Håvard Velle Sjåstad

A Simulation Study of Installation Concepts for Floating Offshore Wind Farms

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

Master's thesis

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Norwegian University of Science and Technology
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Master Thesis in Marine Technology

Spring 2020

Stud. techn. Håvard Velle Sjåstad

"A Simulation Study of Installation Concepts for Floating Offshore Wind Farms "

Background
Today, land based wind energy development projects are creating political controversy. An alternative for Norway could be offshore floating wind - we have the areas, and we have the technologies. A challenge is that this solution is estimated to be about twice the cost of traditional land-based developments, which may be partly due to a more complex and costly solution for the wind turbine itself, but may also be because of current low scale production and an inefficient production and installation logistics solution. Installation of an offshore wind farm is challenging and cost-intensive as a result of harsh weather conditions and limited availability of resources. If we assumed that sufficient capital was raised for a large scale, long term development - how should we design a complete, integrated installation logistics solution for offshore floating wind to gain a competitive position?

Objective
The objective of the master's thesis is to evaluate new installation concepts for Floating Offshore Wind Farms (FOWF). It includes the evaluation of installation vessels and the impact of installation vessel operability on total installation time for a floating offshore wind field. The work should improve the understanding of installation of FOWFs. Offshore wind farm case studies will be evaluated with different installation scenarios. The overall aim of the project is to evaluate possible installation logistics for Floating Offshore Wind, as a tool for improving planning and reduce costs.

Tasks

The candidate should presumably cover the following main points:

1. *Review state of art within the topic.*

2. *Perform a review of existing literature related to cost, operability and simulation within the floating offshore wind market.*

3. *Review problems related to installation of offshore wind farms, with respect to risk and vulnerability of marine operations.*

4. *Find interactions between processes and equipment for installation in order to derive different fleet compositions for installation of floating offshore wind farms.*

5. *Create discrete-event simulation models where the different fleet compositions are implemented.*

6. *Perform case studies of installation of floating offshore wind farms, and compare the different installation solutions.*

7. *Perform a cost-benefit assessment of the installation solutions.*

8. *Conclude and give recommendations for further work.*

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

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

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

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

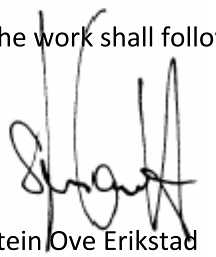
Deliverables

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

Modus operandi

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

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



Stein Ove Erikstad
Professor/Responsible Advisor

Summary

Today, land based wind energy development projects are creating political controversy. An alternative for Norway could be floating offshore wind. We have the areas, and we have the technologies. A challenge is that this solution is estimated to be twice the cost of land-based developments, which may be partly due to a more complex solution for the turbine itself, but may also be because of current low scale production and an inefficient installation logistics. A simulation study is applied to evaluate possible installation logistics for Floating Offshore wind, as a tool for improving planning and reduce costs.

The total installation cost of an floating offshore wind farm is heavily dependent on weather. Installation during the summer months gives a higher operability compared to the other seasons. The installation should take place during the summer months in order to reduce cost. The report reveals that the towing and hook-up process together with the suction anchor installation are most sensitive to weather and most costly, and these operations should be targeted for developing a better solution rather than simply employing vessels with increased operating capacity.

Furthermore, the report reveals that the installation logistics for Floating Offshore Wind Farms should include modular vessels with cable laying and construction capabilities in order to introduce flexibility in planning. The simulation study shows that the vessel with modular capabilities is more expensive than the conventional fleet, but by reviewing previous installation projects, it is predicted that it will reduce the total installation cost, considering disturbances in the supply chain. Introducing feeder vessels to the installation logistics is beneficial when the distance from shore increases. The utilization of installation vessels increases and it highlights the importance of not using high-charter cost vessels for sailing back and forth from the wind farm.

Cost adds linearly with wind farm size. The distance from shore highly influence the cost, and removing the number of transport legs between the assembly port and the wind farm is the first step towards cost reduction. Increasing the number of towed floating offshore wind turbines from one to four per round trip reduces the cost with 60 % for a wind farm size of 100 turbines located 66 nautical miles from shore.

Preface

This thesis is part of the Master of Science degree in Marine Technology with specialization in Marine Systems Design and Logistics at the Norwegian University of Science and Technology (NTNU). The report counts as 30 ECTS credits and was written during the spring of 2020. The thesis focuses on evaluating the design of integrated installation logistics for Floating Offshore Wind Farms with the use of Discrete-Event Simulation.

A considerable part of the insight into the work was obtained during the Fall of 2019 related to the Project Thesis. This includes marine operations for installation of Floating Offshore Wind Farms and literature related to the topic. Parts of the work has been transferred and adapted to fit the Master's Thesis.

I would like to thank my supervisor Stein Ove Erikstad for the help and guidance throughout the process of writing the thesis.

	06.07.2020
Candidate	Date

Table of Contents

List of Tables

List of Figures

Abbreviations

AHTS	=	Anchor Handling Tug Supply
Appx.	=	Appendix
CAPEX	=	Capital Expenditure
Ch.	=	Chapter
CLV	=	Cable Laying Vessel
DWT	=	Deadweight Tonnage
Eq.	=	Equation
Fig.	=	Figure
FOWT	=	Floating Offshore Wind Turbine
FOWF	=	Floating Offshore Wind Farm
HCV	=	Heavy Construction Vessel
KPI	=	Key Performance Indicator
kW	=	Kilowatt
MPV	=	Multi-purpose Vessel
nm	=	Nautical miles
PSV	=	Platform Supply Vessel
ROV	=	Remotely Operated underwater Vehicle
Sec.	=	Section
Tab.	=	Table

Chapter 1

Introduction

According to IEA (2019), global energy-related CO_2 emissions reached a historic high in 2018, driven by an increase in coal use in the power sector. In spite off an increase for renewables, fossil fuels account four two-thirds of electricity, which is the same amount as 20 years ago. The transition to a low carbon society is a big challenge, but it also means big industrial organization possibilities. The world faces a major common problem in the man-made global warming as a result of greenhouse gas emissions. Through the Paris Agreement, the countries of the world have committed themselves to an ambition to limit climate change to a 2 degree rise, and preferably not more than 1.5 degrees. The climate targets require a rapid green restructuring of the world economy, and the countries which can restructure fast have the biggest chance of going from green restructuring to green growth. The need for low-carbon technologies to produce electricity is more pressing than ever.

A possible gamechanger could be offshore wind.

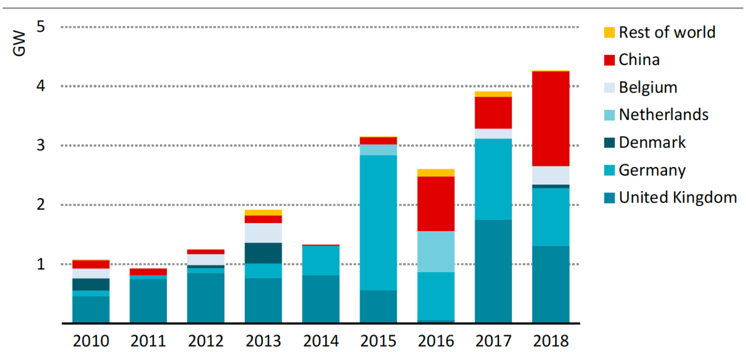


Figure 1.1: Annual addition of offshore wind capacity from 2010 to 2018 (IEA 2019)

Development of renewable power generation is central in the green restructuring. For the third year on a row in 2018, it was invested more capital in the renewable energy sector than in the oil and gas sector globally. It estimated that offshore wind will play a central role in the future renewable energy industry, and some forecasts say that 1000 GW will be developed up to 2050 against 22 GW today. Floating offshore wind is not as developed as bottom-fixed, but it is seen as a possible game-changer for the offshore wind industry. It has a significant potential for scale benefits in manufacturing and installation since the turbines are assembled onshore and thereafter towed out to the wind farm. Furthermore, floating offshore wind opens the possibility of power generation in ocean areas where the bottom conditions are poor or water depth is to deep. Fig. 1.2 shows a map of water depth ranges around Europe. Bottom fixed turbines are not relevant in areas deeper than 60 meters.

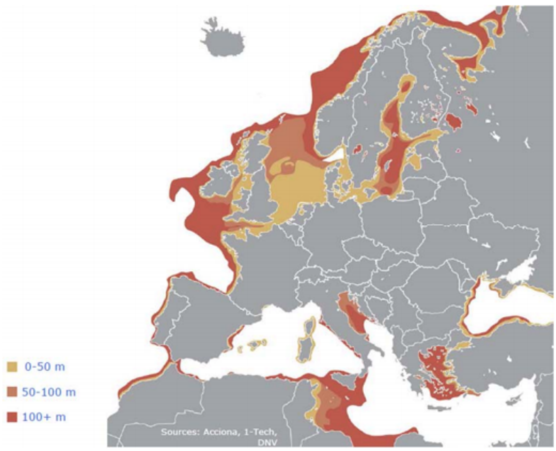


Figure 1.2: Sea depth around Europe (Goldsmith 2018)

A relatively immature market gives opportunities of taking the lead and take significant shares in a growing market. Fig. 1.3 shows the cumulative installed capacity of floating wind to 2022. In addition, Norway has decided to develop Hywind Tampen, which will consist of 11 (8MW) turbines. Hywind Tampen, together with the other projects in the figure, are pilot projects and are not cost-effective. Further development and practice are needed for commercializing floating offshore wind. A six times larger wind farm than Hywind Tampen is needed to commercialize floating offshore wind.

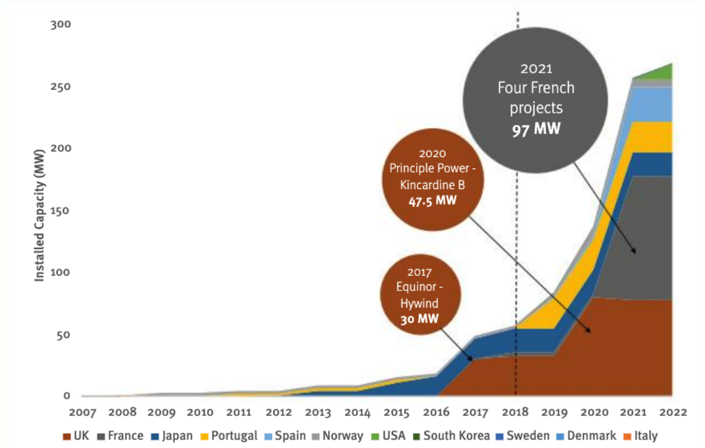


Figure 1.3: Cumulative installed capacity of floating wind to 2022 (DNV GL 2019a)

Winje and Hernes (2019) expects that the development of floating wind will follow what is shown in Fig. 1.4. The grey curve shows the low scenario, the dotted shows the basis scenario while the orange one shows the high scenario. The estimate is based on the growth in the bottom-fixed market from the last 10-15 years. The market size is a product of the development rate and the cost development. More cost-effective solutions are needed in order to commercialize floating offshore wind.

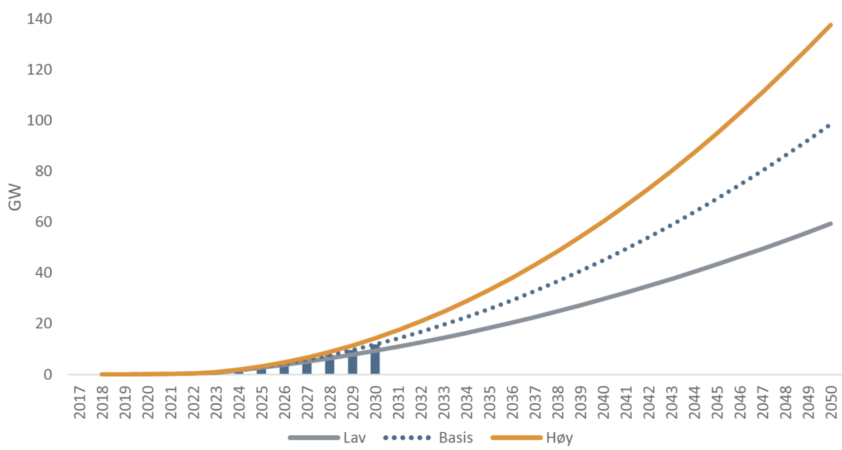


Figure 1.4: Expected development of floating offshore wind globally (Winje and Hernes 2019)

1.1 Research Question

The aim of this thesis is to investigate the robustness of installation strategies for floating offshore wind with regards to the operational and commercial aspect. Some pilot projects has been developed, and some pre-commercial projects are today under development. According to Winje and Hernes (2019), the general consensus among the experts is that that floating wind parks must be at least six times Hywind Tampens 88 MW wind park for the technology to become commercially viable. If this commercialisation takes place outside Norway, the competitiveness that has been developed is likely to be negatively impacted and the long-term potential for value creation in Norway will fall as a consequence. One of the research question thus becomes:

> How does the installation concepts used to this date cope with the increase in number of turbines and distance from shore?

How do we known whether the concepts used to this date are viable for installing floating offshore wind turbines? Most of the vessels used for installing floating offshore wind turbines comes from the oil and gas sector. Should this strategy still withstand or should we take the next step and develop specialized vessel for floating offshore wind? This brings us to the second research question:

> How does the fleet used to this date compare with a specialized fleet for floating offshore wind. If so, should the fleet consist of more specialized vessels or multi-purpose vessels?

In general, the problem can be formulated as how we can capture potential opportunities in the value chain of floating offshore wind.

1.2 Structure of the report

The structure of this report is organized in the following way:

System Description
Ch. 2 gives the reader a introduction to the floating offshore wind industry. Previous installation concepts will be presented, including an introduction to marine operations. The purpose of this chapter is to give insight to restrictions and regulations that apply for the floating offshore wind market. Important considerations for decision making will also be presented. A literature review on simulation, operability and cost is given in Ch. 3

Methodology
Ch. 4 presents the methodologies that will be used for the analysis. The method for House of Quality and Design Structure Matrices is first presented. These methods are used for generating new fleet concepts for installing floating offshore wind, and focuses on functions for the different processes. Furthermore, simulation as a tool is described with the use of MATLAB's SimEvents.

Case study
In Ch. 5, operational scenarios are presented. We model these scenarios with discrete-event simulation in Ch. 6. The steps for deriving the scenarios and fleet compositions are also presented in this chapter.

Results and discussion
The results are presented in Ch 7. The results from the analysis is compared and evaluated. Discussion of the overall objectives in the thesis are present in the same chapter. In Ch. 8, we conclude and give recommendations on further work.

Chapter 2

System Description

2.1 Floating Offshore Wind Farms

A wind farm comprises a number of wind turbines and is placed in areas with relatively shallow water not far from the coastline. A substation is also present in an Offshore Wind Farm. The substation receives power from the wind turbines through inter-array cables. The power is transformed in the substation and is thereafter exported onshore with export cables. The principal world developments in offshore wind farms focuses on wind turbines with seabed foundations, where the technologies are transferred from onshore to the sea. The constraints for seabed foundations are the distance to shore and depth. Fixed foundations are restricted to operate at 50-60 m water depth, however much of the regions with the highest available energy request to operate deeper. The different foundation technologies are illustrated in Fig. 2.1. It is expected that fixed-bottom offshore wind farms will continue to dominate up to 2030, but the next 5-10 years will be an important development period for floating technology for preparing the technology for commercial projects from 2020-2025.

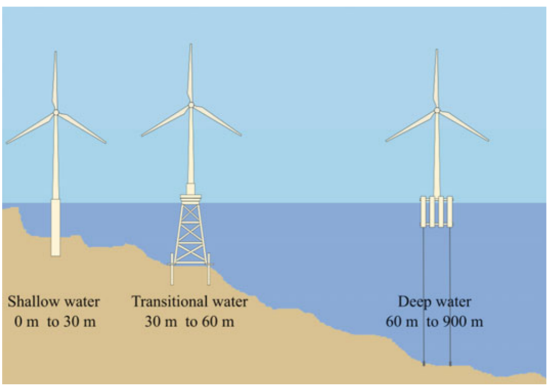


Figure 2.1: Shallow, transitional and deep water technology (González and Diaz-Casas 2016).

There are several configurations of floating platforms to support wind turbines as sea, and they are divided into three general categories based on the physical principle to achieve static stability (See Fig. 2.2): semi-submersible platform (1), Spar Buoy (2) and Tension leg Platform (3).

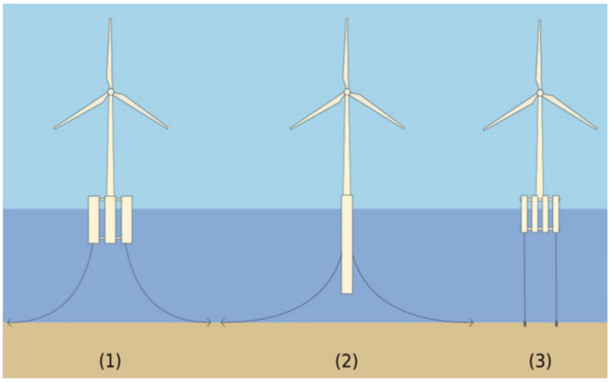


Figure 2.2: Floating wind turbines concepts (González and Diaz-Casas 2016)

The spar buoy concept will be considered in the thesis. The simple structure of the spar-buoy is typically fairly easy to fabricate and provides good stability. The large draft requirement can create logistical issues during assembly, transportation, and installation. The most known spar-buoy concept is Hywind from Equinor. It conists of a slender, ballast-stabilised cylinder structure. The floater has a low water plane area that minimises wave induced loading. The simple structure minimises production cost as well. This concept has been applied to the field Hywind Scotland, located 15 miles east of Peterhead, Scotland, at water depths ranging between 95 and 120 meters. The most common mooring configurations are taut spread mooring systems (used in TLPs) and catenary mooring systems (which are used in spar buoys and semi-submersibles platforms. For catenary mooring, steel chains whose with weight and curved shape holds the floating platform in position. There is also a number of anchoring solutions, depending on the seabed conditions, mooring configuration and holding capacity required. The different anchor solutions is illustrated in Fig. 2.3.

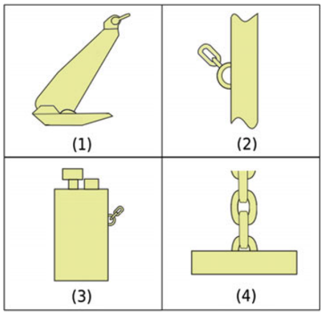


Figure 2.3: Anchor solutions in floating offshore wind: Drag anchor (1), Driven pile (2), Suction Anchor (3) and Gravity Anchor(4).

Drag anchors are suitable on soft-beds (gravel or sand) and when forces do not change too much in direction. Gravity anchors can be used in most seabed conditions and performs independent on the force angle. Pile anchors can be expensive in rock at deep water while suction anchors could be affordable in soft seabed conditions. (González and Diaz-Casas 2016).

2.2 Upstream Floating Offshore Wind Supply Chain

According to Chandra and Grabis (2016), ”a supply chain is a network of supply chain units collaborating in transforming raw materials into finished products to serve common end-customers. The supply chain contains elements like transport, installation and maintenance. The upstream offshore wind supply chain is illustrated in Fig. 2.4.

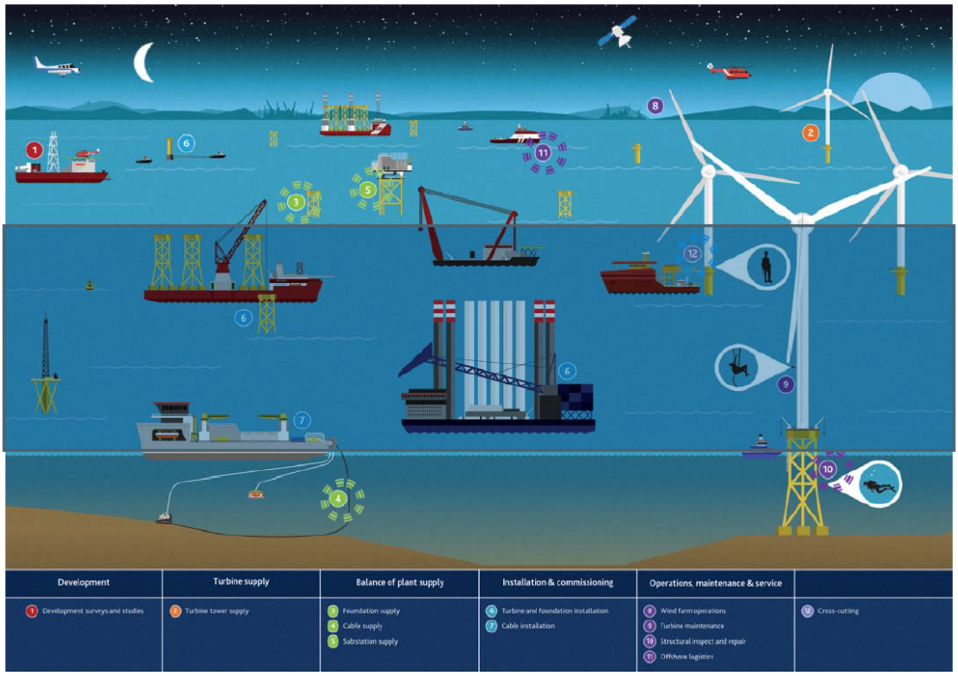


Figure 2.4: Illustration of offshore wind supply chain (BVG Associates 2019)

BVG Associates (2019) reviews the strengths of the existing Norwegian chain supply chain and its opportunities with offshore wind. The report follows a breakdown of the the percentage contribution of each area to the lifetime project cost, which is shown in Fig. 2.5. For installation and commissioning, the opportunities are summarized in Tab. 2.1.

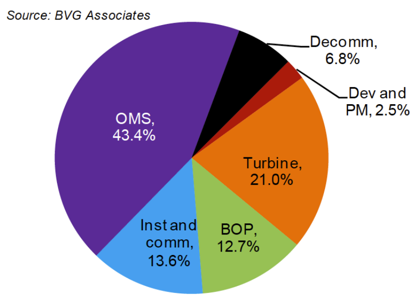


Figure 2.5: Cost breakdown of an offshore wind farm

Table 2.1: Conclusion of Norwegian supply chain opportunities in Installation and Commisioning

Sub-element	Opportunity
Turbine and Foundation installation	High
Anchor and Mooring installation	High
Inter-Array installation	High
Substation installation	Moderate
Export cable installation	Moderate

The installation processes for a floating offshore wind are described by the flowchart in Fig. 2.6. The thesis will focus on processes within the dotted line in the figure. This being a result of the conclusions in Tab. 2.1 and the fact that installation of Turbine, Foundation, Anchor, Mooring and Inter-Array Cables are the most time consuming. The Norwegian Supply Chain has great experience in Marine Operations, and there are synergies that can be transferred from the oil and gas industry to the installation of Floating Offshore Wind Turbines.

