Master's thesis

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

Ingunn Salvesen Haldorsen

Optimization of Combined Fleet and Installation Process for a Floating Offshore Wind Farm

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2020

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Master's Thesis in Marine Systems Design

Stud. techn. Ingunn Salvesen Haldorsen

Spring 2020

Optimization of Combined Fleet and Installation Process for a Floating Offshore Wind Farm

Background

The rising need of alternative energy sources has resulted in an increasing interest in wind energy. In recent years, land-based wind power has reached a cost-competitive level motivating mass production and exploitation of potential installation sites. However, finding suitable locations has turned out to be difficult as the construction often disturbs neighboring communities and environment.

By moving the wind farms to offshore locations, the impact on people and their environment is reduced and larger wind turbines can be installed. However, the large-scale offshore wind projects built so far have almost exclusively been bottom-fixed structures. The shallow ocean areas are limited in Norway, arising the need of floating offshore wind turbines. Today, these are costly compared to bottom-fixed turbines. Partly as a result of low scale production and installation, and inefficient processes requiring expensive resources. Further research and willingness to invest in new and large-scale projects might change this cost-competitiveness problem and create an important economic opportunity for Norway.

Overall aim and focus

The overall aim of this thesis is to optimally execute a specific installation concept for a floating offshore wind farm. A possible solution for offshore wind farm installation needs to be conceptualized and presented. The work should identify and evaluate different concepts of installation, fleet configurations and installation schedules.

Considering published installation concepts for offshore wind farms, an assessment of technological and economic feasibility will be performed. Due to scarcity of experience and publicly available information on floating offshore wind installations, the basis for this work will be Equinors' installation architecture for floating wind farms. The installation stages should be outlined, and optimization models describing both scheduling and fleet selection should be developed as a decision support for future floating offshore wind farm installations. The model should seek to minimize total costs through strategic decisions, that is decision on schedule planning and vessel selection.

Scope and main activities
The candidate should presumably cover the following main points:

1. *Considering published installation profiles for offshore wind farms, present potential installation steps for floating offshore wind farms.*

2. *Select a suitable wind farm installation concept and define an installation scenario. This includes documenting main trends published within the topic of floating offshore wind, specifically focusing on the installation of Hywind Scotland.*

3. *Review and investigate potential vessels and fleets for floating offshore wind installations.*

4. *Create an optimization model as a decision support for floating offshore wind installations. The models should include decisions on scheduling and vessel selection.*

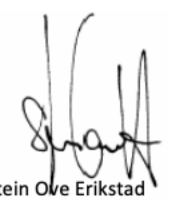
5. *Using the created optimization models, analyze cost-effective planning and vessel strategies for the installation process. This should be done a using specific, realistic and real time installation case.*

6. *Discuss and conclude.*

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

The work shall follow the guidelines given by NTNU for the MSc Project work. The report shall be written in English and edited as a research report, including literature survey, descriptions of mathematical models, descriptions of algorithms, optimization results, model test results, discussion and a conclusion, including a proposal for further work. Potential source code should be provided on a memory stick or similar. It is assumed that the Department of Marine Technology, NTNU, can use the results freely in its research work, unless otherwise agreed upon, by referring to the student's work.

The thesis should be submitted in June, 2020.



Stein Ove Erikstad
Professor/Responsible Advisor

Summary

The rising need of alternative energy sources has resulted in an increasing interest in wind energy. In recent years, wind farm locations have shifted from land-based sites towards offshore solutions. Shallow waters, defined as depth zones below 100 m, comprise only 5.56% of the total sea surface area. This small share has triggered the industry towards floating offshore concepts. Numerous floating offshore wind sites have been suggested for development, both along the Norwegian coastline and internationally, for example at the shorelines of Japan and the US. Associated with these plans, is the search for designs or concepts minimizing the life cycle costs of the offshore wind farms. A cost reduction in the installation of the floating offshore wind farm, which may account for almost 20% of the life cycle costs, is crucial in order to be cost-competitive to other sources of energy.

Based on Hywind Scotland and studies on offshore wind installations, eight major installation steps have been identified. These include transportation of components and anchors, assembly in port, tow-out, anchor and cable installation, hook up and final commissioning. In contrast to bottom fixed wind farms, the entire assembly takes place in port. Different fleet concepts have been proposed as solutions for the installation execution. The installation of floating turbines does not require big jack-ups or other heavy lift vessels, and smaller vessels are sufficient for the operations. The suitable vessel categories capable of completing the operations, include AHTS vessels, tugs, cable laying vessel and transportation vessels.

The analysis of the installation process and its requirements are fundamental for the development of a continuous optimization model. This model identifies the optimal fleet and schedule, thus minimizing the installation costs. Implementation of the model is done in Python, using Gurobi as an optimization tool. A case example, similar to the Hywind Scotland project, is used to analyze the installation costs, optimal fleet and installation schedule. It is found that mobilization costs, day rates, fuel costs and execution times are significant cost contributors. The installation of one floating turbine is estimated to take 28 days, while five turbines can be installed in 82 days. Furthermore, increasing the farm size provides major cost reductions. One turbine has an estimated installation cost of 533,000 £, while a farm consisting of fifteen turbines incurs an installation cost per turbine of 469,000 £. This implies a cost reduction of 12%, only considering the costs associated with the charter of the fleet. Assuming a strategy installing the turbines successively, the fleet is found to be constant for farm sizes exceeding three turbines. For a case example located at the shore of Norway, results show that a fleet of five vessels is sufficient for successful installation.

In this work, a model for optimization of the combined fleet selection and installation schedule has been developed. This has been done to provide a cost-effective installation and to provide a decision tool for future floating offshore wind projects.

Sammendrag

Det økende behovet for alternative energikilder har resultert i en større interesse for vindkraft. I løpet av de siste årene, har mange vindmølleparker blitt flyttet fra land til lokasjoner til havs. På verdensbasis består 5,56 % av det totale havoverflatearealet av vanndybder under 100 meter. Norskekysten består hovedsakelig av dype vannområder, og har bidratt til at næringen har beveget seg mot flytende offshore-konsepter. Mange flytende havvindprosjekter er foreslått for utbygging, både langs den norske kystlinjen og internasjonalt, for eksempel langs kystlinjene i Japan og USA. Tilknyttet disse planene er søken på design eller konsepter som minimerer livssykluskostnadene til havvindparker. En kostnadsreduksjon i installasjonen av flytende havvindparker, som ofte utgjør nesten 20 % av livssykluskostnadene, er avgjørende for at næringen kan bli konkurransedyktig mot andre energikilder.

Basert på Hywind Scotland og studier om havvindparker, er åtte viktige installasjonstrinn identifisert. Disse inkluderer transport av komponenter og forankringer, montering, tauing, anker- og kabelinstallasjon, tilkobling og endelig igangsetting. I motsetning til bunnfaste vindparker, foregår hele monteringen av turbinen i havn. Ulike flåtekonsepter har blitt foreslått som løsninger for å utføre installasjonen. I motsetning til installasjon av bunnfaste vindparker, kreves ikke jack-ups eller andre store løftefartøyer. Installasjon av flytende vindparker kan gjøres med mindre fartøyer. Egnede fartøykategorier inkluderer AHTS-skip, slepebåter, kabelleggingsfartøy og transportfartøy.

Analyser av installasjonsprosessen og dens krav har skapt grunnlaget for utviklingen av en optimaliseringsmodell. Modellen identifiserer den optimale flåten og tidsskjemaet for installasjonen, ved å minimere installasjonskostnadene. Implementering av modellen gjøres i Python, og Gurobi er brukt som optimeringsprogram. Et eksempel, basert på gjennomføringen av Hywind Scotland, brukes til å analysere installasjonskostnadene, optimal flåte og tidsskjema for installasjon. Resultatene viser at mobiliseringskostnader, dag-rater, drivstoffkostnader og utførelsestider er betydelige bidragsytere på den totale kostnaden. Installasjonen av én flytende turbin er beregnet å ta 28 dager, mens fem turbiner kan installeres på 82 dager. Én turbin har en anslått installasjonskostnad på 533 000 £, mens en vindpark bestående av femten turbiner gir en installasjonskostnad per turbin på 469 000 £. Dette innebærer en kostnadsreduksjon på 12 %, kun knyttet til leie av flåten. Forutsatt at turbinene blir installert suksessivt, holder størrelsen på flåten seg konstant for vindparker større enn tre turbiner.

I dette arbeidet er det utviklet en modell for optimalisering av kombinert flåtevalg og installasjonsplan. Dette er gjort for å gi en kostnadseffektiv installasjon og for å lage et beslutningsverktøy nyttig for fremtidige flytende offshore vindprosjekter.

Preface

This thesis is the concluding work of the Master of Science degree in Marine System Design at Department of Marine Technology (IMT) at the Norwegian University of Science and Technology (NTNU), in Trondheim, Norway. The work has been written in its entirety during the spring semester 2020, with a workload corresponding to 30 ECTS.

The master's thesis is a continuation of the work done in the project thesis written in the fall semester 2019, equivalent to a workload of 7,5 ECTS. The project thesis gave an introduction to the field of Norwegian offshore wind industry and some introductory topics from this work is included in this master's thesis.

The master description was formulated in the beginning of the semester. The first part of the semester was used to continue research and obtain further knowledge on the topic. Additionally, studies in Python and Gurobi was needed in order to formulate the optimization model developed in this master's thesis. Starting this work, I had little knowledge in Python nor Gurobi. The second half was mostly used to evaluate results and write the report. I would like to thank my supervisor for this master's thesis, Professor Stein Ove Erikstad. He provided professional support and advise throughout the semester. In the beginning of the semester, Professor Erikstad gave good guidance on how to formulate and tackle the problem. Later on, he fostered good discussions and conversations.

Trondheim, June 10, 2020

Ingunn S. Haldorsen

Ingunn Salvesen Haldorsen

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Abbreviations

AHV	Anchor Handling Vessels
AHTS	Anchor Handling Tug Suppliers
AUV	Autonomous Underwater Vehicle
BHP	Break Horse Power
CAPEX	Capital Expenditure
CEEO	Copenhagen Environment and Energy Office
CFFS	Continuous optimization model for Fleet Selection & Scheduling
DEA	Direct Embedded Anchors
DEPLA	Dynamically Embedded Plate Anchors
DFS	Discrete optimization model for Fleet Selection
DP	Dynamic Positioning
DSM	Design Structure Matrix
DWT	Deadweight
EWEA	Previous European Wind Energy Association, now WindEurope
EU	European Union
E&P	Exploration and Production
FOWT	Floating Offshore Wind Turbine
GBF	Gravity Based Foundations
HLV	Heavy Lift Vessel
HF4	High Flow Installation 4
IEA	International Energy Agency
LCOE	The levelized cost of energy
MILP	Mixed Integer Linear Programming
NTNU	Norwegian University of Science and Technology
OPEX	Operation Expenditure
OST	Offshore Support Tug
OSV	Offshore Supply Vessel
OWF	Offshore Wind Farm
O&M	Operation and Maintenance

PDPA	Pile Driven Plate Anchors
SEPLA	Suction Embedded Plate Anchors
ROT	Remotely Operated Tool
ROV	Remotely Operated Vehicle
TIV	Turbine Installation Vessel
VIV	Vortex Induced Vibrations
VRP	Vehicle Routing Problem

Chapter 1

Introduction to Wind Energy

1.1 Motivation

The rising need of alternative energy sources has resulted in an increasing interest in wind energy. In recent years, land-based wind power has reached a cost-competitive level motivating mass production and exploitation of potential installation sites. However, finding suitable locations has turned out to be difficult as the construction often disturbs neighboring communities and environment.

By moving the wind farms to offshore locations, the impact on people and their environment is reduced and larger wind turbines can be installed. However, offshore wind farms are relatively costly compared to onshore turbines. This is especially true for floating offshore wind farms. Partly as a result of low scale production and installation, and inefficient processes requiring expensive resources. Further research and willingness to invest in new and large scale projects might change this cost-competitiveness problem and create important economic opportunities.

This master's thesis will investigate the installation of floating offshore wind farms. It will start by introducing background information and development of the offshore wind industry. Followed by a thorough investigation of the installation process of floating offshore wind farms. This information will be used to develop optimization tools as a decision support for installation scheduling and fleet selection.

1.2 Definitions

In the literature, a vast range of terms are used in the context of wind energy. These include wind farm, windmills, wind turbines, bottom-fixed and floating wind turbines. The following definitions are applied in this work: *a wind farm* is a large number of wind turbines built close together. It functions as a single power plant and sends electricity to a grid (Rosvold 2019). *Windmills* refer to a system generating only mechanical energy, which is in contrast to *wind turbines* generating electrical energy (Mæhlum and Rosvold 2019) (Hofstad and Rosvold

2019). *Bottom-fixed wind turbines* are fixed to the sea bottom, while *floating wind turbines* are floating and anchored to the sea floor.

1.3 Objectives

As stated in the enclosed master's thesis description, the main objectives of this thesis includes the following:

1. Considering published installation profiles for offshore wind farms, present potential installation steps for floating offshore wind farms.
2. Select a suitable wind farm installation concept and define an installation scenario. This includes documenting main trends published within the topic of floating offshore wind, specifically focusing on the installation of Hywind Scotland.
3. Review and investigate potential vessels and fleets for floating offshore wind installations.
4. Create an optimization model as a decision support for floating offshore wind installations. The model should include decisions on scheduling and vessel selection.
5. Using the created optimization model, analyze cost-effective planning and vessel strategies for the installation process. This should be done using a specific, realistic and real time installation case.
6. Discuss and conclude.

1.4 Scope and Limitations

As defined by the enclosed master description, this thesis studies the feasibility and cost aspects of the installation of a floating offshore wind farm located at the Norwegian continental shelf. The report is delimited to include only the installation process related to the wind farm. It will not include operation and maintenance, decommissioning, production logistics or other parts of its life span.

Furthermore, the scope of this thesis has been limited to include installation of floating offshore wind turbines, not focusing on bottom-fixed solutions. The motivation of this report is not to provide an economic analysis, but to investigate the possibilities and decision parameters related to the scheduling and fleet selection in a floating offshore wind installation. Environmental considerations related to the installation of the wind turbines are indisputably important, effecting both above and below sea level. However, this problem will not be further investigated in this master's thesis.

1.5 Approach

In the analysis, the Hywind Scotland project and the installation strategy planned for Hywind Tampen have made the basis for the installation solution and optimization model developed. To evaluate the potential fleets and schedules, the installation cost per turbine is used. Furthermore, the time utility is used as a measure for evaluating fleet optimality. The cost of the installation is calculated in terms of time charter costs and mobilization costs of the fleet. The mobilization costs are any expenses incurred for the vessels to be ready for the operations to start. This includes time charter and fuel costs sailing to site, in addition to expenses associated with preparing required equipment.

The installation process is divided into key operations before implementation in the optimization model. The operations are based on the planned steps outlined by Equinor for Hywind Tampen. The operation requirements and execution times are defined and used in the model. The cost approximate are based on historical time charter rates and methods for estimating mobilization costs.

The developed optimization models minimizes the costs associated with the installation. It is done by selecting an optimal fleet and installation schedule. Based on these models, analysis investigating the influence of mobilization costs and farm size is done.

1.6 Structure of the report

The report is organized as follows:

- **Chapter 2:** Gives a **background** of the field of offshore wind energy by providing a brief overview of the forces that drive and restrict the wind industry. Furthermore, it provides an introduction to the theory behind the wind turbine, and existing designs of floating offshore wind structures.
- **Chapter 3:** Provides a literature review of the historical development and costs of wind farms. Moreover, an overview of relevant optimization models applied to installation of offshore wind farms is given. Lastly, a short explanation of this works position in already existing literature is discussed.
- **Chapter 4:** Gives a thorough investigation of the operations associated with a floating offshore wind farm installation. Moreover, it evaluates the operation steps and characteristics, connecting suitable vessels to the operations.
- **Chapter 5:** Presents a simple version of the optimization model developed in this master's thesis. Furthermore, a case study on the installation of an offshore wind farm located on the Norwegian continental shelf is performed.
- **Chapter 6:** Introduces an improved optimization model as a support for decision making in installation scheduling and fleet selection. Furthermore, the influence of farm size and mobilization costs on the fleet selection and scheduling is investigated.

- **Chapter 7:** Gives the results of the optimization models, comparing them and commenting trends found from the analysis of the models.
- **Chapter 8:** Provides a discussion and a critical assessment of the work and the results.
- **Chapter 9:** Presents the **conclusion** and suggestion for further work.

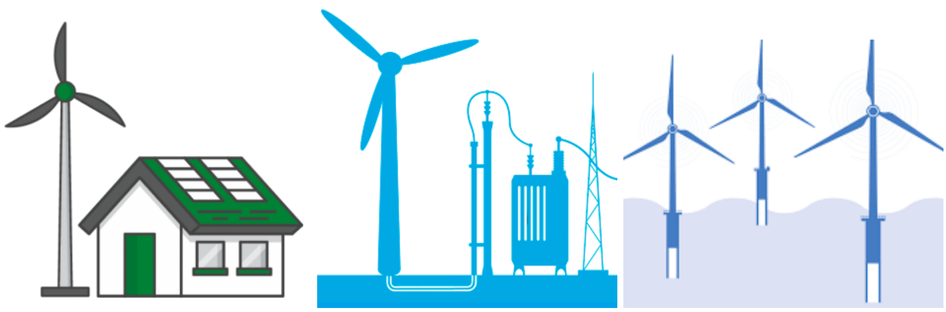
Chapter 2

Background

This chapter presents some background information on offshore wind energy. It gives an outline of drivers in the offshore wind market and an overview of historical trends within the industry. Furthermore, an overview and elaboration of the components and design of a wind turbine is presented.

2.1 Introduction to Wind Energy

Wind energy is the process of creating electricity using the wind or air flows as an energy source. The modern wind turbines capture kinetic energy from the wind and generate electricity that can be used to power homes around the globe. Wind energy is often divided into three main types, including floating offshore wind energy, which is in the main scope of this work. The three wind energy classes are briefly introduced below.



(a) Distributed wind **(b)** Utility-scale wind **(c)** Offshore wind

Figure 2.1: Wind energy generation types (Amarican Wind 2019)

1. **Distributed wind** are small, single wind turbines typically below 100 kilowatts that are not connected to the grid, but are used as direct power for a home, farm or a smaller

business (Amarican Wind 2019).

2. **Utility-scale wind** are wind turbines that produce power in the range between 100 kilowatts to multiple megawatts. The energy generated from these turbines are connected to the grid and as such distributed to users by power systems (Amarican Wind 2019).

3. **Offshore wind** turbines are erected as large bodies in the ocean. These are typically much larger than land-based turbines and as a result generate significantly more energy (Amarican Wind 2019). Floating offshore wind turbines are a part of this category.

2.1.1 Basic Wind Foil Theory

When the wind blows past a wind turbine, the blades on the turbine starts rotating because of the foil shaped blades. The kinetic energy is then turned into mechanical energy. The relative wind speed, v_r, meets the blade with an angle of attack, α. The foil is made to let the air pass over the top faster than it passes beneath, while still letting the air pass as a smooth and laminar flow. According to Bernoulli's theory, this causes a lift because the sum of the pressure and velocity of the air is constant. The lift force from this phenomena is the basis for the rotation of the turbine (Twidell and Gaudiosi 2009). An illustration of the wind turbine foil can be found in Figure 2.2 below. Notice that the blade is turning perpendicular to the oncoming free wind. The unperturbed speed is notated as u, and γ represents the angle of attack.

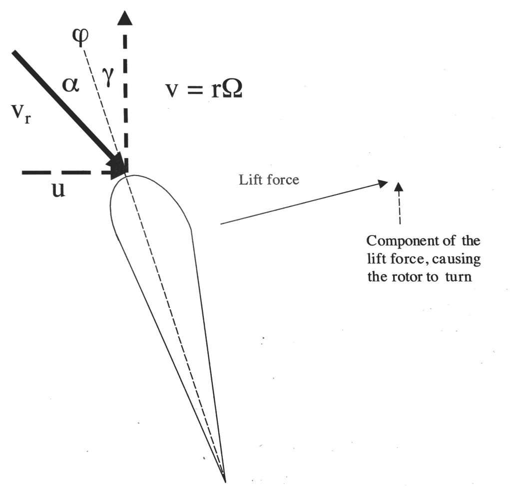


Figure 2.2: Wind turbine foil (Twidell and Gaudiosi 2009)

The optimal rotation frequency and angle of attack on the blades depend on the wind velocity. At a certain speed, approximately 24-27 m/s, the power production shuts down as the forces acting on the turbines are too high (Skaugset 2019). Figure 2.3 shows the relationship between the forces acting on the wind turbine. The incoming wind hits both the blades and the tower. Additionally, huge excitation forces from waves and currents must be considered when designing the wind turbines. If these forces are too strong, the power production stops in order to resist the stresses.

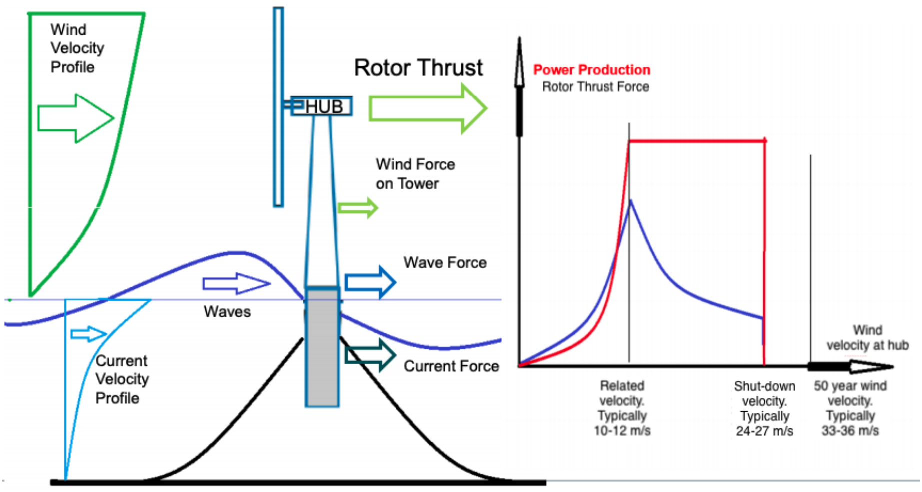


Figure 2.3: Forces on turbine (Skaugset 2019)

2.2 Wind Energy Drivers

According to predictions done by DNV GL, the global energy consumption will peak by 2030, as energy efficiency gains outpace economic growth. The electrification is said to be the biggest contributor to the reduced energy use. This means that in the next decade, the energy market will be influenced by the increased need of energy supply. At the same time the increased focus on sustainable ways of energy production has resulted in renewable energy sources taking gradually bigger shares of the total energy consumption. The expansion and development of wind energy is a great example of the rising need and interest in alternative energy sources. By the end of 2018, the cumulative installed wind energy capacity was approximately 189 GW, which is about 14 % of the total EU electricity demand (GL 2019).

In recent years, land-based wind power has reached a cost-competitive level motivating mass production and exploitation of potential installation sites (IEA 2019). However, finding suitable locations has turned out to be difficult as the construction often disturbs neighboring communities and environment. By moving the wind farms to offshore locations, the impact on people and their environment is reduced and larger wind turbines can be installed. By the end of 2018, offshore installed wind power reached 18.5 GW, by which 2.6 GW was installed in 2018. According to The European Wind Association this was a result of 409 new offshore wind turbines distributed among 12 projects (GL 2019). For reference, the total installed wind power was approximately 189 GW at the same time, and trends show that the offshore fraction of the industry is increasing. Table 2.1 summarizes the main drivers for the development of offshore wind farms.

Table 2.1: Drivers and restricting forces for offshore wind farms

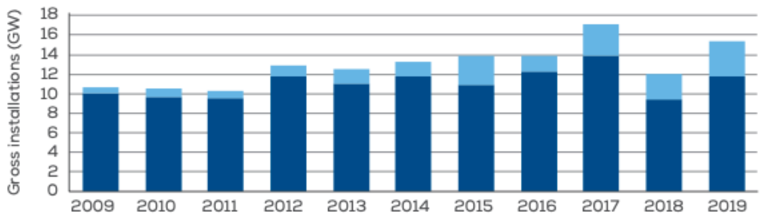
	Society	**Industry**
Primary Drivers	Global economic growth. Global increase in power demand.	Innovative and risk tolerant actor. High competence in related area of technology.
Secondary Drivers	Increased focus on sustainable and renewable energy resources. Emerging appliances and markets.	
Restricting Forces	Price volatility. Cost competitiveness.	Availability of finance. Financial uncertainty.

2.3 Offshore Wind Industry

As stated in the report by Wind Europe (Komusanac, Brindley, and Fraile 2020), offshore wind energy is essential to the global economy and renewable energy development. The industry generate crucial energy, employment and economic development on a global scale. Moving to deeper waters has proven to be an important source of scaling the energy generation within the industry, and has taken increasing shares of the total offshore wind energy generation (IEA 2019). Shallow water areas, defined as depth zones below 100 m, comprises only 5.56% of the sea surface area (Costello, Cheung, and De Hauwere 2010). It therefore seem evident, that expanding to floating offshore concepts can increase the offshore share even more. International Energy Agency, IEA, estimates solid reports on future energy development, predicting offshore wind bonanza in the near future (P. IEA 2020).

2.3.1 Offshore Market Share

Figure 2.4 shows the annual gross installations within the offshore and onshore wind industry. It shows a clear trend of moving offshore, with increasing shares of investments going to offshore installations. In 2019, 24% of wind installations came from offshore wind (Komusanac, Brindley, and Fraile 2020).



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Offshore	0.6	0.9	0.8	1.2	1.5	1.5	3.0	1.6	3.2	2.7	3.6
Onshore	10.0	9.6	9.5	11.7	11.0	11.7	10.9	12.3	13.9	9.4	11.7
Total	10.7	10.5	10.3	12.9	12.5	13.3	13.9	13.8	17.1	12.1	15.4

Figure 2.4: Annual gross installations (Komusanac, Brindley, and Fraile 2020)

In 2019, 15% of EU's electricity demand was covered by wind energy, including 2.3% from offshore wind energy. This is especially high compared to other places world wide. The development require high investment costs and challenging technology, which is seen in countries that are highly developed (United Nations Department for Economic and Social Affairs 2020). The pioneer countries within wind offshore wind energy are all highly developed countries, including Germany, Denmark, UK, US and Japan. Furthermore, statistics show that the average wind speeds are significantly higher in Northern and Southern parts of the globe, making these areas ideal for efficient offshore wind generation (Liu, Tang, and Xie 2008).

As Figure 2.4 shows, the share from offshore wind is gradually increasing. The same trends are seen in Figure 2.5, suggesting that the floating offshore wind industry will expand drastically. Contributing to its increasing share in the market is the high capacity factor of 38% offshore, compared with 24% onshore (Komusanac, Brindley, and Fraile 2020).

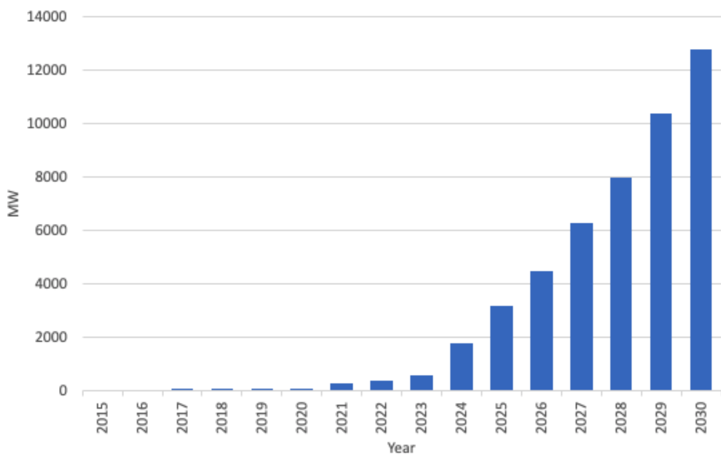


Figure 2.5: Floating offshore market overview (N. Equinor 2020c)

2.3.2 Historic Wind Energy Prices

The wind energy generation is highly seasonal, and does not have the same ability to store energy as for example oil and gas. However, statistics show that the wind energy generation often complement the solar energy production having opposite seasonal peaks. Figure 2.6 suggests that the wind energy production in both United States and United Kingdom reaches maximum during winter seasons, while solar production is at its minimum. The opposite is true for India and China. Utilizing these trends along with other energy sources can make it possible to meet the demand while sustaining electricity prices at a reasonable level.

