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MASTER THESIS

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Abstract

For the planning stage in any wind farm development, there are many concepts and locations to be analyzed at the point of cost, schedule, and project shareholders. Especially, the marine operation requires careful planning for an offshore wind farm. The reasonable numerical analysis can reduce costs and support decision-making properly to assess uncertainties from the project schedule or offshore installation method. Additionally, in the offshore project, environmental factors such as wave, wind, and currents are associated with uncertainty. In other words, the same project scope can make different results based on the field location. An increasing number of wind farms will be developed in the future, with the complexity of marine operations and correct decisions before a final investment decision.

The objective of this thesis is to assess the uncertainty band of expected total duration for offshore installation, based on a specific parameter from hindcast data with operational limits derived from numerical modeling or previous work. The specific parameter will be developed from H_S with a weather window based on the lowest operational limit. Used randomly-chosen locations in the North Sea, simulation can be carried out to determine the weather window parameter of H_S to total offshore duration for the development field. Hindcast data from randomly-chosen locations affect the reduction of the simulated model as increasing sample data.

Parameterizing hindcast data to estimate a total duration for offshore installation can be utilized to assess the validity of the installation method and total offshore campaign with the nameplate of a wind farm under specific environmental conditions. Through this, the suitable environmental conditions and its uncertainty band of offshore duration can be identified easily. Because the offshore duration can be directly connected to the chart period of the installation vessel or other equipment, this parameterization can be a baseline to estimate the cost.

Keywords: offshore wind farm, Uncertainties, weather window analysis, metocean modeling, time-domain simulation, extreme value method, project planning, parameterization

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I would like to express my gratitude and respect to my family, wife, Heejung, son, Kanghyeon, and daughter, Seohyeon, for enabling me to successfully complete this master's thesis. Mostly, I want to express my sincere heart to my love, Heejung, believing, and supporting me perpetually, regardless of any danger and difficulty.

Finally, I would like to present this thesis in memory of my father in heaven now.

Table of Contents

List of Figures

List of Tables

List of Acronym

ALARP	As low as reasonably practicable
BOP	Balance of plant: all infrastructure and facilities of a windfarm except the turbine
CDF	Cumulative distribution functions
Capex	Capital Expenditure
DNV GL	Det Norske Veritas and Germanischer Lloyd
DAF	Dynamic amplification factor
FEED	Front End Engineering Design
LCOE	Levelized cost of energy
Metocean	Meteorology and physical oceanography
MC	Monte Carlos simulation
NORA10	Norwegian hindcast database for wind and waves with 10km resolution (1957 – Present)
TLP	Tension leg platform
GEV	A general extreme value model
WT	Wind turbine
WTIV	Wind turbine installation vessel
WSP100	Average wind speed at 100m height

List of Notations

A	swept area (m^2)
C_p	Power coefficient
H_s	Significant wave height (m)
T_p	Peak wave period (s)
T_p^*	Original peak wave period (s) in NORA10
A	Alpha factor
ρ	Air density (kg/m3)
T_R	Reference period
T_{POP}	Planned operation period
T_C	Contingency period
P	Power output
U_r	Average wind speed at the reference height
Z_r	reference height

Chapter 1. Introduction

This chapter provides the background and direction of the thesis. Nowadays, the world can show the general trend of the energy transition from fossil to renewable, and the necessity of offshore wind is rising due to the prevention of global warming. For the energy transition and net-zero emission, there are many options to achieve this purpose. However, wind power is focused as the primary option and started to flourish in the prospective future with a lesson learned from the oil and gas industry. To meet the trend of the energy transition, the wind power industry needs to reduce the cost to keep this bright future. This thesis will research the parameterization of hindcast data to optimize offshore wind installation and the uncertainty band of offshore installation during the planning stage to support the project decision among many development options quickly.

1.1. Motivation

In 2020, we had many historical events that the world has never faced after 2000, for example, COVID-19, an increase of green-house gas, and minus oil price in April 2020. Regardless of these unfavorable events, the energy sector has proposed a new vision of the net-zero emission strategy leading by significant energy companies and most European countries. British Petroleum has primarily supported the new vision by its expectation of global energy demand and a substantial change in primary energy sources described in their outlook. In Figure 1-1, renewable energy can have a maximum of 60% share in primary energy sources; meanwhile, traditional hydrocarbon energy has 20% in global energy sources in energy outlook 2020 BP (2020, p. 64).