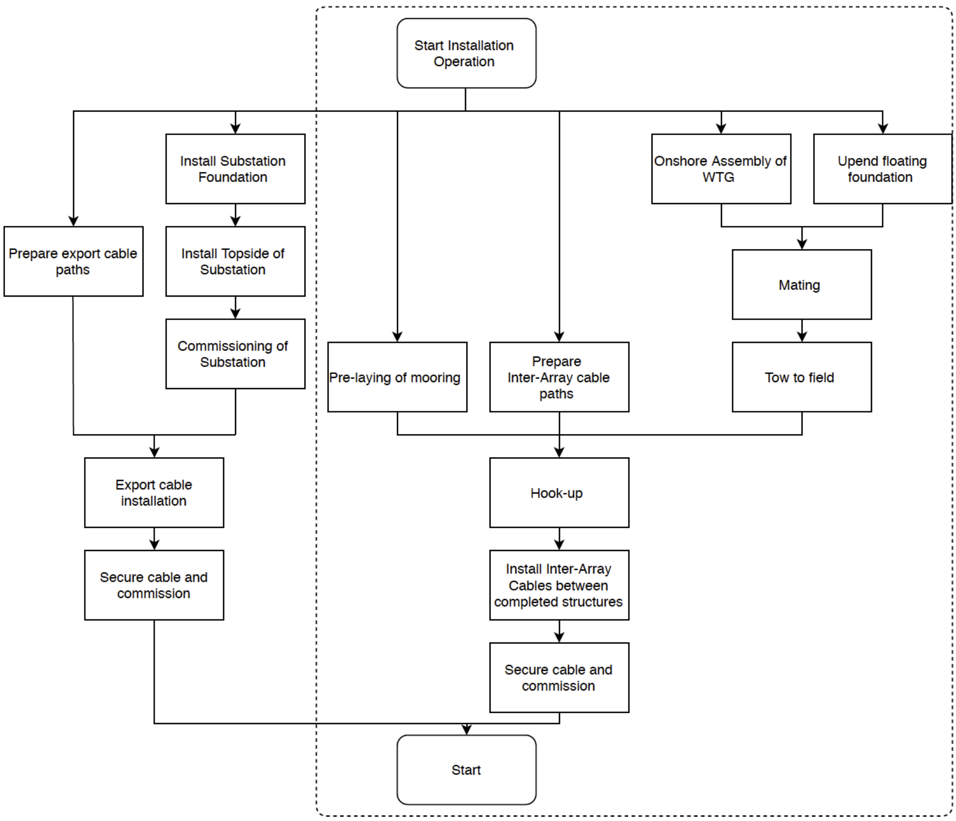


Figure 2.6: Flowchart of Floating Offshore Wind installation

2.3 Marine Operations

Marine operations related to the installation of a floating offshore wind farm will be discussed in this section. A marine operation is a non-routine operation of a limited defined duration related to handling of object(s) and/or vessel(s) in the marine environment during temporary phases. A marine operation shall be designed to bring an object from one defined safe condition to another safe condition. A safe condition is a condition where the object is considered exposed to normal risk for damage or loss. Normal in this context is a risk similar to the risk expected during in-place, permanent condition (Kjell Larsen 2019a).

A marine operation is classified either as a weather restricted or weather unrestricted operation. A weather restricted operation shall be of limited duration and the planned operation time shall be less than 72 hours. The operation can take place in a favourable weather forecast and can then be designed and planned for considerably lower weather condition than the seasonal, statistical extremes used for weather unrestricted operation. A weather unrestricted operation can take place safely in any weather condition that can be encountered during the season. Statistical extremes for the area and season should be considered. The planned operation time is normally longer than 72 hours. The tow is normally categorised as an weather restricted operation; it can take place safely within the limits of a favourable weather forecast (Kjell Larsen 2019a). The weather condition could be described by the parameter significant wave height. The characteristic significant wave height can be calculated by Equation 2.1.

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

α and β are Weibull parameters for the probability function of the observed significant wave heights. The α-factor takes uncertainty into account for the forecasted weather, which leads to a reduced weather limit for operation compared to design weather conditions. It is a number between 0 and 1, where 1 reflects optimal weather foreacst, which means that the operational and design criteria will be the same. The α-factor will increase safety for weather restricted operations in case the weather is worse than forecasted (DNV GL 2011a).

According to DNV GL (2011a), limiting operational environmental criteria OP_{LIM} shall be established and clearly described in the marine operation manual. It is also known as the design criterion and works as a weather condition used for calculation of design load effects. The limiting operational criteria shall never be greater than the maximum environmental criteria, conditions for safe working of personnel, equipment restrictions or limiting conditions for diving systems and station keeping systems. The operational criterion shall also be established during the planning process. It gives the maximum weather condition for execution of the marine operation. The relationship between the design criterion and the operational criterion is stated in Equation 2.2.

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

Kjell Larsen (2019b) states that the α-factor shall be estimated based on the weather uncertainty for the actual site and the planned length of the operation. The planned operation period, T_{POP}, should be based on a detailed, planned schedule for the operation. The factor also includes that is is harder to estimate the wave height for small sea conditions than for larger seas. DNV GL (2011a) states that the α-factor should be calibrated to ensure that the probability of exceeding the design criterion (OP_{LIM}) with more than 50 $\%$ is less than 10^{-4}. Typical characteristics of the α-factor is that it decreases with the planned duration (T_{POP}) of the marine operation. In other words, the longer the planned duration of the operation is, the greater is the difference between the operational criterion and the design criterion.

2.3.1 Operation reference period

According to Kjell Larsen (2019a), the duration of marine operations shall be defined by an operation reference period, T_R:

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

where T_{POP} is the planned operation period and T_C is the estimated maximum contingency time. The contingency time shall be added to cover general uncertainty in T_{POP}, possible contingency situations and weather sensitive operations that will require additional time to complete the operation. The contingency time should not be less than 6 hours.

2.3.2 Surface Tow

Towing is transport of a self-floating object by single or multiple tugs. This can be self-floating objects and large structures, objects on transportation barges, emergency towing or long, slender objects. Towing operations is usually classified as weather restricted operation. If the operation takes several days ($>> 72hours$) it should be classified as weather unrestricted, but it can be planned as a weather restricted operation if there is a continuous surveillance of weather forecast or safe havens are defined along the route. An overview of the different towing configurations are given in Tab. 2.2. Definitions of the different towing types are given in Tab. 2.3.

According to DNV GL (2017), important loads to consider when wet towing are:

- hydrostatic loads due to external water pressure on submerged structures or internal water pressure in water filled compartments.
- wave slamming loads, normal wave and current induced loads
- aero- and hydrodynamically induced vortex shedding and the risk of vortex induced vibrations (especially when transported vertically)
- interaction between the towed component and the propeller race
- increased draught due to interaction between the seabed and the towed component
- channel effects in narrow passages.

Table 2.2: List of different tow configurations (DNV GL 2015).

Tugs		*Objects*		*Tow called (see notes)*
No.	*Position*	*No.*	*Position*	
1	NA	1	NA	Normal
2 or more	Parallel	1	NA	Parallel
2	Series	1	NA	Serial
3 or more	Series	1	NA	
1	NA	2	Parallel	Double
1	NA	3 or more	Parallel	
1	NA	2 or more	Series	Tandem

Table 2.3: Definition of Tow Types (DNV GL 2015).

Tow Type	**Definition**
Normal tow	One tug towing one object.
Parallel tow	Two or more tugs in parallel. Each tug is connected by its own towline to the same towed object.
Double tow	Two towed objects each connected to the same tug with separate towlines. One of the towlines is of sufficient length to pass well below the first towed object.
Tandem tow	Two towed objects in series behind one tug, i.e. the second object is connected to the stern of the first object.
Serial tow	Two tugs in series. The towed object is connected to the second tug and this tug is connected to the leading tug.

Inshore tow

Maneuverability is important when towing inshore and it increases when using shorter towlines, lower speed and multiple tugs. A typical risk for inshore towing is that the towed object run over the tugs. The towing configuration for the Heidrun platform is shown in Fig. 2.7. Three tugs are towed astern to counteract if any stopping is required. The inertia of the platform makes it hard to maneuver, and extra tugs can be put port side and starboard to increase it (Riahi 2019).

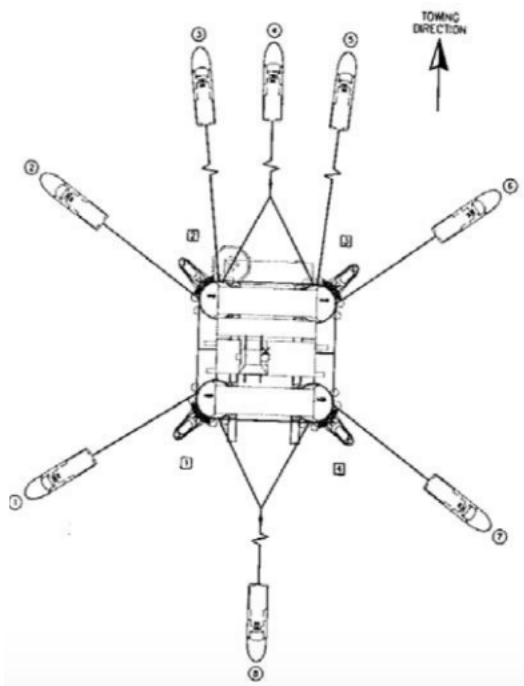


Figure 2.7: Inshore towing configuration of Heidrun platform (Nielsen 2007)

Offshore tow

According to Nielsen, during the offshore part of the tow, towing velocity and loads in the towing lines are important considerations. This is done to reduce cost and time of the towing operation given long towing distances. Longer towlines are used and almost all available thrust is applied in the same direction. An illustration of offshore towing of the Heidrun platform is given in Fig. 2.8.

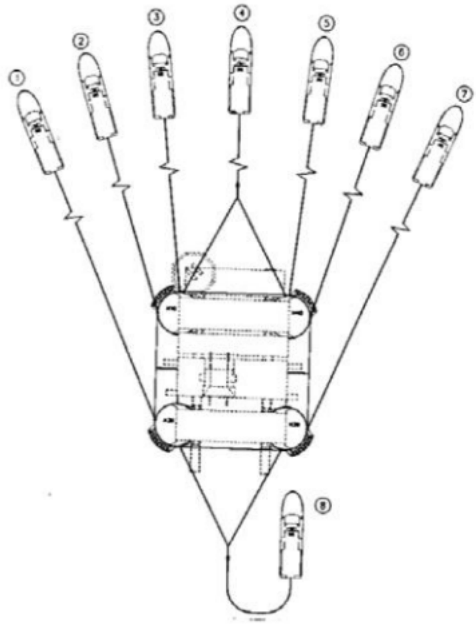


Figure 2.8: Offshore towing configuration of Heidrun platform (Nielsen 2007).

2.3.3 Transportation

The top-structures and substructures are most likely produced at a location away from the assembly port, often in a foreign country as a consequence of cost. The substructures must therefore be transported from the fabrication site to the assembly port. Transport can either be done on water, on road or in air. According to Yttervik (2013), the advantages and dis-advantages of transport on water are listed in Tab. 2.4.

Advantages	Dis-advantages
Transport many units at the same time	Dependent on the weather
Transport large units	Components are not generally designed for transport and installation offshore
No road construction necessary	Need of seafastening
No problems with public traffic	

Table 2.4: Advantages and Dis-advantages of transport on water

Transport planning shall start in the early stage of a project to ensure safe, workable and economical transport of wind power plants. The process of transport planning shall aim at the reduction and elimination of potential risks by continuous adaptations during each project phase. See illustration in Fig. 2.9.

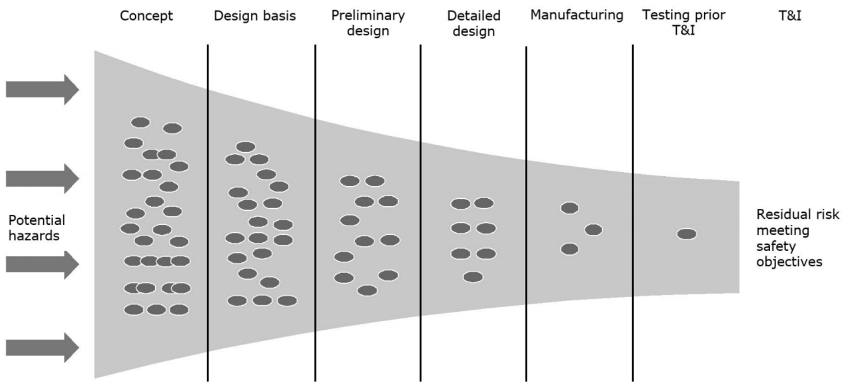


Figure 2.9: Achievement of the safety objectives (DNV GL 2017)

Safety objectives are the criteria to be met to ensure safe execution of transport of a wind power plant. The safety objectives may be quantified by key fig such as personnel health and safety risk, financial loss, delays or impact of the environment. The objectives may achieved by performing a formal safety assessment.

2.3.4 Lifting

Kjell Larsen (2019a) states that a lifting operation usually involves a crane, crane vessel, transport vessel/barge and the lifted object. The five phases of a crane operations is illustrated in Fig. 2.10.

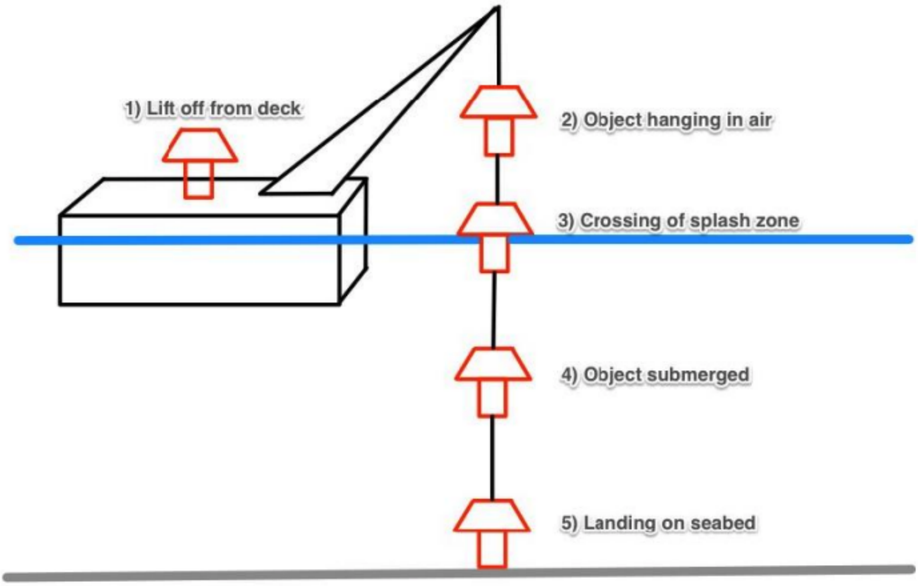


Figure 2.10: Five phases of crane operations (Kjell Larsen 2019b).

A lift is either considered a light lift or heavy lift. In light lifts, the lifted object is very small compared to the crane vessel. The weight of the lifted object is less than 1-2 % of the displacement of the crane vessel, typically less than a few hundred tons. In heavy lifts, the weight of the object more than 1-2 % of the vessel displacement and typically more than 1000 tons (DNV GL 2011b).

Phase 1 - Lift off

This operation starts with removing the sea fastening. The time spent is dependent on whether the object is strapped or welded. The lift of an object is either done from a separate barge by a crane vessel, or from the the the deck of the crane vessel. Vertical and horizontal motions of the crane tip should be considered because this could lead to snap forces in the wire. The lift off is a simple operation if the transport has taken place on the crane vessel, since the relative motion between the crane-top and the vessel is marginal.

Phase 2 - Object hanging in air

When the object is hanging in the air, the stability of the vessel is changing by the fact that the centre of gravity increases. Ballast operations should be implemented to counteract the heeling moment. Other factors to consider are safe handling of the object in order to prevent damage on structures and personnel.

Phase 3 - Crossing of splash zone

During lowering through the water surface, the object is subject to different forces. Important loads to consider are drag forces, inertia forces, water entry forces and varying buoyancy force. Snap forces due to slack in the wire should also be considered.

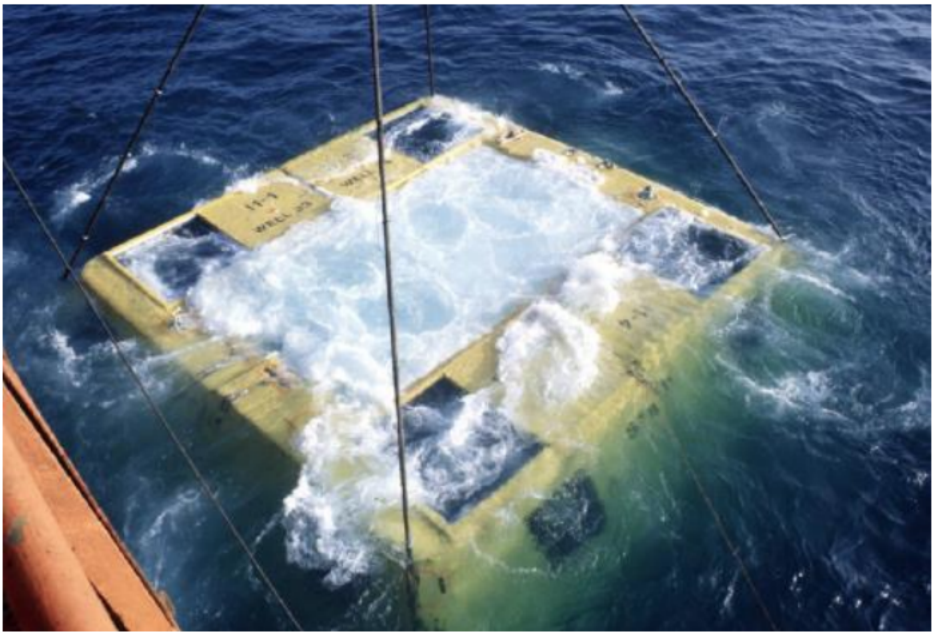


Figure 2.11: Object crossing splash zone (Kjell Larsen 2019b).

Phase 4 - Object submerged

Lifts performed in deep water are complex and there are effects that should be considered. The cable could be exposed to stretch due to self-weight and weight of lifted object. Furthermore, horizontal offset is often a problem. The offset is due to current and the current velocity is time-dependent and its magnitude and direction can vary with water depth. Other effects to consider are dynamics and possible vertical resonance due to wave induced motion of vessel crane tip. A Heave Compensation System could be used to compensate for the vertical motion of the vessel. The compensator is used to control the motion of the lifted object and tension in the lifting line. The compensator may be divided into two main groups: passive heave compensators (PHC) and active heave compensators (AHC). A passive heave compensator is in principle a pure spring/damper system which does not require any controlled energy input. An active heave compensation system compensates for the unwanted motion of rope exit point (REP) by paying in an out the rope. An illustration of the two systems are given in Fig. 2.13 and 2.12.

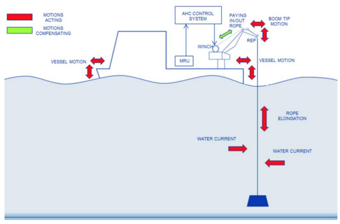


Figure 2.12: Active Heave Compensation (DNV GL 2019b)

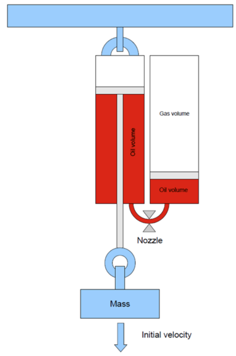


Figure 2.13: Passive Heave Compensation (DNV GL 2019b).

Phase 5 - Landing on seabed

The anchor is lowered down to seabed in a sling from an installation vessel being exposed to wave action. Accordingly to DNV GL (2011b), during lowering the vertical motion of the anchor is given by a constant downwards velocity plus an oscillatory heave motion caused by the wave induced motion of the vessel. The final step is to position the object correctly on the seabed. This is difficult considering current loads on the object. The current is time-dependent and the direction and magnitude varies with water depth. This is seen in Fig. 2.14.

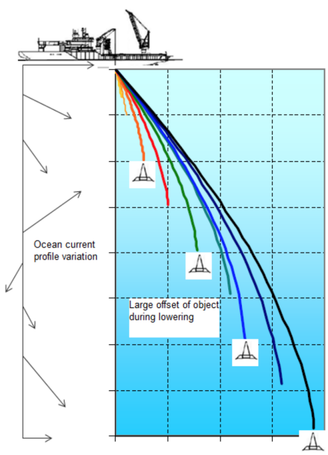


Figure 2.14: Offset of object increases with water depth (Kjell Larsen 2019b).

2.4 Previous and planned installation concepts

2.4.1 Hywind Scotland

Equinor and Masdar partnered up to realise Hywind Scotland, which started producing electricity in 2017. According to Equinor (2019), the project achieved a 60-70 % cost reduction compared to the Hywind Demo project in Norway. The wind farm is estimated to power 22 000 households and the farm consists of five 6 MW turbines.

Figure 2.15: Hywind Scotland Pilot Park

According to Lien (2016), the suction anchor and bottom chain pre-installation were performed in two different campaigns. The first planned operation was the installation of suction anchors, which were expected to take approximately two weeks. Technip FMC was the main contractor for marine operations, but additional companies was subcontracted to provide some of the vessels needed (Solstad, van Oord). The new Offshore Support Vessel, Deep Arctic (Technip FMC) was used for the anchor installation. The next step was the mooring chain pre-installation, and was also expected to last for two weeks. The tug Normand Prosper (Solstad) was used for the mooring chain pre-installation. The same vessels was used for hook up when the wind turbines arrived. An illustration of pre-installation is given in Fig. 2.16.

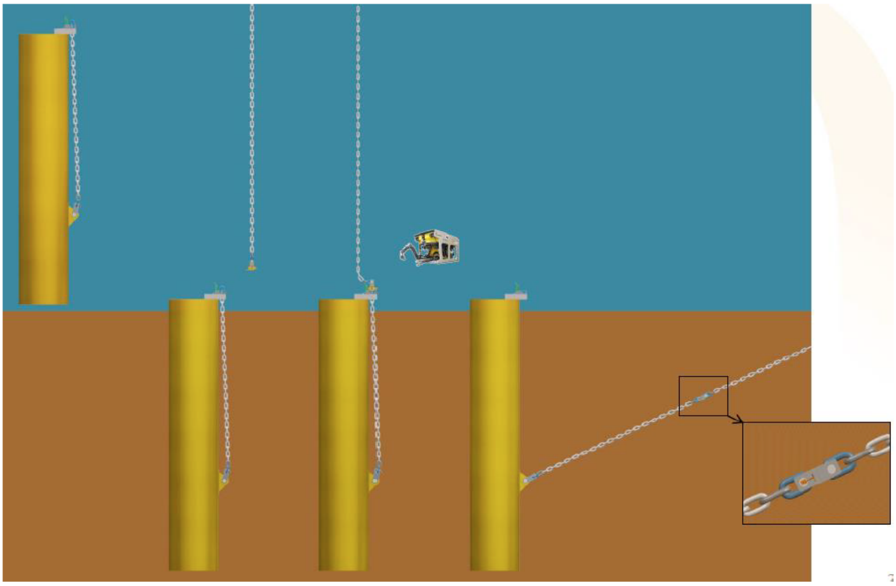


Figure 2.16: Mooring system pre-installation

The substructures were produced at Navantia Yard in Fene, Spain. The substructers were transported from the yard to the assembly port in Stord, Norway. A FLO-FLO (Float-on/Float-off) Vessel was used for transport. The substructure and a FLO - FLO vessel is illustrated in Fig. 2.17 and 2.18 , respectively.

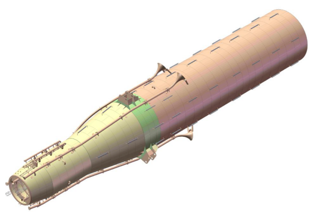


Figure 2.17: Typical substructure for Floating Offshore Wind (Lien 2016)

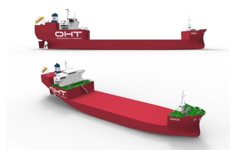


Figure 2.18: FLO-FLO Vessel (Lien 2016)

When the substructures arrived at the assembly port, the next operation was to upend them. Water is then pumped from a floating barge into the substructure. Tugs are used for controlling the upending. The process is illustrated in Fig. 2.19.