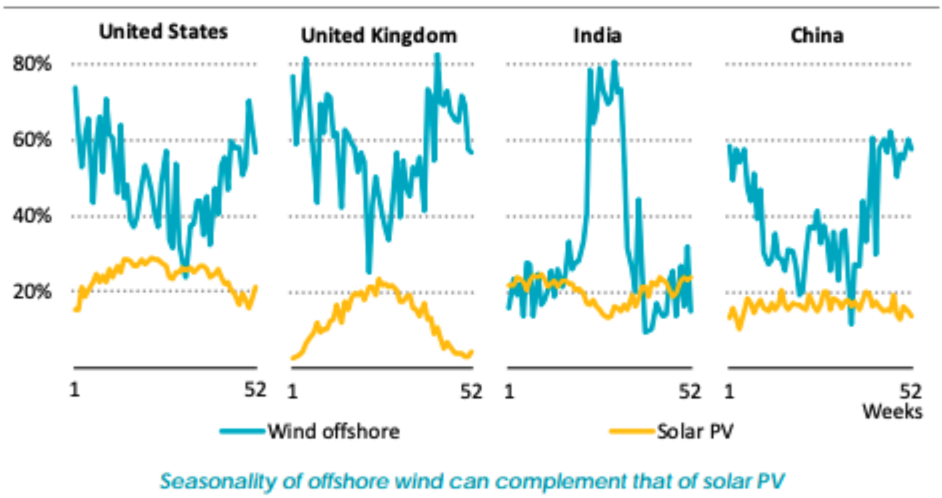


Figure 2.6: Seasonal energy generation (IEA 2019, p. 22)

According to research done by Mosquera-López and Nursimulu 2019, determinants for electricity spot prices are found to be wind power and solar generation. The effects are recognized to vary with time (Mosquera-López and Nursimulu 2019). The increasing share of renewable energy sources has contributed to the overall historical decrease in electricity prices. However, as the spot market is highly dependent on the energy generated from renewable energy sources, the increased share has resulted in higher market prices volatility. Detailed graphs on these trends can be found in Appendix A.

2.3.3 Life Time Costs of Offshore Wind Farms

As the offshore wind industry has made drastic technological improvements since its birth, the LCOE has seen a steady decrease over the years. The strike prices in Europe for offshore wind indicate significant cost reductions within the industry. Some prices can even match the wholesale electricity prices. This trend can partly be explained by the improved technology, but also moving into deeper waters subsequently moving to better resources. Figure 2.7 shows the decreasing LCOE trend of offshore wind farms, suggesting that its competitive position in the energy supply might strengthen in the future (IEA 2019).

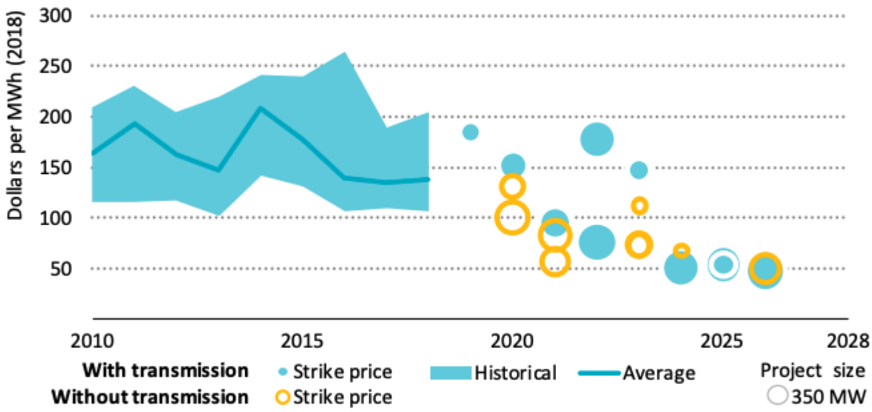


Figure 2.7: Historical LCOE of offshore wind farms in Europe (IEA 2019)

In order to minimize the overall life cycle costs of a wind farm, the relative sizes of the life cycle costs are of interest. They give an indication of where changes can result in big reductions in the overall cost of the farm. Myhr et al. 2014 suggest the cost distribution in Figure 2.8.

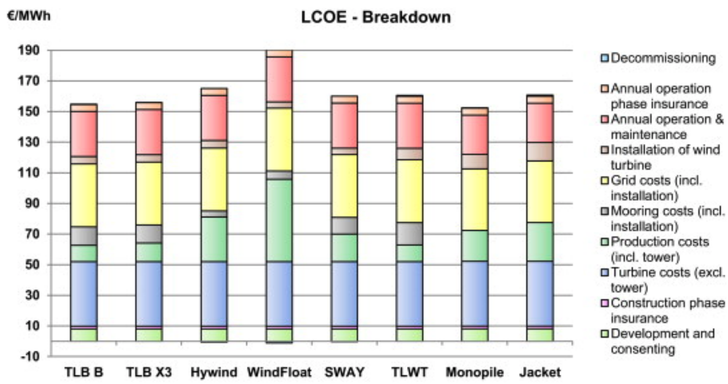


Figure 2.8: Levelized Cost of Electricity (LCOE) for an offshore wind farm (Myhr et al. 2014)

The findings suggest that the main costs are associated with maintenance & operation, installation and material. The installation of the turbine, including the investment costs, is the major cost driver, contributing to around 70% of the LCOE, and will thus be the center of investigation in this master thesis.

2.4 Offshore Wind Turbines

2.4.1 General Features

In general, an offshore wind farm is built to generate energy, utilizing the strong and steady winds offshore. The wind turbines are typically located along a coastline, transporting the generated energy with cables along the sea floor. The turbines are either bottom fixed or floating structures as illustrated in Figure 2.9.

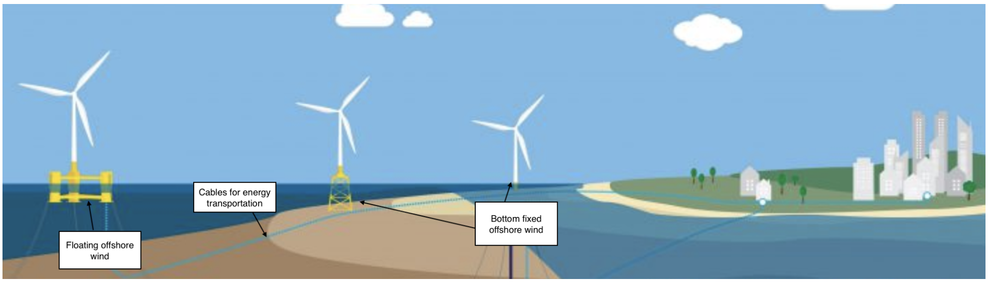


Figure 2.9: Wind farm illustration (OffshoreWIND 2017)

The design is highly dependent on the water depth and several concepts exist. In shallow waters, the wind turbines are typically bottom fixed, while floating structures are used in deep waters anchored with mooring lines (Guachamin Acero 2016).

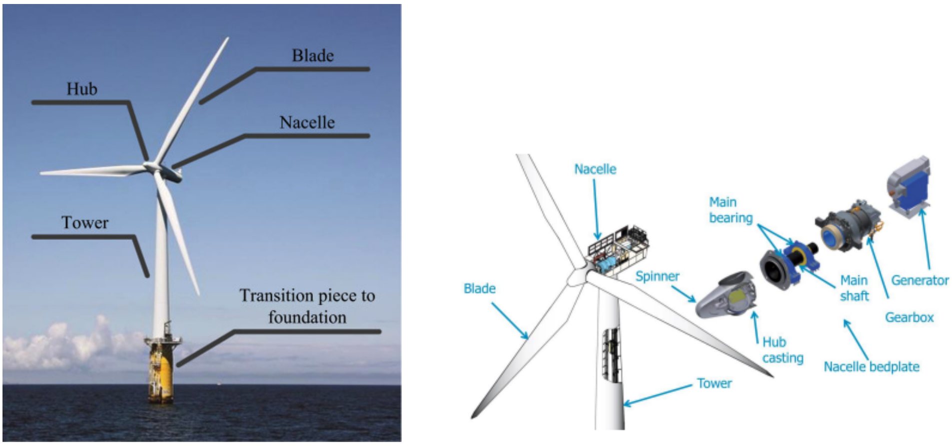
There are several challenges associated with the process of going offshore. The most notable challenge is higher project costs due to a need for specialized installation vessels and equipment. Furthermore, the operating conditions and accessibility is more challenging. Both these factors need to be carefully addressed when planning offshore wind farms.

2.4.2 Wind Turbine Components

The main components of the wind turbine are divided into three constituents; sub-structures (foundations), top-structures and cables connecting the farm to the electrical grid (Backe and Haugland 2017). SINTEF Ocean suggests that the production and designs of top-structures are dominated by international actors having delivered parts to the onshore wind industry (Giæver Tande 2020). Contrarily, the sup-structure designs are heavily influenced by Norwegian actors making specialized solutions based on their experience from the oil and gas industry (IEA 2019). Furthermore, the ocean wind farms consist of one or more sub-stations to collect energy generated from the farm. Both the cables and substations are not in the scope of this master thesis, and will not be elaborated further.

2.4.3 Top-Structure

The top-structure can again be divided into smaller parts consisting of the turbine tower, the nacelle and the blades (Guachamin Acero 2016). A visualization of the components can be found in Figure 2.10.



(a) Wind turbine parts

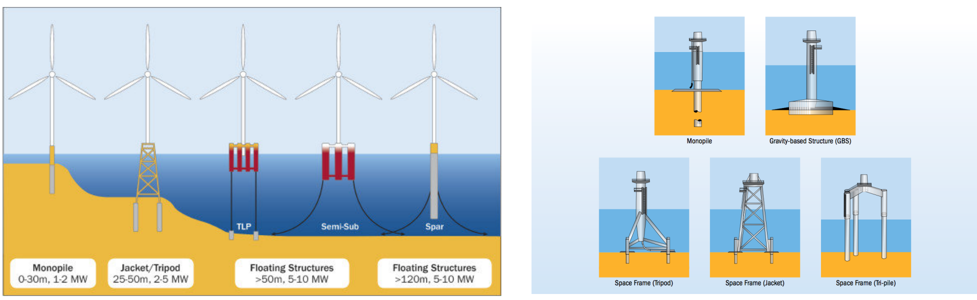
(b) Overview of blades and nacelle

Figure 2.10: Wind turbine components

The wind turbines normally consist of three blades connected to a nacelle. The nacelle is compiled by the main shaft connected to a gearbox and a generator. These components control the speed of rotation and transform mechanical energy to electrical energy.

2.4.4 Sub-Structure/Foundation

The design and technology for each part varies greatly. Fixed structures include Gravity Based Foundation (GBF), Monopile, Tripod or Jackets. Floating design examples are TLP, Semi-sub and Spar structures. Figure 2.11a illustrates some of the common designs for offshore wind turbines, while Figure 2.11b shows a collection of common bottom fixed foundations.



(a) Offshore wind turbine foundation designs

(b) Fixed offshore foundations

Figure 2.11: Wind turbine foundations (James and Costa Ros 2015)

Floating Foundations

As the offshore wind industry has moved towards deeper waters, the floating offshore designs have seen a rapid development in recent years. With increasing water depth at the site, the adaption to floating structures has proven to be more cost efficient. The three dominant structures within this domain are:

1. **Semi-submersible platform:** The platform floats semi-submerged on the surface of the ocean, while fastened to the sea bottom with anchors. The structure needs to be large and heavy in order to maintain stability. However, the low draft allows more easy installation and can be assembled in relatively shallow ports compared to the SPAR-design (James and Costa Ros 2015). Dr. Techn. Olav Olsen has developed a novel semi-submersible design called OO-STAR, with special focus on easy installation and assembly (Landbø 2018a)

2. **Spar-buoy:** The structure is typically cylindrical with a center of gravity below the center of buoyancy, ensuring a stable structure. This design is relatively easy to fabricate, but does often create logistical challenges in the process of installation, transportation and assembly. The Hywind Scotland SPAR-design developed by Equinor is an example of this type of architecture (A. Equinor 2019).

3. **Tension leg platform (TLP):** This is also a semi-submerged buoyant structure, anchored to the seabed. The mooring lines are tensioned providing a stable structure. This design shows advantages providing a light structure, but the high stresses in the anchor system is a weakness of the design (James and Costa Ros 2015).

2.4.5 Novel Sub-Structure Designs

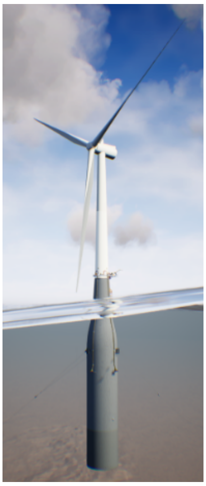
As an alternative to the SPAR-design used by Equinor in Hywind Scotland, Dr. Techn. Olav Olsen has developed the OO-Star Wind Floater. One of the main drivers behind the design is simple assembly and installation, in addition to robustness, longevity and scalability of large turbines.

The OO-Star is designed to float stably with a small draft, both with and without the turbine mounted. The intention is that the substructure can be launched outside a quay using a ship lift, drop or a submersible barge. After launching, the unit can be moored to a dock with 12-15 m water depth, which is significantly shallower than for SPAR-designs. With the help of a land mounted crane, the top and sub-structure can be fully assembled in port. This frees the concept from dependence on expensive offshore lifting vessels and makes the implementation model much safer and predictable as everything takes place in sheltered waters. Furthermore, the idea opens up for installation on coast lines with shallow waters (Landbø 2018b).

The comparison of the key characteristics for a SPAR-design and the OO-Star Wind Floater is found in Table 2.2.

Table 2.2: Key characteristics sub-structure examples

	SPAR Monopiles	**OO-Star Wind Floater (Semi-sub.)**
Design	Monopile	3-leg semisubmersible
Ballast	-	Passive ballast system
Material	Steel/Concrete	Steel/Concrete
Draft	Large	Small
Assembly site requirement	Deep waters	Can be shallower



(a) SPAR monopile (A. Equinor 2019)

(b) OO-Star wind floater (Landbø 2018b)

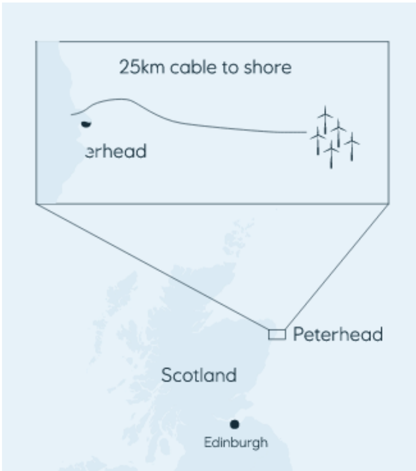
Figure 2.12: Substructure designs

2.5 State of the Art Projects

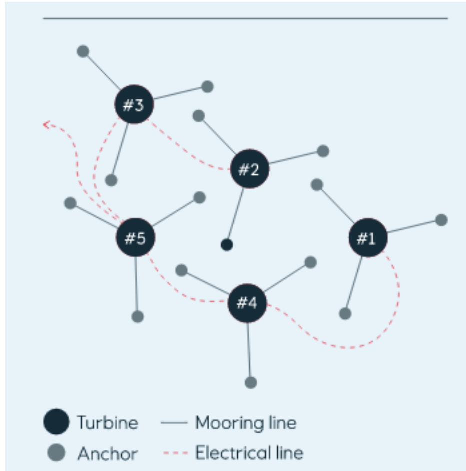
2.5.1 Hywind Scotland: First Commercial Floating Offshore Wind Park

Equinor has been a leading actor within floating offshore wind and in charge of Hywind Scotland, a pilot project within the industry. The wind farm is a great example of combining existing offshore experience with new and novel technology. It is considered the most viable floating offshore wind farm of today and has made a foundation for new and innovative solutions for future projects (N. Equinor 2020a).

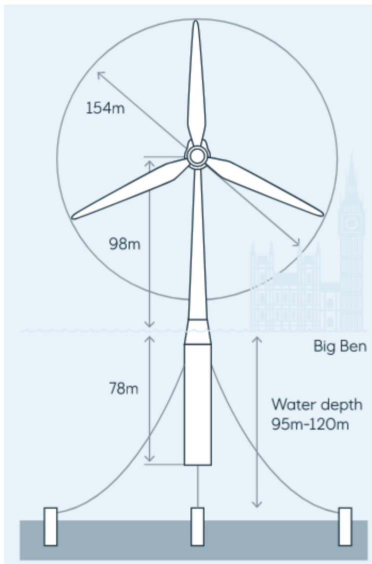
The substructure and design of Hywind Scotland, is selected based on the local conditions. The wind farm is located at the coast line of Scotland and proned to challenging weather conditions and climate. However, with the right technology, the harsh condition can impose high electricity generation and system efficiency (N. Equinor 2020a).



(a) Location



(b) Configuration



(c) Dimensions

Figure 2.13: Hywind Scotland characteristics (A. Equinor 2019)

As with many pioneer projects the costs are often high because of little or no previous experience. The same applies to Hywind Scotland ending up with a total investment cost of £152 millions. Equinor estimates that the costs can be reduced by 40-50% by 2030 realistically, making it competitive without support regimes. These costs can be cut in operations, yield, sub-structure, supply chain, infrastructure and installation. Table 2.3 shows the main characteristics of the Hywind Scotland project. The details will be further investigated in later chapters.

Table 2.3: Main characteristics of Hywind Scotland (N. Equinor 2020a)

Characteristics	**Value**
Dimensions	Height: 258 m
Park size	5 turbines
Location	Coast of Scotland
Design	SPAR monopile
Electricity generation	6 MW x 5 turbines

2.5.2 Future Projects

Multiple new offshore wind projects are planned for the future. On the coastline of Norway, Hywind Tampen, a floating wind farm consisting of 11 wind turbines are planned to supply the Snorre and Gullfaks offshore fields with electricity. Its combines capacity is estimated to 88 MW. Located at approximately 140 km from shore, the water depth is between 260 m and 300 m, making it the deepest wind farm location in the world (Equinor 2020).

In addition to the Hywind Tampen project, there are multiple other big plans for the offshore wind industry. Table 2.4 lists some of the most prominent projects planned for the coming years.

Table 2.4: Major offshore wind projects under development (SSE and Equinor 2020), (Equinor 2020)

Name	**Characteristics**
The Dogger Bank Wind farm, UK	• Worlds largest wind farm under development • Bottom fixed • Located at the North East coast of England • Total capacity up to 3.6 GW
Hywind Tampen	• Floating farm • Supplying Snorre and Gullfaks offshore fields • Total capacity of up to 88 MW

Chapter 3

Literature Review

The focus this far has been on the offshore wind industry in general; the main characteristics of the industry and its development. In the following chapter, the focal point will be more concentrated on the problem statement, i.e. investigate possible installation methods and optimization strategies to minimize installation costs. A literature review on what is already done on the topic will provide a framework for the analysis to be done.

Firstly, some important articles related to the objective of this work will be presented. These reviews serve both as a guidance and as a foundation for the work developed in this thesis. The literature review consists of two parts; a review work done on the development and cost aspects and a thorough presentation of work concerning installation optimization for offshore wind farms. The chapter is concluded with a short description of this works contribution to already existing literature and some final remarks.

3.1 Offshore Wind Development and Costs

In order to make offshore wind competitive to other means of energy sources, life time cost investigations, experiential studies and optimization of offshore wind farms have been a popular field of interest within academic studies. The academic studies on the topic have had an important contribution to the advancement of the industry. Thus, the next sections will briefly introduce some research done over the last decade, which serves as a basis for the work done in the master thesis.

3.1.1 Offshore Wind Development

The industry has seen drastic development since its birth, and studies on experience from ongoing projects has been essential for the development (J. H. Larsen et al. 2005) (Lange et al. 1999) (Junginger, Faaij, and Turkenburg 2004). Following experiences from the first Swedish offshore wind farm, Bockstigen, Lange et al. (1999) point at the importance of innovative concepts on the cost of the wind farm. In 1999, drilled monopile foundations, efficient jack-up barge installation and novel control systems for power generation monitoring, were identified as essential in the substantial cost reduction compared to previous offshore projects. Furthermore, Junginger, Faaij, and Turkenburg (2004) identify three main drivers for cost reduction. Design improvements and upscaling of wind turbines, the development of efficient installation methods and vessels, and economies of scale for the wind turbine production.

One of the first contributors to finding the optimal offshore wind turbine design, was done in 1998 by Fuglsang and K. Thomsen (1998). In the beginning of the offshore wind adventure, the turbine designs were very much based on the on-shore wind turbine designs (J. H. Larsen et al. 2005). For offshore wind turbines, they suggest increased swept area with reduced rotor speed and tower height, as compared to on-shore wind turbines. Similarly, J. H. Larsen et al. (2005) found that optimal offshore wind turbines should be slightly different from common practise onshore. Furthermore, turbines connected in series was found to be unsuitable for offshore wind farms, as repair on one would result in down time for all of the turbines.

With increased amount of experience within the offshore wind industry, numerous books have been written on the topic (Kaiser and Snyder 2012b) (K. E. Thomsen 2014). Kaiser and Snyder (2012b) introduce methodology framework to assess installation and decommissioning costs, using examples and experience form European offshore wind. The book provides a reliable point of reference for actors developing generalizable installation and decommissioning cost estimates.

3.1.2 Cost Estimation of Offshore Wind Farms

Studies on Bottom Fixed Offshore Wind Farms

Gonzalez-Rodriguez (2017) have done a thorough work on summarizing the costs and most important economical factors in an offshore wind farm. He has included the installation of foundation, electrical cables, design management and operation/maintenance. Similarly, Ioannou, Angus, and Brennan (2018) have created a model understanding the impact of different deployment factors on the overall cost of wind farms. These models are especially useful when evaluating available deployment sites and predicting cost estimates based on global decision variables.

Some of the cost estimates presented in the previous paragraph are used in the work by Dicorato et al. (2011) to evaluate the investment costs of an offshore wind farm based on the layout of the farm. It looks at the most suitable connection solution in order to minimize the cable installation costs.

Studies on Floating Offshore Wind Farms

As early as in 1998, Tong (1998) did a study on the technical and economic aspects of a floating offshore wind farm, specifically focusing on the FLOAT design. Issues regarding legal, environmental, fabrication and installation operations are considered and discussed. Conclusively, an example of a farm producing an output of 12.4 MW had an estimated capital cost of £30 millions. Accounting for inflation and size, the example estimate is found to be approximately the 80% of the costs found for the Hywind Scotland project (A. Equinor 2019).

Myhr et al. (2014) have taken the economical investigations a step further, evaluating the levelised cost of energy for offshore floating wind turbines in a life cycle perspective. They found that one of the major contributions to the total costs is the investment cost; including installation and cost of producing the parts. However, optimized concepts is found to result in a levelized cost of energy (LCOE) ranging from 82 €/MWh to 236 €/MWh for the upper bound (Myhr et al. 2014).

Similarly, a cost breakdown of floating wind farms has been analyzed by Laura and Vicente (2014). The results allow consciousness regarding the most important costs and promote work to minimize these costs. They identified several major costs related to the main phases of the life cycle; definition cost, design cost, manufacturing cost, installation cost, exploitation cost and dismantling cost. These can in tern be minimized, fostering more competitiveness for the offshore wind industry. This thesis will look specifically into the installation cost minimization problem.

3.1.3 Cost Optimization

There has been a great focus on reducing costs related to the offshore wind industry, and a great number of studies have been done on optimization of maintenance routing and scheduling. C. A. Irawan, Ouelhadj, et al. (2017) introduce a mathematical model for routing and scheduling of maintenance vessels, minimizing the operational costs comprising travel, technicians, and penalty costs. They also propose a MILP model for generating all feasible routes. Tests on existing data show that the model outperforms both schedules at test wind farms with an average of 12.21% and the model suggested by Dai, Stålhane, and Utne (2015). Similarly, Sperstad et al. (2016) look at the bigger picture; the timing of crew transfer, annual services and pre-determined jack-up vessel schedules. They find that correct planning of these maintenance operations could reduce the cost significantly. However, they are pruned to higher stochastic variability and uncertainty than other decision problems.

Decommissioning optimization is also an important part of reducing the total life span costs of an offshore wind farm. C. Irawan, Wall, and D. Jones (2019) present an optimization model proposing cost optimal schedules for the decommissioning of an offshore wind farm. The costs accounted for include a jack-up vessel, transfer vessel, inventory, processing and on-land transportation costs. The paper also investigates strategic issues relating to the decommissioning process.

3.2 Offshore Wind Farm Installations

As found in multiple studies, the installation cost is a major expense of the life time costs of an offshore wind farm. As follows, the correct installation strategy is essential and decisive for the installation costs. K. E. Thomsen (2014) have written a book on the most common installation strategies, pointing out the advantages and disadvantages of the methods. Additionally, EWEA (2009) have provided an overview of the technology, economics and installation methods. These works, in addition with novel installation methods used in Hywind Scotland, have provided a basis for the model developed in this work.

3.2.1 Optimization Applied to Installation of Offshore Wind Farms

Most central to the work in this master thesis is the optimization applied to installation of offshore wind farms. Among the first studies on the topic is the work done by Scholz-Reiter et al. (2011). They found that the main cause of installation delays are bad weather conditions. As a mean of handling this problem, they suggest a mathematical model using mixed integer linear programming (MILP). It calculates the optimal installation schedule by observing different weather conditions, with the goal of reducing vessel operation times.

Both Sarker and Faiz (2017) and C. A. Irawan, Dylan Jones, and Ouelhadj (2017) have suggested methods to optimize the installation of offshore wind farms. Sarker and Faiz (2017) try to minimize costs by an optimum selection of variables of transportation and installation operations, exemplified by the level of pre-assembly and their rated power output. The results show that the total cost is significantly impacted by the turbine size and its level of pre-assembly. Similarly, C. A. Irawan, Dylan Jones, and Ouelhadj (2017) use bi-objective optimization in order to account for two potentially conflicting objectives; installation cost and completion period. They develop a mathematical model using integer linear programming (ILP), testing the model on two sets of data. The results show that some cases produce an optimal solution.

As the installation of an offshore wind farm involves a considerable level of uncertainty regarding weather conditions, simulation has been introduced to account for this stochastic nature. Barlow et al. (2018) introduce a mixed-method optimization and simulation framework as a decision support for offshore wind installation. The optimization tool identifies the optimal sequencing of the operations, while the simulation tool determine robust start-dates regarding seasonality. Similar work is performed by Rippel et al. (2019), but instead trying to incorporate uncertainties of weather predictions into the planning by estimating expected duration of offshore operations. Their result show increased efficiency of generated plans.

3.3 Position in Existing Literature

As previous sections have introduced, some works have been done on cost reduction and optimization of offshore wind farms. Furthermore, a substantial number of works have been done on optimization of offshore wind farm installations. However, literature on the use of optimization for planning of floating offshore wind installations is, as far as known, scarce. This work will serve as a decision support for selecting optimal schedule and fleet for the installation of floating offshore wind farms, which is currently not existing in academia.

Chapter 4

Offshore Wind Farm Installation and Fleet Development

This chapter presents the installation steps of a floating offshore wind farm with its associated technical and functional requirements. Additionally, an investigation of potential vessels for the operations will be presented.

4.1 State of the Art Installation

The installation processes used to build offshore wind farms has this far been greatly influenced by practice in the oil and gas industry. The vessels used in the pilot offshore wind installations have been mostly adapted from similar industries. Equinor, originally an oil and gas company with offspring from Norway, has been a pioneer in the floating offshore wind market. Starting with the commissioning of Hywind Scotland in 2017 (A. Equinor 2019).

4.1.1 Hywind Scotland Installation

The installation of Hywind Scotland consists of a series of steps involving collaboration between multiple companies and actors. These include everything from suppliers of small subparts to huge shipbuilding contractors. The collaboration and company constellation is essential for a cost efficient and smooth launching.

The Hywind Scotland installation can easily be divided into ten steps. A sequential strategy, installing one turbine at a time, was selected for the Hywind Scotland project. The main operations associated with each turbine installation can be found in Figure 4.1, and can be understood as a circle, starting every time a new turbine is installed (Nedrevåg 2020).

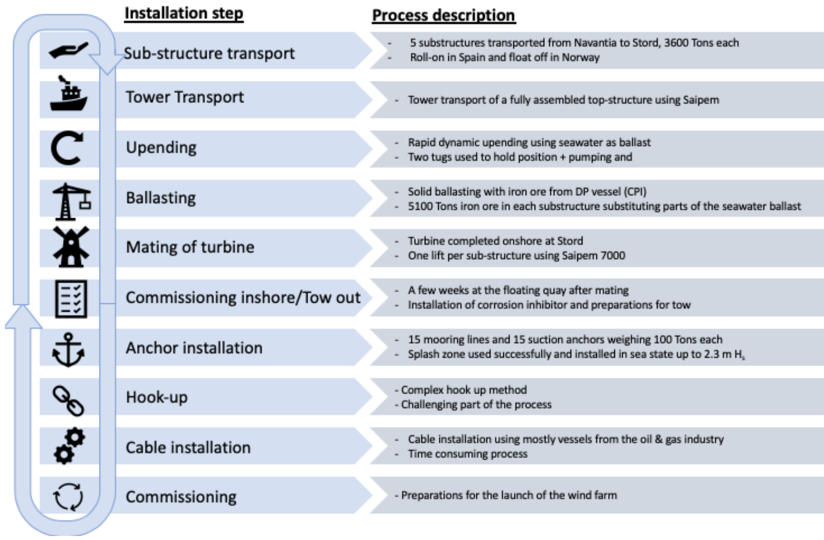


Figure 4.1: Hywind Scotland installation overview

In Hywind Scotland, both top- and sub-structures were produced in Navantia, Spain, by a Spanish state-owned shipbuilding company. They were then transported to Stord for upending, ballasting and mating of turbine. These steps were very challenging and required huge and expensive vessels for installation (N. Equinor 2017).

Before transportation of the fully assembled wind turbine, a thorough preparation and commission process inshore was completed. At site, the turbine was hooked up with a pre-installed anchor system. The anchors were produced in Scotland and installed by TechnipFMC at site (N. Equinor 2017). The hook-up process is especially challenging and sensitive to harsh weather. However, it is relatively quick and was done without huge challenges.

