the HLV is terminated the running variable costs for HLV will stop. The second loop is depicted in figure 10.3

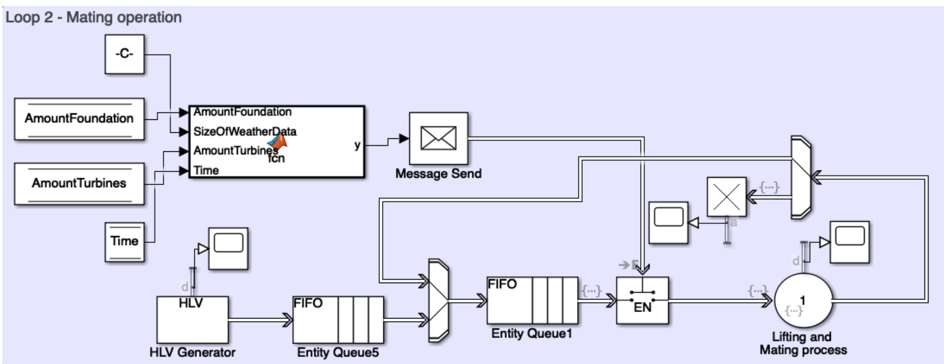

Figure 10.3: Loop 2 - Mating operation.

Towing operation

The third loop starts with the tugs entering from the first loop. In this loop, the tug goes through an entity gate checking if there are any turbines from the mating operation that are ready for towing. Then the tug enters an entity input switch followed by a FIFO queue. After the queue, the tug will enter an entity batch creator which creates batches of two tugs. Then this batch enters a FIFO queue followed by an entity composite creator where it is merged with another entity, an AHTS vessel, from the fourth loop. Next, the tug and

AHTS will pass another FIFO queue before they enter an entity gate. The criteria of this gate are; a weather window for the towing operation meeting the weather restrictions set in this Master Thesis. The weather window for the towing operation must for at least 36 hours as the sailing time is about 30 hours, but the towing might be affected by the waves. The model calculates the time waiting for a weather window to open. When these criteria are met the towing operation is simulated in a server taking the significant wave height at the start of the towing into account the same way as for the HLV during the mating operation. After this, an entity composite splitter splits the tug from the AHTS and sends the AHTS into an entity gate which checks if there are enough anchors installed for hook-up of a turbine. After this, the AHTS enters loop four. The tug is sent into an entity batch splitter before sending it into a FIFO queue. From the queue, the tug goes through an entity output switch triggered by an entity attribute. This attribute sends the tug to loop 4 for the hook-up operation if there are enough anchors installed at the site for the hook-up operation to happen and where it will merge with the AHTS. If this is not the case, the tug into an entity input switch before entering a FIFO queue. After this, the tug enters into a server simulating the sailing time (service speed 15 knots and a factor multiplied from wave state) back to the installation port. After the server is an entity output switch. This attribute will initially send the tug through the first port and back into loop 1. When all the turbines hooked up at the site of the wind farm the entity attribute will make the tug go through port number two and into an entity terminator, stopping the running variable costs. The third loop is depicted in figure 10.4 below.

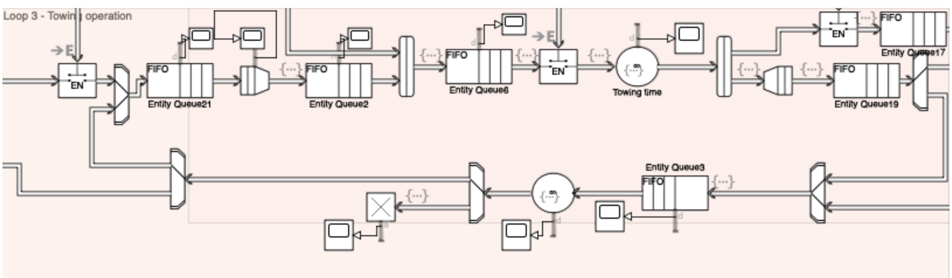

Figure 10.4: Loop 3 - Towing operation.

Hook-up

In the fourth loop, an entity generator creates the AHTS vessels. From here, the AHTS is sent into an entity input switch followed by an entity output switch. After this, it enters a FIFO queue before it is sent into an entity output switch which sends it into the third loop for towing if there are tugs ready for towing and the installation of enough anchors for a turbine is started. If this is not the case, the AHTS is sent into loop number 5 for the anchoring & chains operation. After loop 3 is finished, the AHTS enters the entity composite creator and merges with the tug as mentioned in 10.3. When the AHTS and the tug have merged they are sent into an entity queue before they enter an entity gate. Once the AHTS and the tug have passed the entity gate they enter another FIFO queue before they enter a server simulating the hook-up operation. This server is set to only handle one turbine at a time and when the AHTS and the tug exit the server the model will add an installed turbine to a global variable, *AmountInstalled*. After this, an entity composite splitter sends the tug back into loop three and the AHTS into a FIFO queue followed by an entity input switch. Then the AHTS then enters an entity server simulating the sailing time back to port (service speed 11 knots and a factor multiplied from wave state) and enters an entity input switch before the route is decided by an entity output switch triggered by an entity attribute. This attribute will initially send the AHTS through port number one, back into loop 4. When all the turbines are installed on-site, the entity attribute will send the AHTS through port number two and terminate the AHTS, stopping the running variable costs. The fourth loop is depicted in figure 10.5 below.

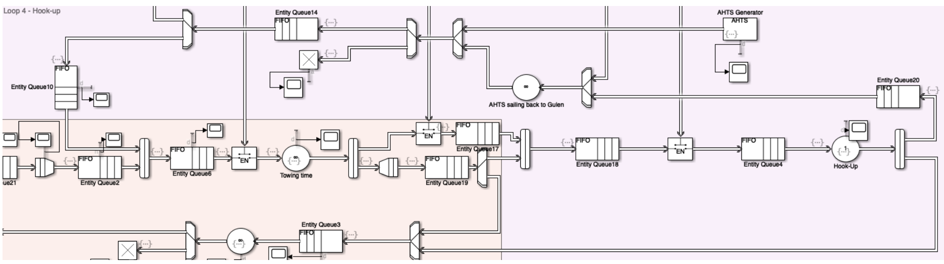

Figure 10.5: Loop 4 - Hook-Up.

Anchoring & Chains

In loop 5 the AHTS enters a FIFO queue before it enters an entity gate. This gate only opens if the weather window for the next 144 hours is below the significant wave height set for this operation. When the AHTS can pass the entity gate it enters a FIFO queue before a server simulates the anchoring & chains operation. Every time an AHTS finish this operation, three anchors are added to a global variable named *AmountAnchors*. After the server, the AHTS enters back into the forth loop through an entity input switch and sails back to port. The fifth loop is depicted in figure 10.6.

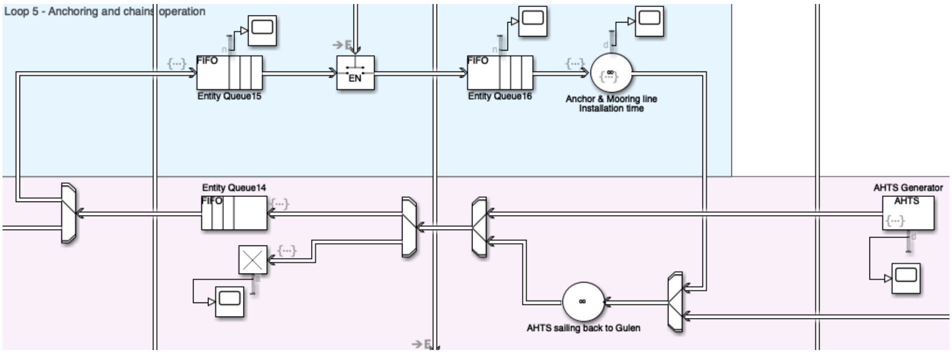

Figure 10.6: Loop 5 - Anchoring & Chains.

Cable-laying

In the final loop, an entity generator creates the CLV when it gets a signal from the system that all the turbines have been hooked up. When the CLV leaves the entity generator the fixed and variable costs are added to the global variables *FixedCostCLV* and *CostCLV* respectively. After this, the CLV enters a FIFO queue followed by an entity gate. This entity gate opens if the significant wave height is at an allowable level during the next 96 hours. When the CLV passes the entity gate it enters two entity servers in a row simulating the cable installation of the static parts and the dynamic parts respectively. After this, the CLV enters another entity server simulating the sailing back to port. Once it enters this server the model adds a cable installed to a global variable named *AmountCables*. After this, the CLV is terminated and the whole simulation stops because all the operations for the installation process are completed. The sixth loop can be seen in figure 10.7 below.