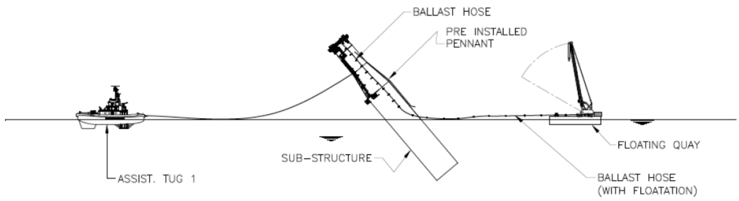


Figure 2.19: Upending of substructures (Lien 2016)

The substructures were thereafter dry-ballasted with approximately 5000 Tonnes of magnetite each with the help of a rock installation vessel. De-ballasting of water is done simultaneously in order to maintain draft.

The towers were produced at Navacel in Bilbao, Spain and the wind turbine generators (WTG) were produced at Siemens Wind Power in Camberley, UK. The towers and WTGs were shipped from their respective fabrication sites to the assembly port in Stord. The tower and WTG was assembled on the qauay before the mating. The mating was performed by Saipem 7000, and the process is illustrated in Fig. 2.20.

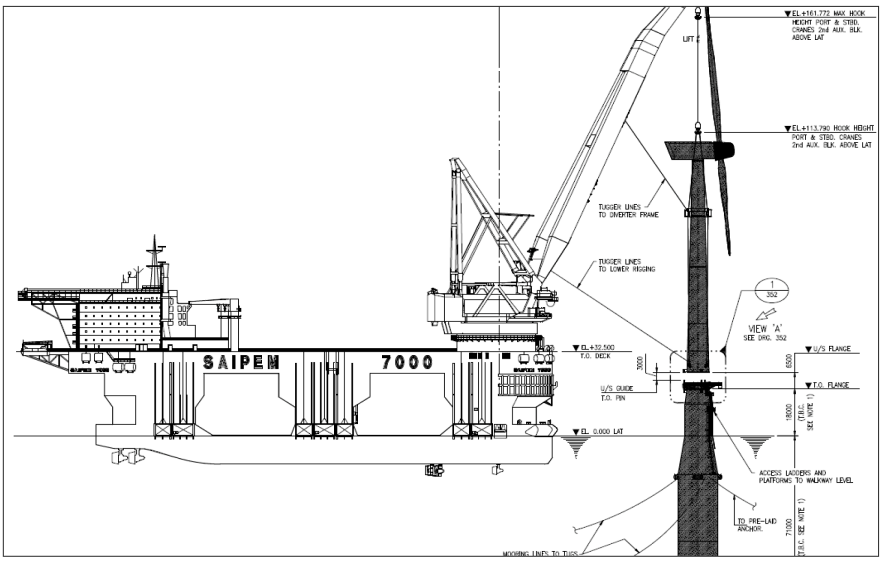


Figure 2.20: Mating of Floating Offshore Wind (Lien 2016)

Towing of the turbines was performed by a main tug and assisting tugs. When arriving at the farm, the turbine was hooked up with the mooring chain. The mooring hookup sequence can be seen in Fig. 2.21.

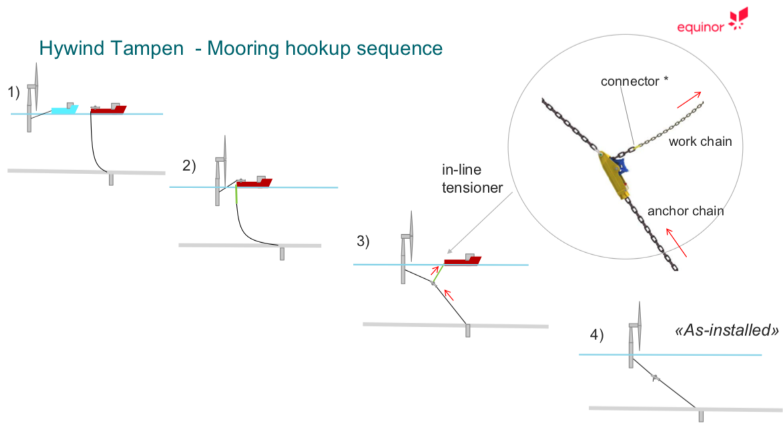


Figure 2.21: Mooring hookup sequence (Skaugset 2019).

Equinor contracted Subsea7 for the cable installation. This includes installation of vertical riser anchors and mattresses for crossings, installation of export cable, installation of in-field cables, trenching of export cable, rock installation. It was estimated to take 5 weeks. All installation works were planned to take place during the spring and summer 2017. A guard vessel was on the site throughout the construction period until the first floating wind turbine was installed. This is done for safety purposes, and the vessel communicated with other fishing vessels.

According to Guttormsen (2017), the following types and number of vessels were planned to be employed in the installation works:

- 1 Offshore Support Vessel (Deep Arctic) - suction anchor installation.
- 1 Tug (Nordmand Prosper) - mooring system installation.
- 1-2 Main tugs - towing and installation of FWT's.
- 1-2 Supporting tugs - support during towing and installation of FWT's.
- 1 Cable laying vessel (Skandi Acergy).
- 1 Trenching Support Vessel - cable trenching and rock protection.
- 1-2 Guard vessels (i.e. fishing boat supplied by SFF)
- 2 Crew Transfer Vessels - transporting personnel to the FWTs
- 1 Ultra-Heavy Lifting and Deepwater Pipelaying Vessel (Saipem 7000)

2.4.2 Hywind Tampen

April 8, 2020, the Ministry of Petroleum and Energy approved the development plans for Hywind Tampen. This will be the world's largest floating offshore wind farm and Norway's first. The project serves as a restructuring of the power supply on the Snorre and Gullfaks field, where a third of the gas power on the platforms will be replaced with renewable wind power. Parameters for the Hywind Tampen field are listed in Tab. 2.5.

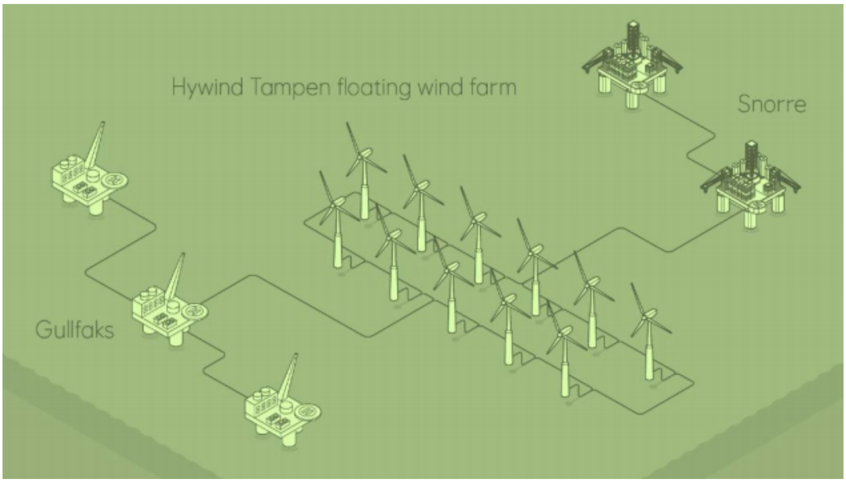


Figure 2.22: Hywind Tampen floating wind farm

Table 2.5: Parameters for Hywind Tampen

Power Capacity	11 x 8.0 MW
Draught	90m
Displacement	˜ 22.000t
Hub Height	105m
Water depth	270 - 300m
Hull weight	Concrete 9000t
Wall thickness	˜ 500-800mm
Fixed ballast	˜ 10.000t
Rotor diameter	167m
Design life	25 years
Anchor	Suction Anchor (shared)
Mooring	124 mm ø R3 Ø80mm spiral strand bridles

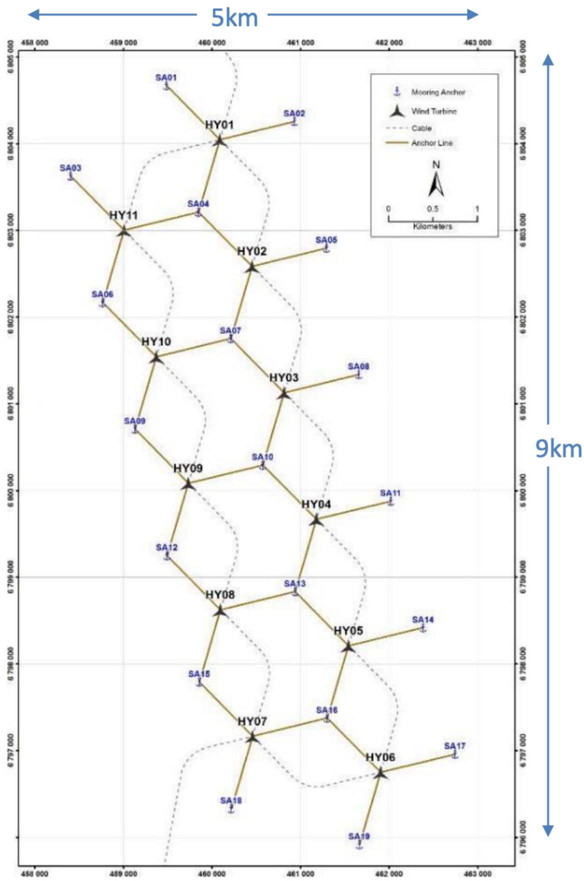


Figure 2.23: Layout for Hywind Tampen

From an installation perspective, most of the concepts discussed in Section 2.4.1 will also be used for Hywind Tampen. But, for Hywind Tampen the substructure will be built in Norway. Slipforming of the lower part will be done at the dry dock at Kværner, Stord, before it is towed to Dommersnes, where the remaining slipforming will be done at a deep water site. At completion, the substructure will be towed to its assembly site at Gulen. One of the differences is that mating will be done by an onshore crane, shown in Fig. 2.24. This could be a result of the earlier usage of the high charter cost semisubmersible crane vessel, Saipem 7000, illustrated in Fig. 2.20.

Figure 2.24: Illustration of onshore crane in assembly port, Gulen.

Chapter 3

Literature review

3.1 Simulation

E. Barlow et al. (2014) propose an offshore wind farm simulation tool to a test-case installation project. The simulation tool combines a realistic model of OWF installation with a synthetic weather model in order assess the duration and cost of a OWF installation. Furthermore, the test-case demonstrate the impact of four key vessel characteristics on the duration of the installation. The assessment shows that relatively small improvements in vessel performance could reduce the total installation time and cost considerably. E. Barlow et al. (2014) states that the simulation tool could be used as an decision-making tool for OWF developers.

Euan Barlow et al. (2015) propose a holistic two-stage approach which can be used to evaluate innovations to installation vessel design and operation, and innovative technological developments to the process. The first stage identifies critical operations that are sensitive to weather delays, and the second stage investigates the installation process where innovative developments were capable of reducing the sensitivity of weather for critical operations. The report revealed that the installation of turbines and jackets were most sensitive to weather, and that targeting these operations for development is a better solution than simply employing vessels with increased operating capacity.

Matha et al. (2017) identifies fabrication and installation constraints for floating offshore wind. Finding a suitable construction site and infrastructure is often a key challenge. The constraints for picking a dry-dock as a construction site is cost and serial production capacity. Only a few dry-docks has the dimensions to support floating substructures. The constraints are fewer when picking a barge or a quayside as a construction site, but most of the ports infrastructure need to be upgraded. The required upgrades are draft, area size or access. In connection with the installation, there are a few challenges that needs to be met. The port choice is also important for the installation process, and the distance to the wind farm should be considered. A key challenge is to choose the vessels for the installation process. Charter cost, cost of personnel and equipment are the main cost drivers, and the resulting cost is dependent on weather and port location. Essential specialized vessels for installation are anchor handling vessel and cable lay vessel. A small number of simple and and economic vessels are favourable for the cost, but if more advanced vessels allow operation under worse conditions, it could end up more cost-effective. Recommendations of more advanced tugs are given as a result of this. The daily charter rates has fluctuated the last years, but it is assumed that it will increase over the next years as a result of the oil prize stabilizing. Lastly, the report states the importance of estimating the weather conditions correctly to avoid interruptions in the installation process.

3.2 Operability

Operability is a measure for the expected available time an operation can be executed. The uncertainity in environmental conditions based on weather forecasts has been studied in Natskår, Moan, and Alvær (2015). Uncertainty is quantified by comparing forecasted and hindcasted weather, and a method to assess the reliability of weather forecasts is proposed. The report also discuss the uncertainty imposed by weather-restricted operations and weather-unrestricted operations. The difference between them were discussed in Sec. 2.3.

Acero et al. (2016) propose a general methodology for assessing the operational limits and the operability of marine operations during the planning phase with emphasis on offshore wind turbine installation activities. Operational limits are derived by numerical analyses of real execution phases, i.e loading conditions of the various critical activities. Furthermore, the operability of marine operations was assessed by comparing allowable limits of sea states for activities and hindcast wave data time histories.

Gintautas and Sørensen (2017) presents a methodology of weather window prediction for weather offshore wind operations. The methodology uses physical offshore vessel and equipment responses to establish the expected probabilities of operation failure by evaluating the probability of relevant equipment responses exceeding their respective maximum allowable magnitudes. The probabilities of the critical events are combined in order to represent total probability of operation failure.

3.3 Cost

Bertram et al. (2015) propose the top-down and bottom-up approach for estimating vessel production cost. The top-down approach uses global parameters such as LOA, DWT and block coefficient for determining the production cost. The relation between cost and global parameters are found by evaluating previous vessels. The bottom-up approach divides the project into elements of work and the cost estimate is built up by a detailed engineering analysis. Typical for this approach is to use quantities and unitary cost together with man-hours.

A set of parametric cost models during the concept and preliminary phases of ship design is proposed by Deschamps and Greenwell (2009). These cost models produce quick assessments of costs and risk for design and mission trade-off alternatives. The parametric cost estimation is based on the use of cost estimating relationships (CER). They represent a wide cross-section of current and historical shipyard construction cost based on metrics like: crew size, kW power and cargo volume.

Myhr et al. (2014) presents an analysis and comparison of the Levelised Cost of Energy (LCOE) for different types of wind turbine concepts. Both floating and bottom-fixed concepts are assessed. It is found that offshore assembly of floating turbines is three to four times more expensive than inshore assembly and towing of the complete turbine. Other results from the analysis shows that floating wind turbines could be produced at equal or lower LCOE than bottom-fixed concepts.

A Vessel charter rate estimation for offshore wind OM activities is presented in Dalgic, Lazakis, and Turan (2013). Summer rates are significantly higher than winter rates. The report states that the offshore wind market is heavily dependent on the oil and gas industry, which drives costs up significantly. In order to eliminate the dependency, new vessel concepts has to be developed and a shift from port-based to offshore-based strategies could be a solution.

Chapter 4

Methodology

4.1 Fleet Generation

4.1.1 Needs-Function-Form mapping model

Engineering design is often described by the mapping from a set of needs via a set of functional requirements to a description of the system form, which is illustrated in Fig. 4.1. The needs are stated in a value proposition and describes what the stakeholders care about. The functional requirements describes what the system is supposed to do, while the system form explains what the system will look like in terms of design parameters/general arrangement. The mapping between the functional domain and the physical domain will be focused on in order to derive different fleet concepts.

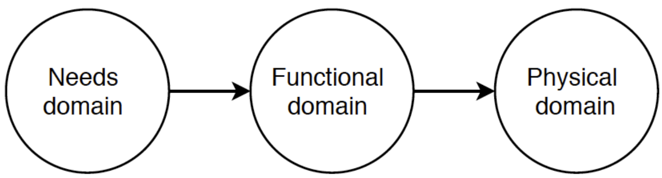


Figure 4.1: Needs-Function-Form mapping model

4.1.2 House of Quality

Processes and capacities needed for the installation of a floating offshore wind farm were identified in Chapter 2. The dependencies will be presented in a House of Quality (HOQ). According to Temponi, Yen, and Amos Tiao (1999), it represents matrices of the iterative process Quality Function Deployment (QFD). The idea of HOQ is that products should be designed to reflect customer needs. QFD employs usually four matrices to establish relationship between company functions and customer satisfaction. The four following matrices are usually used; planning matrix, design matrix, operating matrix and control matrix. The HOQ matrix can be also be describes as a ”what-how” matrix. A typical HOQ matrix is illustrated in Fig. 4.2. The first step is to identify the WHATs and sequence them in organized activities. The next step is determining the HOWs, describing how the process should be covered. Afterwards, the relationship matrix is filled out by judging the relationship between the WHATs and HOWs. Lastly, the correlation matrix is filled out by finding the relationships among the HOWs. The matrix domain will work as a mapping tool between processes and capacities.

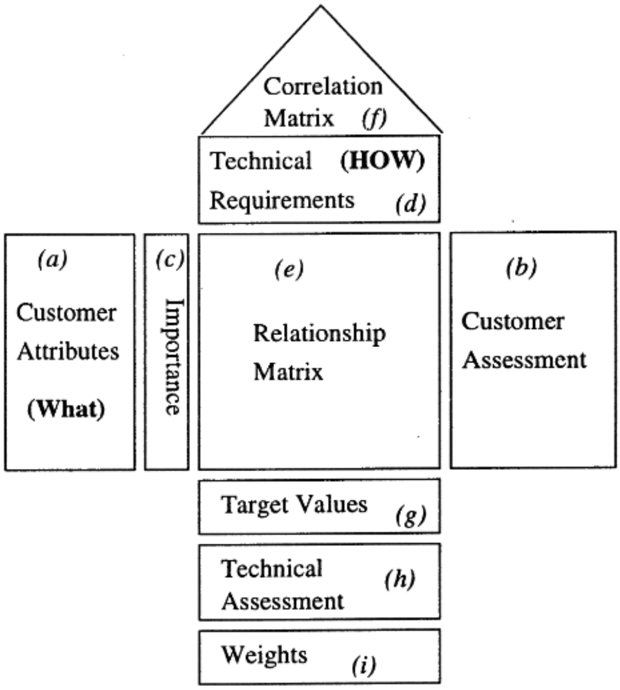


Figure 4.2: House of quality (Temponi, Yen, and Amos Tiao 1999).

4.1.3 Modularity

Modularity is known as a complex system being split into several components which is then assigned to modules in a specific architecture. According to Baldwin and Clark (2006), modularity is used for three main purposes from an engineering perspective:

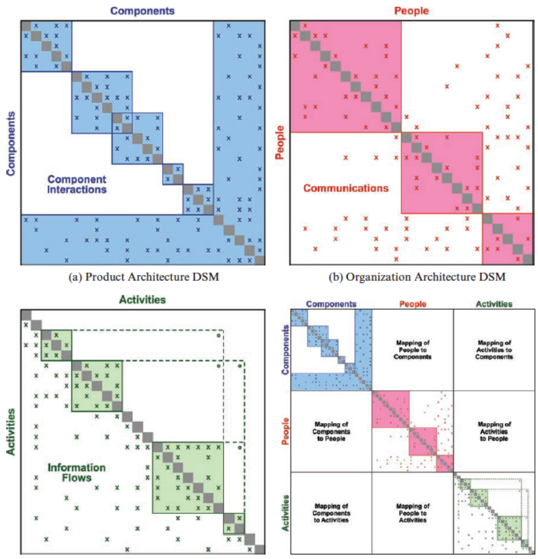
- To make complexity manageable
- To enable parallel work
- To accommodate for future uncertainties

Modularity has the ability to improve many phases of a vessels life cycle. Introducing modularity in the operation phase could increase flexibility by offering several types of operation. A growing trend is to build multi-purpose vessels. These vessels have a lower mission-specific efficiency than conventional vessels. The vessel is then not optimized for one mission, which could limit the quality and ability of operations. Modularity also opens the possibility of reducing the fleet size. According to Erikstad (2009), there is no direct relation between modularization and emissions, and states that they should be considered separate issues since environmental efficiency is primarily related to the functional performance of the technical solution. But there are indirect effects of modularization that may influence the environmental footprint of the solution, both in a positive and negative direction. This includes:

- Modularity comes at a price which is dependent on size and weight. A conventional vessel with the same technical performance will typically be more energy efficient. This has a negative environmental impact.
- Modularity can lead to an overall fleet reduction that might lead to reduced emissions
- Modularity may contribute to a higher degree of customized solutions, which could improve the mission-specific efficiency of the solution. This is relevant since there is no customized vessel for installing FOWTs at this time. This could have a positive environmental effect.

Another perspective of modularity is the choice between versatility and retrofittability. Versatility is the ability of a system to satisfy diverse needs, without change of form. Retrofittability is the ability of a system to satisfy diverse needs, by change of form. The time aspects are important when considering this issue. Generally, strong markets tend to favour versatile vessels, while weak markets and a high degree of uncertainty tend to favour retrofittability. It is assumed that the floating offshore wind market will be strong in the future. Therefore, only versatility will be considered in the operation research.

According to Eppinger (2012), the Design Structure Matrix (DSM) is a network modeling tool used to represent the elements compromising a system and their interactions, thereby highlighting the system's architecture. A system is "a combination of interacting elements organized to achieve one or more stated purposes and the system architecture is the structure of a system - embodied in its elements, their relationships to each other, and the principles guiding its design and evolution - that gives rise to its functions and behaviors. .The DSM is represented as a square N x N matrix, mapping the interactions among the set of N system elements. The DSM is categorized in four different models, which is shown in Fig. 4.3.

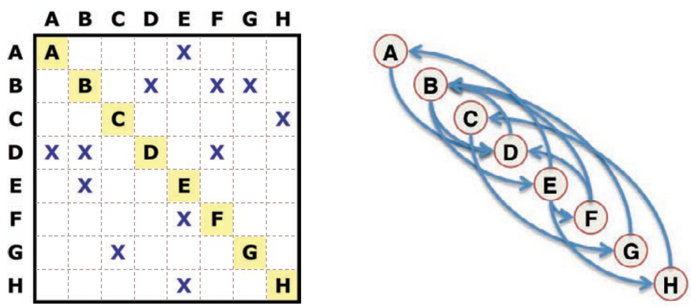


(a) Product Architecture DSM (b) Organization Architecture DSM

(c) Process Architecture DSM (d) Multidomain MDM

Figure 4.3: The four main models of DSM (Eppinger 2012)

The primary benefit of DSM compared with other network modeling methods, is the graphical representation of the the matrix display format. It gives a intuitively readable representation of the system architecture. Fig. 4.4 shows the benefit of using a DSM compared to a diagraph.



(a) (b)

Figure 4.4: Binary DSM (a) and its equivalent in diagraph form (b)

Further attributes of the interactions, such as the number of interactions and/or the importance, impact, or strength of each - which might be represented by using one or more numerical values, symbols, shadings, or colors instead of just the binary marks in each of the off-diagonal cells.

Interactions from the DSM model can be partitioned into modules by using a variety of analytical methods. The most common is clustering, which is shown in Fig. 4.5. Clustering applies primarily to the kinds of interaction networks found in product and organization architecture DSM models, where interaction marks are largely symmetric about the diagonal. A high density of interactions could indicate a module.

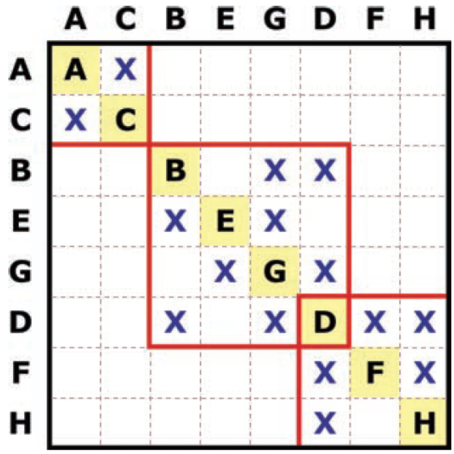


Figure 4.5: DSM partitioning by clustering (Eppinger 2012).

The results from the ”House of Quality” model are applied to the DSM. These results give interactions between equipment based on processes. The correlation matrix shown in Fig 4.2 gives both postive and negative correlations. The negative correlation will not be applied to the DSM. This process is followed in order to generate fleet concepts that have the capacities to perform the processes required for installing a floating offshore wind farm.