The last two steps involve cable installation and commissioning of wind turbines. The cable installation vessels are well optimized from the offshore oil industry, and is suitable to use for cable installations in offshore wind as well. This process can thus be considered relatively well optimized. Table 4.1 gives an overview of the major steps in the installation of Hywind Scotland, with corresponding time estimates, vessels involved and challenges specific for the steps.

Table 4.1: Hywind Scotland installation

Step	Time estimate	Vessels used	Challenges
Sub-structure transport	3 rounds (4-5 days/way)	Albatross (Roll-on/off)	Space for transport equipment. Water depth and ballasting when loading the vessel. Structural integrity during transport.

			Avoid clashing when floating off. Large sea fastening scope (380 Tons).
Tower Transport	Approx. 4 hours	Saipem 7000	Very sensitive to wind and waves.
Upending	Approx. 8 hours	Two tugs Union Manta (Chain inst. vessel)	Difficult to hold position.
Ballasting	Couple of hours	Nordnes (Crane vessel) UR7 (Barge) BB Lifter (Inshore vessel)	Clogging experienced at first attempt. Water injection and lower. Simultaneous discharge of ballast water.
Mating of turbine	1 day/ turbine	Saipem 7000	Very sensitive to wind and waves.
Commi-ssioning inshore	Couple of weeks	BB Lifter BB Server Smitbarge 6 (Barge) Mariner (Inshore)	Unpredictable tasks may appear.
Tow out	Approx. 2 days	Union Lynx Union Manta	Weather sensitive.
Anchor installation	Approx. 6 hours	Deep Explorer	
Hook-up	Approx. 1 day	Norman prosper Norman Ranger Olympic Poseidon	Often located in challenging weather conditions. Difficult operations
Cable installation	Couple of weeks	Siem Moxie	Time consuming process
Comm-issioning	Couple of days		

4.1.2 Hywind Tampen and Future Installations

As industries gain experience and make new technological movements, the designs and project manufacturing tend to promote optimality. History shows that the biggest progressions are made in the infancy of the industries, which is expected to happen also for floating wind application. Hywind Scotland is considered to be the first floating wind farm in the world, and is thus a basis for further improvement in upcoming projects. Hywind Tampen and future installation processes are expected to somewhat deviate from the installation of Hywind Scotland, in order to reduce installation costs.

In Figure 4.2, an overview of the expected development of the installation of floating wind farms is presented. In Hywind Tampen, the sub-structure is made of concrete, and will be produced in port using a technique called sliding framework. The concrete casting is formed continuously using jackets or specialized devices. The method is particularly useful for tall structures and was frequently used in the construction of concrete platforms (Thue 2019).

As a result of the method introduced above, some of the installation steps present in Hywind Scotland is eliminated. Transportation of tower to assembly site, upending and ballasting is no longer necessary. These steps will be done in port (Nedrevåg 2020).

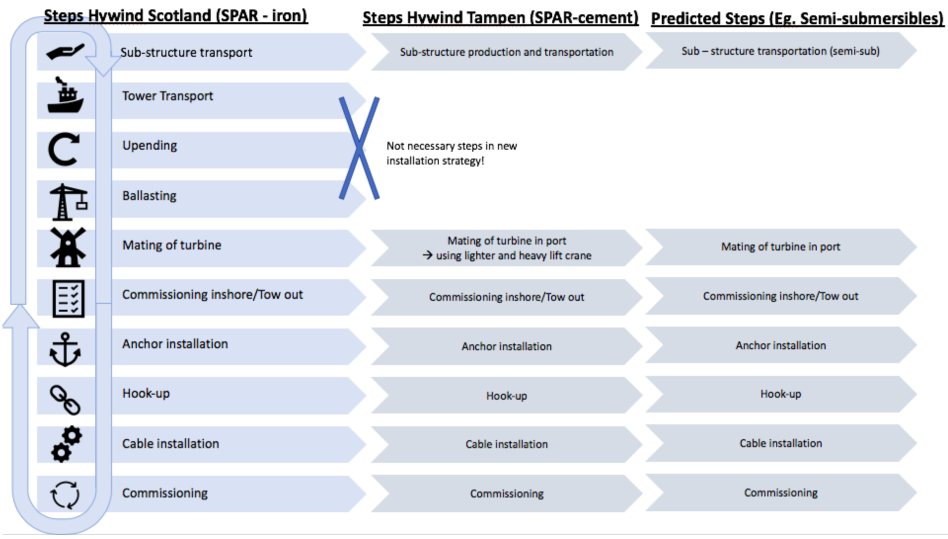


Figure 4.2: Future projects installation overview

For future floating offshore projects, the installation process consists of eight major steps. These are reflected in the Hywind Tampen installation, and will also make up the basis for the optimization models explored in later chapters.

4.2 Installation Steps as a Basis for the Model

Based on the trends and development for installation of floating offshore wind farms, an optimization model investigating decision parameters for the installation process will be developed. It should help to provide a suitable fleet and schedule for the installation. The first iteration of the model will look at a specific installation schedule, and find an optimal fleet. As a basis for the installation plan, the planning of the installation of Hywind Tampen will be used. The steps are summarized in Table 4.2.

Table 4.2: Vessel requirement in operations

No.	Operation	Location
1	Substructure transport	Production location → Port of assembly
2	Turbine Assembly	Port
3	Tow out	Port → Farm site
4	Anchor transportation	Production location → Farm site
5	Anchor installation	Farm site
6	Hook-up	Farm site
7	Cable installation	Farm site → Electricity grid hook-up
8	Final commissioning	Farm site

In the next sections, a detailed investigation of the eight operations will be presented.

4.2.1 Sub-Structure and Parts Transportation

This step includes the transportation of components and sub-structures to the port of assembly. Depending on the strategy, these components might be made on the same location or delivered by multiple actors located in different ports (Sarker and Faiz 2017). Thus, the transportation vessels visit at least one port per round trip. Figure 4.3 gives an overview of the steps involved.

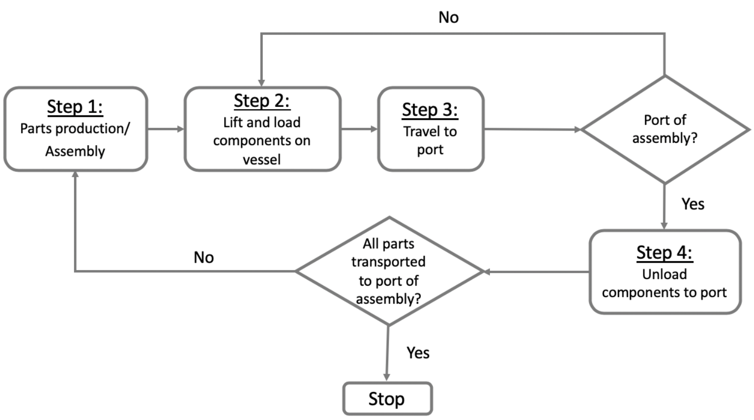


Figure 4.3: Transportation of components cycle

The main factors influencing the vessels needed for the transportation tasks involve:

- **Size of wind turbine:** Reflects the dimension of the turbines to be installed. The required size of the transportation vessels often increases with wind turbine size.
- **Level of assembly:** Decides the size of the combined structure to be transported. In general, the number of trips required increases with the level of assembly (Sarker and Faiz 2017).

- **Installation strategy:** Refers to the type of transportation including either self floating or dry transportation.
- **Turbine number:** The number of turbines or turbine components being transported per cycle is evident for required size of the transportation vessel.

4.2.2 Turbine Assembly in Port

There are many options for turbine installations. The turbines consist of multiple components typically delivered by several actors. The individual components normally consist of a nacelle, a hub, three blades, and at least two tower sections. These parts are put together in port of assembly and attached to the sub-structure before it is towed to site. The planning and time frame of the assembly is considered to be a function of the number of required lifts. Figure 4.4 illustrates the number of lifts required in port, before the entire structure is attached to the sub-structure.

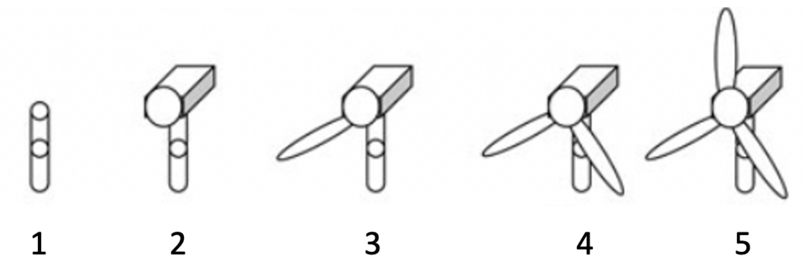


Figure 4.4: Lifts in turbine assembly

Rising the fully assembled top-structure is the limiting lift of the operation. This is the heaviest lift and the selected crane must meet the dimensions and capacity requirements for this step. Table 4.3 summarizes the required lifts of the assembly operation, with corresponding approximate weights based on the structure used in Hywind Scotland.

Table 4.3: Overview lifts based on Hywind Scotland (A. Equinor 2019)

Lift Number	Lifted Component	Weight of Lift (Approximate values)
1	Tower section	167.5 tonnes
2	Nacelle + Hub	100 tonnes
3	Blade No. 1	25 tonnes
4	Blade No. 2	25 tonnes
5	Blade No. 3	25 tonnes
6	Top structure	800 tonnes

4.2.3 Tow Out

Towing operations are non-routine operations of a limited defined duration and shall be designed to transport an object from one **safe condition** to another. It is common to classify the towing operations as either weather restricted or unrestricted. For weather restricted operations the weather forecast must be within certain limits for a certain time period, referred to as reference time (K. Larsen 2019).

$$T_R = T_{POP} + T_C \tag{4.1}$$

In equation 4.1, T_{POP} is defined as the planned operation period based on the planned schedule for the operation. T_C is the contingency time covering general uncertainty in T_{POP} and possible situations and weather sensitive operations that require additional time to complete the operations.

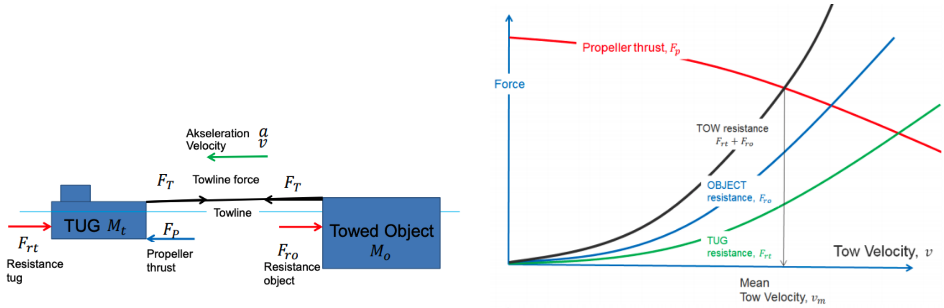
Expected duration of an operation relies on the expected weather condition for a specific period and location. The likelihood that an operation can be executed is based on the persistence of the weather, and the expected time below or above the operational criteria. Calms, notated τ_c, are periods with weather conditions better than the operational criteria. Storms are notated τ_s and represent time periods with weather worse than the operational limit. Based on the occurrence and duration of the calm periods, an estimate of the operability of an operation can be made. The best hindcast data base for the Norwegian continental shelf is the Norwegian hindcast data base, NORA10. The data base gives wind and waves every 3 hour for the whole Norwegian continental shelf (K. Larsen 2019). However, accounting for weather uncertainty is difficult in an optimization model, and simulation should be used to account for such uncertainties. The weather aspect of the installation will thus not be further investigated in this master's thesis.

The preferred towing arrangement, layout and procedure depends on the transported object and the course of the transportation. Inshore towing has stricter requirements than similar towing in open sea (DNVGL 2015). Table 4.4 shows multiple common towing configurations used in the offshore industry. The normal configuration refers to one tug towing one object, while parallel towing indicates two or more tugs in parallel. Double towing is a strategy where two towed objects is connected to the same tug, but with separate towlines. One of the towlines is sufficiently long to pass below the first object. Lastly, serial tow tugs two objects in series.

Table 4.4: Typical towing configuration (DNVGL 2015)

Tugs		**Objects**		
No.	**Position**	**No.**	**Position**	**Towing strategy**
1	NA	1	NA	Normal
2 or more	Parallel	1	NA	Parallel
2	Series	1	NA	Serial
3 or more	Series	1	NA	Serial
1	NA	2	Parallel	Double

Studies show that the resistance on the towing clearly depend on the speed and the towing configuration (Hyland et al. 2014). Figure 4.5b shows the relationship between forces displayed in Figure 4.5a and speed. The resistance on the structure increases with the square of towing velocity.



(a) Illustration of normal towing configuration (K. Larsen 2019)

(b) Resistance towing

Figure 4.5: Towing configuration and resistance (K. Larsen 2019)

Until now, parallel towing has been the most common strategy within offshore wind. For the towing of the wind turbines to site, it is assumed that parallel towing is used. This is also the strategy that will be used in the optimization model presented later.

4.2.4 Hook-up at Cite

After anchor installation is done, the hook-up of the turbine can start. The pre-installed mooring lines are attached to a buoy, which can easily be accessed when attaching the wind turbine to the anchor system. The process requires 2-3 vessels, and the buoy serves as the basis for the location of the wind turbine. Diagonally opposite lines are tensioned together to avoid significant movement of the buoy. When the line stiffening is completed, the lines are locked off and the winches moved to the next pair of diagonal lines. The precision of the location is more important for offshore wind turbines than for oil platforms as they typically are a part of a farm (Tong 1998).

4.2.5 Anchor Installation and Transportation

In contrast to conventional floating systems seen in oil & gas production, floating offshore wind towers are deployed in farms covering wide areas. This adds complexity to the mooring system required for an offshore wind farm. It also rises possibility for cost savings as multiple towers can be connected to one anchor (Diaz et al. 2016). According to Diaz et al. (2016), each turbine should ideally be attached to four anchors in case of an anchor failure. In the case of three anchor attachments, the failure of one could result in six unusable turbines. Thus, the multi usable anchors provide cost efficient solutions, but does also result in higher safety precautions. Examples of alternative anchor configurations can be seen in Figure 4.6.

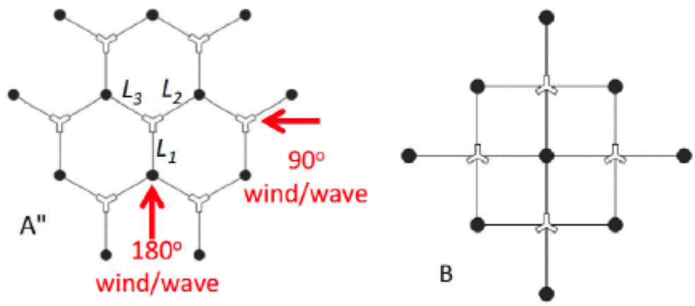


Figure 4.6: Potential wind farm configurations (Diaz et al. 2016)

Design Criteria

The most common deep water mooring systems are either vertically loaded plate anchors or suction caissons. However, a number of other systems have proven to be efficient, exemplified by suction embedded plate anchors (Zook and Keith 2009) or dynamically installed anchors (Brandão et al. 2006). In the selection and design phase of the mooring system some factors are of major interest:

- **Soil conditions** should be considered when designing mooring systems. Sea floor soil vary greatly between locations. In areas with weak compressible sediments, pile structures have historically been the preferred design. These areas are found many places, for example in the Gulf of Mexico. In the North Sea, the soils are primarily stiff clays and sands. These grounds are typically able to support massive structures with shallow foundations because of the high shear stresses present on the sea floor. Lastly, collapsible calcareous soils are common on the sea bed. These conditions require special designs and are commonly found in areas around Australia. Example of designs are drilled and grouted piles (Aubeny, Murff, and Roesset 2001).
- **Load orientation** is more or less important depending on anchor design. Adapting to a design with multiple mooring lines connected to an anchor is straightforward in the case of vertical axis symmetry. By contrast, plate anchors are design with preferred mooring line direction precluding simple mooring line attachments. Despite this obstacle, multi line designs are still possible by adding the mooring lines to an intermediary load ring transmitting the load to a certain direction on the plate anchor (Diaz et al. 2016).
- **Efficiency** including the trade off between capacity and weight. Additionally requirements regarding anchor handling vessels (AHV) and equipment are of special interest.
- **Precision of positioning** is more or less crucial depending on the importance of stable location.
- **Installation cost** varies depending on the mooring design and installation method.
- **Sustained loading performance** includes the mooring systems ability to maintain its mooring location and strength.

Anchor Designs

The anchor designs have varying costs, installation methods, efficiencies and sustainability. The most common anchor categories used in deep water mooring systems are listed below.

- **Pile anchors:** These anchors can be installed by driving, suction or free fall through the water column (Diaz et al. 2016). This category includes Driven Piles, Dynamically Installed Piles (DIP) and Suction Caissons.
- **Anchor plates installed by dragging:** These anchor plates are installed by dragging with a chain or wire line, exemplified by drag embedded anchors (DEA) and vertically loaded anchors (VLA)(Diaz et al. 2016).
- **Direct embedded plate anchors:** This category include dynamically embedded plate anchors (DEPLAs), suction embedded plate anchors (SEPLAs), and pile driven plate anchors (PDPAs). They are installed using direct embedment (Diaz et al. 2016).

Figure 4.7: From left: Pile anchor (suction caissons); Anchor plates (DEA); Direct embedded plate anchor (SEPLA) (Diaz et al. 2016)

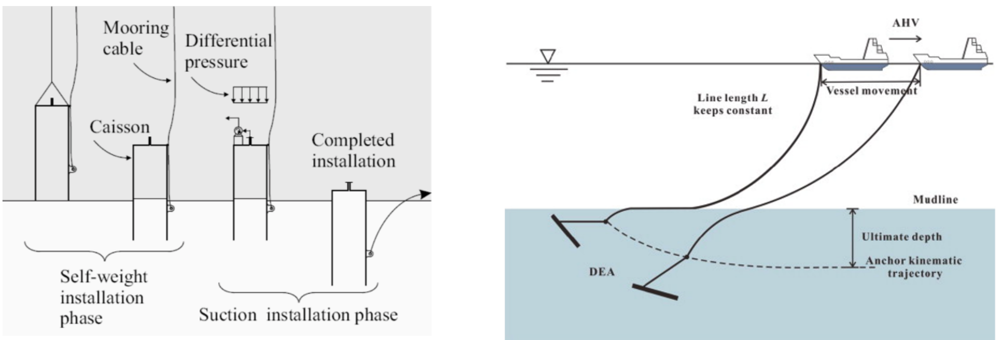
Installation Process

The anchor installation process have small variations depending on the design of the anchors. Some of the a anchor designs have specific equipment requirements, which is summarized in Table 4.5. However, the number of vessels needed in the installation process is the same.

Table 4.5: Anchor characteristics (Diaz et al. 2016) (Forrest, Taylor, and Bowman 1995)

Class	Type	Transportation	Costs	Equipment	Requirement
Pile Anchors	Driven Piles	Big deck area requirement	High	Working platform	Diverse foundation possible
	DIP		Low	Minimal equipment	Medium diverse foundation
	Suction Caissons	Large transport vessel, repeated vessel trips	Medium	Minimal equipment	Homogeneous clays & sands

Anchor plates (dragged)	DEA		Medium	Vessel for dragging	Flexible precision
	VLA		Medium	Vessel for dragging	Soft clay soil profiles. Difficult with multiline.
Direct embed-ded plate anchor	DEPLA/ SEPLA	Small deck area and DWT	Medium	Minimal equipment	Soft clay soil profiles
	PDPA	Small deck area and DWT	Medium	Installation Platform	Any soil type: soft clay, stiff clay or sand.



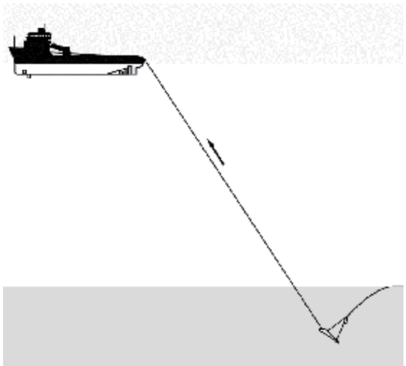
(a) Suction caisson (Malhotra 2007)

(b) DEA (Wang et al. 2014)

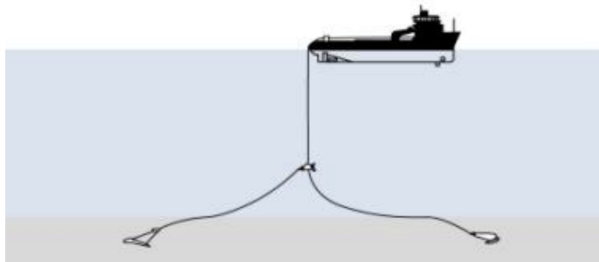
Figure 4.8: Examples anchor installation

It is found that the relevant capacities for the choice of vessels in the anchor installation includes deck area and bollard pull. The AHV must be able to pull the necessary length of mooring line out to the position where the anchor should be placed. Similarly, the chosen AHV must have a winch capacity to pull the anchor loose from the seabed. Furthermore, the vessel transporting the anchor must have sufficient DWT capacity to carry the anchors.

The installation of mooring systems related to offshore wind need at least two AHV at a time. Typical installation procedure involves installing opposite anchors simultaneously to obtain equal tension on the lines. This can be done either with the novel stevtensioning solution or by using two separate AHVs. Figure 4.9a illustrates how one anchor installation is done, while Figure 4.9b depicts the installation to anchors simultaneously.



(a) Single anchor installation



(b) Double anchor installation

Figure 4.9: Examples anchor installation (Diaz et al. 2016)

4.2.6 Cable Installation

General on Cables and Umbilicals

Cables are one-dimensional structures being inherently flexible. They tend to have a high slenderness, aspect ratio and relatively low bending rigidity. The cable concept can often be classified as structural cables, signal cable and power cables. Structural cables are typically used in lifting operations, while signal cables carry different types of signals. Power cables consist of power conductors made of metal wires (Sævik 2019). Within the offshore wind industry, umbilical cables are typically used; consisting of multiple cables supplying requires consumables to an offshore wind farm (Srinil 2016). The electrical transmission system for offshore wind farms includes:

- **Inter-array:** Links multiple wind turbines to an offshore collector platform to gather generated electricity before transferring to onshore facilities (Srinil 2016).
- **Inter-platform:** Usually, a number of offshore collector platforms are needed to gather power from wind turbine generators. These platforms are connected with an inter-platform cable. This is done to reduce the energy loss during transportation to onshore facilities (Srinil 2016).
- **Export cables:** These cables efficiently transport the generated wind power to onshore facilities, and are usually much longer than both inter-array and inter-platform cables (Srinil 2016).

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Figure 4.10 displays configuration of the cables usually present at an offshore wind farm.

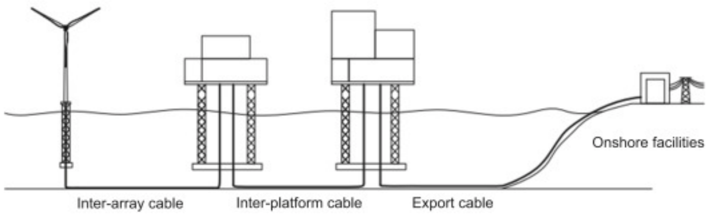


Figure 4.10: Offshore wind farm cables (Kaiser and Snyder 2012b)

Cables made of composite materials have associate key design mechanical parameters including outer diameters, dry and submerged weights, lengths, axial and bending stiffness, and end connections. These parameters are chosen based multiple factor like physical characteristics of wind farm site, environmental conditions and distance from shore (Srinil 2016).

Cable Installation

Cable installations are normally done using a J-lay strategy. This method was developed to enable deep water cable or pipeline installations. The cable is held in an almost vertical plane allowing it to exit the vessel with small bending curvatures. The optimal cable-laying solution depends on the size and length of the cable. Possible options include reels, carousels and winches to bundle the cables (Worzyk 2009).

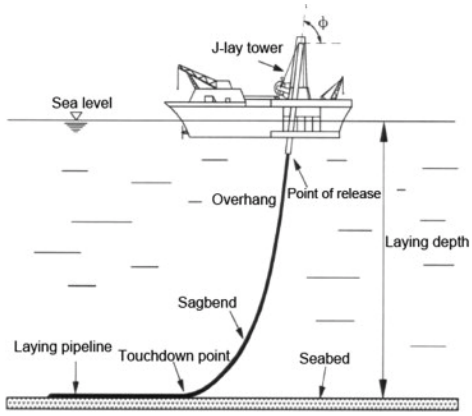
There are several cable installation methods common in the offshore wind industry. They include:

1. *Simultaneous lay and bury.* This process is normally done using a plow being pulled by a cable laying vessel or barge. The plow buries the cable below the seabed surface, usually in a trench of approximately 2 m depth. This is done using a high pressure water jet which fluidizes the mud or sand present at the sea floor. This is the most common cable installation method, especially for export cables (Kaiser and Snyder 2012b).

2. *Pre-excavate.* Pre-excavation can be done using a backhoe dredge, followed by laying the cable in the trench using a cable laying vessel. Lastly, the trench is filled with the dredge (Kaiser and Snyder 2012b).

3. *Lay and trench.* A cable laying vessel is used to lay the cable, while a ROV does the trench work (Kaiser and Snyder 2012b).

(a) ROV used for trenching in cable installations (Kaiser and Snyder 2012b)



(b) J-Lay (Q. Bai and Y. Bai 2014)

Figure 4.11: Cable installation

The cable installation require a cable installation vessel. The additional equipment required depends on the type of laying strategy; either in need of a ROV, a dredge or a plow.

4.2.7 Final Commissioning

Final commissioning refers to the activities after all components are installed, but before commercial power production starts. This includes turbine and cable inspection, electrical testing and quality control of relevant activities. Furthermore, the communication system is tested for secure and efficient communication from onshore (Kaiser and Snyder 2012b).

4.3 Fleet Development

4.3.1 System Outline

As described by Equinor (Nedrevåg 2020), the fleet for a typical installation of a floating offshore wind farm comprise the following:

1. Tug Vessels
2. Transportation Vessels
3. Anchor Handling Vessels
4. Cable Laying Vessels

Towing vessels are used to tow the fully assembled wind turbine from port to site. Depending on the design of the sub-structure, the towing vessels can also tow the sub-structure from production site to port of assembly. Lastly, the vessels can be used in the final commissioning process. The transportation vessels are used to transport the individual turbine components to port of assembly. Anchor handling vessels are mainly used for anchor transportation and installation, but can also assist in the hook up and final commissioning. Lastly, cable laying vessels are essential in the cable installation connecting the wind farm to the onshore grid. Figure 4.12 illustrates the main components of the system.

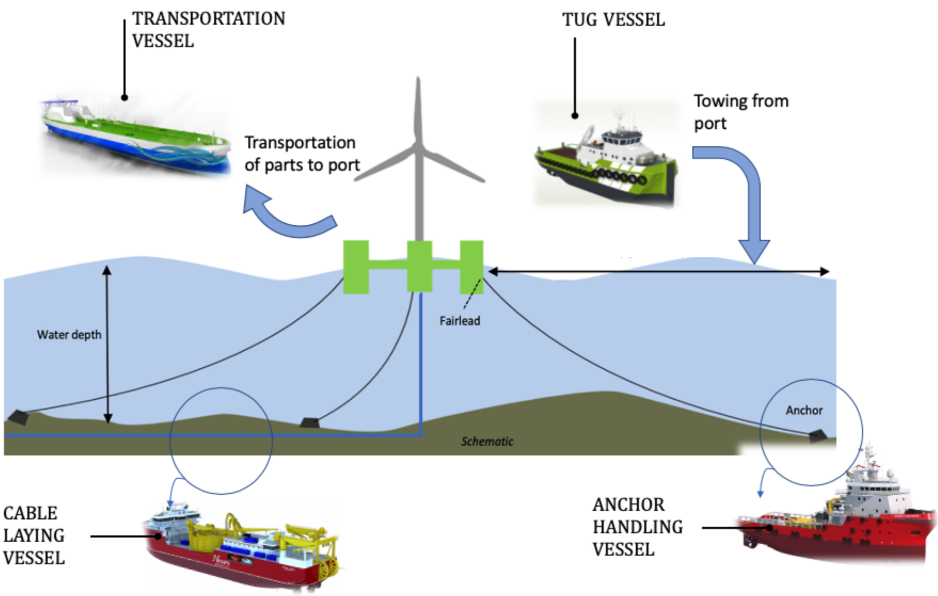


Figure 4.12: Overview of installation system

Table 4.6 gives an overview of the requirements for the operations. This helps to identify a suitable fleet for the installation. The parenthesis indicates that the equipment could be required either because it is necessary for the operation method or because it makes the operation easier. Furthermore, it is assumed that there is no crane requirements for the transportation operations as they are loaded by cranes fixed in the ports. The estimates are approximate and based on common values from previous projects (Houlsby and Byrne 2000).