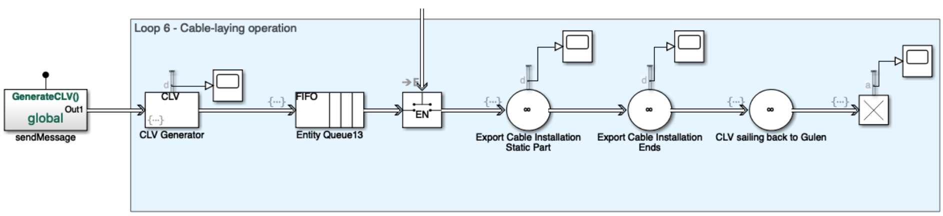

Figure 10.7: Loop 6 - Cable-Laying.

10.4 Model output

The simulation model is supposed to validate the results from the optimization model. This is done by entering the optimal fleet given by the simulation model. When the simulation model finishes the output is times and costs for the total installation time as well as the costs of the different vessels chartered. The output can be used to see how the fleet will perform for different weather situations and what operations that affect the time of the installation the most.

Chapter 11

Simulation results

The results from the simulation model are presented in this section. They are based on 100 iterations of the simulation in order to analyze how this system behaves for different weather conditions during the installation process. The simulations were run for 11 turbines and with a vessel fleet based on the optimal fleet size and mix for this wind farm size. The plots showing time on the x-axis are stopped at 800 hours or about 33 days because 85 % of the iterations had installed all turbines by then.

11.1 Weather simulation

The weather data simulated was new for every simulation ran due to the random seed implemented. This is done because the SimEvents start every process at time step 0 and that would make the list of the weather data the same for every iteration. A plot of the last iteration's simulated significant wave heights and wind speeds at Gulen Industrihamn and significant wave heights at Tampen are shown in the figures 11.1, 11.2 and 11.3 respectively.

Total installation time per turbine

The average total installation time was calculated to be about 26 days, which gives about 2.4 days per turbine. The simulated installation time per turbine is presented for each number of iteration in figure 11.4

When presenting the installation times in the order they have been simulated the spread in

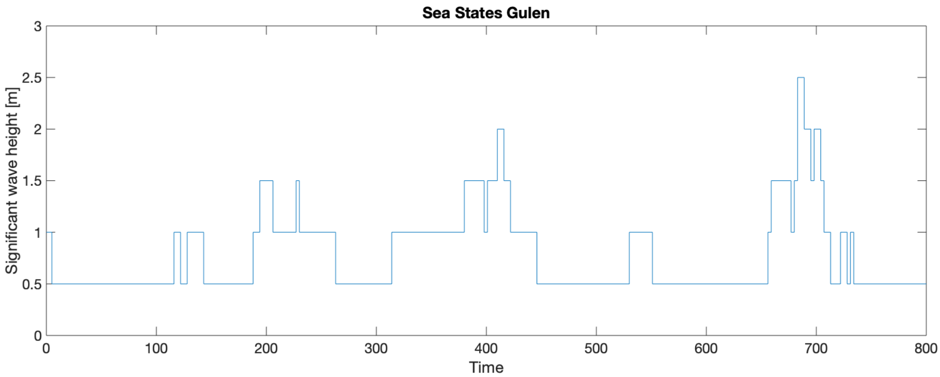

Figure 11.1: Significant wave heights at Gulen Industrihamn

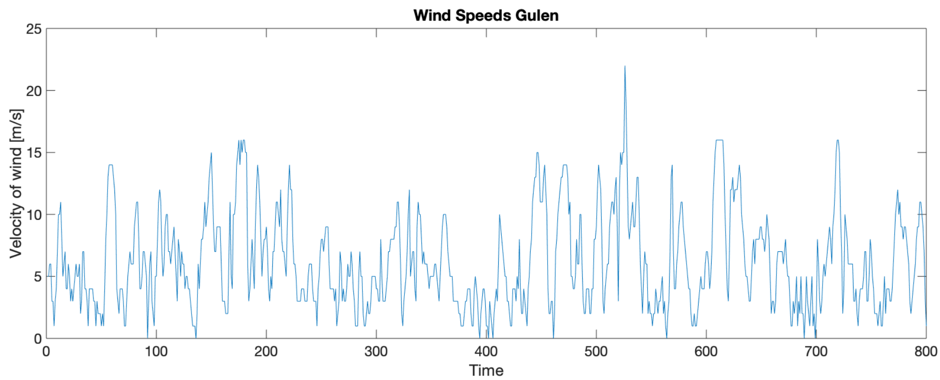

Figure 11.2: Wind speeds at Gulen Industrihamn

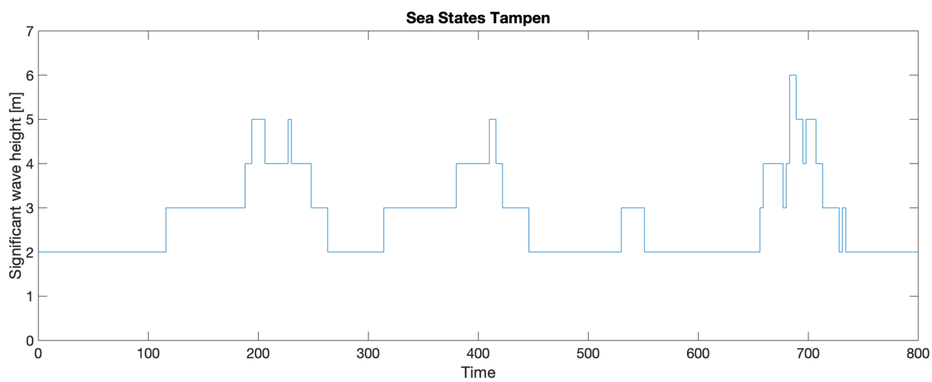

Figure 11.3: Significant wave heights at Tampen

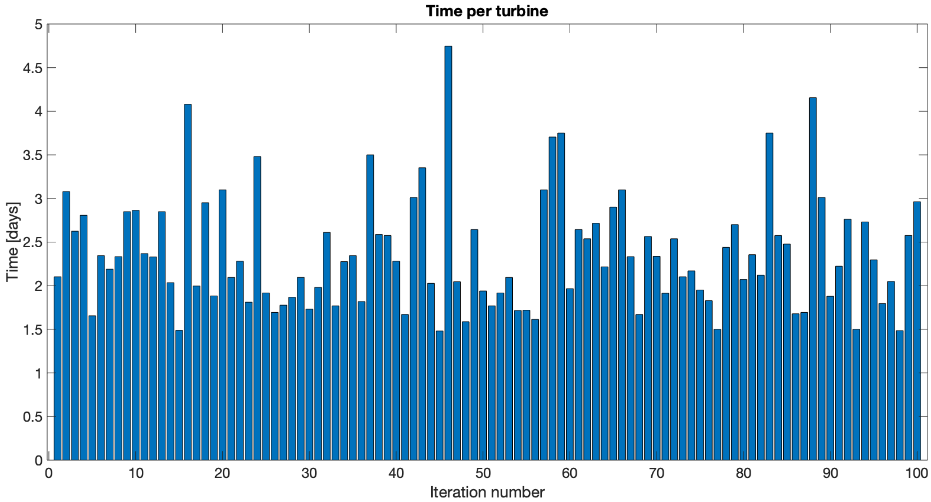

Figure 11.4: Time per turbine for each iteration

installation time per turbines is quite visible. However, to get more out of these numbers the installation times were sorted in a list in Matlab and are presented in ascending order in figure 11.5 below.