4.2 Weather representation

4.2.1 Data

The significant wave height has been analysed. It is known as the average of the highest one third of the waves. The following data applies:

	ERA5-data
First observation	01-01-2009
Sampling (years)	11
Sampling frequency (hours)	1
Number of measurements	96408
Location	59.5 N, 4.5 E

This location represents Utsira Nord which is located west for Haugesund, and is recommended by The Norwegian Water Resources and Energy Directorate (NVE) as a wind field for installing floating wind turbines. An illustration of the field is shown in Fig. 4.6.

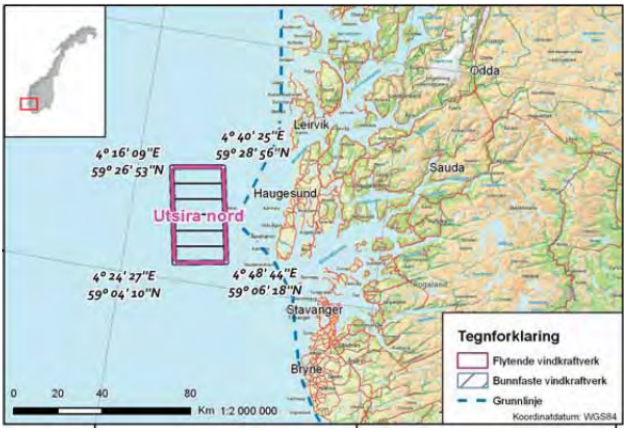


Figure 4.6: Wind field chosen for this project (Viseth 2019)

In order to account for seasonality, the data set is split into winter, spring, summer and autumn.

4.2.2 Markov chain model

According to Hagen et al. (2013), a Markov Chain is a discrete stochastic process which satisfies the Markov property. This means the process is without memory, and a Markov chain for weather modeling assumes that the next state of weather is only dependent on the current state of the weather, and not of the weather in the past. In other words, the current state of the weather contains all the relevant information about the weather and its future development. Stochastic transitions describes the development of the weather.

The process variable X_t takes on discrete integer values representing the state at time t. The number of states is denoted by N and are finite. This means that the possible values for X_t is given by $\Omega = 1, 2, 3..., N$. Under the markov property all conditional transition probabilities from state i to state j for arbitrary $1 \leq i, j \leq N$ are independent on time and can be written in matrix form:

$$P(X_{t+1} = j \mid X_t = i) = p_{ij} \tag{4.1}$$

This defines the NxN transition matrix

$$P = \begin{pmatrix} p_{11} & p_{12} & \dots & p_{1N} \\ p_{21} & p_{22} & \dots & p_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ p_{N1} & p_{N2} & \cdots & p_{NN} \end{pmatrix}$$

Each row in the transition matrix is a conditional probability distribution which implies that the row sums of P are equal to one. The matrix combined with a probability distribution of the initial condition $P(X_1 = x_1)$, defines the Markov chain model. Given a sequence X_t of data, the maximum likehood estimator for the transition probabilities is:

$$\widehat{p}_{ij} = \frac{N_{ij}}{N_i} \tag{4.2}$$

where N_{ij} is the number of observed observations from state i to state j, and N_i is the total number of occurrences of the state i in the sequence. The probability of state changes to the current state or to a neighbouring state are set high, while the probability of suddenly going from good weather to bad weather is low.

4.3 MATLAB SimEvents

MATLAB SimEvents provides a discrete-event simulation engine and component library for analyzing event-driven system models and optimizing performance characteristics (MathWorks 2020). Simulation is the imitation of a real world process and it is comprised of a model representing a real system and the operation of the system over time. Simulation is used when the real system is not available for testing and/or when stochasticity makes it difficult to model with other methods. Event-driven means that the state of the system is changed by events. A high-level description of a simulation model is given in Fig. 4.7. Entities, global variables and blocks which comprises the simulation model are described below.

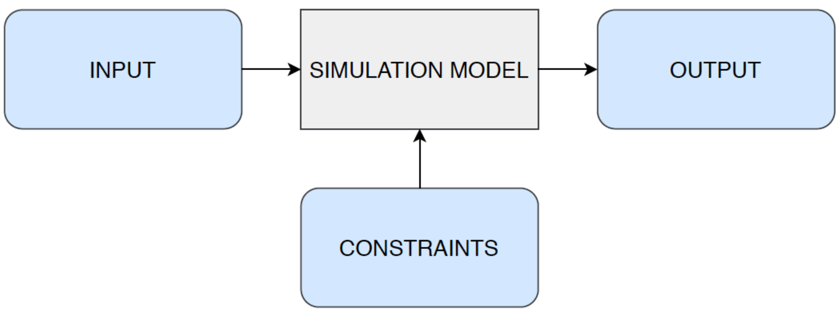


Figure 4.7: High-level description of a simulation model.

Entities
Entities can pass through a network of queues, servers, gates, and switches during a simulation. Entities can carry data, known in SimEvents software as attributes. Attributes can be altered as the entities move from block to block.

Global variables
Global variables are variables that you can access in other MATLAB functions or Simulink blocks like "Data Store Read" and "Data Store Write". This allows different model parts to communicate with each other. Generation of waves can be accessed quickly.

Blocks

Block	Description
Entity Generator	Generates entities, which can carry attributes (Scalar, bus or vector data).
Entity Queue	Storage block which sorts the entities according to the queue policies.
Entity Server	Stores the entities, service them, and then attempts to output the entities.
Entity Switch	Combine or select arrival path.
Entity Gate	Controls when pending entities can advance in the model.
Entity Terminator	Accepts and destroys entities.
Simulink Function	Computational unit that calculates a set of outputs when provided with inputs.
Data Store Write	Copies the value at its input to the named data store.
Data Store Read	Copies data from the named data store to its output.
Data Store Memory	Defines and initializes a named shared data store. Memory usable by Data Store Write/Read.
To Workspace	Writes input data to a workspace
From Workspace	Reads data from a workspace and provides the data at its output as a signal.

The simulation model will be used for evaluating how different fleet compositions behave over different field configurations. These field configurations, together with inputs, outputs and constraints will be described in Ch. 6.

4.4 Cost

Bareboat charter, voyage charter and time charter are the most common contractual arrangements in the maritime industry. The cost and responsibilities are distributed in different ways, which is shown in Fig. 4.8.

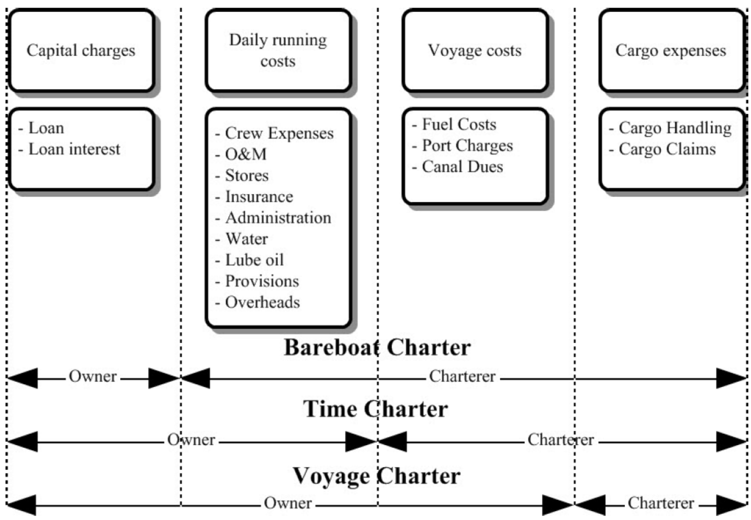


Figure 4.8: Cost distribution for vessel charter strategies (Dalgic, Lazakis, and Turan 2013).

Floating offshore wind installation activities require extensive expertise and specialisation as a result of the marine operations, described in Sec. 2.3, being carried out in harsh environmental conditions. Operators therefore tend to employ technicians and seafarers who have experience in such operations. Bareboat charter is therefore further considered in the analyses.

Dayrates can be estimated from the capital costs of construction. Kaiser and Snyder

(2012) presents dayrates as a percentage of capital expenditures, which is shown in Tab. 4.1

Table 4.1: Vessel dayrates as a percentage of capital costs (Kaiser and Snyder 2012).

Capital cost (million $)	0.05%	0.10%	0.15%
30	15,000	30,000	45,000
50	25,000	50,000	75,000
100	50,000	100,000	150,000
150	75,000	150,000	225,000
200	100,000	200,000	300,000
300	150,000	300,000	450,000

The authors state computed the daily rates for jackup drilling rigs, liftboats, and offshore supply vessels to provide an analog for offshore wind installation vessels. They averaged all dayrate contract for 102 rigs over the 10 year period and divided by the rig CAPEX. In other words, the validity of the data shown in Tab. 4.1 depend on the similarity between the offshore wind market and the rig, liftboat and Offshore Supply Vessels market in terms of rate of return, operating cost and market conditions. Since most of the vessel capacities in the floating offshore wind market are transferred from the oil and gas industry, it is assumed that the data reflects the actual costs.

Chapter 5

Operational Scenarios

In this chapter, we will derive different fleets for installing a floating offshore wind farm. Together with different distances and wind farm sizes, this will give different scenarios that will be tested in discrete-event simulation models. This will work as a tool for understanding what is important in an installation logistics solution for floating offshore wind farms.

5.1 Assumptions and Limitations

The following assumptions and limitations are made:

- The study will only cover the installation logistics of Floating Offshore Wind Farms.
- The estimated daily charter cost covers all operational costs.
- The study will only cover the suction anchor installation, pre-laying of mooring system, towing, hook-up and inter-array cable installation.
- It assumed that all components are available at the assembly port.
- The fleet concepts are compared under the same weather conditions.
- The fleet concepts are assumed to have the same capacity parameters in total. E.g. the HCV can carry the same amount of anchors as the feeder vessel.

5.2 Model scenarios

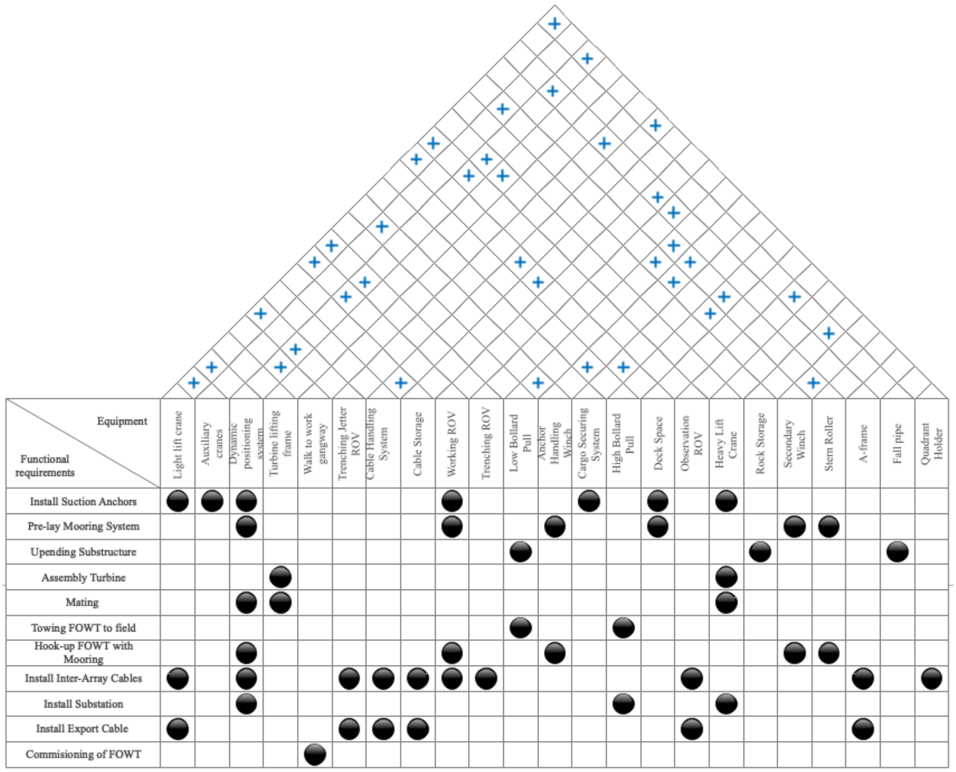


Figure 5.1: House of Quality - Installation of Floating Offshore Wind Farm

As described in Sec. 4.1, the House of Quality Matrix together with the Design Structure Matrix will derive different fleet concepts for installing a floating offshore wind farm. The House of Quality Matrix for installing a floating offshore wind farm is shown in Fig. 5.1. The relationship matrix highlights the relation between functional requirements and equipment. The functional requirements obtain a high-level description of the required steps. For further explanation, see Ch. 2. The correlation matrix highlights the relationship between equipment, and is passed on to the Design Structure Matrix, shown in Fig. 5.2.

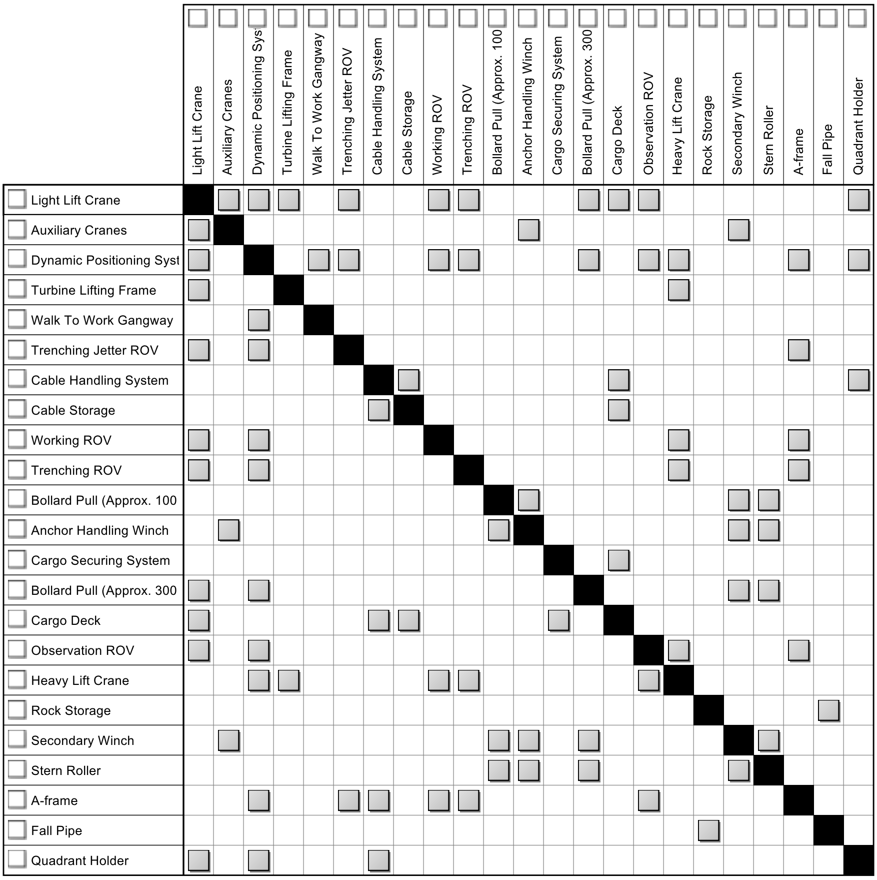


Figure 5.2: Unclustered Design Structure Matrix

Clustering is then applied, and the results are shown in Fig. 5.3.

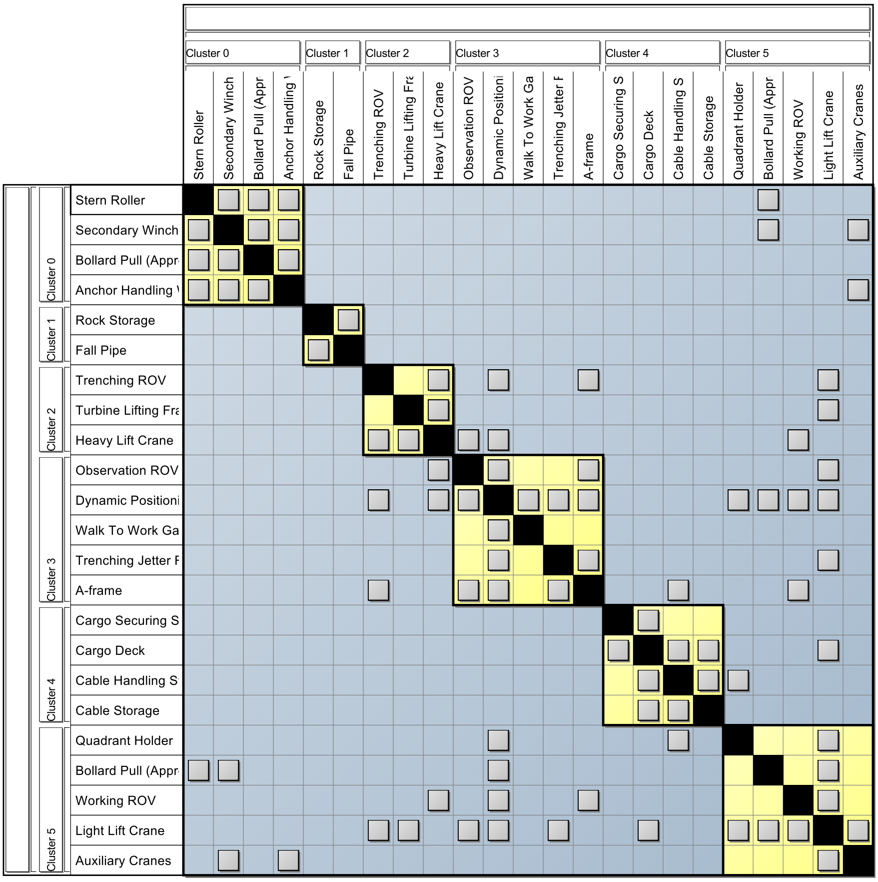


Figure 5.3: Clustered Design Structure Matrix

Six modules are identified in the clustered Design Structure Matrix. As mentioned earlier, the Simulation Model will cover suction anchor installation, pre-laying of the Mooring System, Towing, Hook-up and Inter-Array Cable Installation since they are identified as the most critical operations. From the clustered Matrix, we are able to identify the fleet that was used for the installation of Hywind Scotland (See Sec. 2.4.1). This fleet will considered as the conventional fleet.

Earlier concepts of installation shows that the fleets are large. Is it possible to decrease the fleet, and thereby also reduce the installation costs? The second fleet that will be modelled will have a Multi-Purpose Vessel that takes care of the suction anchor installation and inter-array cable installation. It is found as the most promising combination between two modules, since the wind farm installation starts with suction anchors and ends with inter-array cable installation. Since the processes need to be performed partly parallel to each other, it is difficult to combine other modules. Another aspect is the physical architecture. The most used module within installation of a floating offshore wind farm, is the Anchor Handling with pre-laying of the mooring system, towing and hook-up. This means that the vessels within these operations should be specialized, since combining these operations with other processes could end up making the multi-purpose vessel multi-useless. The pre-laying of mooring system, towing and hook-up will therefore be done by 4 AHTS vessel. The described fleet will be considered as the MPV fleet.

An aspect that is not covered in the House of Quality and Design Structure matrices, is the transportation of entities between the assembly site and the offshore wind farm. As a result of the high cost of the vessels involved, it is vital to have a high utilization for installation at the offshore wind farm. The utilization could be increased by introducing a feeder vessel. Looking at the different processes involved, it is only viable to introduce a feeder concept to the suction anchor installation. Transferring cables and mooring systems from one ship to another offshore, are not considered feasible and would be classified as very complex operations often interrupted by harsh weather conditions. The scenarios for the simulation study is listed in Tab. 5.1 and the fleet description is listed in Tab. 5.2.

Table 5.1: Scenarios of simulation study

Scenario	Distance (nm)	Number of OWTs	Selected concept
S1	66	100	Conventional
S2	66	50	Conventional
S3	66	25	Conventional
S4	132	100	Conventional
S5	132	50	Conventional
S6	132	25	Conventional
S7	66	100	MPV
S8	66	50	MPV
S9	66	25	MPV
S10	132	100	MPV
S11	132	50	MPV
S12	132	25	MPV
S13	66	100	Conventional + Feeder
S14	66	50	Conventional + Feeder
S15	66	25	Conventional + Feeder
S16	132	100	Conventional + Feeder
S17	132	50	Conventional + Feeder
S18	132	25	Conventional + Feeder

Table 5.2: Definition of the vessel fleets considered

Vessels	Conventional	MPV	Conventional + Feeder
Large AHTS	1	1	1
Small AHTS	3	3	3
Cable Laying Vessel	1	0	1
Heavy Construction Vessel	1	0	1
Multi-purpose Vessel	0	1	0
Feeder Vessel	0	0	1

Each concept will be described in the following sections, and the transition from the real world process to models will be explained in Ch. 6.

5.3 Conventional fleet

The flowchart for the conventional fleet is shown in Fig. 5.7. As described earlier, the order of the operations are suction anchor installation, pre-lay of mooring system, towing, hook-up and inter-array cable installation. In general, for offshore installations, they want to install everything on the seabed first as a preparation for when the structure arrives. The inter-array cable installation is independent on the other processes, which means that it could be installed before the turbines arrive at the field or after. It is assumed that the installation of inter-array cables should be done after the arrival of the turbine, as it will save time considering that the cable could be connected to the turbine shortly after it has been laid.

The flowchart shows the process architecture, and the processes starts with loading the objects to the vessel. These operations are assumed not to be weather sensitive, since most assembly sites are located in relative calm waters and the vessels are moored to the dock. In other words, the loading is considered weather unrestricted. The transits between the assembly site and the field are also designed as weather unrestricted operations. This means that the operations can take place safely in any weather condition that can be encountered during the season. When the vessel arrives at the field, it is considered to be in a safe condition. Prior to the installation at the field, the operators check if there is a weather window for installing the object. The weather window equals the duration from where the object is in one safe condition to another safe condition. The next safe condition is achieved when the object is installed. If there is no weather window, the vessel has to wait, which is indicated as Waiting on Weather (WoW) in the flowchart.

If there are more objects, the vessel re-positions to the next location and continues the process described above. If the load is empty, the vessel transits back to the assembly site and if all objects are installed, the vessel is demobilised. The processes described until now applies for suction anchor installation, pre-laying of mooring system and inter-array cables. The towing and hook- up cycle start with mobilising three AHTS vessels. Two small AHTS vessels sail directly to the field, and they are assigned to assist the hook-up, which is illustrated in Fig. 2.21 in Sec. 2.3. These vessels will re-position and wait between each installation of FOWTs. One large AHTS vessel is assigned to tow the turbine from the assembly site to the wind farm. Two tugs assist the towing, but they are not included in the model since they are not within the scope of the master thesis. The assembly of WTGs, upending of substructure and mating are neither included in the model. The assembly and mating are assumed to be done by an onshore crane, and together with the upending, they are not within the scope of the analysis.

The safe conditions for the towing and hook-up cycle are illustrated in Fig. 5.4. The operators will check for a weather window for each operation shown in the figure.

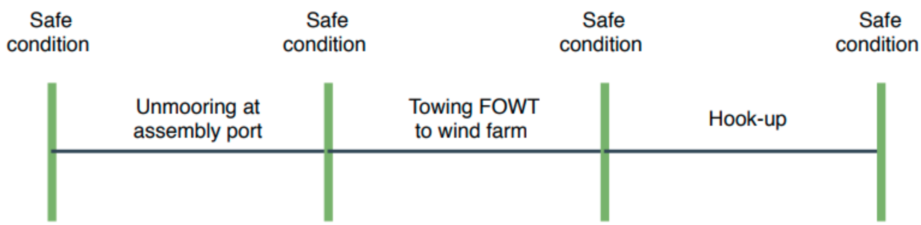


Figure 5.4: Safe conditions for towing and hook-up

In terms of planning, it is important to decide whether the operations should be ordered as sequential processes or parallel processes. Fig. 5.5 illustrates the operations ordered as sequential processes. Sequential ordering could be justified with few turbines at the field, which was done at Hywind Scotland (See Sec. 2.4.1). As the number of turbines increases, the process needs to be ordered as partly parallel process. This will reduce the total installation time substantially, which can be seen by comparing Fig. 5.5 and Fig. 5.6.