Table 4.6: Set of operations and their requirements

	Requirements			
	ROV	Deck space $[m^2]$	Crane [tonnes]	Cable lay Equipment
Transportation Substructure	No	500-1,000	0	No
Turbine Assembly	No	0	$>$800	No
Tow Out	No	0	0	No
Anchor Transportation	No	200-800	0	No
Anchor Installation	(Yes)	200-800	50-300	No
Hook-up	(Yes)	0	0	No
Cable Installation	(Yes)	1,000-2,500	0	Yes
Final Comm.	No	0	0	No

Table 4.7: Estimated spread and operation capability for vessel types

	Tug Vessel	Transportation Vessel	Anchor Handling Vessel	Cable Laying Vessel
Transp. Substruct.	(✓)	✓	-	-
Turbine Assembly	-	-	-	-
Tow Out	✓	(✓)	(✓)	-
Anchor Transp.	-	✓	✓	-
Anchor inst.	-	-	✓	-
Hook-up	-	-	(✓)	(✓)
Cable Inst.	-	-	-	✓
Final Comm.	(✓)	-	(✓)	(✓)

Table 4.7 summarizes the vessels ability to perform the needed installation steps. Parenthesis indicates that the vessel can assist, but not perform the operation alone. Alternatively, it indicates that the vessel need spread vessels or additional equipment to perform the task. These requirements depend on the chosen installation strategy.

4.3.2 Towing Vessels

Offshore Support Vessel (OSV) is a category of vessels used to serve the offshore industry. There are three main types, namely Platform Support Vessels (PSV), Anchor Handling Tug Supply vessels (AHTS) and Offshore Construction Vessels (OCV) (Erikstad and Levander 2012). The vessels used to tow the offshore wind constructions are often AHTS vessels, as they have strong bollard pull and winch pull capacities. Additionally, there are multiple regular offshore support tugs on the market, supporting the towing operation. A common supporting vessel is the Offshore Support Tug (OST). It is a common practice to use a combination of AHTS vessels and support tugs. Parameters influencing the choice of vessels includes maximum bollard pull, deck area, winch pull, total power and maneuverability. A portfolio of potential vessels are listed in Table 4.8.

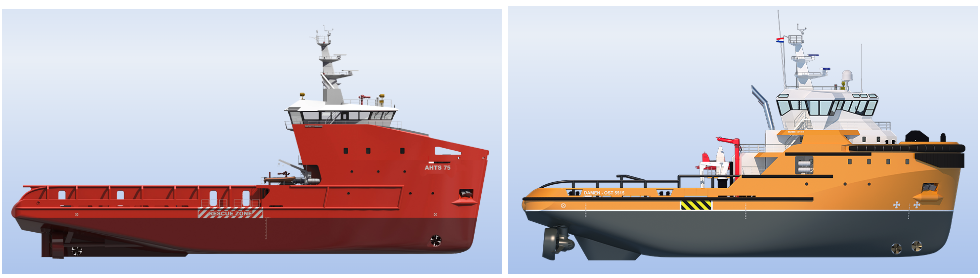
Table 4.8: Damen tug vessels portfolio (Damen 2020)

Type	Name	Max Bollard Pull [tonnes]	Deck Area [m^2]	Total Power [bkW]
Offshore Support Tug	5515	120	290	7680
	4523	80	200	5600
	4914	100	210	6368
AHTS	120	120	-	7,000
	180	180	-	10,500
	200	200	-	13,500

- **Anchor Handling Tug Suppliers (AHTS):** AHTS have a very characteristic design. This is because of their specialized, yet various operations they are designed to perform. They are normally used for placing platform anchors in the right position, relocating them or recovering them. However, towing of big constructions does also require high pulling force and AHTS vessels are well suited for such operations.

  An AHTS has a very large after deck. The starboard and port side of the after deck are normally enclosed by barriers protecting both crew and equipment from the sea. This is because the after deck is close to sea level and thus exposed to weather. However, the open stern allows easy access and employment of towing ropes and anchors.

- **Offshore Support Tug (OST):** These vessels are typically smaller than the AHTS vessels, and are often used to assist the bigger vessels in the towing operations.



(a) AHTS

(b) Offshore support tug

Figure 4.13: Examples tug vessels (Damen 2020)

4.3.3 Transportation Vessels

Within the offshore wind industry, most of the components are voluminous and heavy. The blades, towers, nacelles and substructures are all heavy components. Thus, most of the relevant transportation vessels are typically heavy load carriers (OffshoreWIND 2018). They normally enhance high lifting capacity and have big carrying ability. Some heavy load carriers are presented in Table 4.9.

Table 4.9: Heavy load carriers portfolio (VesselFinder 2011)

Name	**DWT [tonnes]**	**Deck Area $[m^2]$**	**Max. lifting capacity [tonnes]**
Siem Topaz (Siem Offshore Rederi AS)	7,473	813	150-250
Siem Spearfish (Siem Offshore Rederi AS)	8,878	1,350	250
Eems Dublin (Amasus Shipping)	6,170	1,376	n/a
Jaguar (Amasus Shipping)	6,170	1,376	n/a
Rotra Vente (Amasus Shipping)	8,817	1,899	Bow-Ramp

(a) Eems Dublin

(b) Jaguar

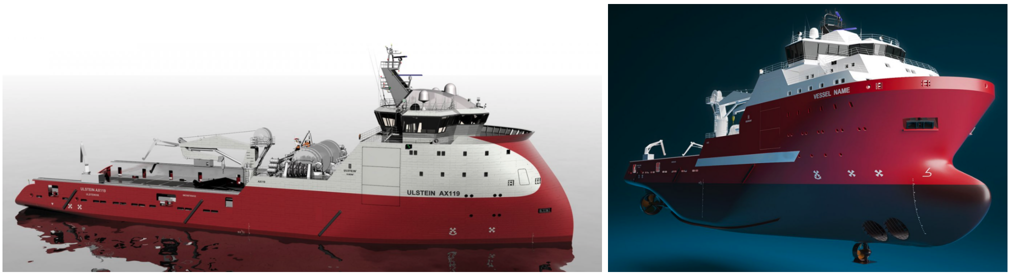
Figure 4.14: Examples transportation vessels (VesselFinder 2011)

4.3.4 Anchor Handling Vessels

The anchor installation operation have different requirements depending on chosen anchor design. Key requirements include DWT, deck area, speed and bollard pull. Table 4.10 displays a selection of appropriate AHV options for an anchor installation.

Table 4.10: AHV examples (Ulstein 2020)

Name	**DWT [tonnes]**	**Bollard Pull [tonnes]**	**Speed [kn]**	**Deck Area $[m^2]$**
A133 (Ulstein)	2,000	120-160	15	450
AX119 (Ulstein)	4,200	210-260	17	720
AX128 (Ulstein)	6,200	350-420	18	1030



(a) Ulstein AX119 **(b)** Ulstein AX128

Figure 4.15: Anchor handling vessels (Ulstein 2020)

Often times AHVs are used for towing operations, depending on availability and prices in the market. AHVs are considered expensive for in many towing operations as less strong vessels can do the job. However, practicalities and transportation costs might favor AHVs.

4.3.5 Cable Laying Vessels

Cable laying vessels make up the foundation of the cable installation process. They are available in all sizes and with all kinds of equipment. CLVs are considered relatively optimized as a variety of offshore industries have made use of the vessel, triggering competition and improved solutions (Worzyk 2009).

Cable installations have made great changes over the last decades, significantly increasing the laying rate (Q. Bai and Y. Bai 2014). Factors to be considered when selecting a cable laying vessel include:

- Load carrying capacity
- Manoeuvrability properties
- Deck space for cable handling equipment
- Sea-keeping properties

Load capacity should be as high as possible to avoid numerous risky cable joints. Depending on the cable, the diameter, length or weight could be the limiting factors when determining the load capacity (Worzyk 2009).

Every cable laying vessel must be able to position them self accurately on the desired direction of the cable. Furthermore, it must be able to move without loosing position control. Some CLVs are equipped with Dynamic positioning (DP) systems allowing high-sophisticated navigation system, keeping the position and heading of marine structures (Morgan 1978). It is expected from the DP system that it stays within pre-specified excursion limits under weather expected for a particular area (Hassani et al. 2017).

Many cable laying activities are only possible with the assistance of ROV equipment. This is especially the case for a lay and trench strategy (Kaiser and Snyder 2012b). The overall mechanical design of an ROV is driven by the tasks it should be able to accomplish. It is equipped with different manipulators and tools; which can include a camera, sensor, manipulator and tools to the worksite. Needless to say, the payload must be integrated with the vehicle and typically operated from aboard the CVL (Christ and Wernli 2007).

(a) Cable Laying Vessel (Nexus; Von Oord)

(b) ROV with grip manipulators and cameras (Worzyk 2009)

Figure 4.16: Cable laying system

The turntable or carousel stores the cables in a vertical axis, typically being loaded in horizontal layers starting from the bottom. Some vessels even have two turntables, efficiently installing two cables simultaneously.

Typical devices needed in a cable installation includes cableways, rollers, laying and pick-up arms, chutes, and laying wheels. The composition of equipment must be selected for each specific installation job in order to meet the requirements for the cable installation strategy (Worzyk 2009).

Cable Laying Vessel Portfolio

Table 4.11: Cable laying vessel portfolio

Name	**Max Load [tonnes]**	**Deck Area** [m^2]	**Cable carousel [d]**	**Other**
Daniel Bernoulli (Jan De Nul Group)	4,000	-	16.80 m	Optional ROV Trencher, Workclass ROV
Isaac Newton (Jan De Nul Group)	10,000	-	27.40 m	-
Living Stone (Tideway)	2x5,000	-	-	A-frame 65 tonnes; CBT1100 trenching tool
Maersk Connector (Deepocean)	7,000	2,310	27.40 m	A-frame 60 tonnes
Nexus (Van Oord)	5,000	2,000	26.0 m	2x20 tonnes Vertical Tensioners

Chapter 5

Discrete Optimization Model for Fleet Selection

This chapter will present an optimization model providing an optimal fleet for a specific offshore wind installation schedule. This formulation will be referred to as the discrete optimization model for fleet selection (DFS). It will use the operation steps identified in Chapter 4.2, exploring the potential benefits from using an optimization model in floating offshore wind farm installations. The model presented in this chapter will provide a basis for further model expansions and improvements in the next chapters.

5.1 Model Explanation

For each operation, there are certain requirements regarding both vessel and equipment selection. Furthermore, the installations are assumed to take place within a specific time window as they sometimes are weather restricted operations. The operations are either stationary at one location or transfer operations from one site to another.

5.1.1 Operations

In this model, the transportation routes are defined as operation steps requiring a specific set of vessels. The operations include turbine assembly in port, in addition to the operations done at the offshore wind park site. The eight steps used in this optimization model are based on experience from the industry and include the following operations:

1. **Structure Transportation:** Transportation of the sub- and top-structure components from location of production to location of assembly. For Hywind Tampen, the sub-structure is produced very close to the port of assembly, while the top-structure is transported from a production facility outside of Norway (Nedrevåg 2020).

2. **Turbine Assembly:** Assembly of turbine parts. This is typically done in port using portable mega cranes hired over a longer time horizon.

3. **Tow Out:** Towing of fully assembled turbine from port to site. This is often done using three vessels; two vessels responsible for propulsion and one vessel for maneuverability.

4. **Anchor Transportation:** Transportation of anchor from production location to site.

5. **Anchor installation at site:** Installation of anchors at the site of the offshore wind farm.

6. **Hook-up:** Fixing the total wind turbine structure to the anchors at site.

7. **Cable installation:** Connecting the floating wind farm to the onshore electricity network.

8. **Final Commissioning:** Final preparations and check routines before final launching.

Figure 5.1 gives an overview of the operation steps, and their connection to the operation locations. The eight defined operations are identified with numbers.

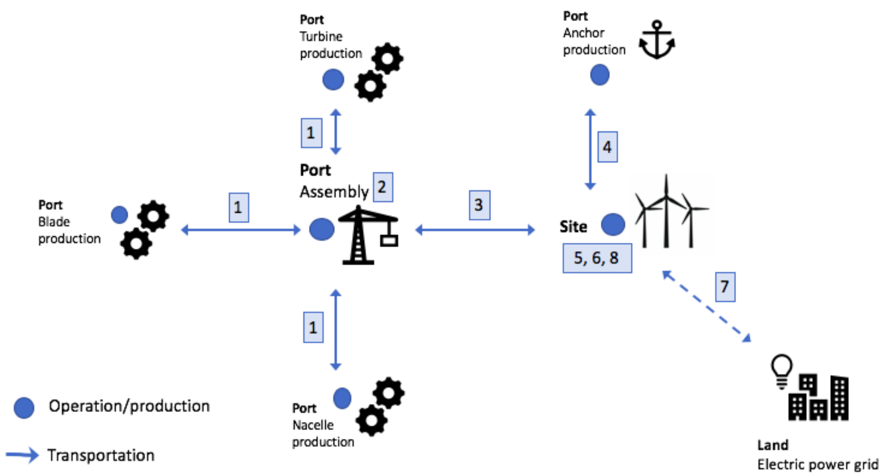


Figure 5.1: Optimization model operations

5.1.2 Time Periods

The time periods are defined according to a predefined schedule of the installation process. Each operation is assigned to a specific time period, and should be performed during this time interval. The time periods are made to reflect common charter periods within the industry. Furthermore, they are defined to reflect the different stages of the installation. The schedule associated with each turbine is divided into four natural time stages of the installation and are assumed to last approximately one week each.

- **Period 0 - Transportation phase:** This time period is characterized by transportation of turbine parts and anchors to the appropriate locations.

- **Period 1 - Transportation & onshore operations:** This phase consists mainly of transportation to port followed by assembly.
- **Period 2 - Structure transportation & Hook-up:** This stage involves transportation of a fully assembled structure and are typically more weather sensitive than the other stages. This stage does also have demanding vessel requirements, typically well equipped.
- **Period 3 - Final completion:** This stage is less sensitive to weather and includes final tasks before completion.

The initial model does only consider a predefined schedule for the time of operations. This will be modified and optimized even further in later model versions.

5.1.3 Fleet Categories

The operations require different types of vessels and equipment. In reality each operation might need multiple vessels or combination of vessels to perform a job. Operation examples where multiple vessels might be required are towing, hook-up and anchoring. For simplicity, the developed model identifies and optimizes based on the main vessel for each operation. It is assumed that with each primary vessel, the required equipment and support vessels are complementary. In practice, this means that a vessel concept is chosen based on the leading or most important vessel needed for the operation.

As a basis for fleet selection, a categorization of potential vessels are identified. Each of the categories are exemplified with vessels used in the installation of Hywind Scotland. The most central categories were earlier identified as:

1. **Anchor Handling Tug Supply Vessels (AHTS):** Used for installation of anchors. The AHTS rates normally correlate with the BHP values (Tønne and Egenberg 2020).
2. **Transportation Vessels:** These are vessels that can transport wind turbine components from production location to port of assembly.
3. **Tug Vessels:** These are naval vessels that are designed for either tugging a ship or other floating objects (Network 2019). Their bollard pulls capacity vary, and the rates typically increases with stronger BHP.
4. **Cable Laying Vessels (CLV):** Sea operating vessels designed to lay underwater cable networks (Aditib 2019).

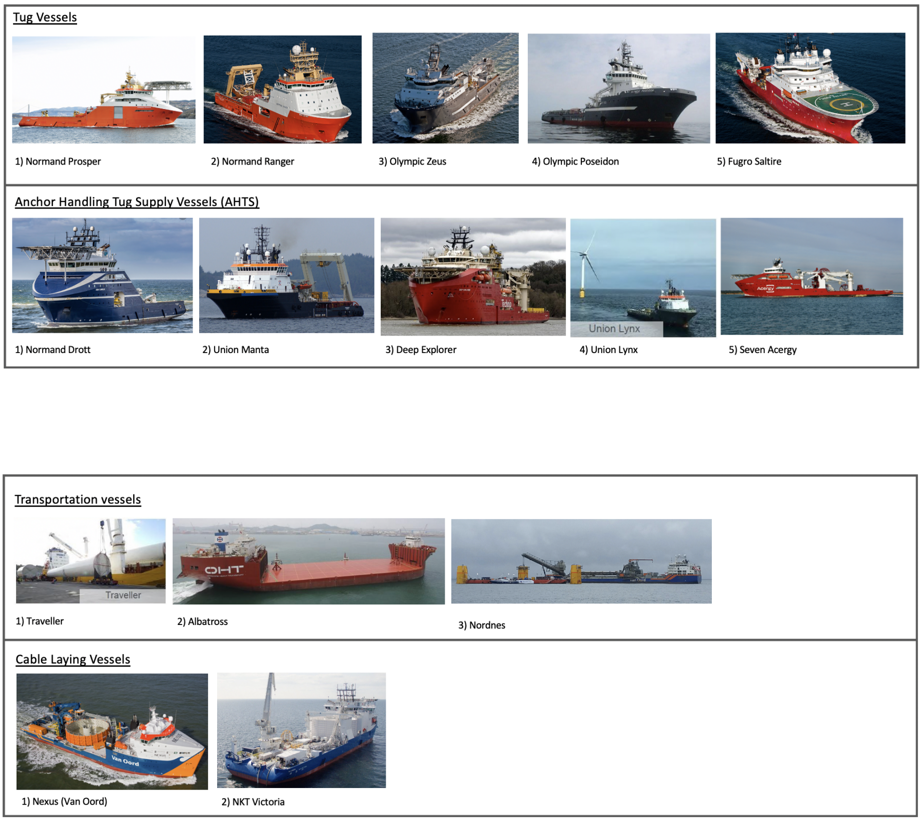


Figure 5.2: Vessel categories with examples from the installation of Hywind Scotland (Nedrevåg 2020)

5.1.4 Charter Costs

In this model, the costs associated with a vessel are divided into two groups; time charter costs and mobilization costs.

Time Charter Costs

A time charter is the hiring of a vessel for a specific time period. The charterer pays for fuel consumption, port charges and a daily hire to the owner of the vessel. The contract duration can be spot, 1-year and 3-year time charter. Time charter rates fluctuate with seasonality and market situations (Kavussanos and Alizadeh-M 2001). The time charter rates are effected by multiple factors and are prone to variations. The major cost determinants are (Sirimanne 2020):

- **Costs**: Naturally vessel owners have incentives to make profits on their vessels, meaning that the rates are often reflected by the owners costs. This can include cost of capital, cost of consumables and crewing costs.

- **Type and size of vessel**: For offshore activities, there exist plenty of sizes and types which are reflected in the rates. For PSVs, deck area often decides the rates. Similarly, AHTS vessels are often priced by both size and bollard pull. However, it is important to notice that demand and supply dynamics also drive the rates.
- **Age of vessel**: Vessel age influences pricing in various ways. The prices at the time of construction clearly influence the rates as the owners naturally want a decent return on their capital. Furthermore, newer vessels tend to have better and more efficient specs then older vessels. Naturally, this will influence the willingness to pay for the hire of a vessel. Lastly, it is reasonable to assume that newer vessels are more reliable than older vessels, minimizing the risk of downtime.
- **Duration of job**: The owners of the vessels may want longer predictability and might be willing to reduce rates in order to ensure long term employment of their assets. However, this is subjective and dependent on the strategy of the owner.
- **Market's demand and supply situation**: Demand and supply tendencies clearly apply to this industry. The willingness to pay for vessels is reflected in the prices. In poor market situations, the owner might even be willing to charter out their vessels at rates below their cost of operating because the laying up costs might be higher then employing it. However, there are also situation in which markets are so good that the owner can expect 30% margin (Jugović, Komadina, and Perić Hadžić 2015).

Time charter costs used in this model are based on historical data in the AHTS and PSV market. Detailed historical data for AHTS globally can be found as graphs in Appendix C.3.1. The shipping market is relatively volatile, resulting in greatly fluctuating markets. Thus, the total cost of the installation fleet is very much dependent on the market situation. In this case example, the prices from the last five years are used to estimate time charter rates in the optimization model. These can be seen in detail in Table 5.1. The AHTS's have BHP ranging from approximately 16,000 to 25,000, with prices in the span of 7,000£ to 10,000£ a day.

Table 5.1: Spot rates estimates for AHTS and PSV (Tønne and Egenberg 2020)

		£/day					
		Avg 2019	**Avg 2020**	**Nov-19**	**Dec-19**	**Jan-20**	**3 month trend**
	10-15,999 BHP	8,417	8,500	8,500	8,500	8,500	0.0%
	16-19,999 BHP	10,417	10,500	10,500	10,500	10,500	0.0%
AHTS	20,000+ BHP	17,833	18,000	18,000	18,000	18,000	0.0%
	500-749 m^2	7,083	7,500	7,000	7,500	7,500	4.8%
	750-899 m^2	8,938	9,500	9,000	9,500	9,500	3.7%
PSV	900+ m^2	11,521	11,500	11,500	11,500	11,500	-1.4%

As data on spot prices for cable laying vessels are not publicly accessible, PSV spot rates are considered a reasonable comparison. The rates found for PSVs will be used to make an estimation of the prices for cable laying vessels. Furthermore, tug vessel prices are assumed to reflect the prices of the AHTS, but are considered somewhat lower since they tend to be less equipped. The day rates for AHTS vessels increase with BHP capacity (Tønne and Egenberg 2020). The range of day rates estimated for tug vessels and cable laying vessels are found in Table 5.2. Notice that the rates are given in pounds, which is somewhat unusual. As the data provided by Tønne and Egenberg 2020 were given in pounds, it was considered reasonable to work with pounds as the base unit. It will therefore be the currency used throughout the work.

Table 5.2: Estimated charter cost rates for tug vessels, cable laying vessels and transportation vessels

Vessel	BHP	Area/Dwt	Day Charter Rate £/day
Tug vessels	6,000-10,000	-	7,200-8,200
Cable laying vessel	12,000-16,000	500-800 m^2	8,000-10,000
	16,000-20,000	800+ m^2	10,000-13,000
Transp. vessel	6,000-10,000	$\sim$ 25,000-45,000 dwt	8,000-12,000

The estimated time charter rates for transportation vessels are based on historical data for different sizes. The numbers are provided by Clarksons Platou and can be found in Appendix C.3.2.

An important part of the time charter costs is the fuel consumption, which vary with the size, speed and bollard pull of a vessel. The relationship between size, bollard pull and fuel consumption used in this work is presented in Table 5.3. The daily fuel costs are added to the day hire for each vessel and make up the total time charter costs. This helps to make a better differentiation between the vessels based on vessel characteristics. Appendix C.3.3 outlines the details behind these estimations.

Table 5.3: Daily fuel cost estimate ranges for different vessel categories

Parameter	Vessel	Unit	Lower	Upper	Average
Daily fuel consumption	AHTS	tonnes/day	12	16	14
	Cable laying vessel		9	11	10
	Transp. vessel		14	18	16
	Tug vessel		10	14	12
Daily fuel costs	AHTS	£/day	2,100	2,700	2,400
	Cable laying vessel		1,500	1,900	1,700
	Transp. vessel		2,300	3,100	2,700
	Tug vessel		1,700	2,400	2,000
Fuel price		USD/tonnes			214.0

Another factor influencing the time charter costs is the insurance. Normally, this is included in the hire, but might be increased if the risk associated with an operation is considered higher then normal. In this work, the insurance is assumed to be a part of the hire, and will not be further elaborated.

Mobilization Costs

Mobilization costs include all activities and associated costs for transportation of crew, equipment and operating supplies to the location of operation. In literature on offshore wind installation, there has been a general perception that the mobilization costs are high (Thresher, Robinson, and Veers 2007) (Henderson et al. 2003). When vessels are moved between operating regions, the cost associated with this movement can be considered mobilization costs. This is a reasonable assumption unless the movement is viewed as a permanent relocation of an asset to a new market (Kaiser and Snyder 2012a).

The mobilization costs can be approximated as a function of transit distance, the vessel day-rate, vessel size and type of transportation. When moving the vessel, there are two common methods; self-propelled or towing. However, the vessels suitable for installation of floating offshore wind farms are mostly self-propelled. Hence, this is the method that is assumed to be the most relevant.

In the case of self-propelled mobilization, the associated mobilization costs can be assumed to be a function of day-rate and fuel costs. The sailing distance will be the dominant factor for deciding the quantity of these contributions. For simplicity, Kaiser and Snyder 2012a, suggests a method for quantifying these contributions with Equation 5.1:

$$(\frac{X}{24V_i})(I + (1.2 \cdot 5P_i)G) \tag{5.1}$$

where X is the transit distance in miles, V_i is the speed in knots and P_i the installed power (hp). I is the installation vessel day-rate (\$/day) and G is the cost of fuel per gallon (\$/day). This estimate will be used as a base for the analysis. A detailed outline of these costs is found in Appendix C.2.

5.2 Mathematical Formulation

In this section, the mathematical formulation of the DFS model will be explained. The planning horizon is divided into time increments of equal length, well suited to capture the time dependency of the system. Notations (sets, indices, parameters and variables) will be presented, followed by an explanation of the objective function and constraints.

5.2.1 Notation

Table 5.4 presents the sets, parameters and variables used in this optimization problem.

Table 5.4: Optimal fleet and task configuration

	Sets	
V	Set of vessels, indexed v	
T	Set of time periods, indexed t	
O	Set of operations, indexed o	
	Parameters	
C_v^{TC}	Time charter cost per time unit for vessel v $\in$ V	[£/day]
C_v^{M}	Mobilization costs for starting chartering of vessel v $\in$ V	[£]
T_{vo}	Time to do operation o $\in$ O for vessel v $\in$ V	[h]
Q_{vo}	1 if vessel v $\in$ V can do operation o $\in$ O, 0 otherwise	
P_{to}	1 if operation o $\in$ O is done in time period t $\in$ T, 0 otherwise	
	Variables	
γ_{vot}	1 if vessel v $\in$ V is used in operation o $\in$ O in time period t $\in$ T, 0 otherwise	
δ_{vo}	Number of vessels v $\in$ V used in operation o $\in$ O	

Sets. In this model, three sets are made to describe the pool of elements involved in the decision process. These include the set of vessels, operations to be performed and the time periods representing the scheduled time horizon of the wind turbine installation.

Parameters. Each vessel $v \in V$ have an associated non-negative duration T_{ov}, representing the execution time for a specific operation. Similarly, each vessel has an associated C_c^{TC} and C_v^M, representing the time charter costs and mobilization costs respectively. Lastly, the operations have requirements related to equipment and execution timing, captured in C_{vo} and P_{to}.

Variables. Two binary variables are introduced to describe the installation problem. γ_{vot} equals 1 if vessels $v \in V$ execute operation $o \in O$ in time period $t \in T$, and 0 otherwise. Similarly, δ_{vo} gets the value 1 if vessel $v \in V$ is used in operation $o \in O$, and 0 otherwise.

5.2.2 Objective Function

The objective function is made to reflect the desired goal from using the optimization; minimizing the costs associated with the fleet used in wind turbine installations. It is assumed that the main costs associated with the chartered vessels are captured in the mobilization and time charter costs. Hence, these contributions should be minimized using the following objective function:

$$min \sum_{v \in V} \sum_{o \in O} C_v^M \delta_{vo} + \sum_{v \in V} \sum_{o \in O} \sum_{t \in T} C_v^{TC} T_{vo} \gamma_{vot} \tag{5.2}$$

In this model, the mobilization costs are only imposed once. This is reasonable as long as the involved vessels do not have long waiting periods between the operations. The potential unemployed time should be minimized when planning the schedule. This is somewhat difficult with this model and will be further improved in the scheduling model presented in the next chapter.

5.2.3 Constraints

Operations. A vessel can only perform one operation in each time period, which is ensured by constraints 5.3.

$$\sum_{o \in O} \gamma_{vot} \leq 1, \quad t \in T, v \in V. \tag{5.3}$$

Flow. If a vessel is used to do an operation in a time period, mobilization costs follow. Thus, δ_{vo} must be forced to 1 if a vessel is used at some point during the time horizon of the model, which is taken care of by constraints 5.4.

$$\sum_{t \in T} \gamma_{vot} \leq M\delta_{vo}, \quad v \in V, o \in O. \tag{5.4}$$

Equipment. Each operation have certain equipment requirements, and the vessel used in an operation must inhabit the needed capabilities. Hence, constraints 5.5 ensure that a vessel cannot be assigned to an operation unless it is suitable.

$$\sum_{t \in T} \gamma_{vot} \leq MQ_{vo}, \quad v \in V, o \in O. \tag{5.5}$$

Timing. Each operation is assigned to a specific time slot by the parameter P_{to}. This is imposed by constraints 5.6, assigning one vessel to an operation $o \in O$ if it is scheduled to time period $t \in T$.

$$\sum_{v \in V} \gamma_{vot} = MP_{to}, \quad o \in O, t \in T. \tag{5.6}$$

Domains. The variables introduced have associated domains where they are valid. Both variables have binary domains and are enforced by constraints 5.7 and 5.8.

$$\delta_{vo} \in \{0, 1\}, \quad o \in O, v \in V \tag{5.7}$$

$$\gamma_{vot} \in \{0, 1\}, \quad o \in O, v \in V, t \in T \tag{5.8}$$

5.2.4 Case Example

In order to analyze the model, a case example will be performed. It is assumed that one floating turbine is to be installed in the North Sea, east of Bergen, Norway. The production and assembly locations are chosen similar to what is planned for Hywind Tampen. The anchor production is located in Scotland and the top structure is produced somewhere in Europe. The assembly is assumed to take place in Gulen, Sogn og Fjordane, on the west coast of Norway (N. Equinor 2020b). Figure 5.3 gives an overview of the operation sites and transportation routes for the case example.