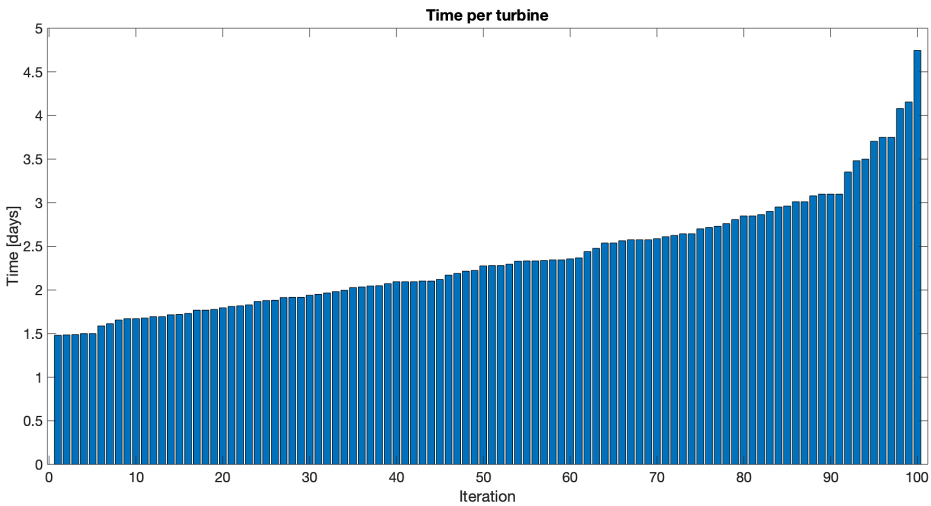

Figure 11.5: Time per turbine for each iteration distributed in an ascending order

In this figure, it is easier to see the distribution of the installation time. For the total installation time per turbine, it is now possible to see that about 40 % (from iteration 0-40) are 2 days or less. One could also see that one iteration (iteration 100) have almost twice the installation time per turbine as the majority of the simulations. This figure also shows that 85 % of the iterations had installed all turbines within 33 days.

Waiting for a weather window

To analyze how the weather affects the installation process the average waiting time per turbine is calculated. This is done for the waiting for a weather window before mating, towing, anchoring & chains, hook-up, and cable-laying. These are shown in figure 11.6.

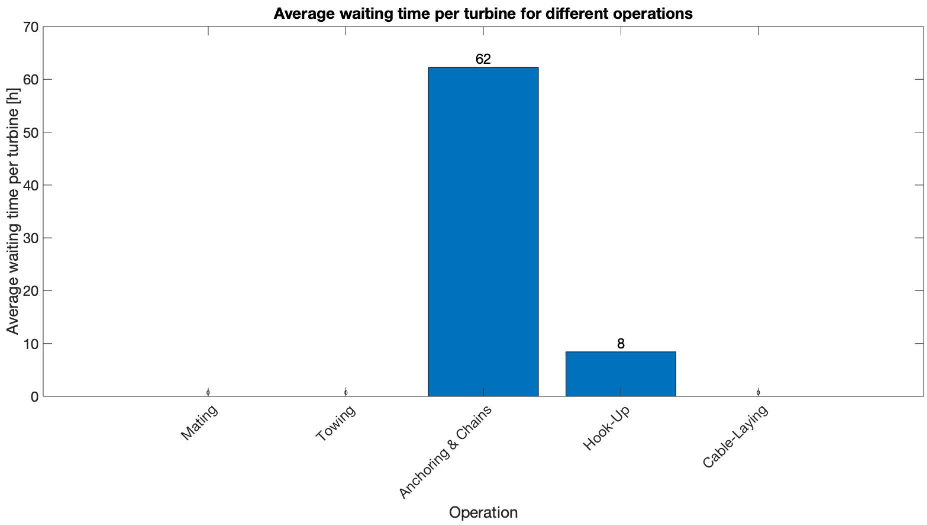

Figure 11.6: Average waiting time per turbine

Waiting for a weather window before anchoring and chains are on average 62 hours per turbine and 8 hours for the hook-up operation. The waiting on the weather before the lifting during the mating operation, towing and cable laying shows that there is no waiting for weather for any of the 100 iterations done.

The distribution of the waiting on weather per turbine before the anchoring & chains operation is given in figure 11.7. This bar chart is the sorted distribution for all the iterations. The distribution for the waiting on weather per turbine for the hook-up operation is presented in figure 11.8.

Figure 11.7 shows that about 30 % (iteration 0 to 30) of the iterations did not encounter any waiting on the weather. Also, about 60% (from iteration 0 to 60) of the iterations have

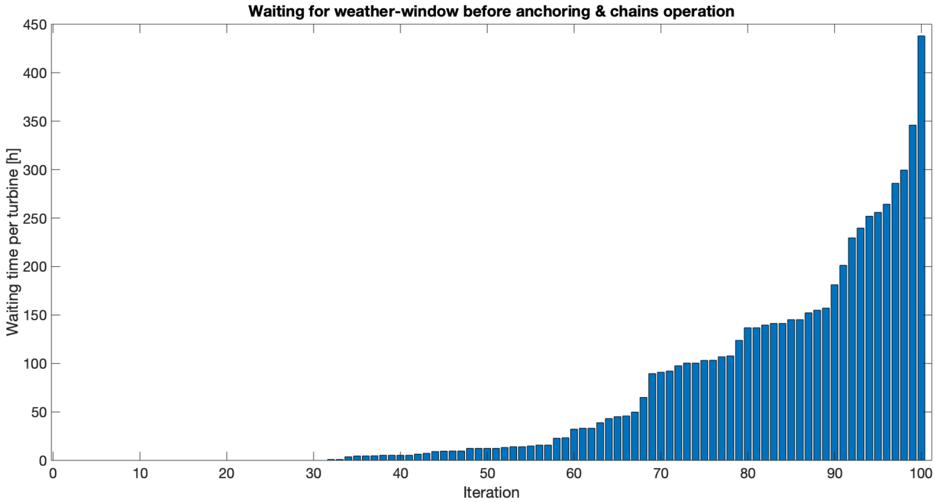

Figure 11.7: Waiting time per turbine for the anchoring & chains operation

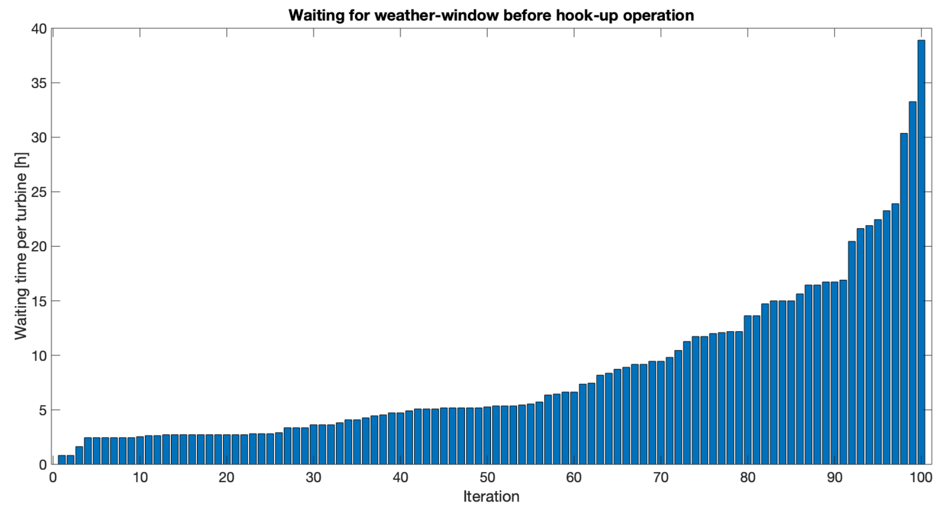

Figure 11.8: Waiting time per turbine for hook-up operation

a waiting time per turbine before the anchoring & chains operation below 50 hours. It also shows two intervals of about 10 % (from iteration 70 to 80) of the iteration with about 100 hours of waiting time and 10 % (from 80 to 90) with 150 hours of waiting. There is also one iteration (at iteration 100) that experienced a very long waiting for weather before the anchoring & chains operation.

In figure 11.8 40 % of the iterations are below 5 hours of waiting for weather before the hook-up. This operation experience waiting for weather for almost all the iterations, but comparing this bar chart to the previous one in figure 11.8 the waiting times per turbines are much shorter. The largest (iteration 100) waiting on the weather for the hook-up operation is about 39 hours of waiting.

In figure 11.9 a representation of when the turbines are hooked up on site. This figure shows how the installation is not happening linearly at the same time between each turbine. At 300 hours three turbines are installed quite fast, while from about 600 hours to about 720 hours no turbines were installed.