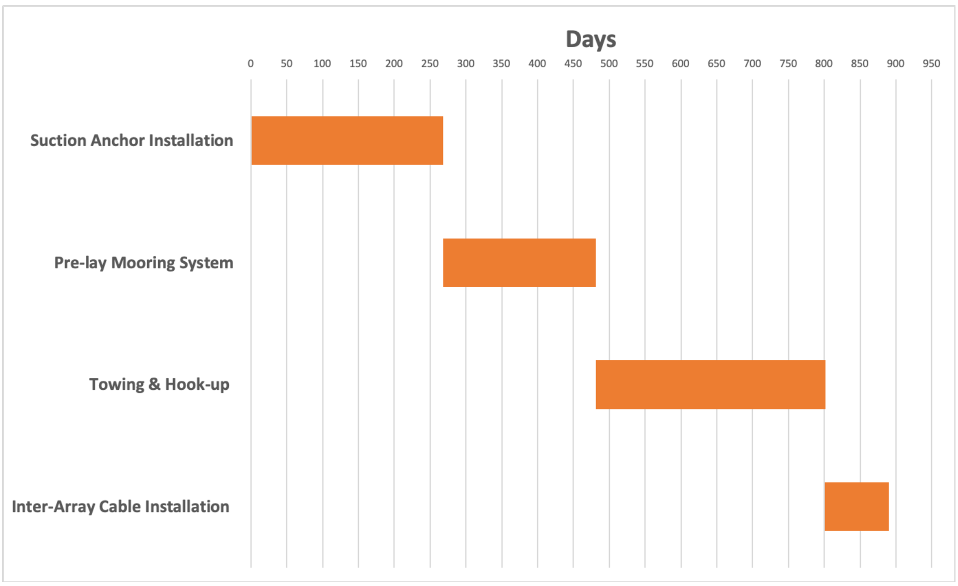


Figure 5.5: Operations ordered as sequential processes.

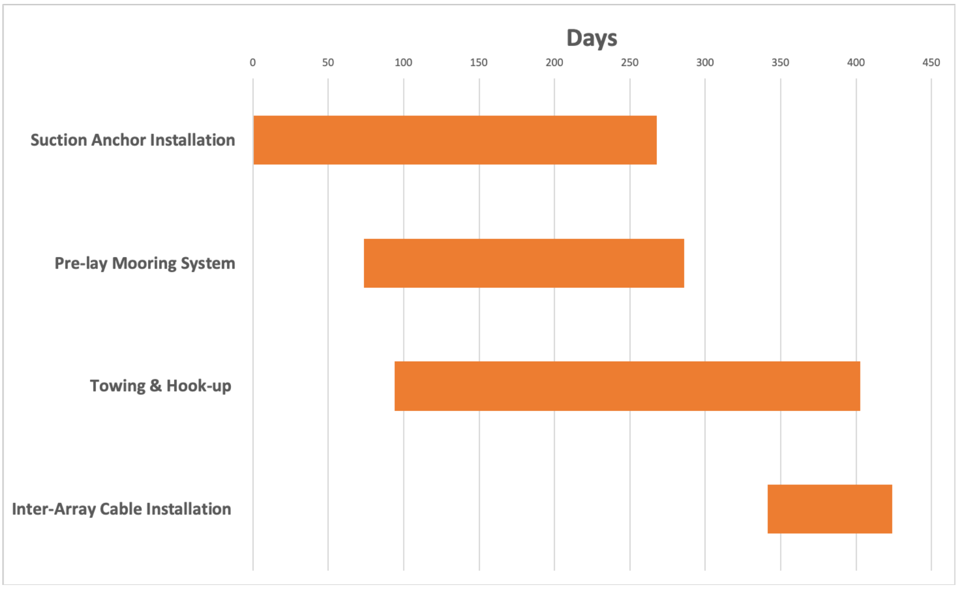


Figure 5.6: Operations ordered as partly parallel processes

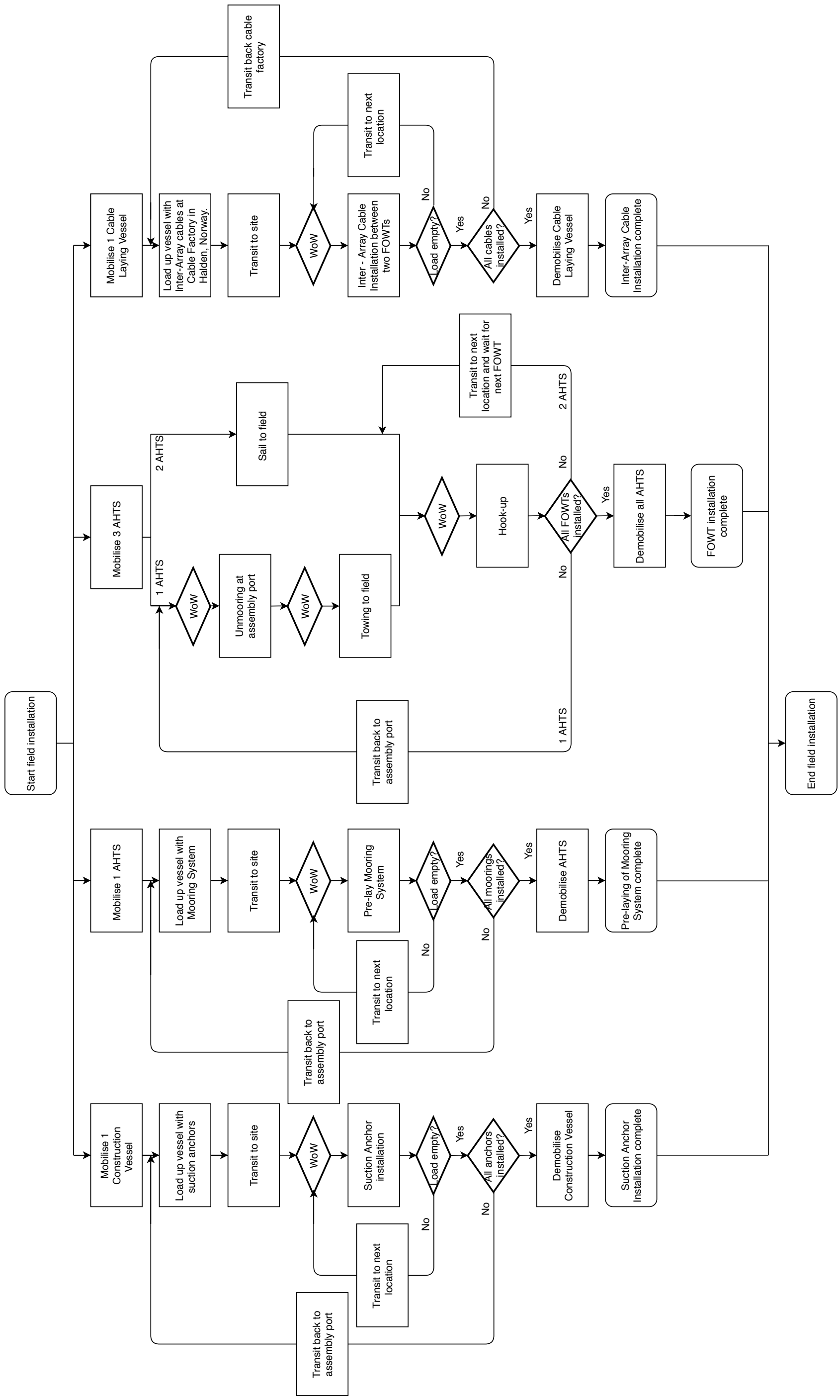


Figure 5.7: Flowchart for conventional fleet

5.4 Fleet with Multi-purpose Vessel

The idea behind introducing a multi-purpose vessel is to introduce operational flexibility. It may contribute to a cost-efficient modernization of obsolete equipment, upgrades, and adaptation to changed external conditions. This may contribute to increasing the operational efficiency of the vessel, as well as extending the vessel's operational life (Erikstad 2009). This applies to the FOWT market as a result of the exponential growth of turbine size. It is expected that the growth will continue.

The type modularity that are being applied to the multi-purpose vessel is sectional modularity. This means that the vessel has modules that have few interfaces between each other which allow a higher variety in the physical layout of the vessel. The sectional modularity allows the vessel to combine suction anchor installation and cable installation. This also implies that we get a larger vessel. This does not directly imply that the vessel get more capacity compared to the conventional fleet. The sectional modularity could ease the cost and complexity of a later conversion as well.

It could be argued that a larger vessel would more be stable and hence, improve the operational limit. But the workability is restricted by the operation itself, and not the vessel. Therefore, the multi-purpose will not have a higher operational limit compared to the conventional fleet. The drawbacks of a modular approach are a less optimized architecture and increased weight. As discussed in Sec. 4.1.3, there is no direct relation between modularization and emissions. The increased weight will lead to more emissions compared to a integral structure with the same technical performance. On the other hand, increasing the operational efficiency will reduce the emissions.

The flowchart for the MPV fleet is shown in Fig. 5.8. The pre-laying of mooring system, towing and hook-up cycles are set up equally as the conventional fleet. As discussed earlier, it was not found feasible to modularize these operations. The multi-purpose vessel is firstly generated, and are assigned to suction anchor installation. The suction anchors are loaded to the vessel at the assembly port before sailing to the wind farm. At the wind farm, the vessel checks for a weather window before installing one suction anchor. If the load is empty, the vessel returns to the assembly port for more. The cycle continues until all suction anchors have been installed. From there on, the vessel changes operation from suction anchor to inter-array cable installation. The vessel sails to the cable factory in Halden for loading, and follows the inter-array cable installation cycle.

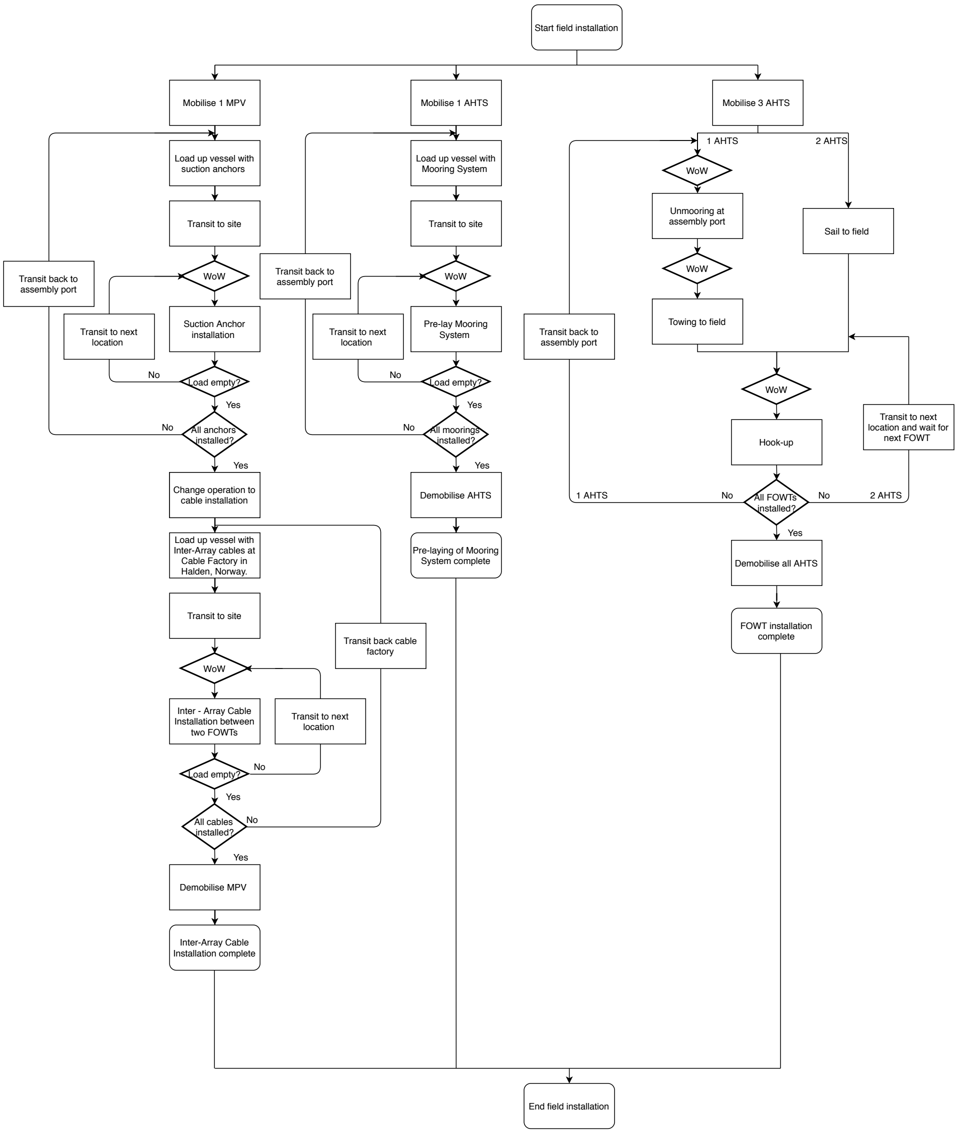


Figure 5.8: Flowchart for fleet with Multi-purpose Vessel

5.5 Feeder Vessel Fleet Concept

The feeder vessel fleet concept is shown in Fig. 5.9. The pre-laying of mooring system, towing hook-up has the same flow as described in the conventional fleet (See Fig. 5.9. At first, the HCV and feeder vessel are mobilised. The feeder vessel loads the vessel with suction anchors, while the HCV sails directly to the wind farm location. In reality, the HCV would load the vessel before the first trip to the farm and the feeder cycle would start when the HCV starts installing. The feeder vessel goes back and forth from the wind farm, while the HCV stays at the field for installation only.

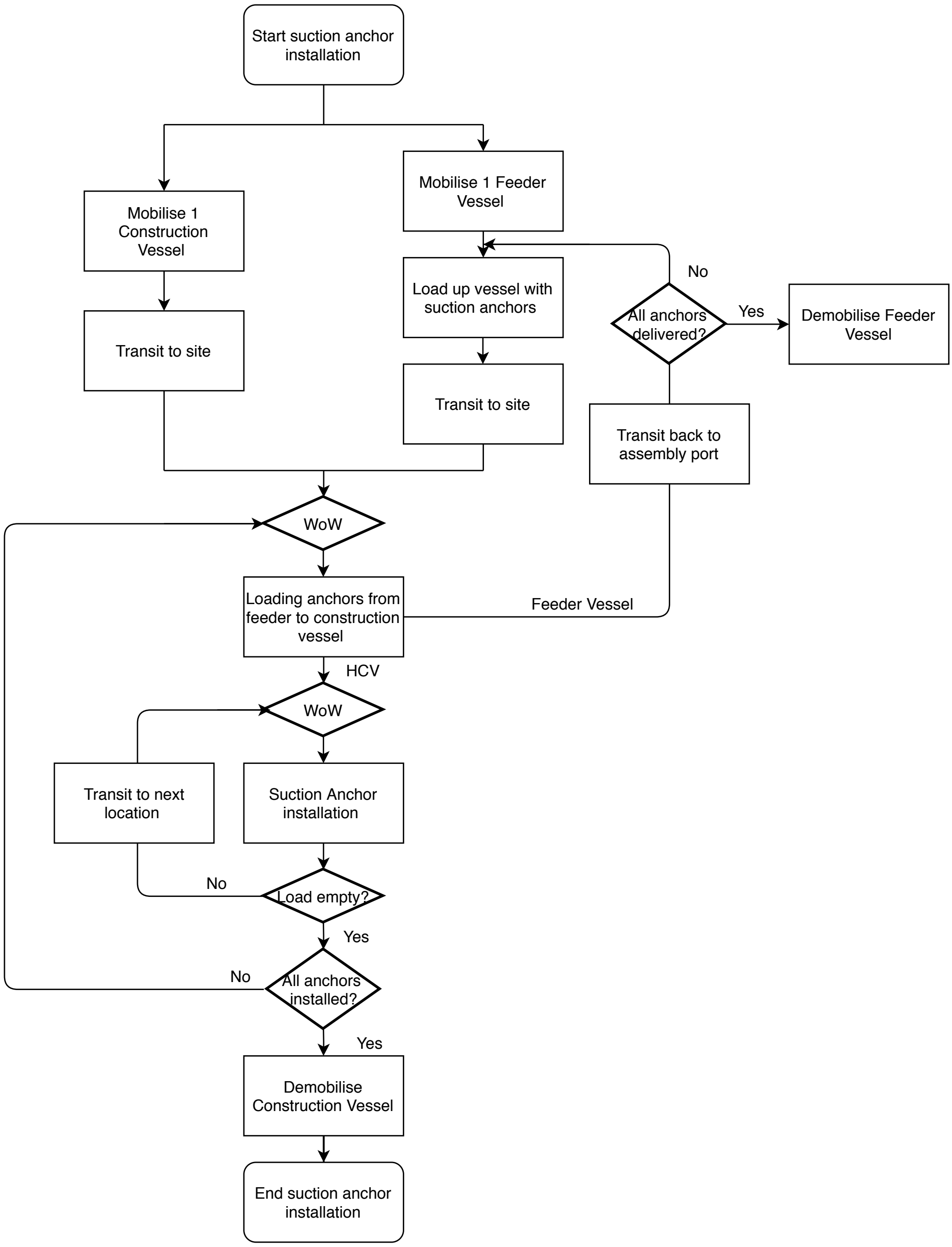


Figure 5.9: Flowchart for feeder vessel fleet concept

Chapter 6

Discrete-event simulation model

The transition from the real world process to the simulation models will be described in this chapter. This will work as a validation of the model as well. The input, constraints and desired outputs of the simulation models will be described in detail. It should be noted that the simulation models can be used as a planning tool for floating offshore wind farm planners. Several ship-specific parameters can be changed for specific projects. This includes the number of vessels used, vessel capacities, speed, operational criterion's, wind farm size and distance from shore.

The structure that applies for all models will be described first, before describing each model specifically. It is assumed that all components are available at the assembly port. In other words, the model does not account for production logistics and inventory management.

6.1 General Model structure

The basics of the model is that entities are generated and are assigned to a designated route by model input. The entities goes through servers, which stores the entities, service them according to model input and then outputs the entities. The model input will be described in Sec. 6.6.

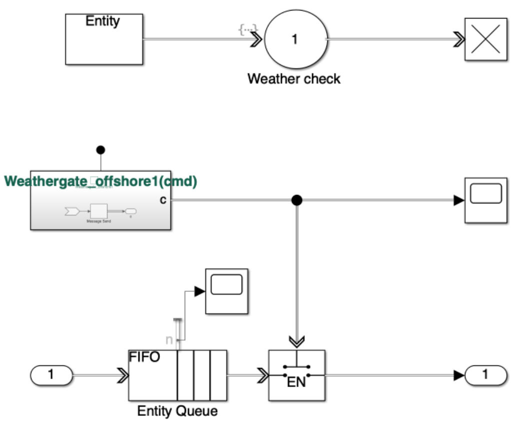


Figure 6.1: Weather check before marine operation

The structure for checking weather windows are shown in Fig. 6.1. Before each installation of an object object, the vessel goes through this structure. A global variable keeps track of time, which enables checking if there is a weather window dependent on the operational limit from the current time to the end of the operation. This means going from one safe condition to another. If there is no weather window, the vessels waits in an entity queue until it gets one.

The models keeps track off objects loaded by attributes and global variables, shown in Fig. 6.2. The global variables stores the total number of entities that shall be installed and the number of objects that has been installed at the current time. The attributes are assigned a value depending on the remaining number of objects to be installed.

```
Chaincapacity = entity.Chaincapacity;
nr = full_field_Mooring;
installed = Mooring_Lines_Installed;
remain = nr - installed;

if Chaincapacity <= remain
    entity.Chainloaded = entity.Chainloaded + Chaincapacity;
elseif remain <= Chaincapacity
    entity.Chainloaded = entity.Chainloaded + remain;
else
    entity.Chainloaded = entity.Chainloaded;
end
```

Figure 6.2: Entry action of loading server

In the same matter, the ”object loaded” - attribute are subtracted by one object each time the vessel passes through the installation server. The service completion action of the installation server is shown in Fig. 6.3. In addition one object is added to the global variable that controls the amount of objects installed. If there are more objects on board, the vessel re-positions to the next location and if the load is empty, it returns to the assembly site to load more objects. The vessel is demobilised if all objects are installed.

```
% Remove a object from vessel after installation
entity.Chainloaded = entity.Chainloaded - 1;
% If there are more object onboard the vessel -> re-positioning
% If not -> sail back to assembly site
if entity.Chainloaded > 0
    entity.Outputport = 1;
else
    entity.Outputport = 2;
end

% Add installed object to global variable

Add_Mooring_Lines();

%Send vessel to be demobilised if all objects are installed
if full_field_Mooring <= Mooring_Lines_Installed
    entity.Outputport = 3;
end
```

Figure 6.3: Service Completion action of installation server

The first vessel is generated at the start of the simulation model. The next vessels are generated by an event-based generation method. This is done to facilitate the partly parallel ordering of processes which were discussed in Sec. 5.3. To a give short example, the structure is set so that the vessel used for pre-laying of mooring chains will be generated when 45 suction anchors are installed at the wind farm. A subsystem sends a signal to the entity generator when this is achieved.

6.2 Simulation Model Calculations

The sailing time and towing time are assumed to be dependent on the weather, which can be seen in Eq. 6.1 and 6.2.

$$Sailing\ time = \frac{Distance}{Transit\ Speed} * 1.02^{Hs} \tag{6.1}$$

$$Towing\ time = \frac{Distance}{Towing\ Speed} * 1.02^{Hs} \tag{6.2}$$

Eq. 6.3 shows that the loading time is dependent on the capacity and loading rate.

$$Loading\ time = \frac{Capacity}{Loading\ Rate} \tag{6.3}$$

According to Kaiser and Snyder (2012), the total required inter-array length is determined by the following relation:

$$Inter - Array\ Length = 0.00067(FC)^2 + 14.6 \tag{6.4}$$

where FC is the wind farm capacity in Megawatts (MW). Each turbine is assumed to be 8 MW.

6.3 Model 1 - Conventional Fleet

The model is split into five subsystems: Suction Anchor Installation (Fig. 6.4), Pre-laying of Mooring-System (Fig. 6.5), FOWT installation (Fig. 6.6), Inter-Array Cable Installation (Fig. 6.7) and the global variables. Global variables will be described in Sec. 6.7. See Appx. B.3 for the whole model. The suction anchor, mooring and inter-array cycles are similar in terms of entity flow.