As another excellent example of the importance of the wind power industry to the energy transition, the Aker group, one of the world's biggest energy companies, changed their business portfolio by using the Aker solution.

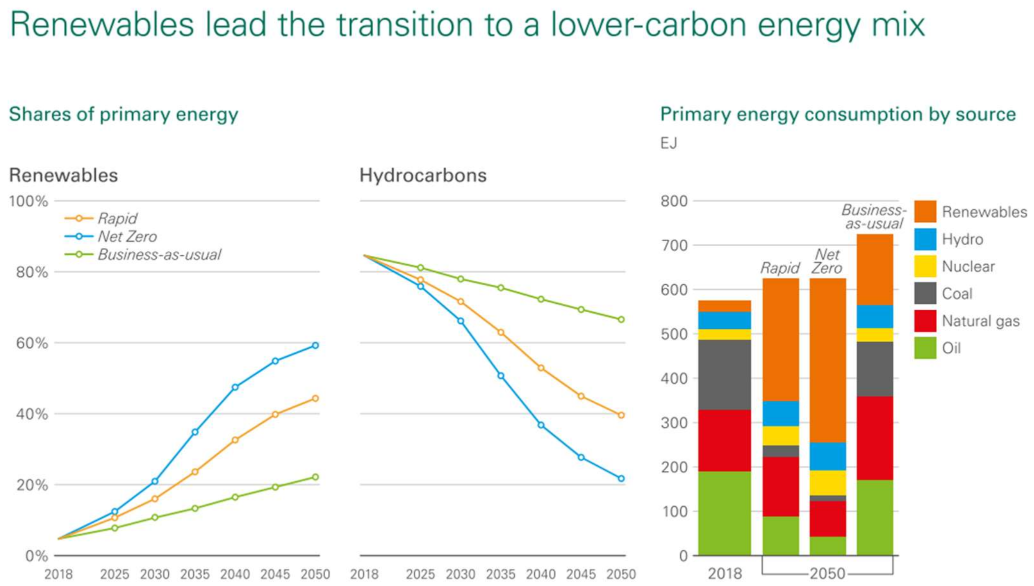

Figure 1-1: Shares of primary energy (BP 2020 energy outlook)

One of the innovational energy service providers, Aker solution, came out with a long-term energy transition strategy and spin-off into Aker offshore wind and Aker Carbon Capture (Aker solution, 2020). This spin-off's remarkable point is that offshore wind can be the most significant renewable energy source, with renewable expectations constitute 60% by 2050 and 25% for offshore wind energy among this, 60% (Aker Offshore Wind, 2020).

Based on the dominant trend of the energy transition, the role of offshore wind energy is getting critical to achieving the net-zero goal in 2050. Because of this, the expectation of the cumulative installed capacity for offshore wind farms increases exponentially in Figure 1-2. Almost 80% of the cumulative installed capacity expected in 2050 is forecasted to be operated after 2030. it means to open the era of wind farms with the economy of the volume from 2030 significantly.

However, the offshore wind industry has faced challenges to reduce LCOE, the Levelized cost of energy, and the longer remoteness of wind farm locations from onshore. Offshore wind installation has 30% of CAPEX's total cost (Paterson, 2019), except material and equipment costs such as wind turbine, the balance of plant including foundation. This installation can be a competitive area to ensure the wind's future as a source of energy.