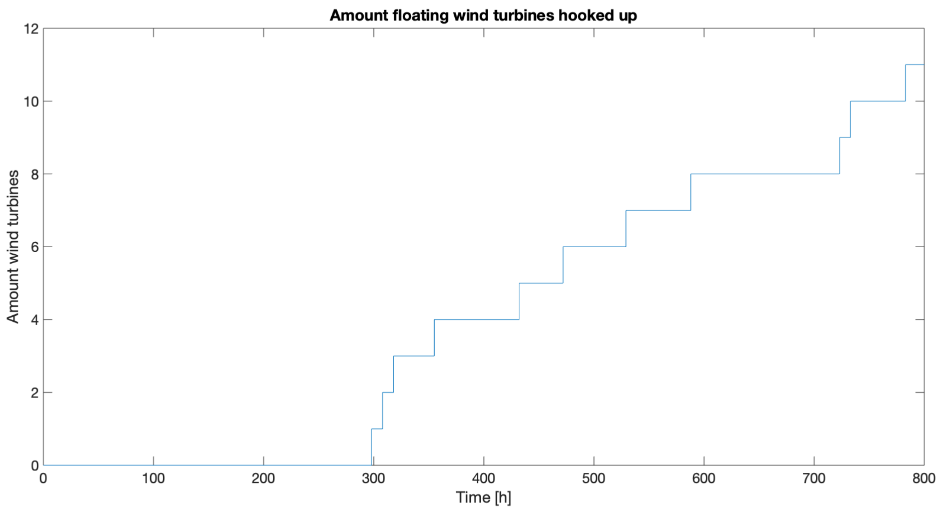

Figure 11.9: Plot showing when the turbines are hooked up on site

Cost

The average total cost for all the marine operations on the Hywind Tampen project ended up being about 29.6 million euros from this model. The cost is highly correlated to time, so the plots for cost look very similar to the plots for time. However, it is interesting to see the costs of the vessels utilized presented in figure 11.10. This may give an indication of what vessels and what operations changes should be sought for.

This plot was made by calculating the average of the total cost, for each vessel, at every time step for every iteration of the simulation model. This plot's x-axis goes up to 800

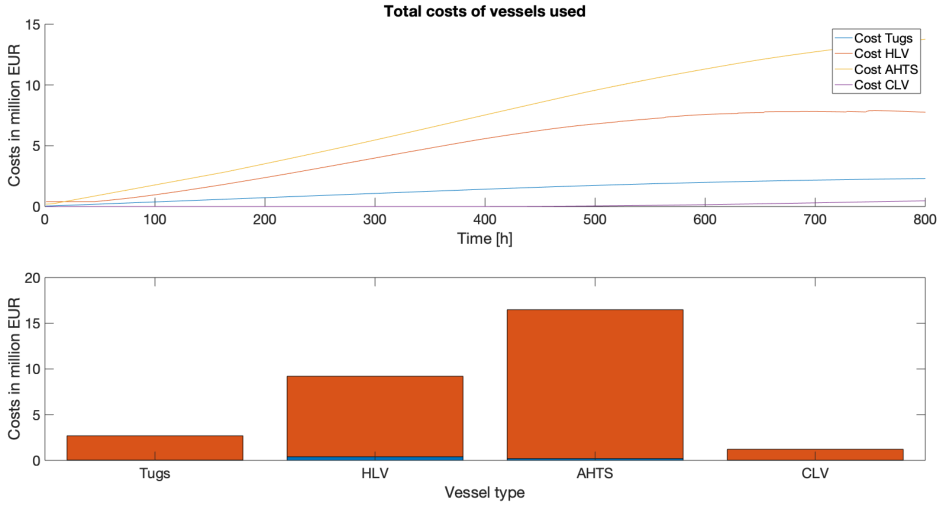

Figure 11.10: Upper subplot: The average total costs for the different vessels accumulated over time. Lower subplot: The average fixed costs are represented by the blue color, while the average variable costs are red.

hours or about 33 days as it is around this time 85 % of the iterations have installed all turbines. In this figure AHTS chartering is the most dominating cost followed by HLV. In the lower subplot, the fixed costs are barely visible for the HLV and the AHTS and the variable costs are definitely dominating the total costs.

Chapter 12

Discussion

The Master Thesis shall try to cover the scope and aim of the problem description presented in . In the first chapters of the thesis an overview of the current status and important development trends related to the installation of FOW are described. Examples of how the installation process could be done are described in 3.4. A case study based on a pool of 10 vessels was performed and the results have been presented in chapter 9 and the previous chapter. These results give insight into how the installation process for FOWFs can be optimized. The optimization model provides the optimal fleet size and mix to minimize the cost of the installation process. The simulation model can then validate how this fleet will behave when it is exposed to weather conditions and restrictions related to these.

12.1 Assumptions

The transport of components from manufacturers to the installation port is not considered in this model. However, to keep the model limited to the area around the installation port and the wind farm site it is neglected. Also, the stone dumping vessel used for the ballast operation is not a part of the models, but the tugs are assumed to be doing this operation as they have to be chartered to transport the substructures between the operations in the installation port.

The pre-determined sequence does not necessarily have to be executed in the order given in this thesis. Of course, some operations have to happen before others, like the ballasting and upending of the substructures have to be done before the top-structure can be mated to the substructure. Still, an operation like the cable-laying could have been done before any of the other operations, but this would have been more expensive as one would need to coil the cables up again to install floating elements, hold-back anchors, and pull-in equipment. This would also increase the risk of damage to the cables.

In the optimization model, an AHTS can do one operation and then return to the depot, without all turbines being hooked-up. While in the simulation model all turbines must be hooked up before it can return to the depot. This will make the AHTS sail for a longer time in the simulation model than in the optimization model, and this can again affect the total costs of the simulation model to be higher than the optimization model.

For this model, the mating operation is assumed to be done by HLVs instead of an onshore crane which is what they are going to use for Hywind Tampen. This was because an HLV was used for Hywind Tampen and it was interesting to see how the HLVs costs affect the total costs.

Another assumption that was made was the fixed costs of the vessel types. This could affect the model if they are very high. In the models, they were assumed to be about half of the day rate for each vessel type. This cost would affect the optimization model in the way of how many vessels to use. If the fixed costs are very high one could assume that the optimization model would choose fewer vessels from the pool and accept a longer installation time. If they are very low one could assume that the model would choose many vessels and shorter installation time.

12.2 Optimization results

The reason for the high CPU time for the larger amount of turbines installed can be explained by the increase in the complexity of the problem. The time to solve the problem will increase exponentially with the problem size and thus it will be difficult to use this model for larger problems. It is very difficult to know how branch-and-bound algorithm for the commercial solver Gurobi chooses to attack the problem and how many nodes it has left before it finds the optimal solution.

It is also interesting to discuss why a pool of 22 vessels finds a solution before a pool of 10 vessels for a wind farm with a size of 11 turbines. A theory might be that the solver has difficulties assigning the vessels to tasks when one vessel has to perform several tasks compared to assigning one task to every vessel before they sail back to the depot node. Since the towing operation demands two vessels every easy feasible solution to find would be to assign two and two vessels to one towing operation. It is important to remember that this is just speculation and that it is difficult to completely understand what goes on in the branch-and-bound tree.

By looking at the optimal fleet compositions it is interesting to see that the number of vessels does not increase linearly. For 3 turbines the model chose 7 tugs, for 4 turbines it chose 10 tugs and for 5 turbines it chose 4 tugs. Looking at the AHTSs for the different amounts of turbines these increase quite steadily except for going down to 6 vessels from 8 when going from 8 to 9 turbines. The reason for this might be because the model tries to find the least cost solution and an increase in tugs might not affect the model as much as the penalty of finishing the installation later. Also, many operations depend on the ballasting operation being done before they can be executed. Another thing to look at is the MIP Gap. If the solver had found a feasible solution with a MIP Gap closer to 1 % the result could have been different.

The cost is pretty much correlated to the total installation time and amount of vessels chartered. This can be seen in the results table as the costs increase pretty linear while the time of the installation process is the same for 1 to 4 turbines. This is because the fleet increase while installation time is the same. Still, the jump from 23 days to 28 days when going from installing 4 turbines to 5 turbines is interesting. This might be because at some point the cost of using many vessels to keep the installation time down exceeds the cost of using fewer vessels and use longer time installing.

Since the installation of 1 to 9 turbines were done with a pool of 10 vessels and the installation of 11 turbines with a pool of 22 vessels, the optimal fleet used in the simulation model was assumed. The assumption made was that the model seemed to have found an optimal amount of tugs, HLVs, and CLV compared to the results for fewer turbines. To make the result be feasible for the pool of 10 vessels the number of AHTSs was assumed to be 10 as this was the only value that was over the limit.