Figure 5.3: Case locations ports and farm site

As a preliminary analysis, two scenarios will be explored. They are characterized as follows:

1. **Scenario 1:** Will investigate the optimal fleet for the installation of **one turbine**. Figure 5.4 gives a visualization of the periods and the associated operations taking place. It is assumed that the operations can take place simultaneously, planning that operations that are prerequisites for another operation should take place at the same time. This is the case for hook-up, being dependent on completed tow out and finished anchor installation.

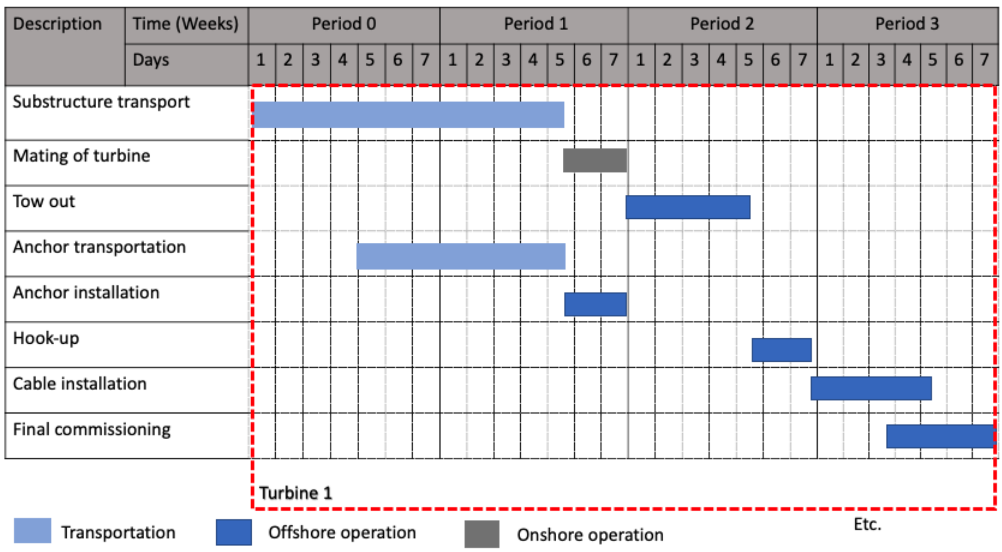


Figure 5.4: Turbine installation schedule

2. **Scenario 2:** Will look at the installation of **three turbines**. Figure 5.5 gives an overview of the planned schedule. In this example, the operations done for each turbine is consid-

ered to be sequential, installing one turbine at a time. When one operation is completed, a similar operation can begin for the next turbine.

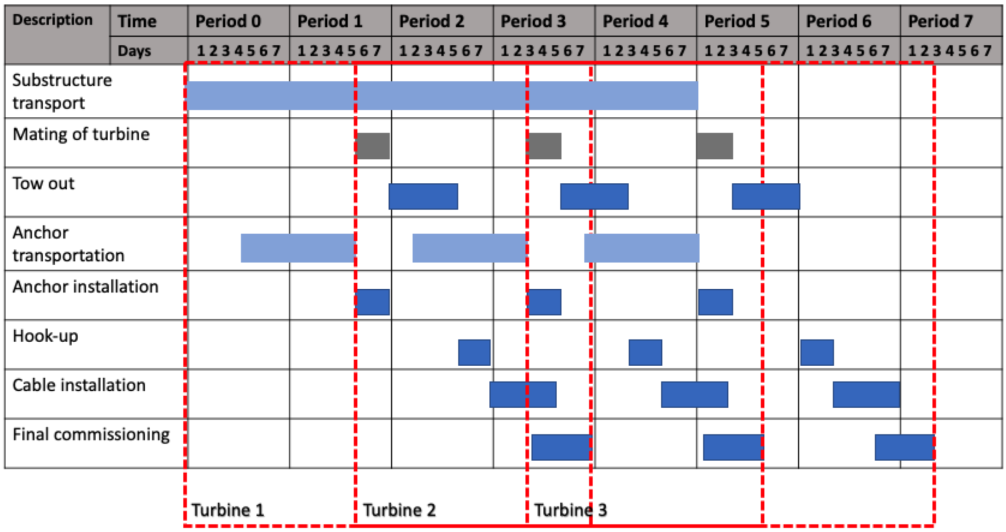


Figure 5.5: Schedule three turbines

5.2.5 Case Example Results

Based on the optimization model, an optimal fleet is found with corresponding time and cost utility approximations. This model assumes that each operation take place in a specific time period, for which the fleet is hired. Thus, an operation is fixed to a certain time interval, resulting in a constant total installation time. An efficient fleet will not result in quicker total installation time, as the schedule is predefined.

It can be argued that the objective function in this model is not ideal. The model optimizes the installation based on the time that each vessel use on an operation. In reality, the vessels may be chartered for a specified period of time based on the predefined schedule. The vessels may be used only partly in each time period, resulting in low utility of the fleet. Thus, it is interesting to investigate the time and cost utility for each time period, and how they are effected by the number of installed turbines. The time utility is defined as the actual execution time over the total scheduled time period for the operation. Similarly, the cost utility is the cost of the fleet while the vessels are performing an operation, over the total cost of the entire scheduled time period.

Results One Turbine

Following the schedule presented in Scenario 1, the time utility is found to be approximately 55%. Similarly, the cost utility has a value of 54%. Figure 5.6 shows the time and cost utility for the installation of one turbine, while Figure 5.7 gives an overview of the fleet size and composition for each time period. It shows that the time utility is especially low for the first three time periods. This is because the vessels have to wait for the next scheduled operation. Alternatively, the vessels are being chartered too long.

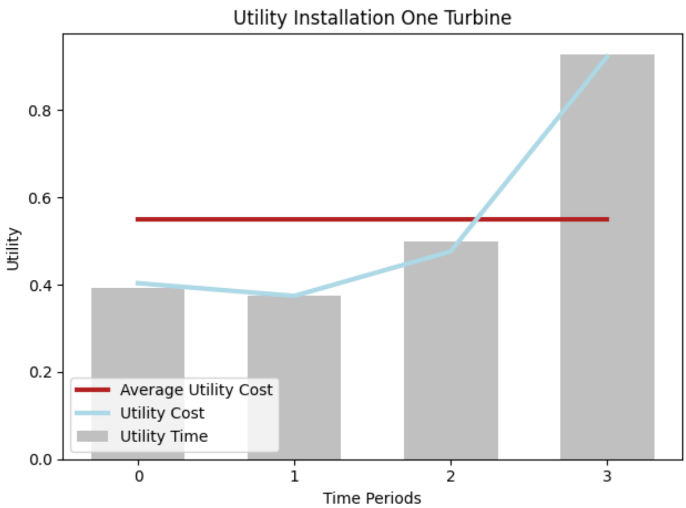
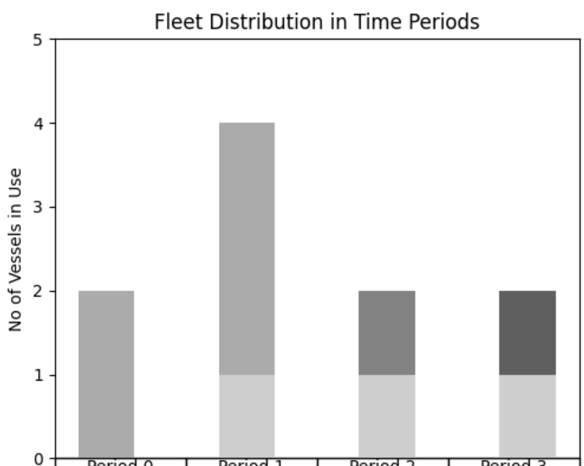


Figure 5.6: Time utility one turbine



	Period 0	Period 1	Period 2	Period 3
Cable Laying Vessel	0	0	0	1
Tug Vessel	0	0	1	0
Transp. Vessel	2	3	0	0
ATHS	0	1	1	1

Figure 5.7: Fleet distribution one turbine

Table 6.3 displays the optimal fleet with corresponding characteristics. With a closer look, it is observed that the vessels are mobilized once, and are being used either in one time period or multiple consecutive time periods.

Table 5.5: Selected fleet

Vessel Category	Vessel No.	Time Period	BHP	Speed [kn]	Day rate [£/day]
AHTS	4	1,2,3	12,000	12	9,000
Transportation Vessel	5	1	10,000	16	14,000
	6	0, 1	9,000	15	13,500
	9	0, 1	6,000	12	12,000
Tug Vessel	14	2	6,000	12	7,200
Cable Laying Vessel	19	3	12,000	12	8,500

Results Three Turbines

As for the installation of one turbine, the time and cost utility can be obtained from the optimization model. It is found that the average time utility is approximately 58%, with a corresponding cost utility of 57%. These values are higher than for the installation of one turbine, suggesting that the fleet has less waiting time between each operation. Ultimately, this gives a decreased installation cost per turbine.

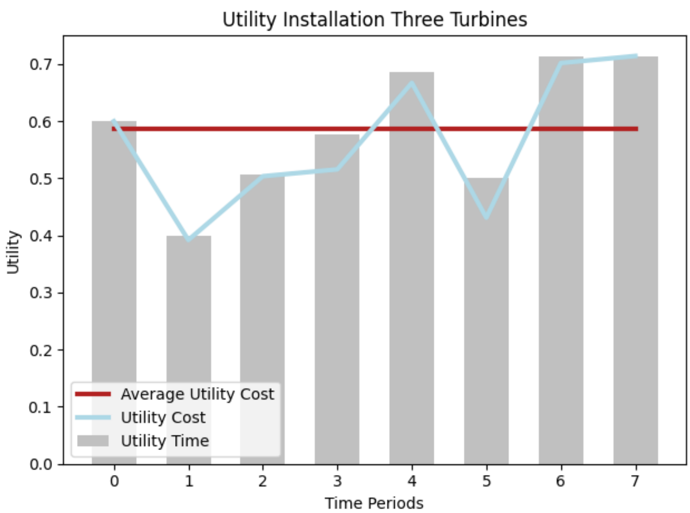


Figure 5.8: Time utility three turbines

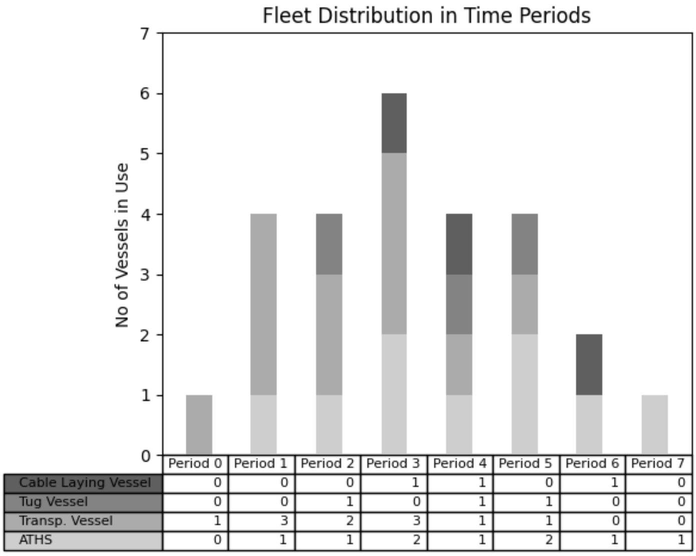


Figure 5.9: Fleet distribution three turbines

From Figure 5.9 it is observed that the fleet size peaks in period 3 with six vessels operating simultaneously. This is a result of the schedule from Scenario 2, having planned for six operations at the same time. As the number of simultaneous operations do not exceed six for any installation independent of size, this fleet size is the maximum for all farm sizes.

Table 5.6: Selected fleet

Vessel Category	Vessel No.	Time Period	BHP	Speed [kn]	Day rate [£/day]
AHTS	0	1, 3, 5	20,000	16	18,000
	4	2, 3, 4, 5, 6, 7	12,000	12	9,000
Transportation Vessel	5	1	10,000	16	14,000
	6	0, 1, 2, 3, 4	9,000	15	13,500
	9	1, 2, 3	6,000	12	12,000
Tug Vessel	14	2, 4, 5	6,000	12	7,200
Cable Laying Vessel	19	3, 4, 6	12,000	12	8,500

The fleet selected for the installation of three wind turbines is similar to the case with installation of one turbine. In addition to the vessels selected for Scenario 1, one additional AHTS is needed. Furthermore, the vessels are used in more time periods as the installation of the farm naturally takes longer. Notice that in this case, some of the vessels are used in time periods that are not sequential. In reality, this could result in mobilization costs for the time periods that are not subsequent. This is not taken into consideration in this version of the model, but will be further explored in the next chapter.

5.3 Comparisons

Table 5.7 presents the the results with different number of turbines to be installed. It clearly shows that the cost per installed turbine decreases with the up-scaling of the wind farm. The installation cost per installed turbine decreases by 61% going from one to fifty installed turbines. Furthermore, it is observed that the time utility of the fleet is better for an increasing number of installed wind turbines. However, the installation process is not fully optimal and an improvement of the model will be presented in the next chapter.

Turbines	Obj. Function	Alt. Obj. Function	Cost per turbine	Cost Utility [%]
1	925,000 £	1,713,000 £	925,000 £	54 %
3	1,750,000 £	3,070,000 £	583,000 £	57 %
5	2,690,000 £	4,737,000 £	538,700 £	57 %
50	18,167,000 £	28,837,000 £	363,000 £	63 %

Table 5.7: Installation costs comparison

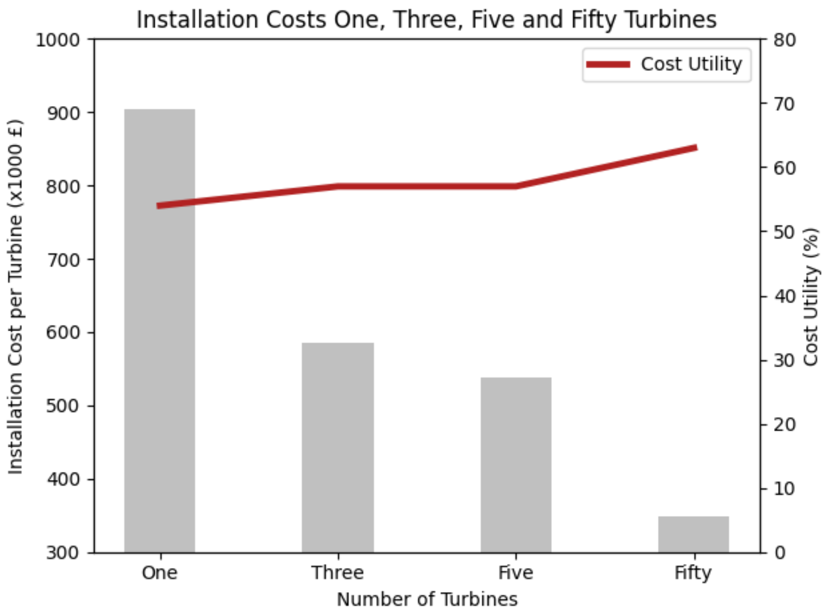


Figure 5.10: Installation cost comparison

In this chapter an optimization model selecting a suitable fleet for a specific installation schedule was developed. Based on the schedule a fleet was selected from a set of vessels. It was found that the installation cost per wind turbine decreased with the number of installed turbines. This is because the time utility of the fleet increased, reducing the unemployed time for the vessels. Furthermore, the mobilization cost per turbine decreases with increasing number of installed wind turbines. However, this model assumed that each vessel must mobilize once. This assumption might be questioned, as some of the vessels are hired in time periods that are not subsequent. In practice, some mobilization cost might incur if the vessels are not used sequentially. This issue will be further addressed in the next chapter.

Chapter 6

Schedule Expansion

This chapter presents an improved optimization model for the fleet selection and scheduling of the installation of a floating offshore wind farm. The model is formulated as a continuous optimization problem for selection of both optimal fleet and schedule for an installation. Firstly, the model is presented and explained. Then, a case analysis using the same set of vessels as in the previous chapter is performed. Lastly, the effect of mobilization costs, time charter costs and wind farm size is analysed and discussed.

6.1 Model Expansion

In the next step of the installation investigation, the tactical time horizon for the planning and scheduling of the installation will be addressed and discussed. The following section defines an alternative for the formulation of the optimization model including scheduling optimization. The continuous optimization model for fleet selection and scheduling will be referred to as CFSS in later discussion. The planning of the floating wind farm can be treated as a vehicle routing problem (VRP). The ”routing” can be considered the assignment of operations to be performed by the installation vessels. ”Scheduling” is used as a term when considering time aspects of the routing problem (Christiansen, Fagerholt, and Ronen 2004). Thus, the scheduling of the installation includes the timing of the operations along a vessels route.

The floating offshore wind installation problem can be modelled as an extension of the Multiple Traveling Salesmen Problem (m-TSP) with precedence constraints (Toth and Vigo 2002). Furthermore, heterogeneous vessels and an opportunity of multiple routes can be included to fully capture the installation problem. Examples of similar work can be found by Fagerholt and Christiansen (2000), applying an extension to the traveling salesmen problem to ship scheduling. It can also be found in the work by Bakker et al. (2017), optimizing the planning of an offshore well plugging campaign.

6.2 Model Explanation

The CFSS is depicted by nodes representing operations to be done in the wind turbine installation. Each node must be visited by one vessel, beginning in a staring dummy node and ending in a dummy end node. Figure 6.1 represents the nodes with corresponding variables presented in the next section.

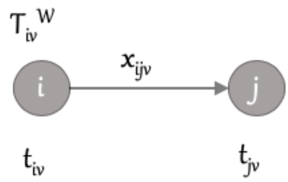


Figure 6.1: Model idea

In order to complete a wind turbine installation, all operations must be executed. This can be modeled, forcing all nodes to be visited by a vessel. An example of how the nodes can be visited is displayed in Figure 6.2.

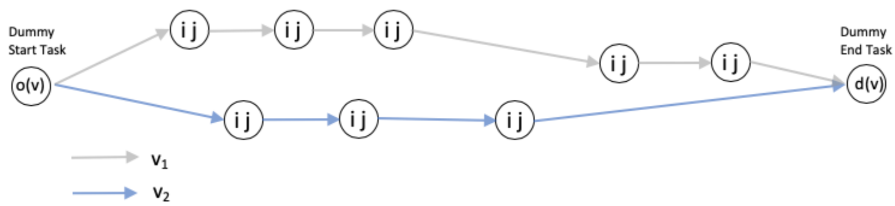


Figure 6.2: Example of two vessels visiting all the nodes (i,j), representing operations

6.3 Mathematical Formulation

In this section, the mathematical formulation of the Mixed Integer Linear Programming (MILP) Model, namely the CFSS formulation, will be presented and explained. Notations (sets, indices, parameters and variables) will be given, followed by an explanation of the objective function and constraints.

6.3.1 Notation

Table 6.1 gives an overview of the notation used in the CFSS formulation. They are made to reflect the key elements of the installation problem.

Table 6.1: Optimal scheduling

	Sets	
V	Set of vessels, indexed v	
O	Set of vertices representing operations, indexed i, j	
O_v	Set of operation vertices that can be visited by vessel $v \in V$, including two artificial nodes representing the vessel origin and destination, $o(v)$ and $d(v)$	
A_v	Represents the routing options as arcs, where $A_v = \{(i, j) : i, j \in O_v\}$	
P	Precedence set with pairs (i, j) where $i, j \in O$, indicating that operation *i* should precede *j*	
	Parameters	
C_v^{TC}	Time charter cost per time unit for vessel v $\in$ V	[£/day]
C_v^{M}	Mobilization costs for starting chartering of vessel v $\in$ V	[£]
T_{iv}^{W}	Execution time for operation $i \in O_v$ with vessel $v \in V$	[days]
Q_{iv}	1 if vessel $v \in V$ can do operation $i \in O$, 0 otherwise	
$[T_i^S, T_i^C]$	Time window for execution of operation *i*, representing earliest start and completion time respectively	
	Variables	
x_{ijv}	1 if operation $i \in O_v$ is done before j $\in O_v$ with vessel v $\in$ V, 0 otherwise	
t_{iv}	Time for start of operation $i \in O_v$ for vessel v $\in$ V	

Sets. In this model, it is fitting to treat the installation operations as vertices and routing options as arcs. These arcs and vertices are included in the sets presented in Table 6.1. Furthermore, some additional sets need to be defined. Given vertex *i*, τ_v^+ is defined as the set of possible vertices *j* that vessel *v* can visit after visiting vertex *i*. That is, the set is a subset $(i, j) \in A_v$. Furthermore, τ_v^- is the set of possible vertices *j* that a vessel *v* may have visited before visiting vertex *i*; also a subset $(i, j) \in A_v$.

Parameters. To capture the cost aspect of the installation, two cost parameters are introduced. C_v^{TC} is the daily time charter cost of a vessel, while C_v^M represents the mobilization costs of a vessel. Time characteristics associated with the installation is captured with T_{iv}^W, T_i^S and T_i^C. They represent the operation time, start and end restrictions respectively. Lastly, the parameter Q_{iv} connects the compatibility between vessels and operations.

Variables. The optimization model presented is based on an arc-flow formulation. Thus, a binary flow variable, x_{ijv} is a suitable choice defining arcs between vertices for a specific vessel. Moreover, a continuous time variable t_{iv} keeps track on the time aspect of the installation operations to be performed.

6.3.2 Objective Function

The overall goal of the model is to minimize the cost associated with the fleet used in the installation of an offshore wind farm. This can be done by minimizing the charter costs imposed for each vessel. It is assumed that a vessel is hired from the start of its first operation until the end of its last assigned operation. Additionally, the mobilization cost for each vessel must be included in the objective function. This objective function, minimizing the complete installation time (CIT), will be referred to as the CIT formulation.

$$min \sum_{v \in V} \sum_{j \in O} C_v^M x_{o(v)jv} + \sum_{v \in V} C_v^{TC} (t_{d(v)v} - t_{o(v)v}) \tag{6.1}$$

6.3.3 Constraints

The constraints related to this installation problem are presented below.

Operations. All installations have to be executed. This is ensured by constraints 6.2. These also ensure that each operation is assigned to exactly one vessel.

$$\sum_{v \in V} \sum_{j \in O_v} x_{ijv} = 1, \quad i \in O. \tag{6.2}$$

Routing. These constraints define the possible routes for the vessels. Firstly, the following constraints ensure that a vessel's route starts at the origin, only performing one route:

$$\sum_{j \in \tau_v^+(o(v))} x_{o(v)jv} = 1, \quad v \in V. \tag{6.3}$$

Similarly, equations 6.4 make sure that all vessels end its route in the end destination. If a vessel from set $v \in V$ is not used, it will go straight from the origin to the end destination without a cost.

$$\sum_{i \in \tau_v^-(d(v))} x_{id(v)v} = 1, \quad v \in V. \tag{6.4}$$

Lastly, a flow balance must be ensured, meaning that if a vessel is used in an operations, it must continue to another operation or move to the end destination.

$$\sum_{i \in \tau_v^-(j)} x_{ijv} - \sum_{i \in \tau_v^+(j)} x_{jiv} = 0, \quad i \in O, v \in V. \tag{6.5}$$

Timing. These constraints ensure schedule feasibility regarding time schedule of the operations, implying that a vessel can only perform one operation at a time. Thus, it must finish one operation before it can begin another, enforced by the following constraints:

$$x_{ijv}(t_{iv} + T_{iv}^W - t_{jv}) \leq 0, \quad (i,j) \in A_v, v \in V. \tag{6.6a}$$

These equations are made linear with the following adjustments:

$$t_{iv} + T_{iv}^W - t_{jv} - M(1 - x_{ijv}) \leq 0, \quad (i,j) \in A_v, v \in V. \tag{6.6b}$$

The operations must be performed within a certain time window. This is both because the operations often require weather windows which are limited. Furthermore, time windows are reasonable to assume as the vessels in reality are available in limited time periods. Time windows for operations are defined as follows:

$$T_i^S \sum_{j \in \tau_v^+(i)} x_{ijv} \leq t_{iv} \leq (T_i^C - T_{iv}^W) \sum_{j \in \tau_v^+(i)} x_{ijv}, \quad v \in V, i \in O. \tag{6.7}$$

These constraints force the time variable for a vessel to zero if the vessel does not perform a certain operation. Lastly, it is reasonable to appoint weather window for the origin and end destination vertices. This is because the length and timing of weather windows are often restricted, thus equations 6.8 should be enforced.

$$T_i^S \leq t_{iv} \leq T_i^C, \quad v \in V, i \in \{o(v), d(v)\}. \tag{6.8}$$

Precedence. In the turbine installation, there exists a strict ordering on the sequence of the operations. By introducing the constraints below, the correct ordering is guaranteed:

$$\sum_{v \in V} t_{iv} + \sum_{v \in V} \sum_{k \in \tau_v^+(i)} T_{iv}^W x_{ikv} - \sum_{v \in V} t_{jv} \leq 0, \quad (i,j) \in P \tag{6.9}$$

Multiple Cycles. The constraints presented above assumes that a vessel must be hired continuously from mobilization until it is finished with its last operation. This assumption is reasonable if the vessel is in subsequent use, starting at a new operation immediately after finishing its previous assigned operation. However, it is likely that a vessel could be used in operations that have a time gap between the executions. Thus, the vessels should be able to be in port or hired by another company, avoiding charter costs in periods were the vessels are not in use. This can be done by redefining the vessel set V. Copies of a vessel is included if the vessel is allowed to do multiple cycles, with holds between the operations. Mathematically, it can be written as follows. $R_v := \{1, ..., N_v^R, v \in V\}$, with N_v^R defining the number of cycles a vessel can take. It is then convenient to define $\overline{V} = \{\overline{v}_{vr} : v \in V, r \in R_v\}$. The following constraints ensure that the operations are done in the correct order:

$$t_{d(\overline{v}_{vr})\overline{v}_{vr}} \leq t_{o(\overline{v}_{vr'})\overline{v}_{vr'}}, \quad v \in V, \quad r, r' \in R_v | r' - r = 1. \tag{6.10}$$

Given that there is two subsequent cycles for a vessel, equations 6.10 ensure that the first cycle must be finished before the second can start. By replacing the vessel set V with $\overline{V}$, the model allows for multiple cycles with the same vessel without generating charter costs in the waiting time. Notice that the hold of a vessel will generate a new mobilization cost, meaning that it is not necessarily cost efficient to put a vessel on hold.

Vessel Requirement. Each operation require a specific set of equipment and requirements demanding different types of vessels. It is assumed that the vessels in the set include potential support vessels or equipment required for an operation. This implies that an ROV is complementary for the chosen cable layer vessel if needed in the cable laying operation. Similarly, a smaller tug vessel might be needed to assist an AHTS in a towing operation. These additional requirements are assumed to generate relatively small costs compared to the major vessel selected, and is for simplicity assumed a part of the main vessel selected. Constraints forcing the correct type of vessels for each operation are added as follows:

$$\sum_{j \in O_v} x_{ijv} \leq MQ_{iv}, \quad i \in O, v \in V. \tag{6.11}$$

Domains. The domains for each variable need to be enforced with constraints. Constraints 6.12 ensure non-negative, continuous values. Constraints 6.13 ensure a binary domain for the arc-flow variable.

$$t_{iv} \in \mathbb{R}_0^+, \quad v \in V, i \in O_v. \tag{6.12}$$

$$x_{ijv} \in \{0, 1\}, \quad (i, j) \in A_v, v \in V \tag{6.13}$$

6.4 Case Study

In order to evaluate the performance of the model, the same case study as for the discrete optimization model is conducted. A wind farm is to be installed in the North Sea, located south west of Norway. Different wind farm sizes and vessel set sizes will be investigated. The vessel set used is similar as for the previous case example and can be found in Appendix C.2.

In the scheduling optimization model, the schedule is not predefined, but made based on precedence requirements and vessel performance. It is obvious that some operations must be performed before others can take place. These precedence relationships are presented below and will be used to estimate the installation cost for different farm sizes. The sequential order of the operation is illustrated in Figure 6.3 and implemented in the Design Structure Matrix (DSM) below.

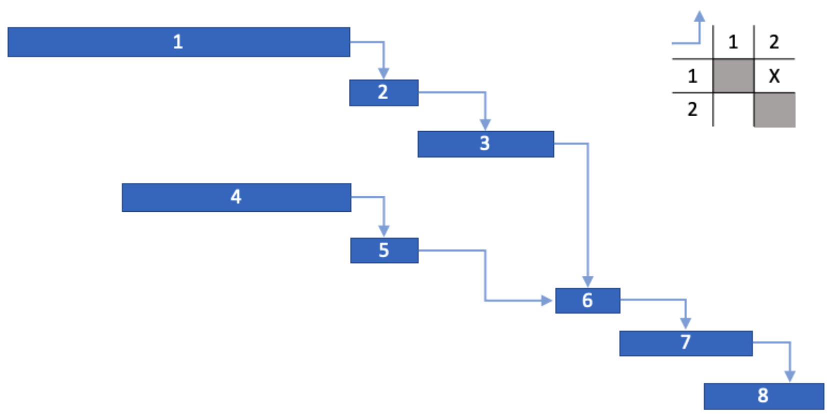


Figure 6.3: Sequential relationship between operations

A sequential relationship between two operations is depicted in the DSM as illustrated in Figure 6.3. If operation 1 must precede operation 2, a cross is put in DSM position (1,2) to illustrate the dependency. This relationship applies to all turbines that are installed. The precedence relationship for the installation of one turbine is found in Table C.5.