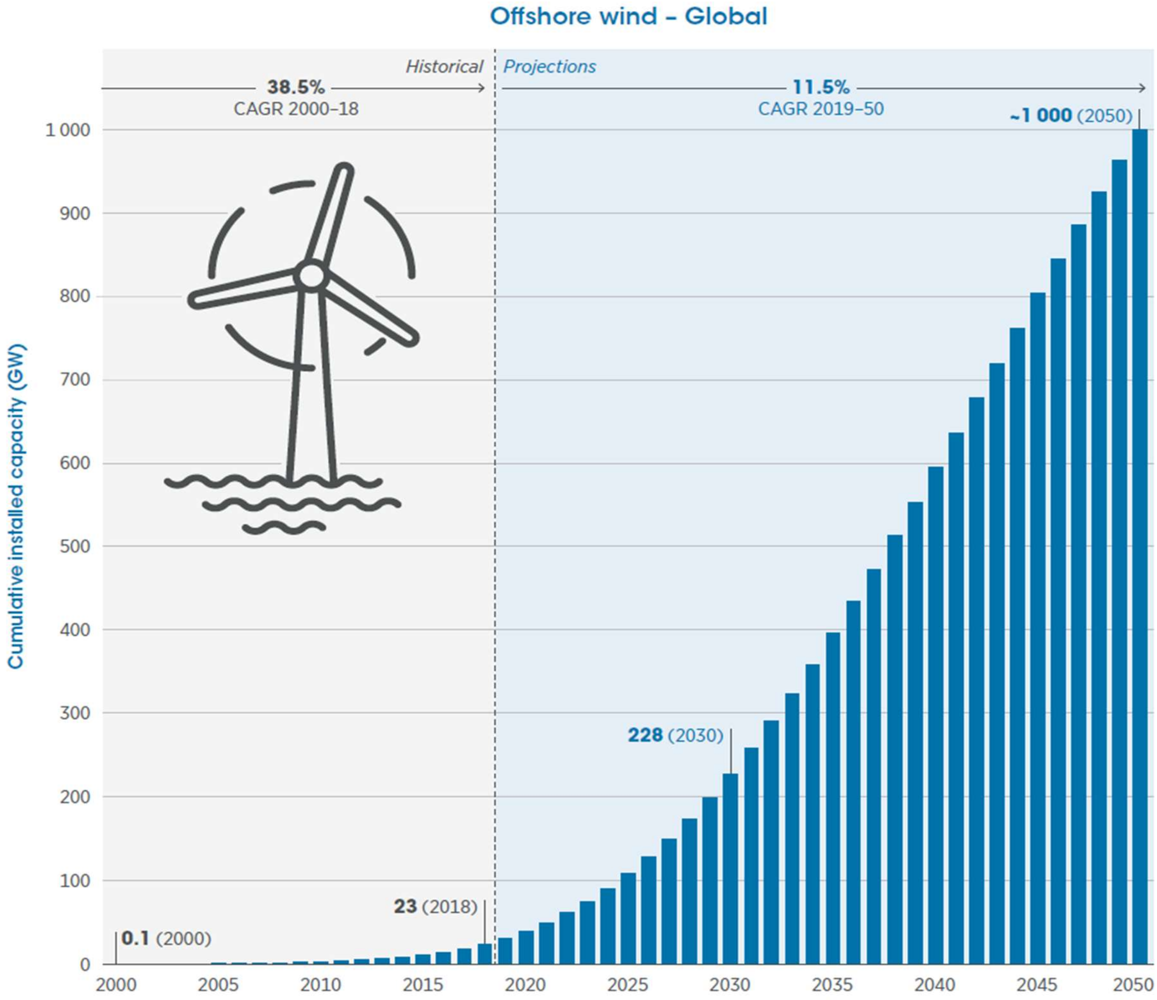

Figure 1-2: Cumulative offshore wind installation from 2000 to 2050 (IRENA, 2019)

Marine operation is vital throughout all life cycle in wind farm development. There are high-accuracy weather window analysis and the reduction of the uncertainty associated with the offshore installation, which can extend the construction schedule and cost in successful marine operation.

This thesis considers the method to assess the uncertainty band of the total duration in the offshore installation with operational limit and environmental factors using many fields' hindcast data. It can prevent the additional cost and repeated trials to find out the optimized solution.

1.2. **Research objective and outline**

The purpose of this research is to develop parameters from the hindcast data to assess the offshore wind farm installation's uncertainty band in the offshore wind's planning stage with ± 30% accuracy. In concept study or the planning stage of the project, it is hard to specify the top priority risks to be applied because its project has each specific environment. Furthermore, there are many options to be analyzed from an economic or schedule point of view during the beginning stage of the project. To assess model uncertainty of the project development schedule rapidly can be valuable to support the management decision for the project initiation during the planning stage and save unnecessary time and effort. Since the planning stage period is relatively shorter than other stages in a project, estimating the uncertainty and allowance of the cost and the schedule needs to be faster. Using hindcast data of the different locations in the North Sea, the maximum project installation duration in the targeted area can be estimated based on the relationship between parameters derived from weather window analysis and forecasted project duration.