12.3 Simulation results

Running the simulation model with the assumed optimal fleet for 11 turbines gave pretty satisfying results. In the results from the optimization model, the total installation time was 33 days while in the simulation model the total time was 26 days. Since we assumed fewer vessels in the fleet composition than the optimization model gave for this result one could assume that the total time should be increased for the optimization problem. Still, since the MIP Gap between the lower and upper bound was 26 %, 26 days does not seem that far off considering that the optimal result could be about 26 % less time chartered.

Then the total time would be around 26 days. Also, one would have to consider the contingency time of 50%. It might seem that the contingency time assumed was a bit high since the time added is equal to 1/3 of the total installation time. Subtracting this from the final result in the optimization model gives 23 days. However, this might just be a coincidence and the contingency time is also there to account for unexpected events and not just the waiting on weather. The simulation model also showed that there was no waiting for weather for any of the other operations than those just mentioned, which can be seen in figure 11.6. In the simulation model, the contingency time of 50 % was added to all the operations.

The results presented in the previous chapter also gives insight into where in the installation process there is potential for more efficient solutions. Especially the operations highly affected by the waiting for weather. Even though it was expected that the weather would have an impact on the time of the installation process the results could give indications to what operations and vessels that are affected the most. Still, the results should be regarded as indicative only as further development of the model is needed.

From figure 11.5 one could see that about 90 % of the iterations have time per turbine between 1.5 and 3 days. From these results, one could use the simulation model as a tool to check if the optimal fleet size and mix could be done within a specified time period. For example, if the installation process for 11 turbines would have to be done within a month, this would mean that we would need a time per turbine less than 3 days. This plot could then provide the project engineers with an answer saying that this could happen with a probability of about 90 %. However, it is important to consider the uncertainties in the model and one should also assess contingency time related to more than only weather conditions.

For the last iteration simulated the plot of the number of turbines hooked up at the site is given in 11.9. In this figure, one could see how the installation of turbines is affected by the waiting for weather. This could be explained by the waiting on weather the anchoring & chains operation experience, seen in figure 11.6. The hook-up operation cannot happen before there are enough anchors installed to hook the turbine up on site. The average waiting time per turbine for the anchoring & chain operation can be explained by the long duration of 144 hours for this operation. By the length of this operation, the operation should have been planned as weather unrestricted, but project planners would still not execute an operation in bed weather. It is also possible to say that this operation consists of two sub-operations, anchoring and chain installation. These two operations are 72 hours each and should then be assumed as weather restricted operation. One could also assume that once the suction anchors are installed the vessels are in a new safe condition as they could sail back to the port should the weather worsen. There are two longer waiting periods during the hook-up installation of the turbines that can be seen in figure 11.9 showing the number of turbines hooked up. These are at about 360 to 420 hours and 600 to 700 hours. Looking at the significant wave heights simulated for Hywind Tampen in figure 11.3 one could see that the wave heights at about 400 hours are higher than the maximum of 3 meters and this happens again at 700 hours. This means that the interval from 600 to 700 hours should not be caused by waiting for the weather. Then the waiting could be because all the AHTSs are busy executing other operations.

Figure 11.6 shows that waiting on the weather before the lifting during the mating operation, towing and cable laying shows that these operations will most likely not have to wait on the weather.

The plots of the vessel costs in figure 11.10 show clearly that the costs of the AHTS are dominating followed by the HLV. These results are highly correlated to the variable costs as one could see from the red-colored bars in the lower subplot. Also, 10 AHTS vessels are operating during the whole installation process. Comparing the AHTS vessels to the HLV vessels one could see that two HLV vessels have cost more than half of the 10 AHTS vessel costs. In the upper subplot, one could see ho the costs accumulate over time. The reason for the declining increase and flattening of the curve is because of the vessel terminations. The curves are also based on the average of all the iterations, so the reason for the smooth curves are because of this. If there were only one single iteration the flattening of the curve would happen more rapidly. From these plots, one could recommend project planners to first seek for solutions to reduce the time of the anchoring & chain operation as this operation has the longest duration and the largest waiting on weather. A lot of time goes by to prepare and transport the suction anchors to the mating site. Making this process more industrialized and standardized like an assembly line will result in less time for the AHTS in idle.

For the HLV the one should also seek a more standardized and industrialized process to make the mating as fast as possible without any idle time. However, the first step has already been taken by renting an onshore crane for the lifts of the turbines for Hywind Tampen. This solution will be cheaper and Another solution might be to eliminate the marine operation of using an HLV altogether. The heavy-lift could be done by a fixed crane in port like in the installation video Kværner made for Hywind Tampen, mentioned earlier in the report. The industry seems to be leaning towards executing most of the installation process onshore or at the installation port, before towing the structures out with standard tugs.

Exploring how the operations could be done more efficient is important. A suggestion could be to tow more than one turbine at a time. Then, the time waiting for weather could be reduced by two or more turbines towed within the same weather window. By doing this one might prevent the risk of a delay waiting for a weather window for every turbine. Nevertheless, more vessels imply higher costs per time unit. Then it is important to figure out the optimal solution between increasing costs per time unit and reducing time. It is also important to find the cost of waiting on weather. If the wind farm is delayed it could have generated revenues instead of costs during this time.

Chapter 13

Conclusion

The objective of this report was to optimize the fleet size and mix for the installation process of floating offshore wind in order to minimize the total installation cost. Thoroughly investigations were made of the FOW installation process both through academic articles, reports, and correspondence with the project and principal engineers from leading companies within the FOW industry. This Master Thesis provides an overview of the current status and important development trends related to FOW. It also presents examples of how the installation process for FOW can be done. The case study performed for Hywind Tampen was done with a pool of 10 vessels and a self-developed optimization model provides the optimal fleet size and mix to minimize the cost of the installation process. The simulation model can then validate how this fleet will behave when it is exposed to weather conditions and restrictions related to these.

The optimization model shows that there is a fine balance between the number of vessels chartered and the total time of the installation. The process of developing and solving the MILP model has also shown how hard it is to solve TDMVRP for large problems. However, implementing the optimal fleet size and mix into the simulation model gave insight to how the fleet behaved for the different operations. The research done simulating the installation process shows that weather conditions have large impacts on the anchoring & chain operation. Reducing the waiting time for this operation will affect the efficiency of the installation process great. Mating the top- and substructure using an HLV seems not cost-efficient. Using one or more onshore cranes for this operation seems to be a better solution. By increasing the number of turbines installed the fleet composition with tugs was non-linear. This might be due to the low cost of chartering tugs, which results in smaller changes for the total cost of the installation process.

This shows that the optimization model together with the simulation model could be a great tool for project planners deciding the fleet composition for a specific wind farm to get information on how this fleet will perform for different weather conditions.

13.1 Further Work

With regard to further work, the optimization model can be simplified to make it more applicable to larger problems. The simulation model can be extended and take more operations into account as well as more environmental loads like current and tide. A lot of parameters in the model can be made into variables. This will make the problem more complex but give a more accurate solution.

Extensions of the simulation model could be adding the transport of turbines and commissioning. It could also include more vessel types, cost of turbines, and the cost of delay on the delivery date. This would make the cost of the installation process more realistic. For the weather simulation, wind can be made stochastic and a random seed should be implemented to make each simulation run the model for different weather conditions. If the model is run enough times with this implementation, trends should be visible in the results.

The limitation regarding the waiting for weather before the towing of the first turbine should be fixed. It is also possible to make changes to the model to see how it will run for other installation strategies. An example could be to start the towing operation as soon as there are available assembled turbines.