Table 6.2: Precedence relationship displayed in a DSM

		1	2	3	4	5	6	7	8
Substructure transport	**1**		X						
Assembly	**2**			X					
Tow Out	**3**						X		
Anchor transport	**4**					X			
Anchor Installation	**5**						X		
Hook-up	**6**							X	
Cable Installation	**7**								X
Final Commissioning	**8**								

6.4.1 Installation One Turbine

Running the model with one turbine, gives the schedule and fleet presented in Figure 6.4. The total installation time is found to be 28 days, with a cost of approximately 533,000 £. The fleet consists of three vessel types; two AHTS vessels, one cable installation vessel and one transportation vessel.

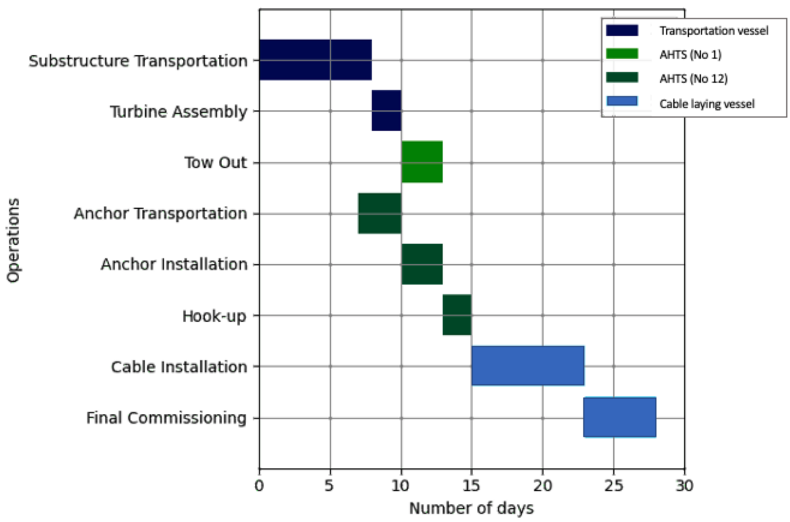


Figure 6.4: Schedule installation of one turbine

The fleet characteristics are found in Table 6.3, with corresponding BHPs, speeds, time charter rates and mobilization costs.

Table 6.3: Fleet characteristics for installation of one turbine

Vessel Category	BHP	Speed [kn]	Time Charter Rate [£/day]	Mobilization Cost [£]
AHTS	20,000	16	18,000	112,000
AHTS	12,000	12	9,000	58,600
Transportation Vessel	9,000	15	13,500	58,300
Cable Laying Vessel	12,000	12	8,500	58,400

6.4.2 Installation Two Turbines

Similarly, the optimal schedule and fleet for the installation of two turbines is investigated. This gives an indicator on how the size of the wind farm effects the cost per installed wind turbine. The precedence relationship for two turbines can be found in Appendix C.4. Figure 6.5 gives an overview of the optimal schedule for the installation.

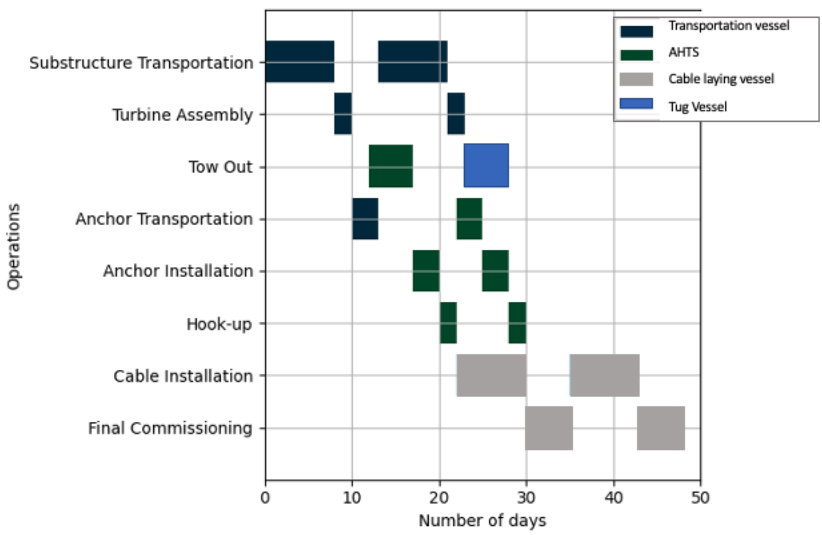


Figure 6.5: Schedule installation of two turbines

Compared to the optimal fleet found for the installation of one turbine, a tug vessel is has replaced one of the AHTS vessels. Other than that, the fleet is exactly the same as for the installation of one turbine. The fleet characteristics are presented in Table 6.4.

Table 6.4: Fleet characteristics installation of two Turbines

Vessel Category	BHP	Speed [kn]	Day rate [£/day]	Mobilization Cost [£]
AHTS	12,000	12	9,000	58,600
Transp. Vessel	9,000	15	13,500	59,500
Tug Vessel	6,000	12	7,200	3,000
Cable Laying Vessel	12,000	12	8,500	58,400

6.4.3 Computation Time

Investigating bigger data sets gives an interesting insight to how the cost and schedule changes with farm size. However, increasing running times are typically a result of bigger data sets. The CFSS model quickly require strong computers, even for relatively small data sets. Thus, small changes to the objective function, set sizes and constraints should be considered in order to reduce the overall computation time. It is found that changing the objective function slightly, reduces the running time significantly. The following alternative objective function is suggested and will be referred to as the operation time (OT) objection function. The original objective function, presented in equation 6.1, is referred to as the CIT formulation, minimizing the complete installation time.

$$min \sum_{v \in V} \sum_{jinO} C_v^M x_{o(v)jv} + \sum_{v \in V} \sum_{i \in O_v} \sum_{j \in O_v} C_v^{TC} T_{iv}^W x_{ijv} \tag{6.14}$$

Objective function 6.14 assumes that only the time used to do an operation will generate a charter cost. The previous objective function, namely the CIT formulation, assumed that potential waiting time between operations also generated costs. The OT formulation error decreases with increasing number of installed turbines, assuming that the waiting time between operations will decrease. The OT objective function will be used as a comparison and applied on bigger data sets to provide a more thorough picture of the cost development.

Decreasing the vessel sets reduces the running time. The set used in the analysis consists of twenty vessels from four different categories. However, by including a vessels ability to go multiple cycles, the vessel set size is significantly increased. This is done to account for the ability for a vessel to wait in port or operate on another contract when it is not working on an operation. This is applied by adding copies of each vessel in the set. In order to delimit the running time problem, the analysis will restrict the number of allowed cycles to one, two and three rounds. The influence of allowing for different number of cycles will also be investigated.

Table 6.5 gives an overview of the solution time for the optimization model. It considers different farm sizes and vessel set sizes. The base set vessel size consists of twenty vessels and is found in Appendix C.2. Thus, the sets $|V| = 20$, $|V| = 40$ and $|V| = 60$, allows for respectively one, two or three cycles per vessel. Furthermore, the computation times are shown for both objective functions. The MIP Gap is a measure used in Gurobi to identify the gap between the lower and upper objective bound. This measure is used when Gurobi utilize the branch and bound method. Specifically, the MIP Gap is the gap between upper and lower bounds divided by the absolute value of the upper bound (Gurobi 2020). It is used as an indicator to evaluate how far the solver is from finding the optimal solution.

Table 6.5: Overview of solution times and gaps for varying vessel sets, farm sizes and objective functions

		$\lvert V\rvert = 20$		$\lvert V\rvert = 40$		$\lvert V\rvert = 60$	
Objective	**Turb.**	**Sol. time**	**Gap**	**Sol. time**	**Gap**	**Sol. time**	**Gap**
CIT (Equation 6.1)	1	1.88 s	0%	3.90 s	0%	14.5 s	0%
	2	648 s	0%	3,600 s	9%	3,600 s	32%
	3	3,600 s	192%	3,600 s	275%	3,600 s	288%
	5	3,600 s	210%	3,600 s	380%	3,600 s	410%
	10	X	X	X	X	X	X
	15	X	X	X	X	X	X
	20	X	X	-	-	-	-
OT (Equation 6.14)	1	0.014 s	0 %	0.048 s	0%	0.060 s	0%
	2	0.049 s	0%	0.082 s	0%	0.160 s	0 %
	3	0.086 s	0%	0.197 s	0%	0.391 s	0%
	5	0.219 s	0%	0.878 s	0%	0.810 s	0%
	10	1.06 s	0%	681 s	0%	4.42 s	0%
	15	1,01 s	0%	3,600 s	2.1%	411 s	0%
	20	3,600 s	3.1%	X	X	X	X

The colored cells indicate running time on a regular computer exceeding one hour without finding an optimal solution. Some were run longer to investigate the MIP Gap development with time. These running attempts are listed in Table 6.6. In order to obtain a bigger set of installation cost results, some of the data sets were run on a stronger computer located on NTNU Gloshaugen. These results are marked with a X and will be used in the analysis presented in the next sections. The - sign indicates that the data set is not further investigated.

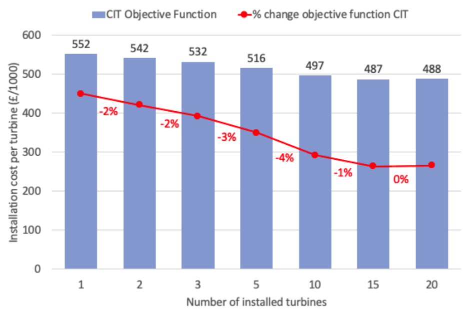
It is worth noticing that even running for hours, the MIP gap does not necessarily reduce significantly. This substantiates the need for stronger computers or constraint adjustments to evaluate bigger data sets. This will not be done in this thesis, but could be an interesting field of investigation in the future works.

Table 6.6: Examples of running time and MIP gap for running times exceeding one hour

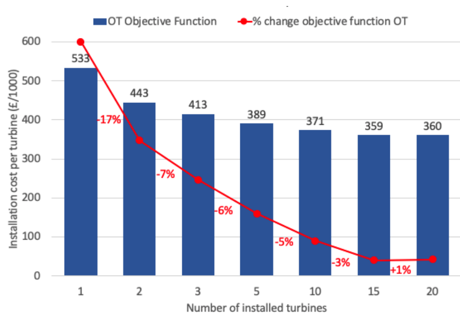
Objective Function	**Turbine No.**	**Set Size**	**MIP gap 1 hour**	**Time**	**MIP gap**
CIT	3	20	192%	51,294s	159.9%
CIT	5	20	210%	4,105s	208%
CIT	3	40	275%	7,132s	264%
CIT	5	40	210%	4,105s	208%
CIT	2	60	224%	16,305s	181%
CIT	3	60	288%	25,246s	261.8 %
OT	20	20	3.08%	68,112s	2.97%

6.4.4 Comparison

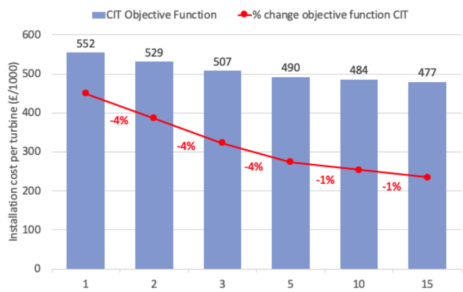
In order to analyze the costs associated with floating wind turbine installations, the best objective for different data sets are plotted in Figure 6.6. The plots on the left represent the results minimizing the CIT. Similarly, the plots on the right reflect the costs using the OT objective function.



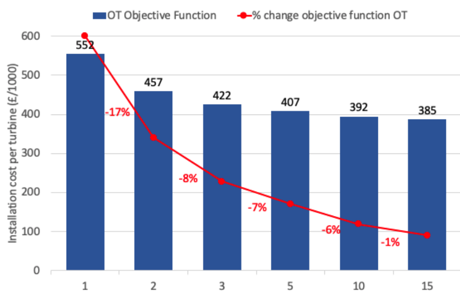
(a) One cycle restriction, CIT objective function



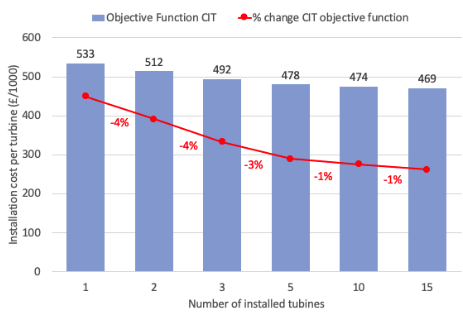
(b) One cycle restriction, OT objective function



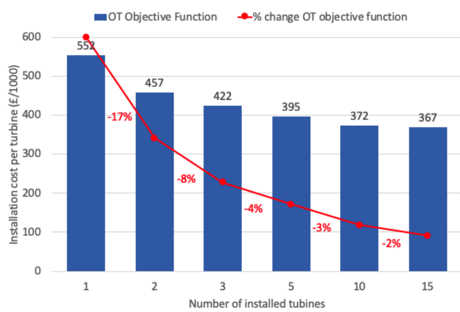
(c) Two cycles restriction, CIT objective function



(d) Two cycles restriction, OT objective function



(e) Three cycles restriction, CIT objective function



(f) Three cycles restriction, OT objective function

Figure 6.6: Installation costs per turbines for different farm sizes and cycle number restrictions

Figure 6.6a and Figure 6.6b show the average cost of installing one turbine with varying wind farm sizes. They display the costs for CIT and OT minimization respectively. It is assumed that each vessel can only take one round, meaning that they are not able to do other contracts between their assigned installation operations. It is observed that the CIT objective function is more expensive than the OT objective function for all farm sizes. This is because OT minimization assumes that the time of operation is the only time generating costs. However, this is certainly a questionable assumption, but can be used as a lower bound for the cost estimate.

The relationship between farm size and the percentage change in unit installation cost is presented in the red line. It displays the percentage change between installation cost from one farm size to the next. For the OT objective function, the change in costs between one and two installed turbines is highest. The additional turbines give decreasing difference in marginal cost reduction. Similarly, CIT minimization gives decreasing difference in cost per turbine. However, the percentage difference is smaller than for the OT formulation.

Figures 6.6c and 6.6d show the same relationships as the previously explained graphs. However, these results are from data allowing two cycles per vessel. Similar trends are seen here; CIT minimization gives higher costs than OT minimization. In contrast to the one cycle results, the maximum change is found between one and two turbines for both objective functions. Furthermore, it is observed that the installation costs for the CIT formulation is reduced for all wind farm sizes. This is less evident in the one cycle restriction case, having approximately zero effect on installation cost from 15 to 20 turbines.

Lastly, similar analysis is done with a three cycle restriction on the vessels. Comparing the results with two and one cycle restrictions, the installation costs for the CIT objective function are decreased, while the OT objective function results seem to be unchanged.

These observations suggest that the decrease in marginal installation costs reduces with increasing number of turbines. This applies to both objective functions. Furthermore, the results from CIT minimization seem to improve when allowing for multiple cycles per vessel. OT minimization appear to remain the same for all cycle restrictions.

It is worth having in mind that the estimated installation costs only include the costs associated with chartering vessels used for the installation. It does not include costs of production, material expenses, etc.

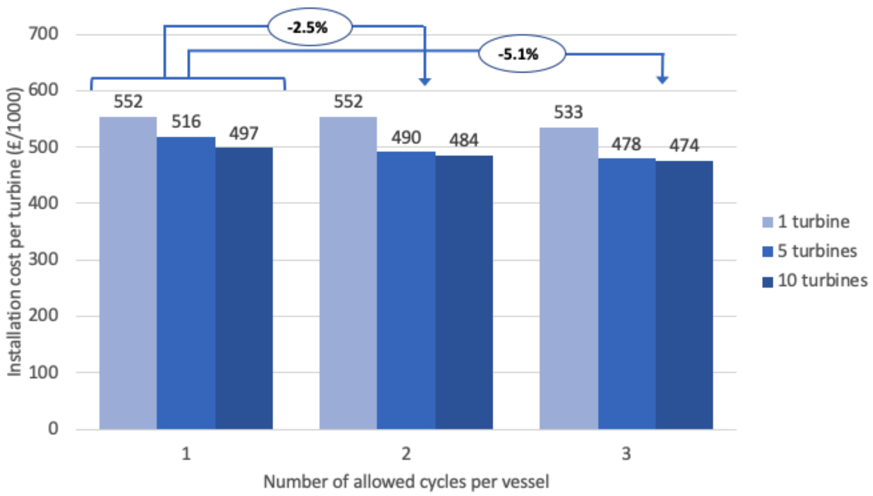
Table 6.7 presents key values for the installation of wind farms of varying sizes. The CIT formulation is used as the basis of the cost calculation and it is found that the installation cost per turbine decreases with the size of the wind farm.

Table 6.7: Installation costs comparison

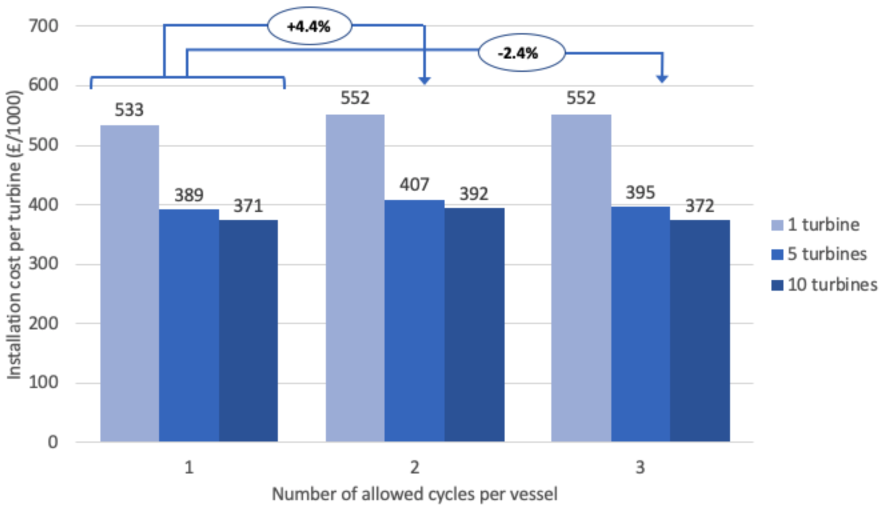
Turbines	Objective Function	Cost per turbine
1	533,000 £	533,000 £
2	1,014,000 £	512,000 £
3	1,657,000 £	492,000 £
5	2,971,000 £	478,000 £
10	4,740,000 £	474,000 £
15	4,692,000 £	469,000 £

6.4.5 Effect of Model Improvement

It is of interest to evaluate the effect of vessels operating in multiple cycles. Limiting the number of cycles reduce the vessel sets and consequently the running time. Figure 6.7a and Figure 6.7b present the costs of installing one, five, and ten turbines for both objective functions. The three columns represent one, two and three allowable cycles per vessel.



(a) Objective function for CIT minimization



(b) Objective function for OT minimization

Figure 6.7: Effect of cycle restrictions on installations cost for both objective functions

From the figures, it is observed that the installation cost decreases significantly for the CIT minimization when allowing multiple cycles per vessel. This is not the case for OT minimization, which seem to generate both a positive and negative change in cost. Notice that the percentages are averages, including the costs for one, five and ten turbines. Based on these findings, it is reasonable to conclude that slacking, leaving and changing both the constraints and objective function effect the quality of the result. However, relaxation still gives a cost indication and can be carefully applied to bigger data sets.

As previously described, these results also show that the installation costs per turbine decreases with increasing size of the wind farm. This applies to all versions of the optimization model.

6.5 Mobilization Costs and Fleet Selection

The mobilization costs of the fleet highly influence the price of installation. The location of the hired vessels clearly connects with the cost of mobilization, generating transportation costs in terms of charter rates, fuel costs and crew costs. The following sections will investigate the effect of mobilization costs on the fleet selection and overall installation expenses. Since the CFSS model is an improvement of the DFS formulation, it will be used in the mobilization cost analysis.

6.5.1 Fleet Size and Mobilization Costs

In the estimation of the mobilization costs, the distance from location of a hired vessel to the site of operation is assumed to be the main cost driver. Thus, it is interesting to investigate the influence of mobilization distance on the cost of installation and selected fleet. In the following analysis, the input presented in Table 6.8 is used. The mobilization distances are assumed to be averages applying for all the vessels. In reality, the vessels may be located at different locations, generating varying mobilization distances. However, in this analysis the effect of the distance generating mobilization costs are investigated and average mobilization distances are considered reasonable. The mobilization costs are calculated based on a formula suggested by Kaiser and Snyder (2012a), presented in Chapter 5.1.4 (equation 5.1).

Table 6.8: Input variables

Input variable name	Values
Mobilization Distances [miles]	0, 50, 100, 200, 250, 300
Turbine Numbers	1, 2, 3, 5, 10, 15
Vessels	20 vessels (Appendix C.2)

Figure 6.8 introduces the findings done by running the scheduling optimization model with different input parameters. By investigating the results, some interesting trends are observed. Increasing mobilization costs result in a more negative cost slope with increasing number of installed turbines. This means that with high mobilization costs, the installation cost per turbine will decrease more for each additional turbine compared to cases with low mobilization costs. Furthermore, the mobilization cost per turbine moves towards a constant value, suggesting that the size of the total mobilization costs will be less significant as the farm size increases.

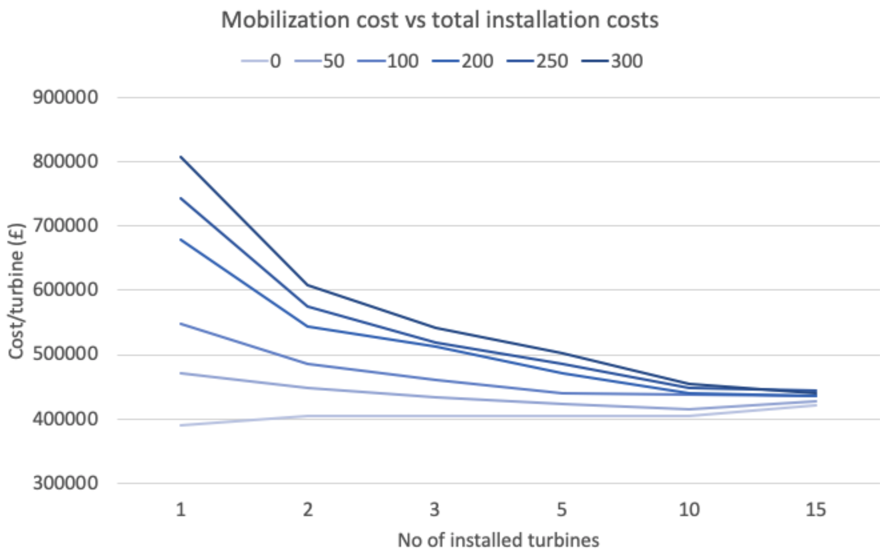


Figure 6.8: The effect of mobilization distance on the installation cost per turbine

It is worth noticing that a negligible mobilization cost gives an increase in the cost per turbine as the farm size rise. These effects are seen as a result of additional vessels needed in order to complete the operations. Figure 6.8 shows an increase going from one to two turbines and from ten to fifteen turbines. Similarly, Figure 6.9 shows that these cost increases aligns with an additional vessel in the selected fleet.

Figure 6.9 presents the fleet size for different mobilization distances. It is worth noticing that the number of vessels selected remains constant or decreases as the mobilization costs increase. This is true for all farm sizes.

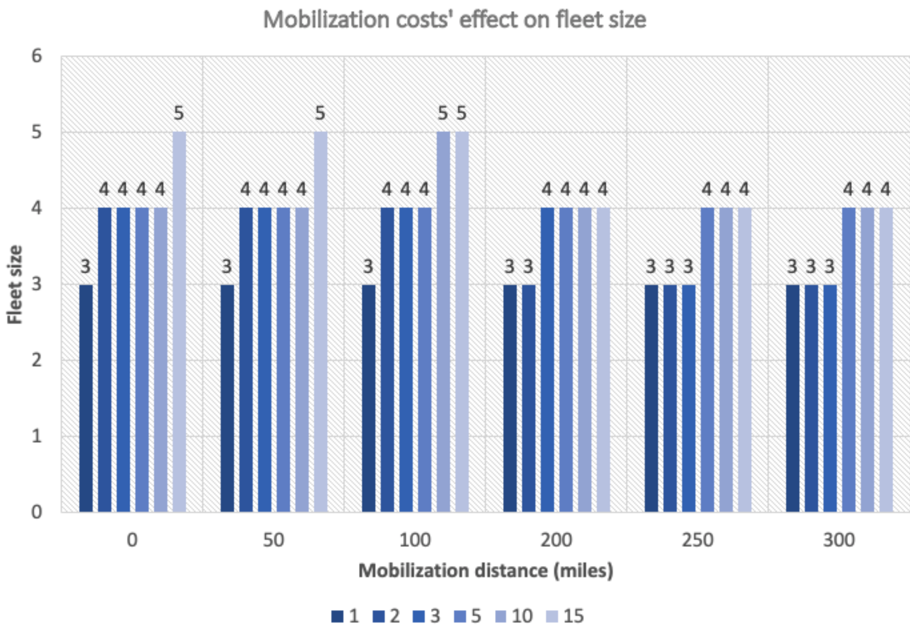


Figure 6.9: The effect of mobilization distance on the fleet size

The results show that there are four fleet configurations. They consist of either three, four or five vessels and are summarized in Table 6.9.

Table 6.9: Fleet alternatives

	Vessel Type	Vessel No.	Charter Cost		Selected when
	ATHS	4	9,000 £/day		• 1 turbine
Fleet 1	Transp. Vessel	6	13,500 £/day	⟶	• Low mob. costs
	Cable Laying Vessel	18	10,400 £/day		
	ATHS	4	9,000 £/day		• 1-3 turbines
Fleet 2	Transp. Vessel	6	13,500 £/day	⟶	• High mob. costs
	Cable Laying Vessel	19	8,500 £/day		
	ATHS	4	9,000 £/day		• 2-10 turbines
Fleet 3	Transp. Vessel	6	13,500 £/day	⟶	• Both high and
	Tug Vessel	12	7,600 £/day		low mob. costs
	Cable Laying Vessel	19	8,500 £/day		
	ATHS	4	9,000 £/day		
	Transp. Vessel	6	13,500 £/day		
Fleet 4	Transp. Vessel	9	12,000 £/day	⟶	• 10-15 turbines
	Tug Vessel	12	7,600 £/day		• Low mob. cost
	Cable Laying Vessel	19	8,500 £/day		

Chapter 7

Results

This chapter will present, evaluate and compare the results from the two optimization models developed. Firstly, the turbine installation costs are compared. Then, proposed schedules and fleet compositions from both models are presented. Lastly, an evaluation of the fleets will be conducted.

7.1 Installation Cost Results

In this section, results from both models are presented. The models have been implemented in Python programming language, and solved with Gurobi Optimizer version 8.0. The analysis has been carried out in computer labs located at NTNU Trondheim and on a MacBook Pro version 10.14.6. Figure 7.1 shows numerical results, comparing the DFS and CFSS formulations.

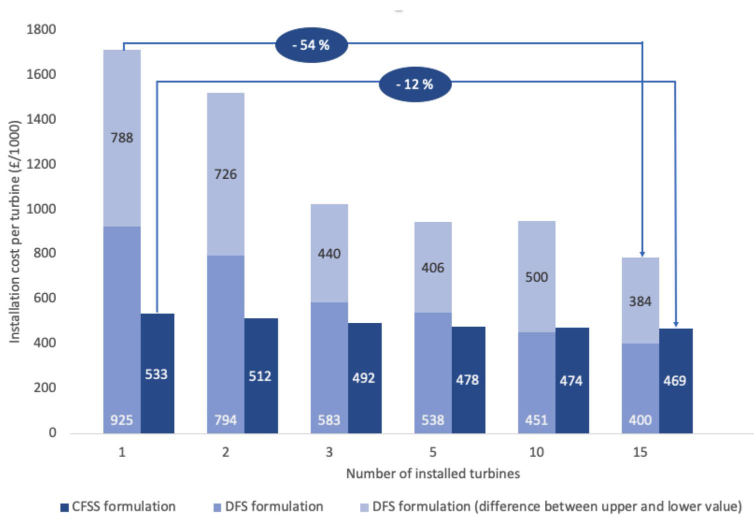


Figure 7.1: Installation cost comparison between DFS and CFSS models

It is observed that the CFSS formulation, the scheduling optimization model, has much better results than DFS. It gives lower installation costs for all farm sizes. However, the lower bound of the DFS formulation is less than the CFSS costs for farm sizes exceeding 10 turbines. It is still worth noticing that the CFSS costs are much lower than the upper bound found for the DFS formulation. The advantage of using the DFS formulation is the relatively low running times, making it possible to quickly give a cost estimate for big wind farms. However, the CFSS performs much better, being less expensive for all wind farm sizes.

7.2 Schedules and Fleet Results

The difference between the CFSS and DFS models is also evident on the choice of fleet and schedule. To illustrate the differences, the results from smaller data sets are presented. Table 7.1 summarizes the findings for farm sizes consisting of one, two, three and five turbines.