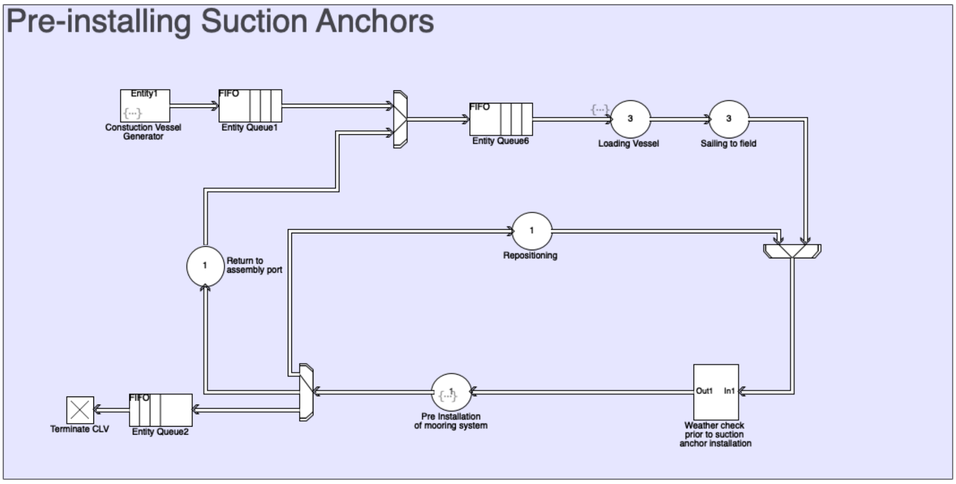


Figure 6.4: Conventional fleet - Installation of suction anchors

The Construction Vessel if firstly generated. At the assembly site, the vessel loads the deck space with suction anchors with the on board crane. This crane needs a capacity of 400 tonnes and active heave compensation. The suction anchors are sea fastened by welding to specialized frames, and the number of anchors loaded are constrained by the area and load per m^2.

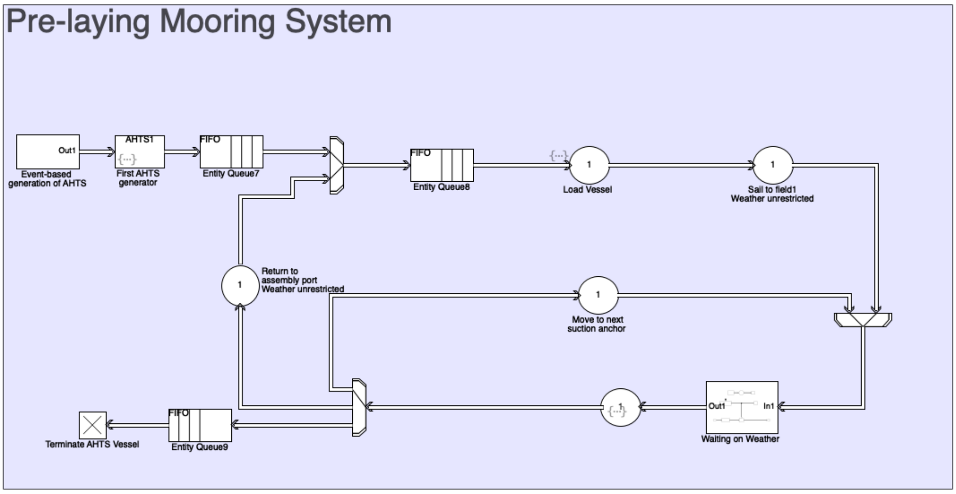


Figure 6.5: Conventional fleet - Pre-laying Mooring System

Hereafter, the other vessels are generated by the event-based generation method which was described earlier. First, an AHTS vessel is generated after a given number of suction anchors have been installed. This number varies with wind farm size. The vessel loads the mooring system on board with the use of a crane and stores chains in a chain locker, while the steel wires ropes are stored at deck in carousels. The capacity of the vessel is modelled to be dependent on the chain locker size, and not deck space. In other word, the chains are the limiting parameter for the vessel load.

When a given amount of mooring lines have been installed, the next set of AHTS vessels are generated. They first meet a entity output switch that determines the path. The output port is decided by an attribute which is imported from a spreadsheet, which is shown in Appx. B.2, together with other attributes. Two small AHTS vessels sails directly to the wind farm, and they are assigned to assist hook-up. One large AHTS vessel is assigned to towing the FOWT. The capacity of the AHTS vessel is one FOWT per roundtrip. When arriving at the wind farm, the vessel, together with two tugs, hold the FOWT at its designated spot. The two other vessel that were sent directly to the farm, performs the hook-up.

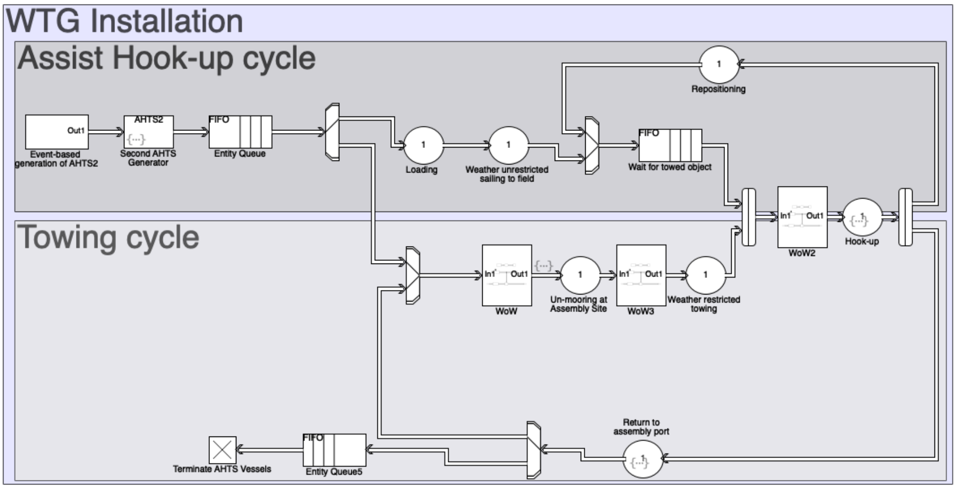


Figure 6.6: Conventional fleet - Towing and hook-up

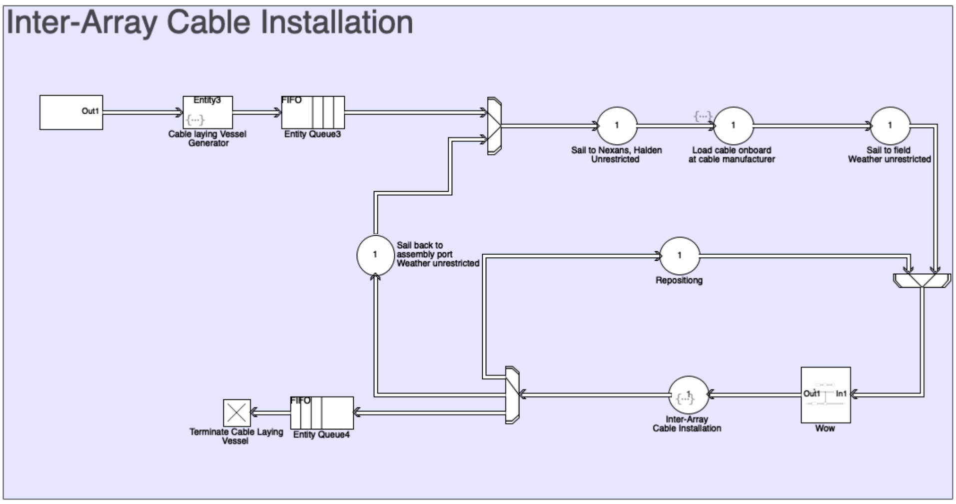


Figure 6.7: Conventional fleet - Cable Installation

At last, the cable laying vessel is generated. It starts the cycle by sailing to the Nexans factory in Halden, Norway for loading of inter-array cables. The cable is loaded directly to the carousel, which rotates while loading. The carousel has a high capacity, which means that there will be few roundtrips. Installation is carried out by laying the inter-array cable and connecting it to the FOWT, before trenching by a jet trenching ROV. The ROV is lifted into the sea by an A-frame.

6.4 Model 2 - Fleet with Multi-purpose Vessel

The model is split into 4 subsystems; MPV cycle (Fig. 6.9), pre-laying of mooring system (Fig. 6.10), towing and hook-up (Fig. 6.11) and global variables. See Appx. B.4 for the whole model. The MPV is generated at the start of the simulation model. The other vessels are generated by the event-based generation method. The MPV is assigned to a mission according to the service completion action shown in Fig. 6.8. The vessel is first assigned to suction anchor installation. If all suction anchors have beeen installed, it changes operation to inter-array cable installation. If all anchors and cables are installed, the vessel is demobilised and terminated. The operation mode is changed by changing the mission attribute, and the entity output switch is set according to the attribute number.

```
if (full_field_anchors <= suctionanchors_installed)
    if (full_field_InterArray <= InterArrayCable_Installed)
        entity.Mission = 2;
    else
        entity.Mission = 1;
    end
else
    entity.Mission = 3;
end
```

Figure 6.8: Service completion action deciding operation cycle

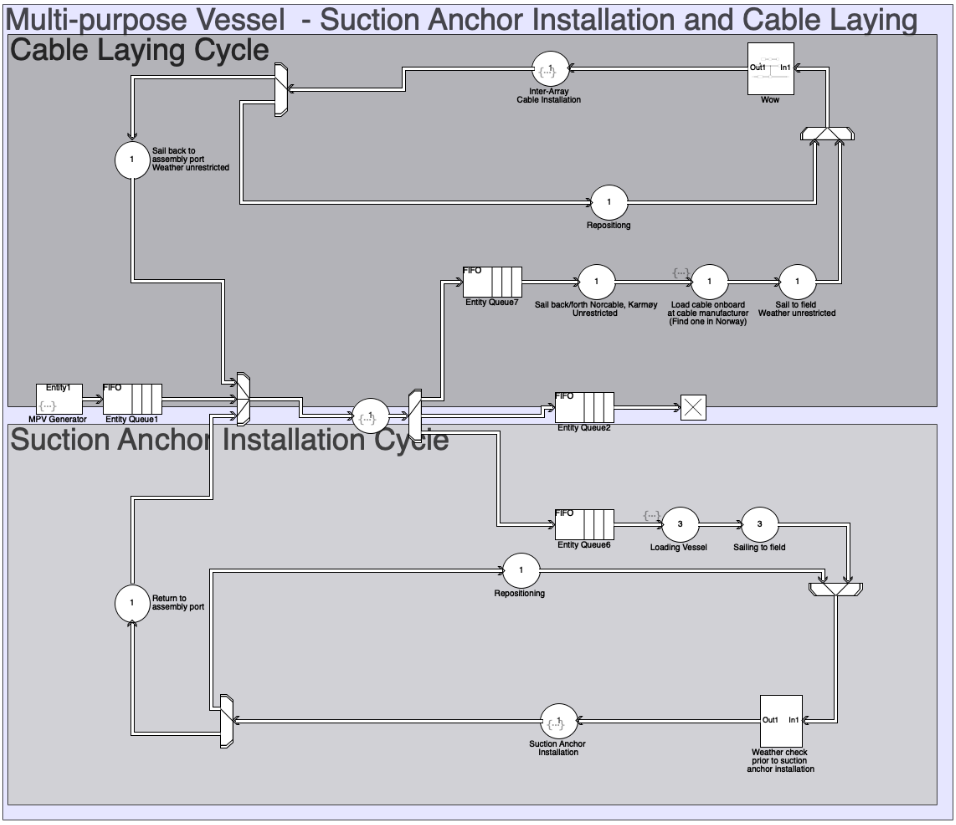


Figure 6.9: Multi-purpose fleet - Suction Anchor Installation and Inter-Array Cable Installation

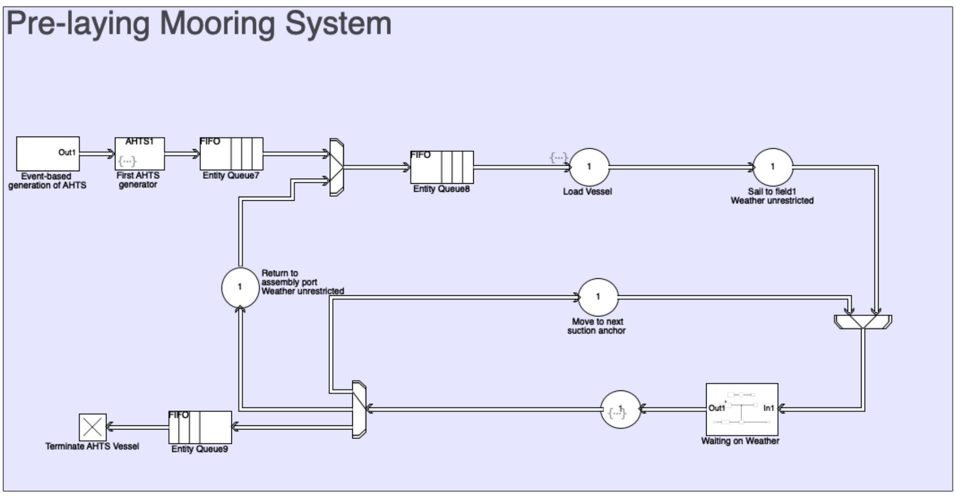


Figure 6.10: Multi-purpose fleet - Pre-Laying Mooring System

The model structure for the pre-laying and FOWT installation is equal to what was described for the conventional fleet.

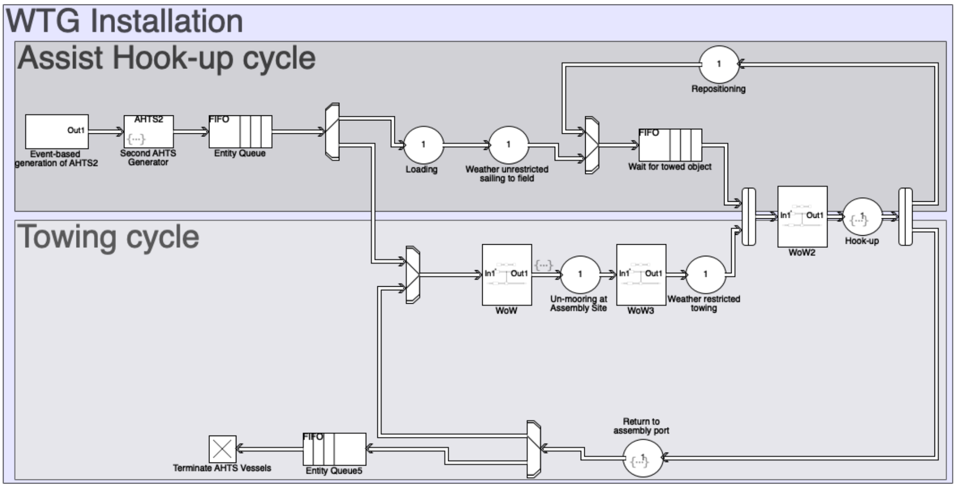


Figure 6.11: Multi-purpose fleet - Towing and Hook-up

6.5 Model 3 - Feeder Vessel Fleet Concept

Model 3 represents the Feeder Vessel Fleet Concept that was derived in Sec. 5.5. The model consists of 5 subsystems, where the suction anchor installation with feeder vessel are shown in Fig. 6.12. The other subsystems, including pre-lay of mooring system, towing, hook-up and inter-array cable installation, have the same model structure as the conventional fleet. See Appx. B.5 for the whole model. These model structures can be seen in Fig. 6.5 - 6.7 under Sec. 6.3. The global variables are explained in Sec. 6.7.

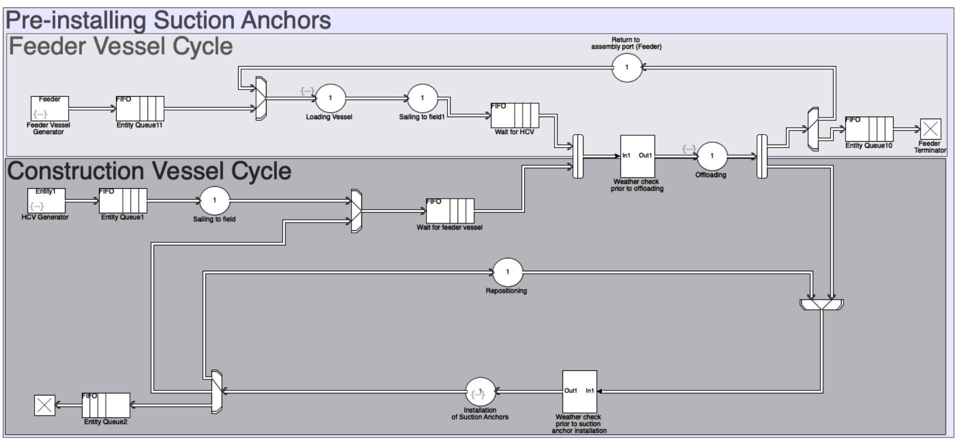


Figure 6.12: Feeder concept - Suction Anchor Installation

Fig. 6.13 shows the code that represents the offloading process between the feeder vessel and construction vessel. When all suction anchors have been delivered, the feeder vessel is demobilised.

```
entity.E11.Nr = entity.E11.Nr - 4;

entity.E22.Nr = entity.E22.Nr + 4;


nr = full_field_anchors;
installed = suctionanchors_installed;
remain = nr - installed;

if remain == 0
    entity.E11.Output_Feeder = 2;
else
    entity.E11.Output_Feeder = 1;
end
```

Figure 6.13: Offloading process from feeder to construction vessel

6.6 Model Input

6.6.1 Weather

As described in Sec. 4.2, the weather data from 2009-2019 were retrieved from the ERA5-database. In order to account for seasonality, the data were ordered after month. Furthermore, the data was brought into a markov chain simulation model, which can be seen in Appx. A. An example of the simulated weather can be seen in Fig. 6.14.

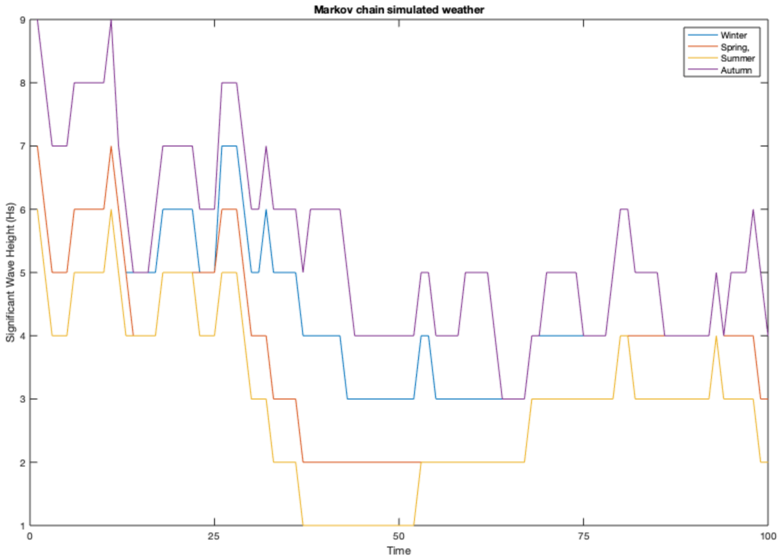


Figure 6.14: Example of markov chain simulated weather

The industry often retrieves weather forecasts each sixth hour. Special contracts with meteorological institutions can be made where the weather forecasts are retrieved with a shorter interval. As the installation of a floating offshore wind farm is known to be sensitive to weather, it is assumed that weather forecasts are retrieved each third hour. This means that each time step in the figure above, represents the weather for the next three hours.

6.6.2 Attributes

The attributes assigned to each entity is shown in Tab. 6.1. The attributes can be changed to match the desired vessel specification. In other words, the model presented can be used for planning purposes, and be used for comparing different fleet compositions. ”-” means that the attribute does not apply for the vessel, while ”#” are assigned to a value as it goes through the model.

Table 6.1: Attributes for vessels

Attribute	Large AHTS	Small AHTS	MPV	HCV	CLV	Feeder
Speed (knots)	12	10	11	12	12	12
Anchor Capacity (pcs)	-	-	4	4	-	4
Mooring Capacity ()	1200	660	-	-	-	-
Cable Capacity (Tonnes)	-	-	5000	-	5000	-
Mission	#	#	#	-	-	-
Output port	#	#	#	#	#	#
Current load	#	#	#	#	#	#

The ”current load” attribute controls the number of components loaded on board the vessel, and decides the value of the output port. The value of the output port signals either that the vessel should re-position and continue installing, or return to the assembly port for loading more components. The mission attribute routes the vessel to the correct operation.

6.6.3 Operational parameters

Tab. 6.2 shows the operational parameters ordered after vessel type. The reference period is included in the entity servers, and the entity server holds the entity for the given simulation period. The subsystems check if the weather for the given reference period exceeds the operational limit. The entity is held in the subsystem until there is a weather window. Some of the operations are classified as weather unrestricted. According to DNV GL (2011a), if the reference period, T_R is less or equal to 3 days, the characteristic significant wave height may be defined as the most probable largest H_s in a 1 month period. This will depend on the season, but assuming that the installation works are taking place in the summer months, the most probable largest value of significant wave height from the data set is 7 meters.

Table 6.2: Operational parameters for vessel type

Vessel	Operation	Significant Wave Height (m)	Reference period
HCV	Loading Suction Anchors to vessel	Weather unrestricted	3h per anchor
	Sailing to/from field	Weather unrestricted	Eq. 6.1
	Cut seafastening and release anchor on deck	3	6h
	Lift-off and lower anchor through splash zone	2	4h
	Lower structure and position anchor on bottom	3	8h
	Set anchor, confirm penetration and disconnect	2.5	6h
	Repositioning at field	Weather unrestricted	1h
AHTS	Loading Mooring System to vessel	Weather unrestricted	0.5h per mooring line
	Sailing to/from field	Weather unrestricted	Eq. 6.1
	Lower mooring end to suction anchor and connect	3	8h
	Pre-lay mooring system at seabed	3	10h
	Repositioning at field	Weather unrestricted	1h
AHTS	Un-mooring at Assembly Site	2	9h
	Towing to location	3	Eq. 6.2
	Hook-up at Wind Farm	2	11h
	Sailing to Assembly Site	Weather unrestricted	Eq. 6.1
	Repositioning at field	Weather unrestricted	1h
CLV	Sailing to Nexans, Halden	Weather unrestricted	24h
	Sailing to/from field	Weather unrestricted	Eq. 6.1
	Load cable onboard at cable manufacturer	Weather unrestricted	6h per 1000 T Cable
	Inter-Array cable installation and trenching	3	16h
	Repositioning at field	Weather unrestricted	1h
MPV	Loading Suction Anchors to vessel	Weather unrestricted	3h per anchor
	Sailing to/from field	Weather unrestricted	Eq. 6.1
	Cut seafastening and release anchor on deck	3	6h
	Lift-off and lower anchor through splash zone	2	4h
	Lower structure and position anchor on bottom	3	8h
	Set anchor, confirm penetration and disconnect	2.5	6h
	Repositioning at field	Weather unrestricted	1h
	Sailing to Nexans, Halden	Weather unrestricted	24h
	Load cable onboard at cable manufacturer	Weather unrestricted	6h per 1000 T Cable
	Inter-Array cable installation and trenching	3	16h
Feeder	Load vessel with suction anchors	Weather unrestricted	3h per anchor
	Sail to/from field	Weather unrestricted	Eq. 6.1
	Cut seafastening and release anchor on deck	3	6h
	Off-loading offshore to HCV	2	12h

6.7 Global variables

The global variables that have been used in the three models are variables that can be accessed in other functions or blocks. The global variables in Fig. 6.15 holds the wind farm size and distance from shore which is set by the user (marked in red). Furthermore, the wind farm size is used to calculate the number of required components. These components are suctions anchors, mooring lines, cable length and number of FOWTs. Additionally, some of the variables controls the number of installed components, which again controls when vessels are mobilised or demobilised. The current time and forecasted weather are also distributed globally, which is again used in blocks.