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Appendix

Appendix A

Python file in PuLP

```python
from pulp import *
import gurobipy
import numpy as np

###SETS###
OPERATION = np.arange(0, 7, 1) #['depot','Cable-Laying','Ballasting','Mating','Towing','Anchoring & Chains','Hook-Up']
VESSELTYPES = np.arange(0, 4, 1) #['TUG','AHTS','HLV','CLV']
VESSELNUMBER = np.arange(0, 22, 1) #indexed by k
TURBINENUMBER = np.arange(0, 11, 1)

FUNCTIONS = np.arange(0, 4, 1) #['BollardPull', 'LiftingCapacity', 'AnchorHandling', 'CableLaying'] #indexed by f

OPERATIONS = np.arange(0, len(OPERATION)+(len(OPERATION)-2)*(len(TURBINENUMBER)-1), 1)


#Oil price $25 to euros
oil_price = 30

#Penalty cost in euros/hour (Q4-Q1 2019 Europe Wholesale Baseload Electricity Prices)
penaltycost = (((43.9 + 47 + 43.3 + 48.9)/4)*0.56*8*len(TURBINENUMBER))/1000

#BIG-M
Big_M = 5001

###DICTIONARIES###

#Dictionary of duration for each operation in hours
#dur = np.array([0, 96, 42, 24, 36, 144, 24]) #Without contingency time
dur = np.array([0, 144, 63, 36, 54, 216, 36]) #With contingency time 50%

#Scaling the array to apply for all turbines
duration = np.concatenate((dur, np.tile(dur[2:7], len(TURBINENUMBER) - 1)))
#print(duration)

#3 suction anchors per turbine and 1 day per suction anchor
#3 chains per turbine and 1 day per chains
#1 day on each end and 2 days for the static part

#Dictionary of fixed costs for each vesseltype in 1000 euro
fixed_cost = {0 : 6,
              1 : 20,
              2 : 200,
              3 : 35}

#Dictionary of variable costs for each vesseltype in 1000 euro
variable_cost = {0 : 12/24,
                 1 : 40/24,
                 2 : 400/24,
                 3 : 65/24}

#Fuelcost for each vesseltype in 1000 euro per hour. (from standard cubic meter/barrel of oil = 0.1590)
fuel_cost = {0 : (20/24*0.1590*oil_price)/1000,
             1 : (35/24*0.1590*oil_price)/1000,
             2 : (50/24*0.1590*oil_price)/1000,
             3 : (25/24*0.1590*oil_price)/1000}

#Dictionary of speed for each vesseltype in knots
speed = {0 : 15,
         1 : 12,
         2 : 9.5,
         3 : 12}


#####PARAMETERS#####


#MATRICES
```

```python
#Distance Matrix in nautical miles TUG = 15kn, AHTS = 12kn and HLV = 9.5kn
Matrix_Dist = np.array([[0, 90, 0, 0, 0, 0, 90], #Depot
                        [90, 0, 90, 90, 90, 90, 0], #Cable-Laying
                        [0, 90, 0, 0, 0, 0, 90], #Ballast
                        [0, 90, 0, 0, 0, 0, 90], #Mating
                        [90, 0, 90, 90, 90, 90, 0], #Towing
                        [90, 0, 90, 90, 90, 90, 0], #Anchoring & Chains #Anchoring starts with loading of anchors in port
                        [90, 0, 90, 90, 90, 90, 0]]) #Hook-Up

#Scaling the matrix to apply for all turbines
Matrix_D = np.concatenate((Matrix_Dist, np.tile(Matrix_Dist[:,2:7], len(TURBINENUMBER) - 1)), axis=1)
Matrix_Distance = np.concatenate((Matrix_D, np.tile(Matrix_D[2:7,:], [len(TURBINENUMBER) - 1,1])), axis=0)


#Function matrix; Bollard Pull and Lifting capacity in tonnes, anchor handling equipment and cable laying equipment for
# each vesseltype

Matrix_Func = np.array([[100, 0, 0, 0],
                        [350, 300, 1, 0],
                        [0, 14000, 0, 0],
                        [0, 0, 0, 1]])

#Requirement matrix; Bollard Pull, Lifting capacity in tonnes, anchor handling equipment and cable laying equipment
Matrix_Requirements = np.array([[0, 0, 0, 0], #Depot
                                [0, 0, 0, 1], #Cable-Laying
                                [0, 0, 0, 0], #Ballast
                                [0, 500, 0, 0], #Mating
                                [300, 0, 0, 0], #Towing
                                [300, 100, 1, 0], #Anchoring & Chains #Assume that the AHTS can carry 3 suction anchors
                                [0, 15, 1, 0]]) #Hook-Up

#Scaling the matrix to apply for all turbines
Matrix_Req = np.concatenate((Matrix_Requirements, np.tile(Matrix_Requirements[2:7,:], [len(TURBINENUMBER) - 1,1])),
                            axis=0)


#Precedence matrix showing which operations that are depending on each other

Matrix_Dependency = np.array([[0, 1, 1, 1, 1, 1, 1], #Depot
                              [0, 0, 0, 0, 0, 0, 0], #Cable-Laying
                              [0, 1, 0, 1, 1, 0, 1], #Ballast
                              [0, 1, 0, 0, 1, 0, 1], #Mating
                              [0, 1, 0, 0, 0, 0, 1], #Towing
                              [0, 1, 0, 0, 0, 0, 1], #Anchoring & Chains
                              [0, 1, 0, 0, 0, 0, 0]]) #Hook-Up



#Scaling the matrix to apply for all turbines
Matrix_Dep = np.zeros([len(Matrix_Dependency)+(len(Matrix_Dependency)-2)*(len(TURBINENUMBER)-1),
                       len(Matrix_Dependency)+(len(Matrix_Dependency)-2)*(len(TURBINENUMBER)-1)])

Matrix_Dep[0:len(Matrix_Dependency),0:len(Matrix_Dependency)] = Matrix_Dependency

for i in range(1, len(TURBINENUMBER), 1):
    Matrix_Dep[0:2, len(Matrix_Dependency):len(Matrix_Dependency)+i*(len(Matrix_Dependency)-2)] = np.tile(
        Matrix_Dependency[0:2,2:7],[1,i])

    Matrix_Dep[len(Matrix_Dependency):len(Matrix_Dependency)+i*(
            len(Matrix_Dependency)-2), 0:2] = np.tile(
        Matrix_Dependency[2:7, 0:2], [i, 1])

    Matrix_Dep[len(Matrix_Dependency)+(i-1)*(len(Matrix_Dependency)-2):len(Matrix_Dependency)+i*(
            len(Matrix_Dependency)-2),
    len(Matrix_Dependency)+(i-1)*(len(Matrix_Dependency)-2):len(Matrix_Dependency)+i*(
            len(Matrix_Dependency)-2)] = Matrix_Dependency[2:7,2:7]
```

```
#####DECISION VARIABLES#####


#BINARY VARIABLES

#1 if vessel k is used for operation i, 0 else
vessop_vars = LpVariable.dicts("VesselUsedOperation",
                              [(i,v,k)
                               for i in OPERATIONS
                               for v in VESSELTYPES
                               for k in VESSELNUMBER],0,1,LpBinary
                              )

#1 if vessel k of vesseltype v sails from operation i to operation j, 0 else
route_vars = LpVariable.dicts("VesselRoute",
                             [(i,j,v,k)
                              for i in OPERATIONS
                              for j in OPERATIONS
                              for v in VESSELTYPES
                              for k in VESSELNUMBER],0,1,LpBinary
                             )


#CONTINOUS VARIABLES

#Time which vessel k of vessel type v starts operation i for turbine number w (all activities preceding node i have been completed
starttime_vars = LpVariable.dicts("TimeOperationOccursForVessel",
                                 [(i,v,k)
                                  for i in OPERATIONS
                                  for v in VESSELTYPES
                                  for k in VESSELNUMBER],0
                                 )

#Time which operation i occurs for turbine number w (all activities preceding node i have been completed
startop_vars = LpVariable.dicts("TimeOperationOccurs",
                               [i for i in OPERATIONS],0
                               )

#Time which vessel k of vesseltype v ends operation i for turbine number w
end_vars = LpVariable("TimeVesselEnd",529
                     )

#Total time of the project
totaltime_vars = LpVariable.dicts("TotalTime",
                                 [(v,k)
                                  for v in VESSELTYPES
                                  for k in VESSELNUMBER],0
                                 )


#SET PROBLEM VARIABLE
prob = LpProblem("FSM", LpMinimize)

#####OBJECTIVE FUNCTION#####
prob += lpSum(fixed_cost[v]*route_vars[(0,j,v,k)]
         for j in OPERATIONS
         for v in VESSELTYPES
         for k in VESSELNUMBER) \
     + lpSum((variable_cost[v]+fuel_cost[v])*totaltime_vars[(v,k)]
          for v in VESSELTYPES
          for k in VESSELNUMBER) \
     + end_vars*penaltycost
```

```
#####CONSTRAINTS#####

# 1 #An operation can not be done more than once by the same vessel
for i in OPERATIONS:
   for v in VESSELTYPES:
      for k in VESSELNUMBER:
         prob += lpSum(route_vars[(i,j,v,k)]
                    for j in OPERATIONS) <= 1
# 2 #
for j in OPERATIONS:
   for v in VESSELTYPES:
      for k in VESSELNUMBER:
         prob += lpSum(route_vars[(i,j,v,k)]
                    for i in OPERATIONS) <= 1

# 3 # All operations must be done
for i in OPERATIONS:
   prob += lpSum(route_vars[(i,j,v,k)]
              for j in OPERATIONS
              for v in VESSELTYPES
              for k in VESSELNUMBER) >= 1

# 4 #All operations must be done
for j in OPERATIONS:
   prob += lpSum(route_vars[(i,j,v,k)]
              for i in OPERATIONS
              for v in VESSELTYPES
              for k in VESSELNUMBER) >= 1

# 5 #A vessel can not travel back to the same operation
for i in OPERATIONS:
   for v in VESSELTYPES:
      for k in VESSELNUMBER:
         prob += route_vars[(i,i,v,k)] == 0

# 6 #Flow conservation: Every operation that is visited must also be left at some point
for i in OPERATIONS:
   for v in VESSELTYPES:
      for k in VESSELNUMBER:
         prob += lpSum(route_vars[(i,j,v,k)]
                    for j in OPERATIONS) \
                   == lpSum(route_vars[(j,i,v,k)]
                         for j in OPERATIONS)


#Functional requirement constraints

# 7 #The sum of the vessels used must satisfy the functional constraints for every operation
for j in OPERATIONS:
   for f in FUNCTIONS:
      prob += lpSum(route_vars[(i,j,v,k)]*Matrix_Func[v][f]
                 for i in OPERATIONS
                 for v in VESSELTYPES
                 for k in VESSELNUMBER) >= Matrix_Req[j][f]


# 8 #For the mating operation there can only be one vessel handling this operation
for j in range(3,len(OPERATIONS),5):
   prob += lpSum(route_vars[(i,j,v,k)]
              for i in OPERATIONS
              for v in VESSELTYPES
              for k in VESSELNUMBER) == 1

# 9 #Towing requires at least three vessels to keep the turbine stable
for j in range(4,len(OPERATIONS),5):
```