Table 7.1: Installation costs with associated schedules and fleets for both models

		DFS formulation				**CFSS formulation**			
Farm size (no of turbines)		1	2	3	5	1	2	3	5
Cost per turbine (£/1000)		925	794	583	452	533	512	492	478
Cost decrease (%)		0	14	27	8	0	4	4	3
Fleet	**AHTS**	1	2	2	2	2	1	2	2
Composition	**Transp. vessel**	3	3	3	3	1	1	1	1
	Cable laying vessel	1	1	1	1	1	1	1	1
	Tug Vessel	1	1	1	1	0	1	1	1
Fleet Size		6	7	7	7	4	4	5	5
Total time (days)		28	40	52	77	28	43	56	82

There are several observations that can be made based on this table. The DFS formulation had a predefined installation schedule, while the CFSS model defined the schedule based on precedence constraints. It is evident that the predefined schedule results in bigger fleets with lower utility, while the CFSS model maximizes the utility of each vessel reducing the fleet size. This partly explains the high installation costs associated with the DFS formulation. It is also worth noticing that because of the big fleet, the DFS formulation generates higher mobilization costs then the CFSS model.

The fleet size seems to stabilize as the number of turbines increases. The selected fleet stays the same when increasing from three to five turbines. This trend is also seen when increasing the farm size even further. This observation can help explain why the cost curves flattens out with farm size, as the mobilization costs remain the same.

It is worth noticing that the overall installation time tends to be slightly longer for the CFSS model compared to the DFS formulation. The CFSS strive to maximize the utility of each mobilized vessel, performing more operations per vessel compared to the DFS. It is worth noticing that the model does not include loss in revenue as a result of reduced operating time.

Thus, the CFSS formulation might be somewhat unreasonably favored as compered to the DFS formulation.

7.2.1 Schedules

The installation schedules are somewhat different in the two models. The DFS model tends to have a slightly shorter installation plan than the CFSS formulation. Figure 7.2 compares the installation schedules for one turbine. For this example, the installation time is the same, but the operation timing is different. Optimizing the schedule helps maximize the vessel utility, ultimately reducing installation costs.

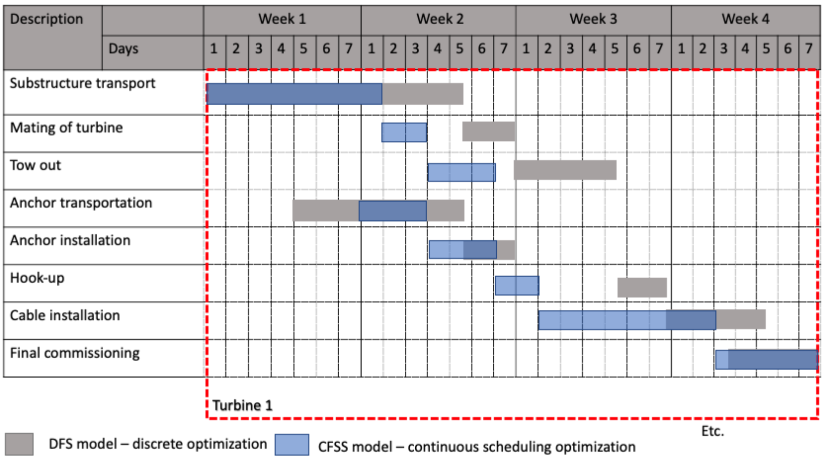


Figure 7.2: Comparison of schedules for installation of one turbine

7.2.2 Installation Cycle

The optimal routes for the vessels depend heavily on mobilization distance, execution times and day rates. However, the fleet size and combination tend to be the same as the farm size increases. Furthermore, the vessel cycles and number of executed operations per vessel depend on the model. It is found that the DFS model tends to have a bigger fleet with vessels performing few operations per installed turbine. On the contrary, the CFSS model selects a smaller fleet with vessels undergoing bigger cycles. Figure 7.3 illustrates the fleet size and vessel cycles for the DFS model. This solution gives a total of seven vessels having one cycle each. Table 7.2 presents the optimal fleet selected for installation of two turbines in the DFS formulation.

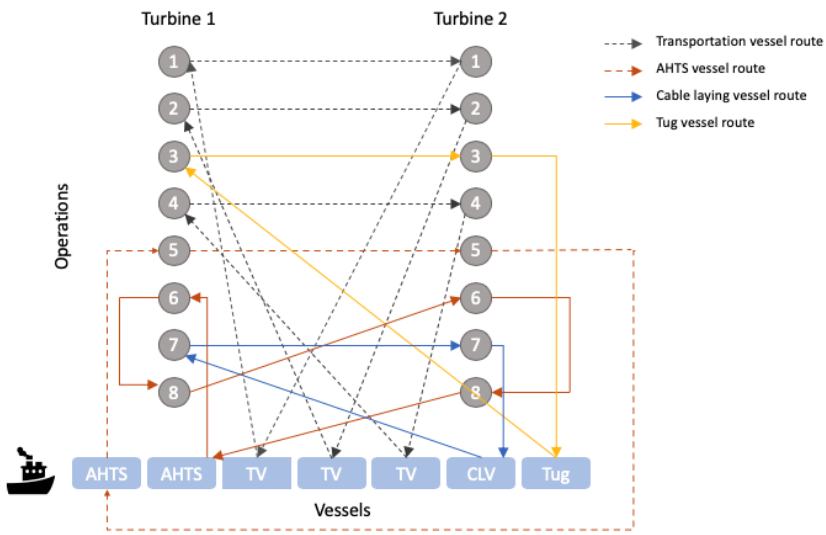


Figure 7.3: Illustration of optimal solution for the DFS model with two turbines

Table 7.2: Fleet characteristics DFS model

Vessel Category	BHP	Speed [kn]	Day rate [£/day]	Mobilization Cost [£]
AHTS	20,000	16	18,000	135,000
AHTS	12,000	12	9,000	59,000
Transportation Vessel	10,000	16	14,000	58,000
Transportation Vessel	9,000	15	13,500	60,000
Transportation Vessel	6,000	12	12,000	32,000
Tug Vessel	6,000	12	7,200	3,000
Cable Laying Vessel	12,000	12	8,500	58,000

Similarly, Figure 7.4 presents the optimal solution for the CFSS model. Four different vessels are selected to perform the required operations. Their characteristics can be found in Table 7.3.

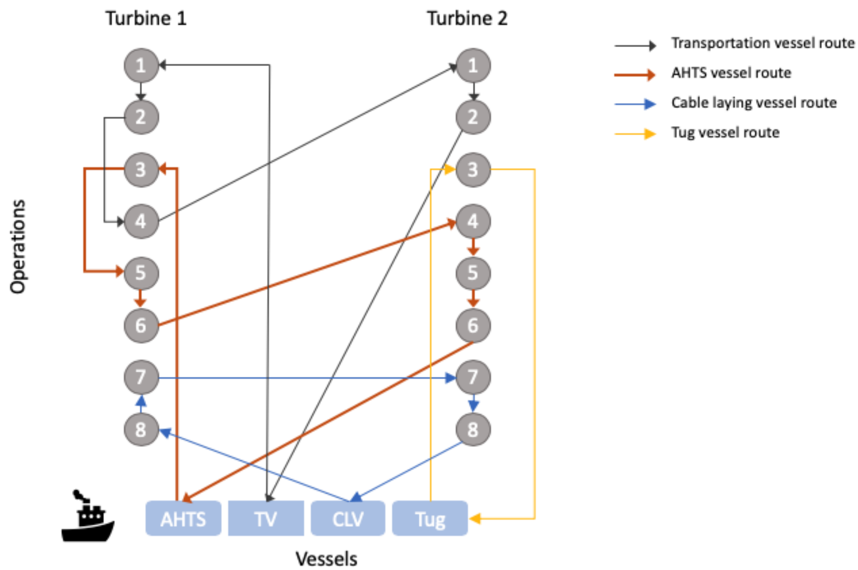


Figure 7.4: Illustration of optimal solution for the CFSS model with two turbines

As stated earlier, the selected fleet depend heavily on the day rate, mobilization cost and operation time. The vessel sets used for analysis on both models where the same and can be found in Appendix C.2. By studying the selected fleets for both models, it is found that the vessels selected in the CFSS formulation is also selected in the DFS formulation. This indicates that both models favor the same vessels.

Table 7.3: Fleet characteristics CFSS model

Vessel Category	**BHP**	**Speed [kn]**	**Day rate [£/day]**	**Mobilization Cost [£]**
AHTS	12,000	12	9,000	59,000
Transportation Vessel	9,000	15	13,500	60,000
Tug Vessel	6,000	12	7,200	3,000
Cable Laying Vessel	12,000	12	8,500	58,000

It can be concluded that the installation costs, schedules and fleet depend heavily on the farm size. The installation cost per turbine is significantly reduced with increasing wind farm size. However, the marginal cost reduction is bigger when the farms are small. Furthermore, the fleet size increases until approximately five turbines assuming installation in series. At this farm size, it is not required to increase the fleet to complete the operations on time. Notice that this is only true for strategies installing the turbines successively, which has been an assumption for both model formulations. A parallel strategy is not considered in this thesis, but would most likely result in further cost reductions.

Conclusively, it is evident that the fleet and schedule depend on the selected optimization model. The DFS model obtained a bigger fleet size, with vessels performing relatively few operations. The CFSS model gave a higher vessel utility, with a smaller fleet and vessels performing more operations.

Chapter 8

Discussion

This chapter will discuss the work and results obtained in this master's thesis. Firstly, an evaluation of the model realism and limitations of the work will be provided. Uncertainties in cost estimates will be considered and modeling weaknesses conferred. Lastly, challenges encountered along the way will be discussed.

8.1 Concept Realism and Limitations of the Optimization Model

8.1.1 Operations

The installation of a floating offshore wind farm involves a complex series of operations. In order to model the problem, multiple assumptions and simplifications were done along the way. This includes the interpretation of which vessels are required for each operation. In this work, each operation is assumed to require one vessel, which in some cases might require a support vessel for successful execution. In order to delimit the complexity of the problem, it was assumed that potential additional support vessels are included in the hire of the main vessel. This is the case for the vessel associated with towing, which need at least one smaller support vessel. These additional vessels and support equipment are not included in the optimization model. The vessel set does only consider the cost of one vessel and does not take the alternative support tool costs into account. An optimal model would consider alternative configurations of multiple vessels for each operation.

Currently, the CFSS formulation assumes that the turbines are installed in series. However, to reduce costs even further, solutions involving parallel installation could be more cost efficient. An example could be the transportation of multiple turbines to port of assembly on the same voyage. Furthermore, the scope of the operations might vary depending on which turbine number is to be installed. Clearly the export cable does only need to be installed once, and the inter-array cables are of varying length resulting in different execution times. These aspects are not ideally captured in the model, as they are currently assumed to be the same for all turbines. In further analysis, incorporating these differences might improve the model even further.

The only current experience from commercial installation of floating offshore wind farms, is the Hywind Scotland, introduced in Chapter 4.1.1. The installation steps and execution times are comparable to what is expected for the future, but is still a result of little experience. Thus the time estimates provided in this thesis are subject to uncertainty. The operations are considered to use a certain time to execute depending on the type of vessel used. However, the execution times are effected by multiple factors that are not fully captured in the optimization models developed in this work:

- **Learning effects** - The assumptions made in the thesis exclude the potential effects of learning. Industry actors have learned that dedicated vessels have a significant reduction in execution times with increasing experience. However, the inclusion of such an effect is challenging, and would generate endogenous running times.
- **Sailing time** - In order to make the model somewhat more realistic, the sailing time between operations should be considered. If a vessel executes towing from port to site, it cannot immediately be back in port again. These considerations could make the model closer to reality.
- **Mobilization time** - The mobilization time between each sequential operation depends on what type of operation is to be performed. Currently, the model includes mobilization costs related to the first operation to be performed by a vessel. This assumption accounts for the relocation costs, crew mobilization costs and equipment preparation costs. However, between each operation some re-mobilization work might be necessary. This could be moving from one turbine to another for hook-up, or reloading new equipment needed for cable installation.

8.1.2 Uncertainties in Nature of Problem

There is a high level of uncertainty associated with the installation problem. In reality, the operations are highly weather sensitive. In the models developed in this master's thesis, the operations are assumed to take a certain number of days, depending on what type of vessel is used. This is considered a reasonable assumption, but in practice the execution times are highly weather dependent. The weather influences a vessels ability to tow, lift and sail, consequently effecting the execution times. As mentioned in Chapter 4.2.3, some operations are weather restricted and can only take place in certain weather conditions. Capturing the uncertainty of weather is difficult with an optimization model, and simulation should be considered as a complementary tool. The combined use of an optimization and simulation model could move the solution towards a better and more robust result.

8.2 Uncertainties in Costs

8.2.1 Time Charter Costs and Vessel Availability

As seen in Chapter 5.1.4, the vessel charters are based on historical rates for the last 10-15 years, and are assumed to stay within the range defined by these data values. Ideally, a huge pool of data with a great variety of vessel types should make a basis for estimating the time charter costs. However, this data is difficult to collect as most of it is not publicly available and extremely expensive to access. As a result, the values used in this master's thesis is mainly based on a set of historical data on PSV and AHTS vessels provided by Clarksons Platou.

The shipping market is well known for being fluctuating, with huge changes in time charter rates. In Norway, the time charter rates for AHTS and PSV vessels, heavily invested in the oil industry, are greatly influenced by the oil price. Thus, the time charter costs associated with the selected fleet are prone to big variations. Ultimately, these costs greatly influence the installation costs of a floating offshore wind farm.

Another aspect important for the selection of the installation fleet, is the availability of the vessels. In practice, the vessels might be on contracts that delimit their availability for charter. In good market situation, it might be both difficult and expensive to access the necessary fleet. However, in poor market situations, the vessels might be easily available for a low charter rate. Sometimes, vessels that are considered overly equipped for a task might be hired as the markets are poor.

8.2.2 Mobilization Costs

As seen in Chapter 5.1.4, the mobilization costs are highly dependent on the transit distance, fuel costs, crew requirements and charter rates. The fuel costs are certainly prone to great variations. In the analysis used in this work, the average fuel cost since the start of 2020 is used in the calculations. However, the oil price has been historically low in this time period and the mobilization costs are expected to increase with the oil price. Again, the vessels with high fuel consumption will be more effected by a rise in the oil price than smaller vessels with lower consumption.

8.3 Modelling Capabilities

Despite being among the best optimization tools on the market, Gurobi still encounters common problems related to long algorithm running times. Various changes were made to mitigate this problem, some of them more effective than others. Changing the objective made the model complexity smaller, but did not yield the same quality of the results. Furthermore, relaxation reduced the running times, but partly resulted in less optimal solutions. In order to overcome these problems in the future, different methods are suggested, including implementation of decomposition techniques. However, this was not in the scope of the master's thesis and changes to the objective functions and constraints were considered sufficient for the analysis.

Various issues were encountered on the path of this work. The most significant are listed below:

- **Running time** - The running time was as mentioned the bottle neck of the analysis and were tackled by changing the objective function and by relaxation of the constraints.

- **Revenue considerations** - The objective functions included in the analysis minimized costs. However, they did not include potential revenue that might be generated as a result of partly finished farms. During the analysis, finishing the farm by parts was considered in order to start power production earlier. This becomes difficult to implement, resulting in contradicting objective functions. However, multi-objective functions might solve the problem.

Chapter 9

Conclusion and Further Work

9.1 Concluding Remarks

Floating offshore wind farms are among the most promising new sources of renewable energy. The rising need of alternative energy sources and the focus on renewable means of energy have contributed to the quick development of the industry. Along the Norwegian coast line, numerous floating offshore wind sites have been suggested and identified as potential for development. Equinor has been a pioneer within the floating offshore wind industry and designed the first floating offshore wind farm in the world, namely Hywind Scotland. This has marked the start of an anticipated bonanza of the industry.

Based on Hywind Scotland and studies on offshore wind installations, eight major installation steps have been identified. These include transportation of components and anchors, assembly in port, tow-out, anchor and cable installation, hook-up and final commissioning. In contrast to the assembly of bottom fixed wind farms, the entire operation takes place in port. Different fleet concepts have been proposed as solutions for the installation execution. The suitable vessel categories capable of completing the operations, include AHTS vessels, tugs, cable laying vessels and transportation vessels.

The main contribution in this master's thesis is a novel formulation of an optimization model used to select a fleet and schedule for the installation of an offshore floating wind farm. This is a field of study, for which few optimization models have been applied. Two optimization models have been developed to capture the installation problem. The CFSS model being an improvement of the DFS formulation. It was found that the optimization model considering the scheduling problem obtained better results for all wind farm sizes. However, the DFS model is easier to run, and have less problems facing high running times and increased data sets. Moreover, it is found that the inclusion of multiple vessel cycles is preferred over a simplified cycle restriction in the CFSS model.

Analysis found that the installation of one turbine takes approximately 28 days, while five turbines can be installed in 82 days. This gives an average installation time per turbine of

16.5 days, decreasing the installation time per turbine with 41.4%. Furthermore, increasing the farm size provide major cost reductions. The CFSS model estimates the installation cost of one turbine to 533,000 £, while a farm consisting of fifteen turbines gives an installation cost per turbine of 469,000 £. Presumably giving a cost reduction of 12%. Similarly, the DFS formulation estimates the installation cost of one turbine between 925,000 £and 1,713,000 £, which is significantly higher than for the CFSS model. However, the cost difference between the upper and lower bound decreases with the wind farm size. Furthermore, the estimate becomes closer to the CFSS cost as the farm size increases. The potential cost reduction between a farm size of one and fifteen turbines is estimated to 54% with the DFS model. Thus, it favors economy of size more than the CFSS formulation.

Results provided in this master's thesis are subject to validation, as the optimization model made approximate constraints of the system. However, the assumptions made are presumable reasonable, but should be kept in mind when using the results as a decision tool. The model is useful as a decision support for planning an installation schedule and for selecting an optimal fleet for the operations. However, it is recommended to run a more extensive set of case analyses to evaluate alternative campaigns and to discover more general rules that can be applied to the problem.

9.2 Further Work

The major problem associated with the CFSS model, which is considered an improvement of the DFS formulation, is the challenge associated with scalability. In order to solve bigger and more realistic case examples, future research might be applied in several directions. To begin with, heuristic approaches not guaranteeing an optimal solution might be considered. They might still perform significantly better than existing planning strategies and generally decreases the problem associated with high running times. Furthermore, literature suggests implementation of decomposition techniques, such as column-generation, exploratory and speculative decomposition (Bakker et al. 2017).

As mentioned in Chapter 8.1.2, there is a high level of uncertainty associated with the installation. Most of the operations are weather dependent, adding stochastic characteristics to the problem. This uncertainty can be addressed by adding simulation models in addition to the optimization formulation. Simulation can adjust for uncertainty, accounting for weather data based on historical measures for a specific location.

Expansions of the optimization model could be considered. As discussed in Chapter 8.1.1, the model assumes that the turbines are installed in series. This assumption can be questioned, and in reality the installation might be executed both in parallel and in series. Furthermore, the operations might install multiple turbines at a time. For example, multiple turbines being transported simultaneously might be reasonable.

Another aspect worth looking into is an alternative objective function. The objective functions included in this thesis look only at costs associated with the problem. Adding revenue to the problem might give incentives to reduce the total installation cost even further.

Finally, it could be interesting to look at the vessels ability to learn from the operations. It might be assumed that they will gradually learn to perform the operations more quickly, affecting and reducing the total installation time of the turbines.

Bibliography

Aditib (Aug. 2019). *What is a Cable Laying Ship?* URL: https://www.marineinsight.com/types-of-ships/what-is-a-cable-laying-ship/ (visited on 03/27/2020).

Adland, Roar, Pierre Cariou, and Francois-Charles Wolff (2019). "When energy efficiency is secondary: The case of Offshore Support Vessels". In: *Transportation Research Part D: Transport and Environment* 72, pp. 114–126.

Amarican Wind, Energy Association (2019). "Basics of Wind Energy". In:

Aubeny, C. P., J. D. Murff, and J. M. Roesset (2001). "Geotechnical Issues in Deep and Ultra Deep Waters". In: *International Journal of Geomechanics* 1.2, pp. 225–247.

Backe, Stian and Dag Haugland (2017). "Strategic Optimization of Offshore Wind Farm Installation". In: *Computational Logistics*. Ed. by Tolga Bektaş et al. Cham: Springer International Publishing, pp. 285–299. ISBN: 978-3-319-68496-3.

Bai, Qiang and Yong Bai (2014). "33 - Installation Design". In: *Subsea Pipeline Design, Analysis, and Installation*. Ed. by Qiang Bai and Yong Bai. Boston: Gulf Professional Publishing, pp. 707–751. ISBN: 978-0-12-386888-6. DOI: 10.1016/B978-0-12-386888-6.00033-X. URL: http://www.sciencedirect.com/science/article/pii/B978012386888600033X.

Bakker, Steffen et al. (2017). "Planning of an offshore well plugging campaign: a vehicle routing approach". In: Springer, pp. 158–173.

Barlow, Euan et al. (2018). "A mixed-method optimisation and simulation framework for supporting logistical decisions during offshore wind farm installations". In: *European Journal of Operational Research* 264.3, pp. 894–906.

Blackburn, John and Simon Hanrahan (2010). "Offshore production system definition and cost study". In: *Nautilus Minerals, 2010*.

Brandão, F.E.N. et al. (Jan. 2006). "Albacora Leste Field Development- FPSO P-50 Mooring System Concept and Installation". In: *OTC-18243-MS*. Journal Abbreviation: OTC-18243-MS. OTC: Offshore Technology Conference, p. 10.

Christ, R. and R. Wernli (2007). *The ROV Manual*. Elsevier Ltd.

Christiansen, Marielle, Kjetil Fagerholt, and David Ronen (Feb. 2004). "Ship Routing and Scheduling: Status and Perspectives." In: *Transportation Science* 38.1. Publisher: INFORMS: Institute for Operations Research, pp. 1–18.

Costello, Mark John, Alan Cheung, and Nathalie De Hauwere (2010). "Surface area and the seabed area, volume, depth, slope, and topographic variation for the world's seas, oceans, and countries”. In: *Environmental science & technology* 44.23. Publisher: ACS Publications, pp. 8821–8828.

Dai, Lijuan, Magnus Stålhane, and Ingrid B. Utne (2015). “Routing and Scheduling of Maintenance Fleet for Offshore Wind Farms”. In: *Wind Engineering* 39.1, pp. 15–30.

Damen (2020). *Damen Anchor Handling Tug*. URL: https://products.damen.com:443/ranges/anchor%20handling%20tug%20supplier (visited on 05/01/2020).

Diaz, B. D. et al. (Sept. 2016). “Multiline anchors for floating offshore wind towers”. In: *OCEANS 2016 MTS/IEEE Monterey*, pp. 1–9.

Dicorato, M. et al. (2011). “Guidelines for assessment of investment cost for offshore wind generation”. In: *Renewable Energy* 36.8, pp. 2043–2051.

DNVGL (Jan. 2015). *Sea transport operations (VMO Standard - Part 2-2)*. DNV GL. URL: https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2015-10/OS-H202.pdf (visited on 04/26/2020).

— (Jan. 2020). *Current price development oil and gas*. en. URL: https://www.dnvgl.com/maritime/lng/current-price-development-oil-and-gas.html (visited on 06/09/2020).

Drewry, Maritime Research (Nov. 2018). *Ship Operating Costs, Annual Review and Forecast*. Drewry Maritime Research.

Equinor (2020). *Hywind Tampen - floating wind power project - equinor.com*. en. Library Catalog: www.equinor.com. URL: https://www.equinor.com/en/what-we-do/hywind-tampen.html (visited on 06/10/2020).

Equinor, ASA (2019). *Hywind – up close and personal - Hywind - facts and figures - equinor.com*. URL: https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us/hywind-up-close-and-personal.html (visited on 12/08/2019).

Equinor, Norway (Oct. 2017). *Full story of Hywind Scotland – world’s first floating wind farm*. URL: https://www.youtube.com/watch?v=PUlfvXaISvc&feature=youtu.be (visited on 03/09/2020).

— (Feb. 2020a). *Floating offshore wind in Equinor*. URL: https://www.equinor.com/en/what-we-do/floating-wind.html (visited on 02/24/2020).

— (Mar. 2020b). *Investing in Hywind Tampen development - equinor.com*. en. Library Catalog: www.equinor.com. (Visited on 03/20/2020).

— (Feb. 2020c). *The market outlook for floating offshore wind*. URL: https://www.equinor.com/en/what-we-do/floating-wind/the-market-outlook.html (visited on 02/24/2020).

Erikstad, Stein Ove and Kai Levander (2012). “System based design of offshore support vessels”. In: *Proceedings 11th International Marine Design Conference—IMDC201*.

EWEA (2009). *Wind energy : the facts : a guide to the technology, economics and future of wind power*. eng. [New ed.]. London: Earthscan.

Fagerholt, Kjetil and Marielle Christiansen (2000). “A travelling salesman problem with allocation, time window and precedence constraints—an application to ship scheduling”. In: *International Transactions in Operational Research* 7.3. ISBN: 0969-6016 Publisher: Wiley Online Library, pp. 231–244.

Forrest, James, Robert Taylor, and Lora Bowman (Mar. 1995). “Design Guide for Pile-driven Plate Anchors”. In: *Naval Facilities Engineering Service Center, Port Hueneme* Technical Report.

Fuglsang, P. and K. Thomsen (1998). *Cost optimization of wind turbines for large-scale offshore wind farms*. Tech. rep. 87-550-2331-2. Denmark, p. 31.

Giæver Tande, John Olav (Jan. 2020). *Havvind*. URL: http://www.sintef.no/havvind/ (visited on 04/15/2020).

GL, DNV (2019). *Energy Transition Outlook 2019*. English. URL: https://eto.dnvgl.com/2019 (visited on 09/20/2019).

GlobalPetrolPrices (2020). *USA gasoline prices, 18-May-2020 — GlobalPetrolPrices.com*. en. Library Catalog: www.globalpetrolprices.com. (Visited on 05/19/2020).

Gonzalez-Rodriguez, Angel G. (2017). “Review of offshore wind farm cost components”. In: *Energy for Sustainable Development* 37, pp. 10–19.

Grigoriou, Rafaila (Apr. 2020). *Price Data*. en-US. Library Catalog: www.energypriceindex.com. (Visited on 04/17/2020).

Guachamin Acero, Wilson Ivan (2016). “Assessment of Marine Operations for Offshore Wind Turbine Installation with Emphasis on Response-Based Operational Limits”. English. In: *NTNU*.

Gurobi (2020). *MIPGap*. URL: https://www.gurobi.com/documentation/9.0/refman/mipgap2.html (visited on 05/29/2020).

Hassani, Vahid et al. (2017). “Robust Dynamic Positioning of offshore vessels using mixed-mu synthesis modeling, design, and practice”. In: *Ocean Engineering* 129, pp. 389–400.

Henderson, Andrew R. et al. (2003). “Offshore Wind Energy in Europe— A Review of the State-of-the-Art”. eng. In: *Wind Energy* 6.1. Place: Chichester, UK Publisher: John Wiley & Sons, Ltd., pp. 35–52.

Hofstad, Knut and Knut A. Rosvold (Nov. 2019). *vindturbin*. nb. URL: http://snl.no/vindturbin (visited on 05/26/2020).

Houlsby, Guy T. and Byron W. Byrne (2000). “Suction Caisson Foundations for Offshore Wind Turbines and Anemometer Masts”. In: *Wind Engineering* 24.4, pp. 249–255.

Hyland, Thomas et al. (Aug. 2014). “Towing tests with the GICON®-TLP for Wind Turbines”. In: *ISOPE-I-14-065*. Journal Abbreviation: ISOPE-I-14-065. ISOPE: International Society of Offshore and Polar Engineers, p. 5.

IEA (2019). “Offshore Wind Outlook 2019: World Energy Outlook Special Report”. In: *Offshore Wind*, p. 98.

IEA, Paris (Apr. 2020). *IEA – International Energy Agency*. en-GB. URL: https://www.iea.org (visited on 04/15/2020).

Ioannou, Anastasia, Andrew Angus, and Feargal Brennan (May 2018). “Parametric CAPEX, OPEX, and LCOE expressions for offshore wind farms based on global deployment parameters”. In: *Energy Sources, Part B: Economics, Planning, and Policy* 13.5. Publisher: Taylor & Francis, pp. 281–290.

Irawan, C.A., G. Wall, and D. Jones (2019). “An optimisation model for scheduling the decommissioning of an offshore wind farm”. In: *OR Spectrum* 41.2, pp. 513–548.

Irawan, Chandra Ade, Dylan Jones, and Djamila Ouelhadj (2017). “Bi-objective optimisation model for installation scheduling in offshore wind farms”. In: *Computers & Operations Research* 78, pp. 393–407. ISSN: 0305-0548. DOI: https://doi.org/10.1016/

j.cor.2015.09.010. URL: http://www.sciencedirect.com/science/article/pii/S0305054815002312.

Irawan, Chandra Ade, Djamila Ouelhadj, et al. (2017). "Optimisation of maintenance routing and scheduling for offshore wind farms". In: *European Journal of Operational Research* 256.1, pp. 76–89.

James, Rhodri and Marc Costa Ros (June 2015). *Floating Offshore Wind: Market and Technology Review*. Tech. rep. The Scottish Government. URL: https://www.carbontrust.com/media/670664/floating-offshore-wind-market-technology-review.pdf (visited on 09/30/2019).

Jugović, Alen, Nikša Komadina, and Ana Perić Hadžić (2015). "Factors influencing the formation of freight rates on maritime shipping markets". In: *Pomorstvo* 29.1. Publisher: Pomorski fakultet u Rijeci, pp. 23–29.