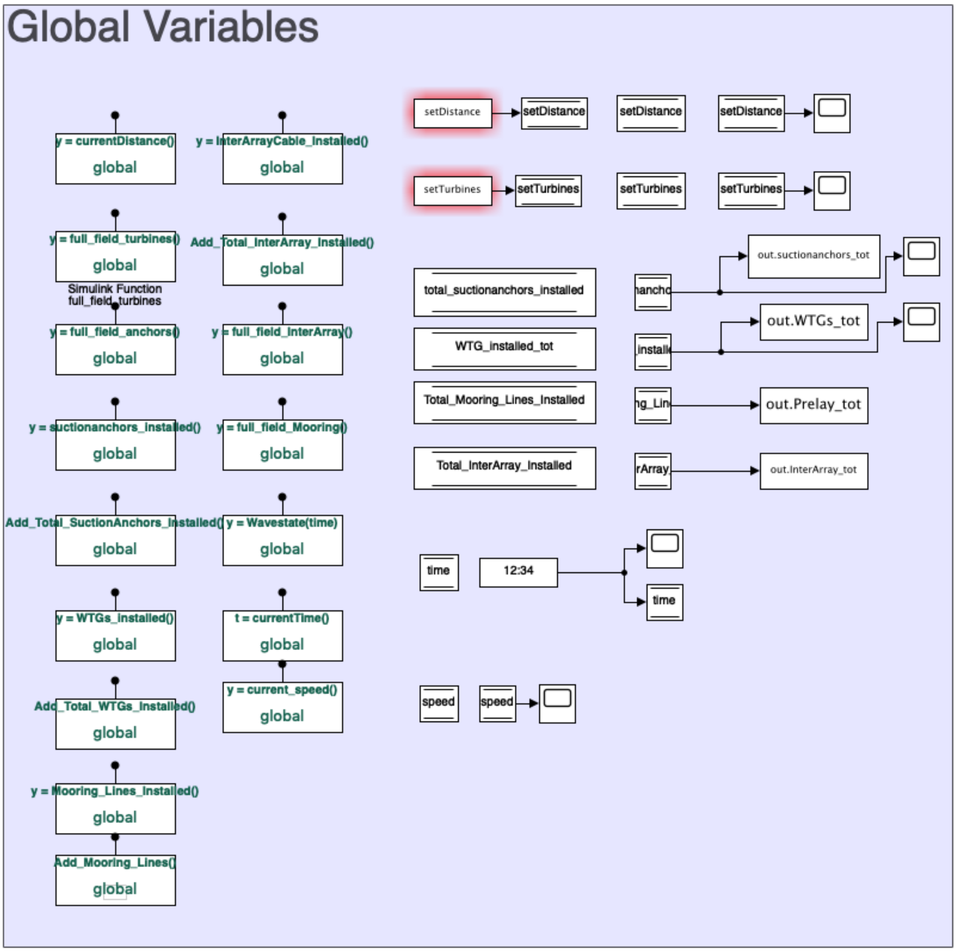


Figure 6.15: Global variables in simulation model

6.8 Model Output

The KPIs that are used for evaluating the different concepts are listed in Eq. 6.5-6.7. The utilization indicates the average time a block is occupied. The utilization is calculated for each entity departure event by the ratio of the total wait time, w_j to the server capacity, C, multiplied with the total simulation time, t_f. The utilization KPI gives answer to how the vessels are used.

$$Utilization = \frac{\sum_{j=1}^{n} w_j}{C * t_f} \tag{6.5}$$

The average wait, w, is the ratio of the simulated time that an entity is within a block, w_j, divided by their total number, n. This parameter is important for finding the time the vessels are waiting on weather.

$$w = \frac{\sum_{j=1}^{n} w_j}{n} \tag{6.6}$$

The vessel cost is calculated by Eq. 6.7, and the day rate for each vessel is found in Tab. 6.3. The day rate estimation is based on the methodology presented in Sec. 4.4. The reference vessels that has been used are listed in Appx. C.

$$Vessel\ cost = \sum_{v} (Days)_v * (Day\ rate)_v \tag{6.7}$$

Table 6.3: Charter rate estimation for vessels in simulation study

Vessel	Year built	CAPEX (NOK MM)	Daily Rates (NOK)
Large AHTS	2009	750	400,000
Small AHTS	2010	400	200,000
MPV	2008	1000	500,000
HCV	2016	1000	500,000
CLV	2007	600	300,000
Feeder	2012	300	150,000

Chapter 7

Results and Discussion

In this chapter, the results from the simulation study will be presented. The first objective is to explore how the conventional fleet behaves by increasing the wind farm size and the distance from shore. The second objective of the simulation study is to investigate potential cost reduction by introducing new installation concepts of floating offshore wind farms, and to see the effect of innovative developments in the installation works. The simulation results will be presented first, before discussing the overall objectives of the master's thesis.

7.1 Results

7.1.1 Conventional fleet

The installation works are heavily dependent on weather, which is shown in Fig. 7.1.

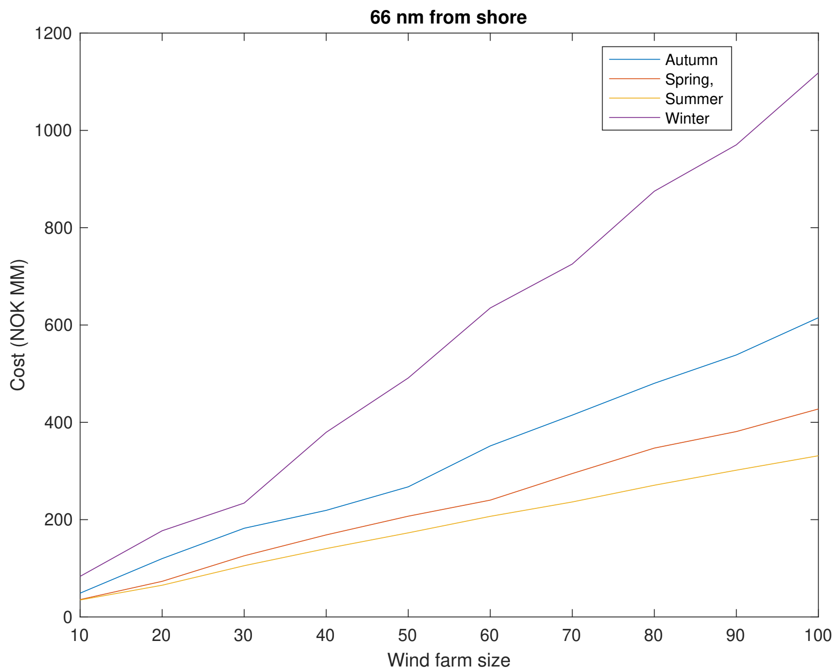


Figure 7.1: Season dependency on total cost for conventional fleet

As a result of the operability being higher in the summer months, the rest of the simulation analysis are based on data from these months. The summer months include June, July and August. The recorded data was based on 11 years of weather data, which were brought into a Markov Chain, which were discussed in Sec. 4.2. Fig. 7.2 shows that suction anchor installation together with towing and hook-up, are the most costly operations.

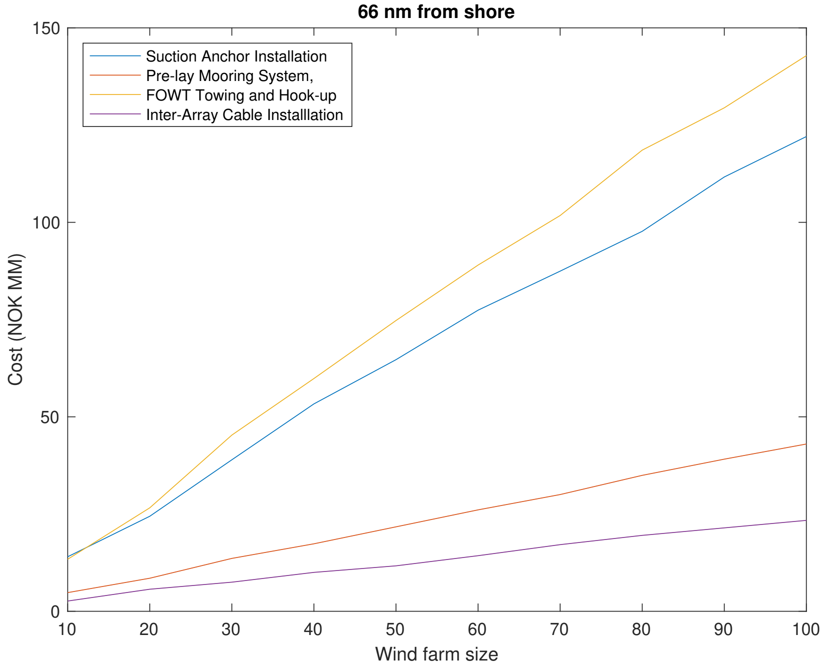


Figure 7.2: Cost for the different type of operations

Which could be explained by the length of the operations and being most dependent on weather, which is shown in Fig. 7.3.

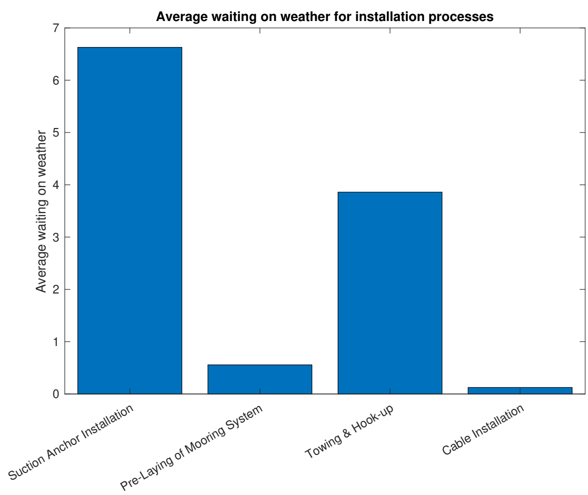


Figure 7.3: Average waiting on weather (hours) for installation processes

Fig. 7.4 shows that the towing and hook-up operation is heavily dependent on the distance from shore. The distance from shore has a minor influence on the cable laying and pre-laying of mooring system, while it has a moderate influence on the suction anchor installation.

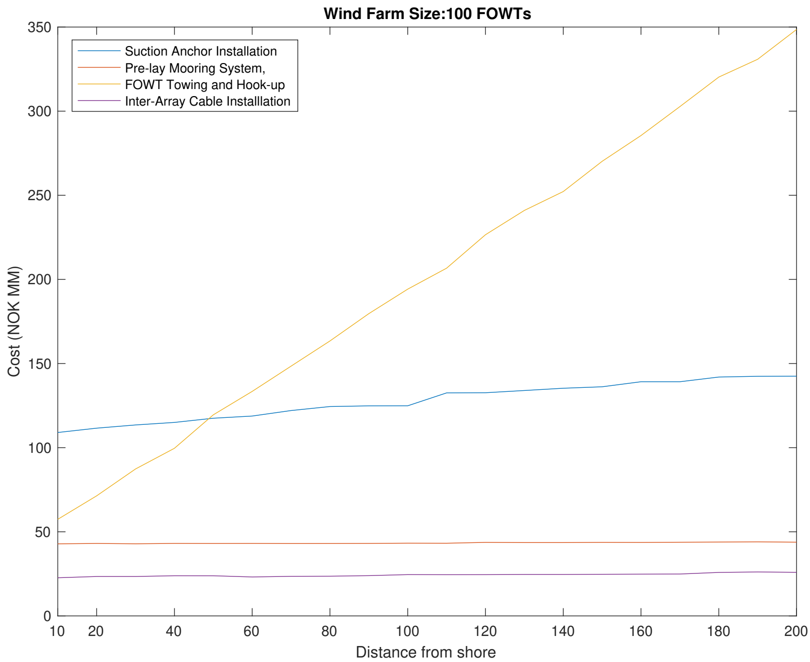


Figure 7.4: Cost influence of distance from shore for conventional fleet

7.1.2 Comparison of fleet concepts

A given set of scenarios with varying wind farm size and distance from shore were derived in Ch. 5. The results of the scenarios are shown in Tab. 7.1. The duration is given in days.

Table 7.1: Results for simulation study of scenarios

FOWF	Scenario	Suction Anchor Duration	Pre-lay Mooring duration	Towing and Hook-up duration	Inter-Array Duration	MPV duration	Feeder Duration	Cost (NOK MM)
66 nm (100 FOWTs)	S1	245	215	178	78			331.3
66 nm (50 FOWTs)	S2	130	109	94	39			173.7
66 nm (25 FOWTs)	S3	69	56	49	23			91.8
132 nm (100 FOWTs)	S4	268	218	301	81			442.7
132 nm (50 FOWTs)	S5	140	109	151	43			225.5
132 nm (25 FOWTs)	S6	75	56	80	22			119.3
66 nm (100 FOWTs)	S7		216	183		316		347.6
66 nm (50 FOWTs)	S8		108	92		164		177.2
66 nm (25 FOWTs)	S9		56	49		84		92.4
132 nm (100 FOWTs)	S10		220	300		347		457.5
132 nm (50 FOWTs)	S11		109	153		181		234.7
132 nm (25 FOWTs)	S12		56	79		96		122.4
66 nm (100 FOWTs)	S13	215	217	181	78		215	351.3
66 nm (50 FOWTs)	S14	114	109	94	39		114	182.8
66 nm (25 FOWTs)	S15	54	56	48	25		54	92.2
132 nm (100 FOWTs)	S16	215	219	300	83		215	448.4
132 nm (50 FOWTs)	S17	114	109	156	43		114	233.6
132 nm (25 FOWTs)	S18	54	56	80	22		54	116.9

The conventional fleet outperforms the MPV fleet concept in terms of cost. The total installation time decreases with the MPV, but the total vessel cost increases as the MPV is a more expensive vessel for the cable laying operation. The feeder concept outperforms the conventional fleet with a distance from shore of 132 nm and wind farm size of 25, but not for 50 and 100 FOWTS. It is not clear that the feeder concept is better than the conventional fleet for the given scenarios, since other operations in the model influence the total cost. But at one point, the feeder concept is a better solution. This is shown in Fig. 7.5. The break-even point for a wind farm of 100 FOWTs is approximately 175 nm from shore.

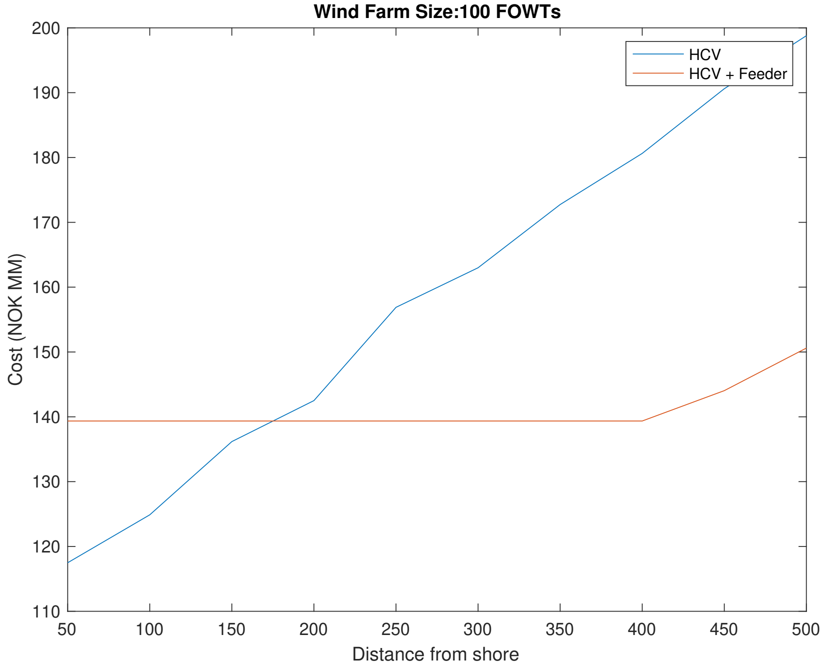


Figure 7.5: Cost influence of distance from shore for feeder concept and conventional fleet

The utilization of the HCV increases at the field by introducing a feeder vessel, shown in Fig. 7.6.

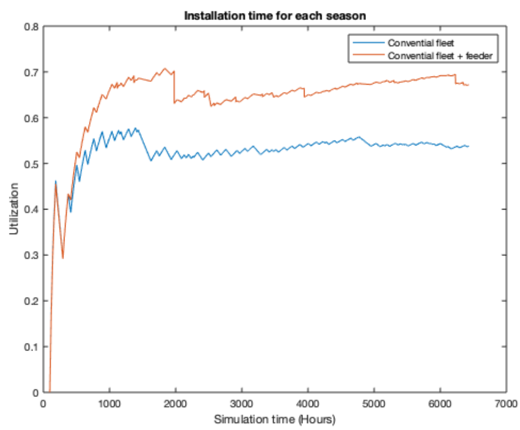


Figure 7.6: Comparison of utilization between conventional fleet and conventional fleet with feeder

The installation cost of 100 FOWTs in Fig. 7.5 is constant until the distance is equal to

400 nm. This is explained by the waiting time at the farm for the feeder vessel, shown in Fig. 7.7. The feeder vessel has a low utilization. In a real-world process, the feeder vessel would wait at the port before being noticed by the construction vessel to supply more anchors. This assumption does not affect the total cost, since the vessel is already chartered. At 400 nm, the construction vessel waits on the feeder vessel, and it will delay the total installation time. It could then be beneficial to introduce two feeder vessels.

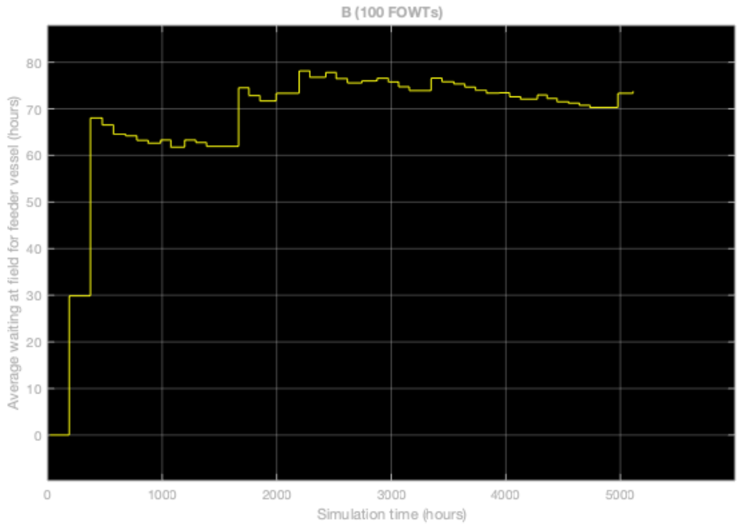


Figure 7.7: Average wait at wind farm for feeder vessel 132 nm from shore

7.1.3 Effect of innovative developments

The simulation model could also be used for exploring the impact of innovative developments in the installation of a floating offshore wind farm. Fig. 7.8 shows how the operational limit affects the total installation costs for the different processes.

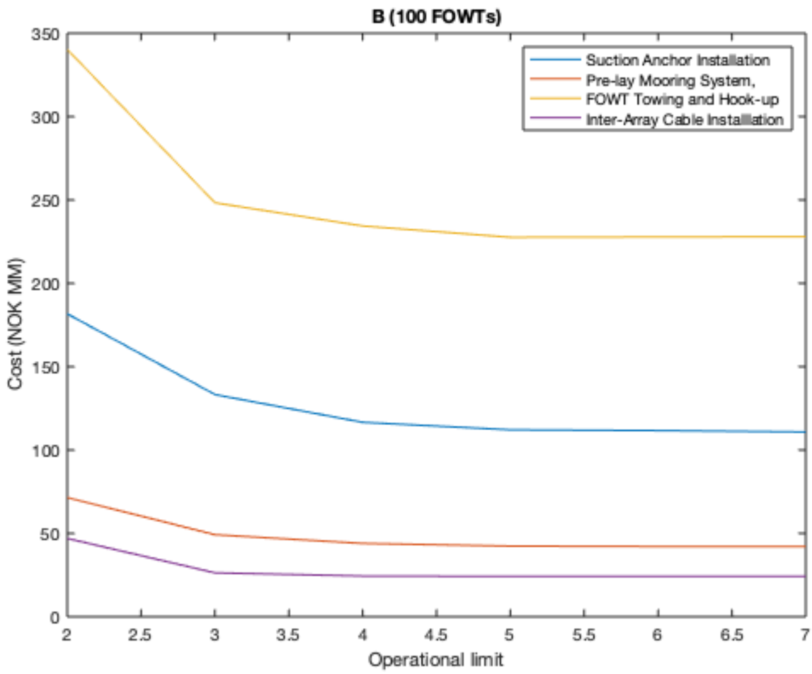


Figure 7.8: Influence of operational limit on total installation cost for processes

Fig. 7.9 shows how the cost is reduced by increasing the number of towed FOWTs per round trip. The calculations does not consider the increased CAPEX involved with towing more objects.

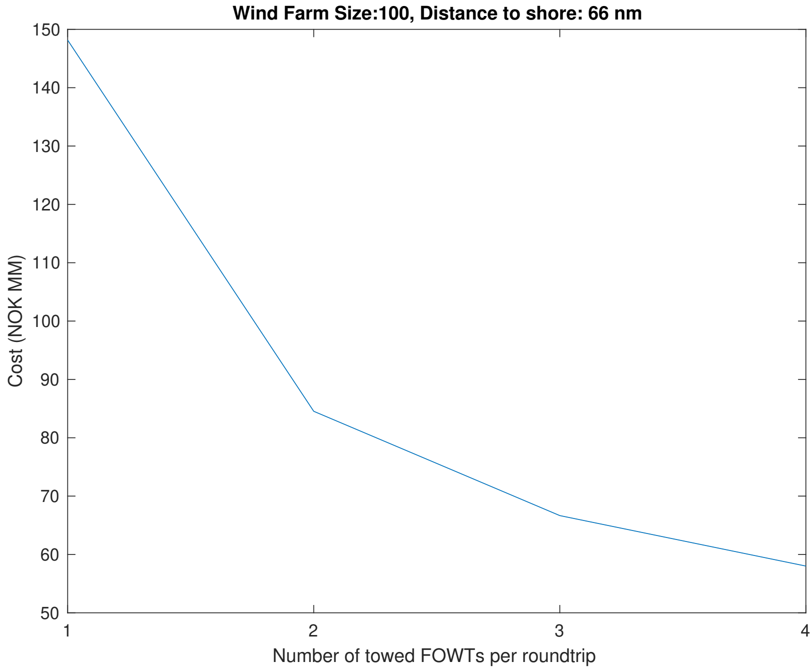


Figure 7.9: Towing & Hook-up cost versus number of towed FOWTs per round trip

7.2 Discussion

7.2.1 Conventional Fleet

The results shows that the towing and hook-up operation and suction anchor installation are most dependent on weather and have the highest contribution to the total cost. These operations should be targeted for developing a better solution. The operations are restricted by the operation itself, and not by the vessels. Employing vessels with increased operating capacity has no effect.

The conventional fleet that has been used in Hywind Scotland can perform better if the capacities of the vessel is larger. Increasing the capacities for these vessel could reduce installation cost in the long run. The CAPEX will be larger, but could be defended by long-term contracts. If there is a desire for large market shares in the floating offshore wind industry, new vessels needs to be built, and it is therefore recommended to increase the vessel size. The utilization of installation vessels will increase if the number of transportation legs are reduced. The floating offshore wind industry is to this date highly subsidised by the government. Going commercial, means that the wind farm will increase to a number between 50-100 FOWTs. Going from low-scale to those numbers, the easiest way to reduce cost is by cutting down the amount of transportation legs and increase the operability of the marine operations.

The installation activities needs to be scheduled over the summer months of 2-3 years in order to decrease the cost implied by the weather. The number of chartered vessels are a trade-off between lost revuene from the FOWTs and the intensity of the installation activities. The wind farm could be installed in bulks of 25 FOWTs per season, and be directly connected to the onshore grid. The lost revenue is then reduced together with the installation costs. Development of new solutions that leads to a higher operational limit will also reduce the installation costs, as shown in Fig. 7.8. This is found to be most critical for suction anchor installation, towing and hook-up. Furthermore, bringing more FOWTs at the same time to the field will reduce cost significantly. This has been looked at in the Hywind Installation Challenge. One of them proposed a frame which could tow 4 FOWTs with substructure to the field. This reduces the number of trips back and forth, and increases the utilization of the AHTS vessels that performs the hook-up.