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    prob += lpSum(route_vars[(i,j,v,k)]
              for i in OPERATIONS
              for v in VESSELTYPES
              for k in VESSELNUMBER) >= 3

# 10 #Towing requires at least one AHTS
for j in range(4, len(OPERATIONS), 5):
    prob += lpSum(route_vars[(i,j,1,k)]
              for i in OPERATIONS
              for k in VESSELNUMBER) >= 1



# 11 #Need two vessels for the hook-up operation
for j in range(6, len(OPERATIONS), 5):
    prob += lpSum(route_vars[(i,j,v,k)]
              for i in OPERATIONS
              for v in VESSELTYPES
              for k in VESSELNUMBER) >= 2


#Vessels used

# 12 #If the sum of routes to operation j for vessel k of vesseltype v and tubine number w are more than 0, it means that operation j is done with vessel k of vesseltype v for turbine number w
for j in OPERATIONS:
    for v in VESSELTYPES:
        for k in VESSELNUMBER:
            prob += lpSum(route_vars[(i,j,v,k)]
                      for i in OPERATIONS) == vessop_vars[(j,v,k)]

# 13 #All operations must be done
for i in OPERATIONS:
    prob += lpSum(vessop_vars[(i,v,k)]
              for v in VESSELTYPES
              for k in VESSELNUMBER) >= 1


#Time-constraints

# 14 #Starttime of depot must be before any other operations
for j in range(1, len(OPERATIONS),1):
    for v in VESSELTYPES:
        for k in VESSELNUMBER:
            prob += starttime_vars[(0,v,k)] + Matrix_Distance[0][j]/speed[v]*route_vars[(0,j,v,k)] \
                <= starttime_vars[(j,v,k)]

# 15 #Time operation starts
for i in range(1, len(OPERATIONS), 1):
    for v in VESSELTYPES:
        for k in VESSELNUMBER:
            prob += starttime_vars[(i,v,k)] - (1-vessop_vars[(i,v,k)])*Big_M <= startop_vars[i]

# 16 #
for i in range(1, len(OPERATIONS), 1):
    for j in range(1, len(OPERATIONS), 1):
        for v in VESSELTYPES:
            for k in VESSELNUMBER:
                prob += startop_vars[i] + duration[i] + Matrix_Distance[i][j]/speed[v] - \
                    (1-route_vars[(i,j,v,k)])*Big_M <= startop_vars[j]

# 17 #If an operation j is dependent on operation i being done first, start time of operation i must be before operation j
for i in range(1, len(OPERATIONS), 1):
    for j in range(1, len(OPERATIONS), 1):
        prob += (startop_vars[i] + duration[i])*Matrix_Dep[i][j] <= startop_vars[j]
```

```
# 18 #Hook-up must happen right after the turbines have arrived on site
for i in range(4,len(OPERATIONS),5):
  prob += startop_vars[i] + duration[i] == startop_vars[(i+2)]


# 19 #The starttime for an operation must be the same for all vessels operating that operation
for i in range(1, len(OPERATIONS), 1):
  for v in VESSELTYPES:
    for k in VESSELNUMBER:
      prob += starttime_vars[(i,v,k)] - (1-vessop_vars[(i,v,k)])*Big_M <= startop_vars[i]

# 20 #
for i in range(1, len(OPERATIONS), 1):
  for v in VESSELTYPES:
    for k in VESSELNUMBER:
      prob += starttime_vars[(i,v,k)] + (1-vessop_vars[(i,v,k)])*Big_M >= startop_vars[i]

# 21 #Totaltime
for v in VESSELTYPES:
  for k in VESSELNUMBER:
    prob += lpSum((Matrix_Distance[i][j]/speed[v] + duration[j]) * route_vars[(i,j,v,k)]
              for i in OPERATIONS
              for j in OPERATIONS) <= totaltime_vars[(v,k)]

# 22 #
for i in range(1, len(OPERATIONS), 1):
  for v in VESSELTYPES:
    for k in VESSELNUMBER:
      prob += starttime_vars[(i,v,k)] + (duration[i] + Matrix_Distance[i][0]/speed[v])*route_vars[
        (i,0,v,k)] - starttime_vars[(0,v,k)] <= totaltime_vars[(v,k)]

# 23 #Endtime of project
for i in range(1, len(OPERATIONS), 1):
  for v in VESSELTYPES:
    for k in VESSELNUMBER:
      prob += starttime_vars[(i,v,k)] + duration[i] + Matrix_Distance[i][0]/speed[v] <= end_vars



#NON-NEGATIVE CONSTRAINTS
for i in OPERATIONS:
  for j in OPERATIONS:
    for v in VESSELTYPES:
      for k in VESSELNUMBER:
        prob += route_vars[(i,j,v,k)] >= 0

for i in OPERATIONS:
  for v in VESSELTYPES:
    for k in VESSELNUMBER:
      prob += vessop_vars[(i,v,k)] >= 0

for i in OPERATIONS:
  for v in VESSELTYPES:
    for k in VESSELNUMBER:
      prob += starttime_vars[(i,v,k)] >= 0

for i in OPERATIONS:
  for v in VESSELTYPES:
    for k in VESSELNUMBER:
      prob += starttime_vars[(i,v,k)] <= 1500