Here is detailed area to be analyzed

1. The spectral peak period (T_P) will be analyzed as operational criteria to estimate the project duration, rather than wind speed by floating installation vessel.

2. Define and analyze the optimized method for wind turbine based on the project characteristics

3. Develop the methodology to decide optimized parameters from hindcast data to estimate total duration using different locations during the project permitting period.

4. Define parameterization, the relationship between an optimized parameter in terms of environmental conditions and project duration in the offshore wind turbine installation and foundation.

1.3. **Literature review**

A few articles or master thesis in the literature review analyze or simulate offshore wind installation schedule to optimize duration or cost. Some of them are focusing on the optimization of planning in submarine cable work and logistics optimization. Many different approaches are used, and uncertainties are also analyzed.

There are many approaches to defining the offshore installation sequence to optimize the offshore wind installation plan. The article by Yohannes presents the method to improve the installation of a wind farm with discrete event simulation (Muhabie, 2018). Discrete event simulation has the concern of only time-related activities into consideration. This simulation approach is suitable to analyze the environmental data because each time of an event can be compared with each time of the change of significant wave height. However, it is hard to define the relationship between activities.

According to the wave and wind speed data per month, the variance of the result can be represented as a standard deviation in the article. Another point of view in hindcast data is the probabilistic approach. The probability distribution over the year hindcast data from the time window of two hours with Hs less than 0.75m and wind speed less than ten m/s compared with the historical data. This distribution is related to workability and time window parameters. Moreover, non-workability can be shown as waiting time in each activity in commercial planning software such as MS Project and Primavera.

Another research to evaluate the offshore installation in a wind farm, related to operability, presents the stochastic parameters using a discrete event simulation approach (Muhabie, 2018). Authors present the discrete-event simulation model with a metocean model, and there are seven main areas of simulation input: installation strategies, assembly processes, manufacturing constraints, resources, the discrete-event simulation, environmental conditions, and operability of resources. Installation methods mentioned in this article are similar to single-lifting, bunny-ear, and rotor-and-hub assembly, one of the methods described in (Kaiser & Snyder, 2010) using feeder vessel to transport pre-assembled component. For proper simulation, the capacity of the transportation vessel for each component is defined. The author used interpolated wind speed value at the hub level from reference height regarding the environmental condition. The relationship between each event is expressed as a conditional probability.

A numerical simulation is used to minimize the installation cost, based on the significant factors to decide a suitable construction strategy (Sarker & Faiz, 2017). Even though the research outcome is related to annual cost, the conclusion can be evaluated in schedule optimization because the cost can be derived from the schedule.

Some of the models about the duration will be introduced. The authors proposed the critical factors for optimizing the installation process and a model developed to estimate the total duration for the transportation and installation process. The model considers distance from the port, jacking time, lifting duration, learning curve, and required space ratio for transportation and total deck area on the vessel. However, there is no simulation of the environmental factors such as significant wave height and wind speed, and the uncertainty of the outcome is not defined. Through this research, distance to the port and required deck space for transportation and the number of turbines to be installed will be parameters to estimate the installation duration and select an optimized installation strategy.

Specific challenges during offshore installation are mentioned in Baluku and Habajurama master thesis (Habakurama & Joseph, 2016). For the Lillgrund wind farm, unexpected soil conditions such as unexcavated sandbar made the breakdown of the cable-laying vessel due to the thruster's damage. Harsh weather conditions made resulted in two months delay after repairing the thruster. As one of the lessons learned, the loading sequence in port should be aligned with the turbine's installation sequence.

In the Lillgrund case, there was unloading and re-loading according to the installation sequence again to fix the error. During the installation of the turbine, the hit and run technique was applied. The hit-and-run technique means the installation was carried out under safety conditions and if not, the vessel was escaped from the site.

For the Anholt wind farm case, Ørsted (Dong energy) had already understood the importance of optimal installation strategy, availability of the specialized installation vessel, and natural challenges such as seabed conditions and weather conditions. However, even though the detailed and robust geotechnical survey, there were unexpected obstacles in the soil to make a project delay, such as gas presence in the seabed and subsea mines installed during World War II. In robust planning, the timing and components of the turbine delivery should be matched with the installation vessel's loading conditions. Lastly, the windfarm's overall layout must consider the constructability and availability of the installation vessels and methods. In Anholt's case, abandoned wind turbine positions happened, and the final farm layout was changed.