Junginger, Martin, André Faaij, and Wim C. Turkenburg (2004). "Cost reduction prospects for offshore wind farms". In: *Wind engineering* 28.1. ISBN: 0309-524X Publisher: SAGE Publications Sage UK: London, England, pp. 97–118.

Kaiser, Mark J. and Brian F. Snyder (2012a). "Modeling offshore wind installation vessel dayrates in the United States". In: *Maritime Economics & Logistics* 14.2. Publisher: Palgrave Macmillan, p. 220.

— (2012b). *Offshore Wind Energy Cost Modeling : Installation and Decommissioning*. English. Green Energy and Technology. London: Springer.

Kavussanos, Manolis G. and Amir H. Alizadeh-M (2001). "Seasonality patterns in dry bulk shipping spot and time charter freight rates". In: *Transportation Research Part E: Logistics and Transportation Review* 37.6, pp. 443–467.

Komusanac, Ivan, Guy Brindley, and Daniel Fraile (Feb. 2020). *Wind energy in Europe in 2019 - Trends and statistics*. English. (Visited on 04/07/2020).

Landbø, Trond (Jan. 2018a). "OO-STAR Wind Floated - The Future of Offshore Wind?" Trondheim. URL: https://www.sintef.no/globalassets/project/eera-deepwind-2018/presentations/closing_landbo.pdf (visited on 04/15/2020).

— (Jan. 2018b). "THE FUTURE OF OFFSHORE WIND?" In: p. 38.

Lange, Bernhard et al. (1999). "Offshore wind farm Bockstigen: installation and operation experience". In: *EWEC-CONFERENCE-*, pp. 300–303.

Larsen, Jens HM et al. (2005). "Experiences from Middelgrunden 40 MW offshore wind farm". In: *Copenhagen offshore wind conference*, pp. 1–8.

Larsen, Kjell (Jan. 2019). "Towing Operations; TMR4225 Marine Operations". Lecture. Published: Lecture. Trondheim.

Laura, Castro-Santos and Diaz-Casas Vicente (2014). "Life-cycle cost analysis of floating offshore wind farms". In: *Renewable Energy* 66, pp. 41–48.

Liu, W. Timothy, Wenqing Tang, and Xiaosu Xie (Aug. 2008). "Wind power distribution over the ocean". In: *Geophysical Research Letters* 35.13. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008GL034172.

Mæhlum, Lars and Knut A. Rosvold (Sept. 2019). *vindmølle*. nb. URL: http://snl.no/vindm%C3%B8lle (visited on 05/26/2020).

Malhotra, Sanjeev (2007). "Design and Construction Considerations for Offshore Wind Turbine Foundations in North America". In:

Mersin, Kadir, Güler Alkan, and Tunç Mısırlıoğlu (2017). "A new method for calculating fuel consumption and displacement of a ship in maritime transport". In: *Cogent Engineering* 4.1. Publisher: Taylor & Francis, p. 1415107.

Morgan, Max J (1978). *Dynamic positioning of offshore vessels*. Tulsa, Okla: PPC Books.

Mosquera-López, Stephanía and Anjali Nursimulu (2019). "Drivers of electricity price dynamics: Comparative analysis of spot and futures markets". In: *Energy Policy* 126, pp. 76–87.

Myhr, Anders et al. (2014). "Levelised cost of energy for offshore floating wind turbines in a life cycle perspective". In: *Renewable Energy* 66, pp. 714–728.

Nedrevåg, Vegard (Feb. 2020). *Inverview with Vegard Nedrevåg in Equinor*. Norsk.

Network, MI News (Jan. 2019). *What are Anchor Handling Tug Supply Vessels (AHTS)?* en-US. URL: https://www.marineinsight.com/types-of-ships/what-are-anchor-handling-tug-vessels-aths/ (visited on 03/20/2020).

OffshoreWIND (Mar. 2017). *DORIS Eyes 30% of Turnover to Come from Offshore Renewables*. en-US. URL: https://www.offshorewind.biz/ (visited on 04/07/2020).

— (Sept. 2018). *Vessel Directory*. OffshoreWIND. (Visited on 04/30/2020).

Rippel, D. et al. (Dec. 2019). "Simulation and Optimization of Operations for Offshore Installations Planning Using a Model Predictive Control Scheme". In: *2019 Winter Simulation Conference (WSC)*, pp. 1719–1730.

Rosvold, Knut A. (Nov. 2019). *vindkraftpark*. nb. URL: http://snl.no/vindkraftpark (visited on 05/26/2020).

Sævik, Svein (Apr. 2019). "Flexible Pipes and Cables; TMR 4225 Marine Operations". Lecture. Published: Lecture. Trondheim. (Visited on 04/27/2020).

Sarker, Bhaba R. and Tasnim Ibn Faiz (2017). "Minimizing transportation and installation costs for turbines in offshore wind farms". In: *Renewable Energy* 101, pp. 667–679. ISSN: 0960-1481.

Scholz-Reiter, Bernd et al. (2011). "A MILP for installation scheduling of offshore wind farms". In: *International Journal of Mathematical Models and Methods in Applied Sciences* 5.2, pp. 371–378.

Sirimanne, Shamika (Jan. 2020). *Review of Maritime Transport 2019 - United Nations Conference on Trade and Development*. English. Tech. rep. New York: United Nations. (Visited on 08/06/2020).

Skaugset, Kjetil (Mar. 2019). "Offshore Wind Turbines". Guest Lecture in Marine Operations TMR4225. Published: Guest Lecture in Marine Operations TMR4225. NTNU Tyholt. (Visited on 04/23/2020).

Sperstad, Iver Bakken et al. (2016). "Investigating Key Decision Problems to Optimize the Operation and Maintenance Strategy of Offshore Wind Farms". In: *Energy Procedia* 94, pp. 261–268.

Srinil, Narakorn (2016). "Cabling to connect offshore wind turbines to onshore facilities". In: *Offshore Wind Farms*. Ed. by Chong Ng and Li Ran. Woodhead Publishing, pp. 419–440.

SSE and Equinor (2020). *Dogger Bank Wind Farm*. Library Catalog: doggerbank.com. (Visited on 06/10/2020).

Thomsen, Kurt E. (2014). *Offshore wind : a comprehensive guide to successful offshore wind farm installation*. eng. 2nd ed. London, England: Elsevier : Academic Press.

Thresher, Robert, Michael Robinson, and Paul Veers (2007). “To Capture the Wind”. In: *IEEE power & energy magazine* 5.6. Place: New York, N.Y. : Publisher: Institute of Electrical and Electronics Engineers, pp. 34–46. ISSN: 1540-7977.

Thue, Jan Vincent (Feb. 2019). *glideforskaling*. URL: http://snl.no/glideforskaling (visited on 03/19/2020).

Tong, K. C. (1998). “Technical and economic aspects of a floating offshore wind farm”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 74-76, pp. 399–410. ISSN: 0167-6105. URL: http://www.sciencedirect.com/science/article/pii/S0167610598000361.

Tønne, Erik and Jens Egenberg (Mar. 2020). *WEEKLY NORTH SEA SPOT MARKET UPDATE Clarkson Platou*.

Toth, Paolo and Daniele Vigo (2002). *The vehicle routing problem*. SIAM. ISBN: 0-89871-498-2.

Twidell, John and Gaetano Gaudiosi (2009). *Offshore Wind Power*. Multi-Science Publishing. ISBN: 978-0-906522-63-9.

Ulstein (2020). *Anchor Handling Tug Supply*. URL: https://ulstein.com/ship-design/ahts (visited on 04/29/2020).

United Nations Department for Economic and Social Affairs (Jan. 2020). *World Economic Situation and Prospects 2020*. en. OCLC: 1141040763. New York: United Nations.

VesselFinder, Ltd (2011). *VesselFinder*. URL: https://www.vesselfinder.com/ (visited on 05/01/2020).

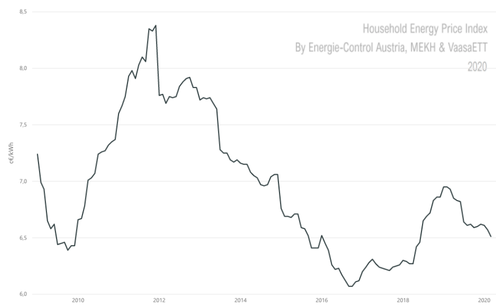
Wang, Li-zhong et al. (2014). “Integrated analysis of drag embedment anchor installation”. In: *Ocean Engineering* 88, pp. 149–163.

Worzyk, Thomas (2009). *Submarine Power Cables: Design, Installation, Repair, Environmental Aspects*. Power Systems. Berlin, Heidelberg: Springer Berlin Heidelberg. ISBN: 978-3-642-01269-3.

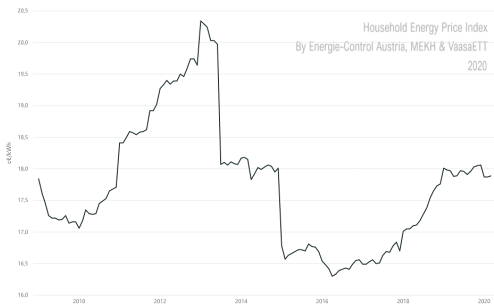
Zook, Jason R. and Arran L. Keith (Jan. 2009). “Improvements in Efficiency for Subsea Operations in Deepwater Angola”. In: *SPE-119651-MS*. SPE: Society of Petroleum Engineers, p. 9.

Appendix A

Historical Electricity Prices



(a) Avg. historical gas prices for EU countries



(b) Avg. historical electricity prices for EU countries

Figure A.1: Energy prices for EU countries (Grigoriou 2020)

Appendix B

Cost Break Down of Life Cycle Costs (LCC)

B.1 Cost Break Down

The break down structure of life cycle costs (LCC) can be applied for both mother systems and sub-systems. Life-cycle cost analysis done on offshore wind farms suggests dividing the costs into OPEX and CAPEX with respective sub-costs (Laura and Vicente 2014).

Cost Elements

$$LCC = CAPEX + OPEX \tag{B.1}$$

CAPEX, or *capital expenditures*, are costs of material, design, fabrication, installation and mobilization. OPEX are *operating expenditures*, i.e., costs associated with operations, including labor costs, storage costs and logistical costs related to transportation of people or material needed for operation.

For offshore wind farms, the costs can be further divided into six components. Each of these groups can be split into sub-costs as seen in Figure B.1 (Laura and Vicente 2014).

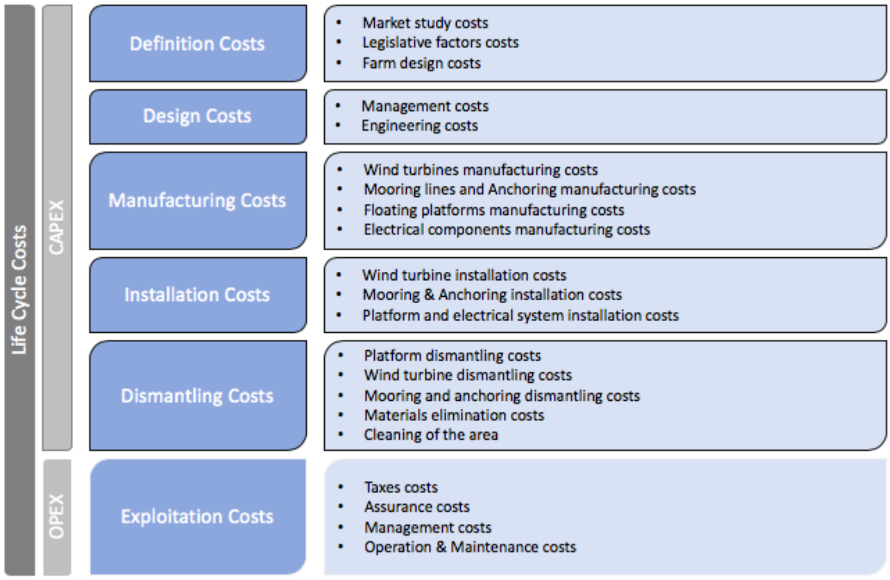


Figure B.1: Subgroup costs ((Laura and Vicente 2014))

Generally, operating costs are influenced by both internal and external factors constantly affecting the running costs of a plant. The three external market driven factors are given in Table B.1 (Drewry 2018). The exchange rates are a result of contracts, revenues and expenditures operating in different currencies. Raw material prices include oil and energy prices. Furthermore, labor costs typically directly reflect the market. Similarly, there are multiple internal factors affecting the wind operation costs. The operating costs tend to rise with the age of the system.

Table B.1: Factors influencing costs

External Factors	Internal Factors
· Exchange rates	· Age of farm
· Raw material prices	· Crew nationality and scale of manning
· Labor costs	· Type and age of maintenance fleet
	· Management
	· Investment funding method

Appendix C

Case Data

C.1 Vessel Requirement

Table C.1 gives an overview of the set of vessels and their ability to do the operations defined for the installation of wind turbines.

Table C.1: Compatibility of vessels and operations

Vessel Type	No.	Sub. Transp.	Asse-mbly	Tow Out	Anchor Transp.	Anchor Inst.	Hook Up	Cable Laying	Final Comm.
AHTS	0	-	-	✓	✓	✓	✓	-	✓
	1	-	-	✓	✓	✓	✓	-	✓
	2	-	-	✓	✓	✓	✓	-	✓
	3	-	-	✓	✓	✓	✓	-	✓
	4	-	-	✓	✓	✓	✓	-	✓
Transp. Vessel	5	✓	✓	-	✓	-	-	-	-
	6	✓	✓	-	✓	-	-	-	-
	7	✓	✓	-	✓	-	-	-	-
	8	✓	✓	-	✓	-	-	-	-
	9	✓	✓	-	✓	-	-	-	-
Tug Vessel	10	-	-	✓	-	-	-	-	-
	11	-	-	✓	-	-	-	-	-
	12	-	-	✓	-	-	-	-	-
	13	-	-	✓	-	-	-	-	-
	14	-	-	✓	-	-	-	-	-
Cable Laying Vessel	15	-	-	-	-	-	-	✓	✓
	16	-	-	-	-	-	-	✓	✓
	17	-	-	-	-	-	-	✓	✓
	18	-	-	-	-	-	-	✓	✓
	19	-	-	-	-	-	-	✓	✓

C.2 Mobilization Costs

The mobilization costs are calculated according to the proposed formula by Kaiser and Snyder (2012a), and expressed in the equation below. The mobilization distances are assumed to be a random selection of ranges reflecting distances in Europe. It is assumed that the transportation from other continents will be ousted by more local vessels as the mobilization costs will become very high.

$$(\frac{X}{24V_i})(I + (1.2 \cdot 5P_i)G) \tag{C.1}$$

where X is the transit distance in miles, V_i is the speed in knots and P_i the installed power (hp). I is the installation vessel day-rate ($/day) and G is the cost of fuel per gallon ($/day). The cost of fuel is assumed to be 2,211 $/gallon (GlobalPetrolPrices 2020).

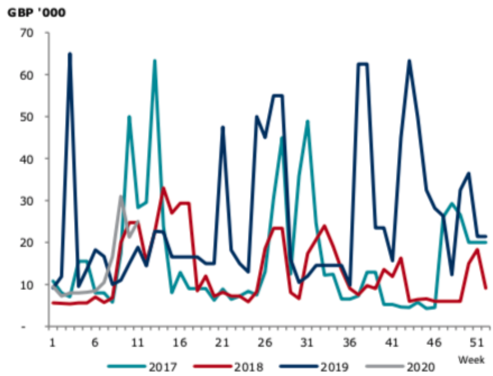
Table C.2: Mobilization costs

Name	**No.**	**Distance [miles]**	**HP**	**Day Rate [£/day]**	**Speed [knots]**	**Mob. Cost [£]**
AHTS	0	181	20,000	18,000	16	111,839
	1	191	18,000	17833	15	114,164
	2	400	16,000	10,500	14	221,331
	3	832	14,000	10,417	13	437,087
	4	120	12,000	9000	12	58,568
Transportation vessel	5	181	10,000	14,000	16	58,276
	6	191	9,000	13,500	15	59,513
	7	400	8,000	13,000	14	119,891
	8	832	7,000	12,500	13	237,987
	9	120	6,000	12,000	12	32,409
Tug Vessel	10	181	10,000	8,000	16	55,448
	11	191	9,000	7,800	15	56,489
	12	400	8,000	7,600	14	113,463
	13	832	7,000	7,400	13	224,387
	14	120	6,000	7,200	12	30,409
Cable laying vessel	15	181	20,000	18,000	16	111,839
	16	191	18,000	17,833	15	114,164
	17	400	16,000	10,500	14	221,331
	18	832	14,000	10,417	13	437,087
	19	120	12,000	8,500	12	58,359

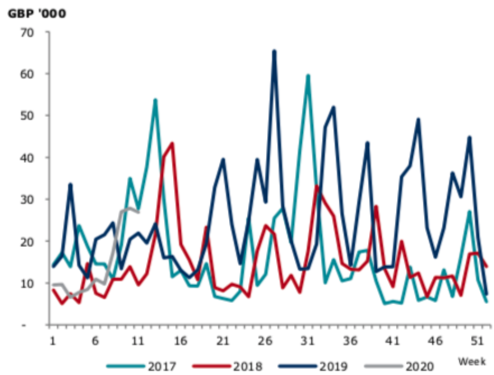
C.3 Time Charter Costs

The time charter rates are defined based on common practise in the offshore industry. SRK Consulting, Blackburn and Hanrahan 2010, state that *"the vessel charter costs include the provision of a vessel and basic marine crew to operate the vessel"*. It is based on historical data from the last 10 years, and are assumed to range between upper and lower values in the data.

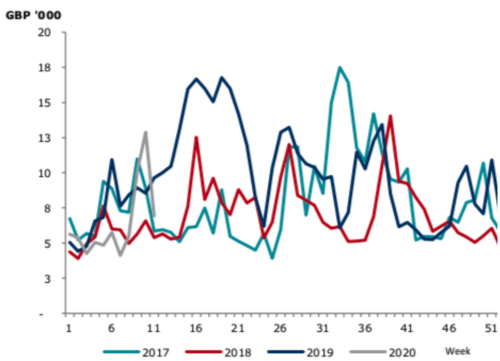
C.3.1 AHTS and PSV Day Hire Rates



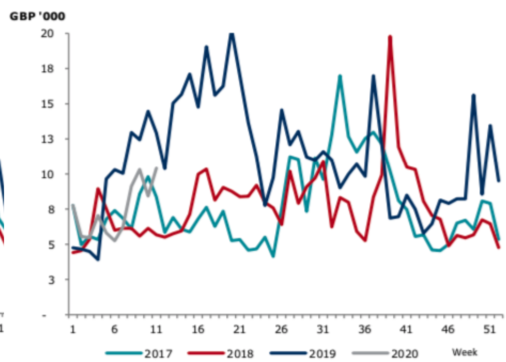
(a) AHTS 16-19,999 BHP



(b) AHTS 20,000+ BHP

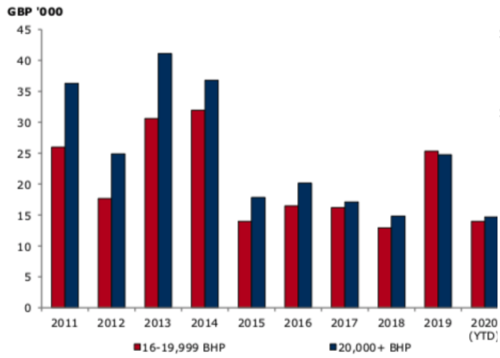


(c) PSV 500-899 m2

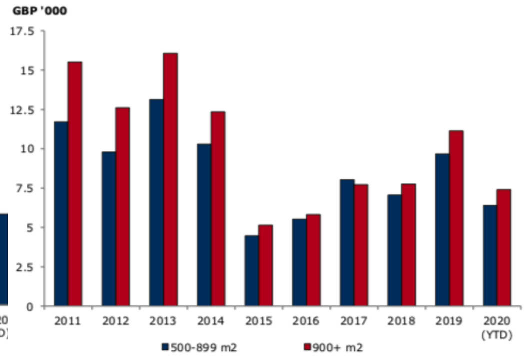


(d) PSV 900+ m2

Figure C.1: North Sea average weekly spot rates for PSV and AHTS (Tønne and Egenberg 2020)



(a) AHTS spot market - Annual averages



(b) PSV spot market - Annual averages

Figure C.2: North Sea AHTS and PSV spot market - Annual averages (Tønne and Egenberg 2020)

As detailed information on day charter rates for cable laying vessels are not publicly accessible, the PSV rates are used as a reasonable comparison. Day rates include the use of the vessel and its crew. It does not include most of the other costs associated with the operations. This include anchor costs, cables, potential cementing and chains.

C.3.2 Transportation Vessel Day Hire Rates

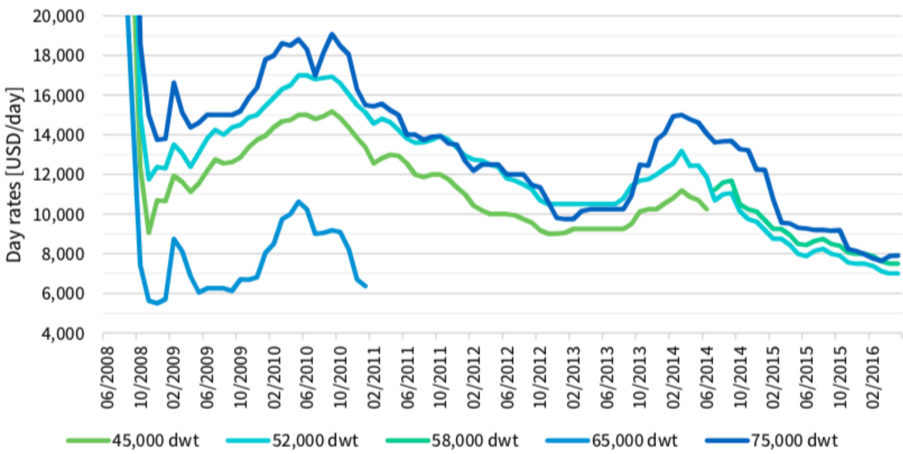
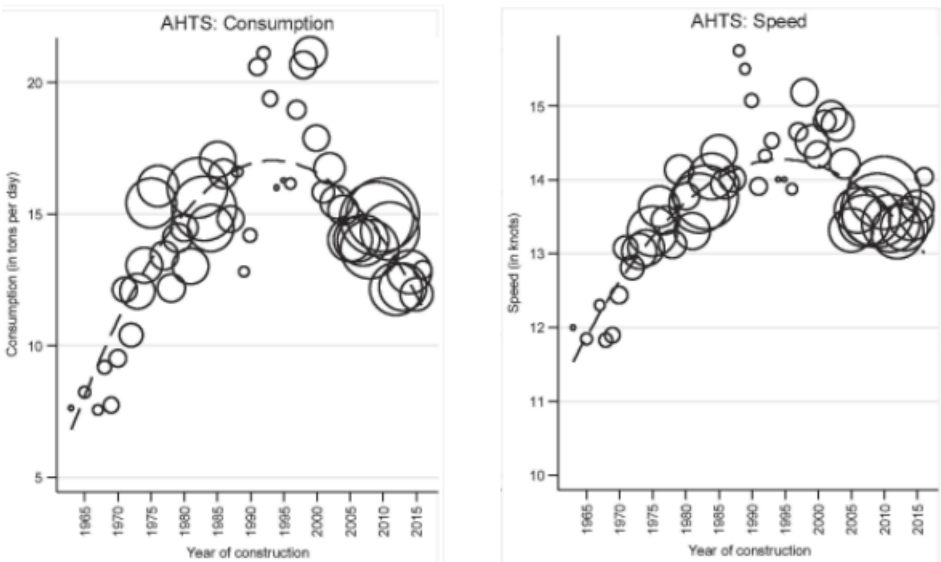


Figure C.3: Time charter costs for handymax (Tønne and Egenberg 2020)

C.3.3 Fuel Costs

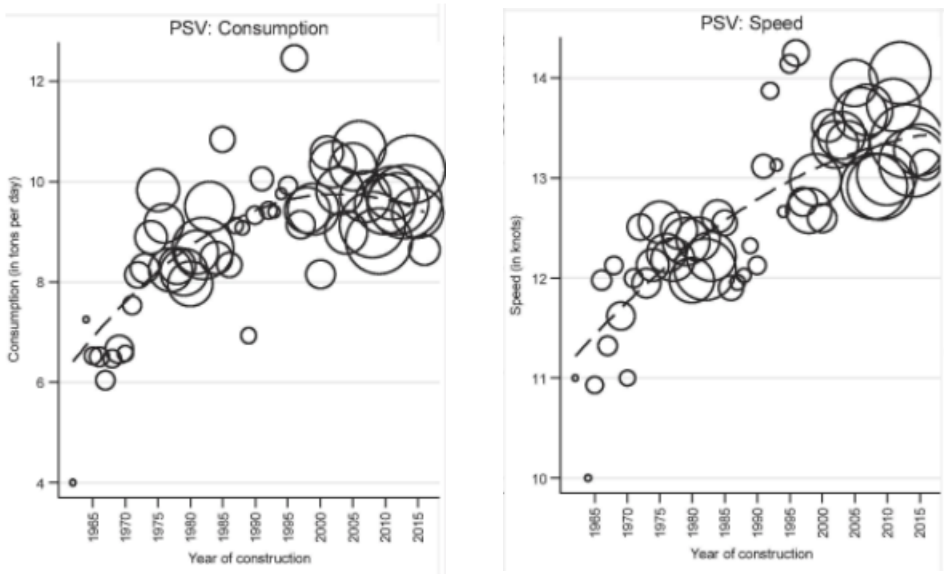
When estimating the fuel costs of a vessel, the fuel consumption and price must be approximated.

Fuel Consumption
There have been multiple suggestions for the calculation of fuel consumption. Mersin, Alkan, and Mısırlıoğlu 2017 suggest a formula involving the square of the speed times a vessel specific constant. This constant is suggested to be a function of the vessel displacement. Adland, Cariou, and Wolff 2019 suggest an estimation of the fuel consumption based on historical data for different vessel categories. This study will be used to make an approximation of the fuel costs in this thesis.



(a) AHTS fuel consumption **(b)** AHTS speed range

Figure C.4: AHTS fuel consumption and speed based on historical data (Adland, Cariou, and Wolff 2019)



(a) PSV fuel consumption

(b) PSV speed range

Figure C.5: PSV fuel consumption and speed based on historical data (Adland, Cariou, and Wolff 2019)

Based on Figure C.4 and Figure C.5, an approximation of the correlation between fuel consumption and speed can be found. Table C.3 summarizes the fuel consumption ranges and speed ranges based on average values for the fleet constructed between 2010 and 2015. In this work, a linear relationship between the two variables will be used as an assumption for fuel cost estimations.

Table C.3: Fuel consumption characteristics for PSV and AHTS vessels (Adland, Cariou, and Wolff 2019)

Vessels	AHTS	PSV
Fuel consumption (tonnes/day)	12-16	9-11
Design speed (knots)	12-16	12.5-15
Deadweight (tonnes)	1,800-2,600	3,200-4,300

Fuel Costs

As the cable laying vessel is regarded relatively similar to the PSV, the ranges for the PSV vessels are used as an estimation for the fuel consumption of the cable laying vessels. Furthermore, the values of the tug vessels are assumed to be a little less than that of the AHTS. The fuel consumption of the transportation vessel is dependent of the size of the vessel. It is thus assumed that their fuel consumption is a little higher than the rates for the AHTS, as they have similar speeds, but a slightly higher deadweight. The price of crude oil is assumed to be 214 USD/tonne, which is the average of April 2020 (DNVGL 2020).

Table C.4: Daily fuel cost estimate ranges for different vessel categories

Parameter	Vessel	Unit	Lower	Upper	Average
Fuel price		USD/tonnes			214.0
Daily fuel consumption	AHTS	tonnes/day	12	16	14
	Cable laying vessel		9	11	10
	Transp. vessel		14	18	16
	Tug vessel		10	14	12
Daily fuel costs	AHTS	USD/day	2,568	3,424	2,996
	Cable laying vessel		1,926	2,354	2,140
	Transp. vessel		2,996	3,852	3,424
	Tug vessel		2,140	2,996	2,568
Daily fuel costs	AHTS	£/day	2,029	2,705	2,367
	Cable laying vessel		1,522	1,860	1,691
	Transp. vessel		2,367	3,043	2,705
	Tug vessel		1,691	2,367	2,029

C.3.4 Manning Costs

Normally, the manning costs are paid by the owner. However, in some cases there might be special requirements for a specific contract where additional training of the crew is necessary. This might be because of challenging or new operations to be performed. Furthermore, costs associated with additional equipment needed might be put on the charterer. This include ROV supervisors or pilots/technicians. In this master's thesis, it is assumed that the day hire is in the upper range to account for some of these costs.

C.4 Precedence Relationship in a DSM

Table C.5: Precedence relationship for installation of two turbines displayed in a DSM

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1		X							X							
2			X													
3						X										
4					X											
5						X										
6							X									
7								X								
8																
9										X						
10											X					
11														X		
12													X			
13														X		
14															X	
15																X
16																

Ingunn Salvesen Haldorsen

Optimization of Combined Fleet and Installation Process for a Floating Offshore Wind Farm

NTNU
Norwegian University of
Science and Technology