for i in OPERATIONS:
```

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    prob += startop_vars[i] >= 0

for i in OPERATIONS:
    prob += startop_vars[i] <= 1500

for v in VESSELTYPES:
    for k in VESSELNUMBER:
        prob += totaltime_vars[(v,k)] >= 0

for v in VESSELTYPES:
    for k in VESSELNUMBER:
        prob += totaltime_vars[(v,k)] <= 1500

prob += end_vars >= 529
prob += end_vars <= 1500

# Symmetry Constraint

for v in VESSELTYPES:
    for k in range(0, len(VESSELNUMBER)-1, 1):
        prob += totaltime_vars[(v,k)] >= totaltime_vars[(v,k+1)]

#SOLUTION

prob.writeMPS("LPModel.mps")


prob.solve(GUROBI(MIPGap=0.01, Presolve=2, Cuts=2, Symmetry=2))
print("Status:",LpStatus[prob.status])


#####PRINT OPTIMAL SOLUTION#####
print("The cost of vessel fleet size and mix in 1000 euros=",value(prob.objective))
print()
for i in range(len(OPERATIONS)):
    for v in range(len(VESSELTYPES)):
        for k in range(len(VESSELNUMBER)):
            if vessop_vars[(i,v,k)].varValue >= 1:
                    print(vessop_vars[(i,v,k)])
                    print(vessop_vars[(i,v,k)].varValue)
print()
for i in range(len(OPERATIONS)):
    for v in range(len(VESSELTYPES)):
        for k in range(len(VESSELNUMBER)):
            if vessop_vars[(i,v,k)].varValue >= 1:
                print(starttime_vars[(i,v,k)])
                print(starttime_vars[(i,v,k)].varValue)
print()
for v in range(len(VESSELTYPES)):
    for k in range(len(VESSELNUMBER)):
        print(totaltime_vars[(v, k)])
        print(totaltime_vars[(v, k)].varValue)
print()
for i in range(len(OPERATIONS)):
    for j in range(len(OPERATIONS)):
        for v in range(len(VESSELTYPES)):
            for k in range(len(VESSELNUMBER)):
                if route_vars[(i,j,v,k)].varValue >= 1:
                    print(route_vars[(i,j,v,k)])
                    print(route_vars[(i,j,v,k)].varValue)

print()
print(end_vars.varValue)
print(end_vars.varValue/24)
```
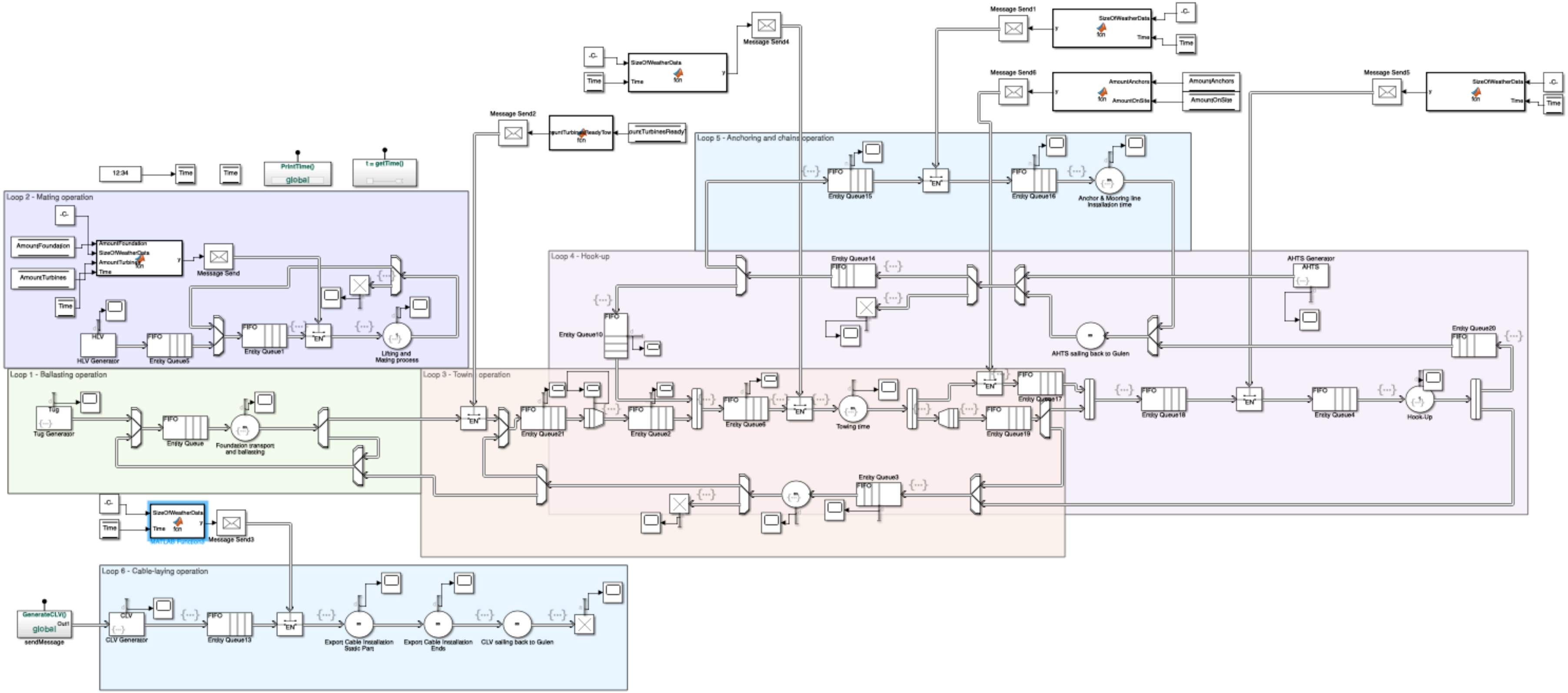

Appendix B

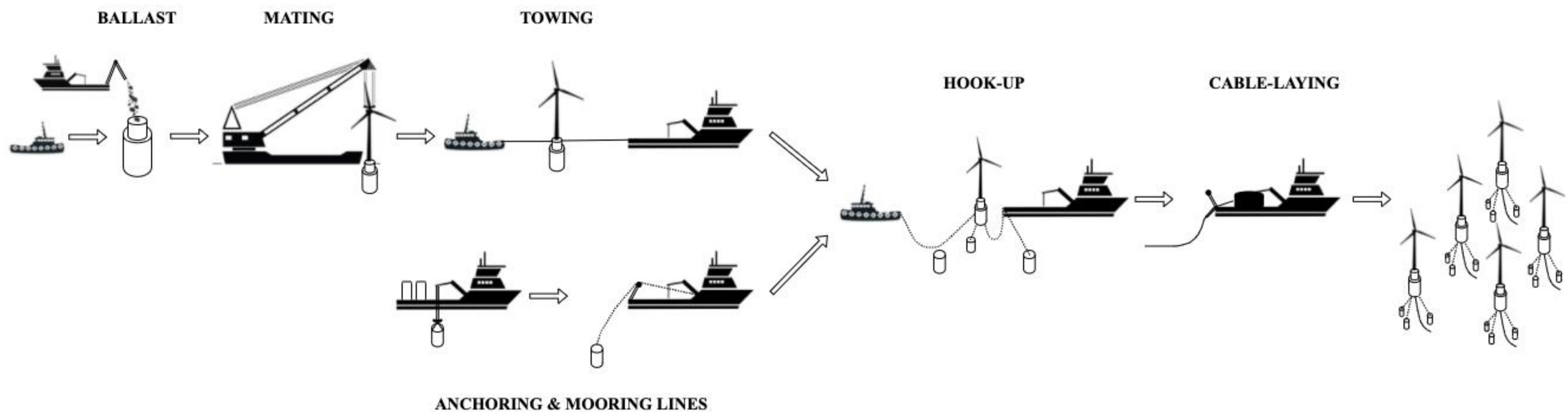
Simulation Model



Loop 1 - Ballasting operation
Loop 2 - Mating operation
Loop 3 - Towin operation
Loop 4 - Hook-up
Loop 5 - Anchoring and chains operation
Loop 6 - Cable-laying operation
Tug Generator
Entity Queue
Foundation transport and ballasting
HLV Generator
Entity Queue5
Entity Queue1
Lifting and Mating process
Message Send
Message Send1
Message Send2
Message Send3
Message Send4
Message Send5
Message Send6
Entity Queue21
Entity Queue2
Entity Queue6
Towing time
Entity Queue19
Entity Queue17
Entity Queue3
Entity Queue10
Entity Queue14
AHTS Generator
AHTS sailing back to Gulen
Entity Queue20
Entity Queue18
Entity Queue4
Hook-Up
Entity Queue15
Entity Queue16
Anchor & Mooring line Installation time
CLV Generator
Entity Queue13
Export Cable Installation Static Part
Export Cable Installation Ends
CLV sailing back to Gulen
sendMessage
PrintTime()
t = getTime()
GenerateCLV()
global
12:34
Time
SizeOfWeatherData
AmountFoundation
AmountTurbines
AmountAnchors
AmountOnSite
FIFO
fcn

Appendix C

Flowchart


BALLAST
MATING
TOWING
HOOK-UP
CABLE-LAYING
ANCHORING & MOORING LINES

Sebastian Erik Løken Rindvoll

Optimizing the Logistics of Floating Offshore Wind during Installation

NTNU
Norwegian University of Science and Technology