Very little research was studied to develop an uncertainty band of total installation duration and use environment statistical value as a parameter to estimate maximum duration and uncertainty.

Chapter 2. Description and background

In 1991, The first offshore wind project was launched on the Denmark coast, with eleven 450kW turbines (Ostachowicz, McGugan, Schröder-Hinrichs, & Luczak, 2016). Until the beginning of 2000, the shallow-water offshore wind farm has been dominated by up to 60m water depths. In shallow-water cases, monopile, one of the bottom fixed substructures, was used very widely (Lacal-Arántegui, Yusta, & Domínguez-Navarro, 2018). As floating technology is more advanced and utilized by the oil and gas industry, the floating wind farm is expected to show the progress from demonstration development in South Korea, Norway, and the USA. In this chapter, the description of each component in offshore wind and project development will be introduced (Aker Offshore Wind, 2020). This chapter looks at the offshore wind farm, offshore installation, and related theory of marine operation.

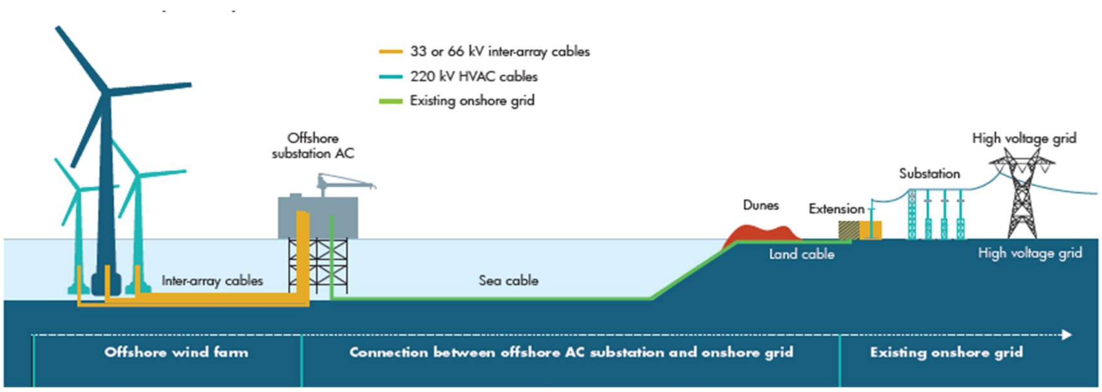

Figure 2-1: Offshore wind farm overview (GWEC, 2020)

2.1. Offshore wind farm overview

The broad point of an offshore wind farm contains the grid connection between the offshore AC station and existed onshore grid, including offshore wind turbine construction. With more massive wind farms expanding further into the sea, grid connection needs to ensure reliability and quickness. In Figure 2-1, There are many significant components for the offshore wind farm except onshore parts.

◦ Substructure (incl tower): the basis of the turbine and two or more steel tubes bolted

◦ Wind turbine

Nacelle, or generator house: fitted on top of the tower

Rotor (blade): three blades connected with a hub on the nacelle

◦ Substation platform: converted from AC to DC to transport the electrical power

◦ Subsea inter-array cable and export cable

However, in the project planning and installation modeling, the turbine's set and foundation are essential parts of wind farms (Kiranoudis, Voros, & Maroulis, 2001). During the wind turbine installation period, many marine operations and equipment are consumed with various uncertainty. Due to the relationship with the simulation, turbine and foundation will be introduced instead of the whole wind farm project scope in this thesis.

A typical turbine in a wind farm consists of 3 major components (Thomsen, 2014). Figure 2-2 shows a tower, including substructure, nacelle, and rotor from the bottom. It will be explained more in Chapter 2.1.1. and 2.1.2.