7.2.2 Multi-Purpose Fleet

Multi-Purpose concepts introduce flexibility in planning. The material flow process and disturbances in the supply chain of offshore wind farms are shown in Fig. 7.10. Disturbances in the supply chain will delay all the processes in the installation of an offshore wind farm, since they are planned partly parallel to each other.

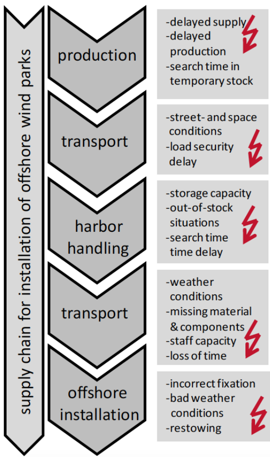


Figure 7.10: Material flow process and disturbances in supply chain for installation of offshore wind farms (Scholz-Reiter et al. 2011)

The simulation model does not consider disturbances in the supply chain, but most of this can be explained by an example. If the production of suction anchors are delayed, this will delay the installation activities of pre-laying of mooring system and the towing and hook-up of FOWTs with the same amount of days. The inter-array cables are not exposed to the same delay, since they could be laid before or after the arrival of the FOWTs. Having a multi-purpose vessel with the ability of installing both suction anchors and inter-array cables removes one vessel that will be impacted by an eventual delay. If the production of anchors is delayed (e.g. five days), it will impose a delay cost of 2.5 million NOK where the vessel is in lay-up. In this case, the order of operations favor a MPV concept with the capabilities of installing both suction anchors and inter-array cables.

One drawback of the simulation model, is that it does not show the advantage of switching operations mode. The simulation model of the MPV concept rather shows that it copes with the conventional fleet. The MPV concept comes close to the conventional fleet with a wind farm size of 25 FOWTs. This is a result of the order of the operations and the short required time for the inter-array cable installation. When the wind farm size increases, it favors the conventional fleet as the chartering cost for the CLV and the HCV are cheaper than the MPV in total. It becomes a trade-off between performance and the value of flexibility in planning.

Offshore wind parks are often delayed, which is shown in Tab. 7.2. All the listed projects have been delayed by months. This is often a result of delays imposed by weather, production logistics and manufacturing. A long term production plan and capacity planning are required and vital in the installation of an offshore wind farm. As mentioned earlier, a disturbance in these lower levels can highly influence the plan, which could lead to fewer days for offshore installation. Vessels has to be rented in advance, and delays would lead to high vessel costs. The MPV is not so sensitive to delays, as it can change operations mode. The utilization of the vessel would also be increased as a result of not being to dependent on delays.

Table 7.2: Data on finished OWFs in Germany (Kostka and Anzinger 2016)

Offshore wind park name	Capacity (MW)	Start of construction	Planned end of construction	Time delay (months)	Planned cost (million €)	Final cost (million €)	Cost overrun (%)
Alpha Ventus	60	August 2007	2009	12	190	250	32
Baltic 1	48	July 2009	2010	6	200	200	0
BARD 1	400	June 2009	2013	24	1500	2900	93
Nordsee Ost	295	July 2012	2013	18	1000	1300	30
Borkum-Riffgat	108	September 2012	2013	6	480	480	0
Global Tech I	400	August 2011	2014	12	1600	1800	13
Meerwind	288	September 2012	2013	18	1200	1300	8
DanTysk	288	December 2012	2014	6	1000	1000	0
					Ø 13		Ø 22

7.2.3 Feeder Vessel Fleet Concept

The results from the simulation study shows the possible cost reductions with introducing feeder vessel concepts when the distance from shore increases. At the time of this report, there are a lot of vessels from the oil and gas industry in lay-up. PSV's can be used as feeder vessels in the installation of a floating offshore wind farm. The chartering cost is low, and could lead to a large reduction in the installation cost for suction anchors. The complication of the feeder concept is the lifting of the components between the two vessels, and are set to be performed in only good weather conditions.

Another interesting concept of the feeder concept, is that components could be transported directly from the production port to the wind farm. This means that the just-in time concept is applied. In the derivation of the simulation scenarios, it was only found feasible to introduce a feeder vessel to the suction anchor installation process. The suction anchors are assumed to be constructed in Stord, Norway, not long from the Utsira Nord field. In other words, this will not lead to a substantial cost reduction for the simulation study. But if, foreign contractors produce the suction anchors, it could be an option. There is a risk involved in using the just-in time principle in case of delays. Having a high capacity of parts in the assembly port, reduces the risk of having delays, but increases the storage cost. Offshore wind farms are placed in areas known for harsh weather conditions, as it produce energy from wind. On days with good weather, the installation activities are speeded up. It is therefore vital to have enough components to install. The installation cost imposed by waiting on components could therefore be assumed to be higher than the storage cost. For this case, the just-in time principle is not found efficient in the installation of FOWTs.

Chapter 8

Conclusion

A discrete-event simulation study was applied to the supply chain for installation of an floating offshore wind farm. A House of Quality matrix identified the connection between functional requirements and equipment. Furthermore, the relationship between equipment was found, and was brought into a Design Structure Matrix in order to derive different fleet compositions. The following fleet compositions were found: conventional fleet, fleet with multi-purpose vessel and the feeder vessel fleet concept.

The installation activities were found to be highly dependent on the weather conditions. Installation during the summer months gives a higher operability compared to the other seasons. The towing and hook-up operation and suction anchor installation are most dependent on weather, and have the highest contribution to the total cost. These operations should be targeted for developing a better solution. The operations are found to be restricted by the operation itself, and not by the vessels. Employing vessels with increased operating capacity has no effect.

Introducing a feeder vessel to the suction anchor installation is beneficial when the distance from shore increases. The utilization of the installation vessel increases and it highlights the importance of not using high-charter cost vessels for sailing back and forth from the wind farm. The multi-purpose vessel proves to be more expensive than the conventional fleet in total, but introduce flexibility in planning which is considered valuable after investigating previous installation projects of offshore wind farms.

The simulation study also explored the effect of innovative developments in the installation of floating offshore wind farms. Finding new solutions which leads to a higher operational limit, proves to be beneficial in terms of cost. Furthermore, introducing a vessel which has the capability of towing more than one FOWT per round trip is found to reduce the installation cost. For the operations that could not be fed by a feeder vessel, it is recommended to increase the capacities of the vessels in order to reduce the amount of transport legs between the assembly port and the offshore wind farm.

8.1 Further Work

Simulation models are time-consuming to build. The detail of the simulation model is proportional with time, but the simulation models provided in this thesis, gives answer to what is important for the installation logistics. The model works as a decision support tool for field developers, but for further work it is recommended to include the production logistics together with inventory management to give a better overall representation.

The effect of learning curves is not implemented in this study. Learning curves shows the decline in cost as more experience is gained. Furthermore, a penalty cost which accounts for the loss of revenue could be added to the model. The loss of revenue could be used as a factor for deciding the intensity of the installation works. In other words, this would account for the fleet size.

Discrete-event simulation provide suitable tools for assessing the impact of decisions on the installation process. The thesis is based on evaluations of different configurations. To determine the optimal schedule or configuration, optimization methods has to be applied. This can be done either by mathematical optimization or simulation-based optimization. For further work, it is recommended to apply metaheuristics together with the provided discrete-event simulation models to optimize fleet size and mix.

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Appendix A

Markov chain Simulation of Weather

A.1 Read weather data from variable in NetCDF data

```
%Script retrieved from the course Ocean System Simulation and adapted to
%fit project. The code reads weather data from variable in NetCDF data
%source retrieved from ERA5 database and writes to excel file
clear;
clc;

map=worldmap([50 75],[-5 25]);
geoshow('landareas.shp', 'FaceColor', [0.0 0.5 0.5])


vardata=ncread('HavardMai20Hs.nc','swh');
lat=double(ncread('HavardMai20Hs.nc','latitude'));
lon=double(ncread('HavardMai20Hs.nc','longitude'));

LAT=[];
for i=1:length(lon)
    LAT=[LAT; lat];
end

LON=[];
for j=1:length(lon)
    for i=1:length(lat)
```

```
        LON=[LON; lon(j)];
    end
end

VD=[];
for i=1:length(vardata(:,1,1))
    VD=[VD; vardata(i,:,1)'];
end


scatterm(LAT,LON,10,VD);

%Making a excel document with the weather data from the
    wanted position
%latitude: 59.5    longitude: 4.5

Vektor = squeeze(vardata(1,1,:));

t1 = datetime(2009,1,1,1,0,0);
t2 = datetime(2019,12,31,24,0,0);
B = t1:t2;
t = B.';



writematrix(Vektor,'Hsdata2009-2019.xlsx')
```

A.2 Markov chain simulation - Significant Wave Height

```
%Script retrieved from the course Ocean System Simulation
    and adapted to
%fit project.
clear all
tic;

SortHsdata;

length_series = size(M,1);

weatherseason = 2;

if weatherseason == 1
    season = [1 2 12];
elseif weatherseason == 2
    season = [3 4 5];
elseif weatherseason == 3
```

```
    season = [6 7 8];
else weatherseason == 4
    season = [9 10 11];
end

Hs = zeros(1);
count = 1;
for i =1:3
    for j = 1:length_series
        if M(j,2) == season(i)
            Hs(count,1) = M(j,5);
            count = count + 1;
        end
    end
end


ul = max(Hs);

ul_rounded = round(ul);

numStates = ul_rounded;

% Find upper limit for Hs values and divide the values into
    even bins

% Find state ranges - first state [0,stateRange] and so on
stateRange = ul_rounded / numStates;
% State values - stateRange, 2xstateRange and so on up til
    ul
stateValues = stateRange:stateRange:ul_rounded;
% Initialize 1D-matrix holding the state of each data point
HsState = zeros(length(Hs),1);

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

```
                break;
            end
        end
    end


for i=1:length(HsState)
    if HsState(i)<=0
        HsState(i)=HsState(i-1);
    end
end


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

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

% Check to see if there are any absorbing states
% i.e. P(i,j) == 1 where i=j
absorbstate = zeros(numStates);
for i = 1:numStates
    for j = 1:numStates
        if P(i,j) == 1
            absorbstate(i,j) = absorbstate(i,j) + 1;
        end
    end
end
if sum(sum(absorbstate)) >= 1
    error('Absorbing states. Stopping. Consider reducing number of states or check data.');
end

```

```matlab


numReplications = 60000; %10000 orginally

rng(12345);

% Setting of starting state - sample randomly
state = randi(numStates);

states = zeros(numReplications,1);

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

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

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

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

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



toc;
```

Appendix B

Simulation models

B.1 Run simulation model

```
%Script for running simulationmodel and finding chartering period for
%vessels. The chartering period is printed to excel sheet, which makes gant
%chart.
clear all
clc
tic;

load('summer.mat'); %Pick Season
run = 1;

for i=10:10:100 % Set the wind farm size
    for j=66 % Set the distance from shore

            windfarmsize = i;
            distancefromshore = j;

            setDistance = [0 0 ; 0 distancefromshore];
            setTurbines =[0 0; 0 windfarmsize];

            load_system('Fleet1'); %Pick between fleet 1, 2 or 3.
            Output=sim('Fleet1');

hh1=find(Output.CVend.signals.values==1);
step1 = hh1(1);
```

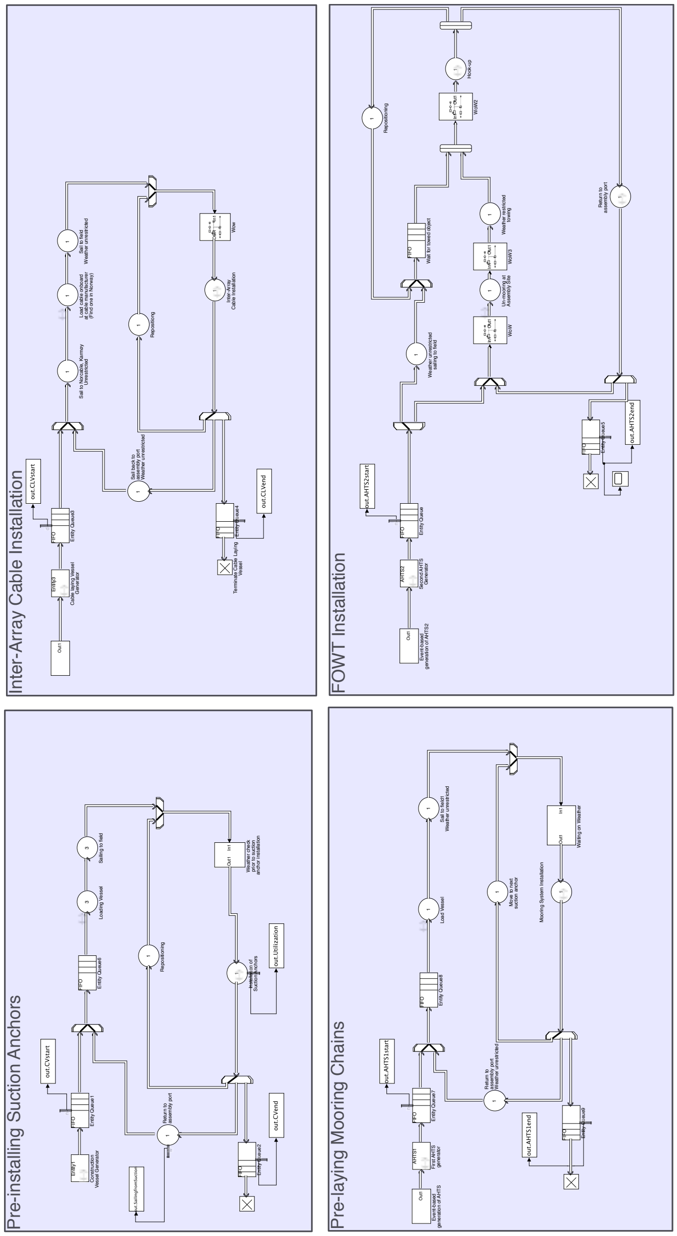
```
CVend= Output.CVend.time(step1)/24;
results_CVend1(run,1)=CVend;

hh2=find(Output.AHTS1start.signals.values==1);
step2 = hh2(1);
AHTS1start= Output.AHTS1start.time(step2)/24;
results_AHTS1start1(run,1)=AHTS1start;

hh3 =find(Output.AHTS1end.signals.values==1);
step3 = hh3(1);
AHTS1end=Output.AHTS1end.time(step3)/24;
results_AHTS1end1(run,1)=AHTS1end;

AHTSlength = AHTS1end - AHTS1start;

hh4=find(Output.CLVstart.signals.values==1);
step4 = hh4(1);
CLVstart=Output.CLVstart.time(step4)/24;
results_CLVstart1(run,1)=CLVstart;

hh5=find(Output.CLVend.signals.values==1);
step5 = hh5(1);
CLVend=Output.CLVend.time(step5)/24;
results_CLVend1(run,1)=CLVend;

CLVlength= CLVend - CLVstart;

hh6=find(Output.AHTS2start.signals.values==1);
step6 = hh6(1);
AHTS2start = Output.AHTS2start.time(step6)/24;
results_AHTS2start1(run,1)=AHTS2start;


hh7=find(Output.AHTS2end.signals.values==1);
step7 = hh7(1);
AHTS2end = Output.AHTS2end.time(step7)/24;
results_AHTS2end1(run,1)=AHTS2end;

AHTS2length = AHTS2end - AHTS2start;

hh8 =find(Output.Utilization.signals.values);
step8 = hh8(1);
Utilization = Output.Utilization.time(step8);

gantchart = [0,CVend;
```

```
                AHTS1start,AHTS1end;
                AHTS2start,AHTS2end;
                CLVstart,CLVend];

writematrix(gantchart,'gantchart.xlsx','Sheet',1,'Range','
    B2:C5')

            run = run + 1;
    end
end

toc;
```

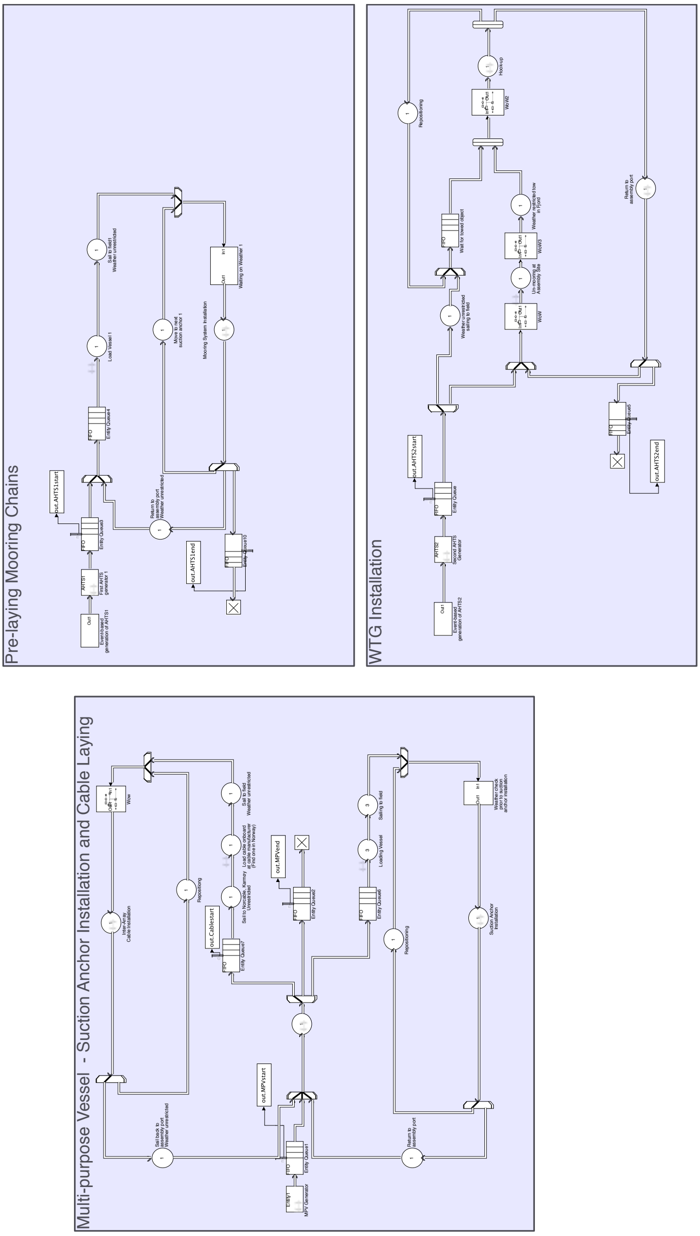
B.2 Input for towing and hook-up cycle

Type	Speed	Towing speed	Nr	FOWT capacity	Output port
1	10	3	0	1	1
1	10	3	0	1	1
2	12	3	0	1	1

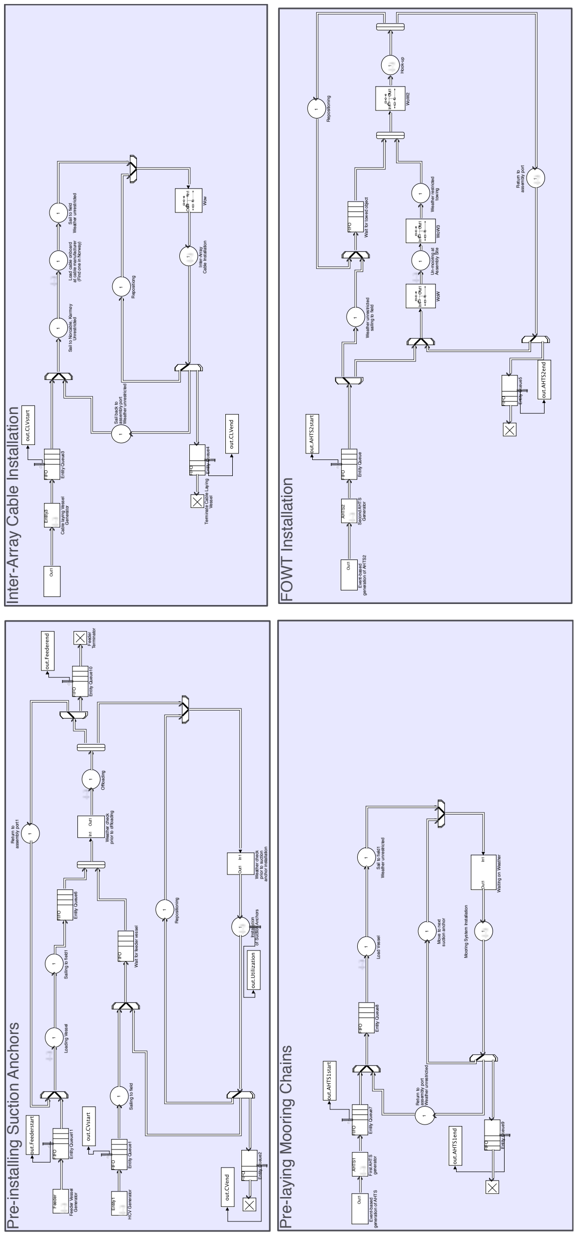
B.3 Fleet 1 - Conventional Fleet



B.4 Fleet 2 - Fleet with Multi-purpose Vessel



B.5 Fleet 3 - Feeder Vessel Fleet Concept



Appendix C

Reference Vessels

Table C.1: Reference Vessel: Large AHTS

Capacities	
Overall length	109.5m
Length between pp.	98m
Breadth	24m
Depth	9.8m
Draft	7.8m
Towing Drum	500 T
Anchor Handling Drum	500 T
Main crane	15 t 15 m
Main Deck Area	1,070 m2
Chain locker	1,190 m3
Maximum speed	18 knots
Economic transit speed	12 knots
Power	15,360 kW
Bollard pull	350 t

Table C.2: Reference Vessel: Small AHTS

Capacities	
Overall length	87.4m
Length between pp.	75.5m
Breadth	21m
Depth	9.3m
Draft	7.3m
Towing Drum	625 T
Anchor Handling Drum	420 T
Main crane	N/A
Main Deck Area	755 m2
Chain locker	664 m3
Maximum speed	17 knots
Economic transit speed	10 knots
Power	9,000 kW
Bollard pull	251 t

Table C.3: Reference Vessel: CLV

Capacities	
Overall length	123m
Breadth	27.5m
Depth	9m
Draft	5.8m
Cable carousel	5000 T
Dynamic Positioning System	DP Class 2
Main crane	100 tons
Main Deck Area	755 m2
Chain locker	664 m3
Speed	12.4 knots
Power	10,9480 kW
Accommodation	90 persons

Table C.4: Reference Vessel: HCV

Capacities	
Overall length	157m
Length between pp.	138m
Breadth	27m
Depth	12m
Draft	6.5m
Dynamic Positioning System	DP Class 3
Main crane	400 tons at 11m
Deck Area	1700 m2
Active heave compensation	
Maximum speed	16.5 knots
Power	20,200 kW
Accommodation	140 persons
ROV	2 x 3,000m Work Class
	1 x 1,500m Observation Class

Table C.5: Reference Vessel: MPV 1

Capacities	
Overall length	157m
Breadth	27m
Depth	12m
Draft	7m
Dynamic Positioning System	DP Class 3
Main crane	400 tons at 11m
Deck Area	1700 m2
Active heave compensation	
Maximum speed	15 knots
Power	19,300 kW
Accommodation	140 persons
ROV	2 x 3,000m Work Class
Cable carousel	5000 T

Table C.6: Reference Vessel: Feeder Vessel

Capacities	
Overall length	205m
Breadth	42.5m
Depth	12m
Draft	9m
Max deck load	30mt per m2
Deck Area	5,400 m2
DWT	35,000 T
Speed	13 knots
Power	14,000 kW
Accommodation	39 persons

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