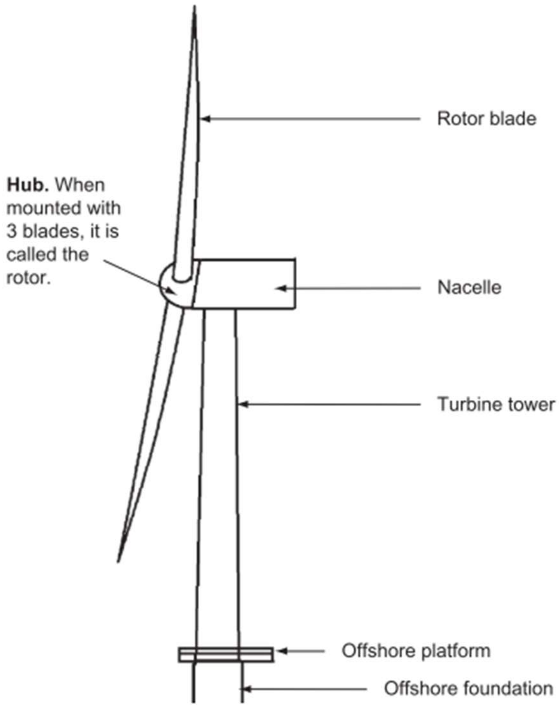

Figure 2-2: Components of a wind turbine. (Thomsen, 2014)

2.1.1. Foundation in Balance of Plant

Balance of plant is defined as "all the supporting components and auxiliary systems of a power plant needed to deliver the energy other than the generating unit itself" (Wikipedia, 2020a). In this chapter, the types of the foundation as a significant area in BOP will be introduced.

Fixed-type foundation

At the beginning of offshore wind, the turbine's size and weight does not need a heavy or oversized size of the foundation (water depth 30m to 60m), so monopile was the best appropriate solution and widely applied for the basic design in an offshore wind farm under 60m water depth. (ATKINS, 2019) however, regardless of the size of the turbine, the offshore turbine needs four additional factors to be considered in the application of a foundation design (Thomsen, 2014):

1. Water depth: the height of the foundation can afford the air gap of the turbine
2. Wave load: Wave induced load and bending moments should be considered
3. Ground condition: the composition of the seabed such as clay or sand so on
4. Turbine-induced frequencies: compared with onshore, wave load can be added and make a higher load to the foundation.

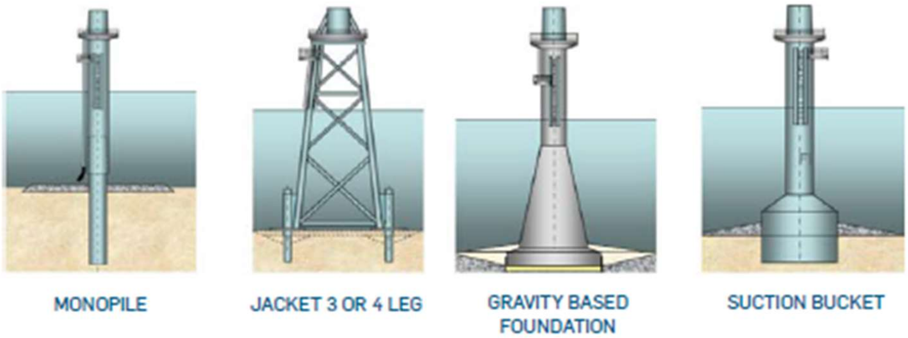

Figure 2-3: Typical substructures (ATKINS, 2019)

Out of the beginning era of the wind farm concept, the more nameplate of windfarm needs the turbine's bigger size. The foundation needs to sustain the giant turbine and environmental conditions; this requirement makes the jacket and tripod design.

Table 2-1 shows the pros and cons of each type of fixed foundation. Furthermore, monopile is the dominant type, and gravity-based is rare to apply in real (Lacal-Arántegui et al., 2018).

Type	Advantage	Disadvantage
Monopile	Easy to handle	Up to 25m water depth Week bending moment
Gravity based	Cheap to build	Expensive and time consuming to install in offshore
Tripod	High stability Easy to calculate wave-induced load	High production cost Difficult to handle
Jacket	Considerable resistance to wave	High production cost Weak ice protection

Table 2-1: Advantage and disadvantage of various substructure (Thomsen, 2014)

Floating type foundation

Over 60m of the water depth, the bottom fixed substructure has no longer valid economic effects (Global Wind Energy Council, 2020).

Semisubmersible type is applied for many prototype projects for floating wind farm project because it is easy to be built, there are many lessons learned from oil and gas industry, and it has relatively low installation cost. Spar type was used for Hywind Scotland, and it has the advantage of a harsh environment. Typically, it can be assembled in sheltered water and towed to the field as ready for operation.

The last TLP type is not well known in the floating wind. However, the TLP type has the smallest heave movement among the floating structures to operate the turbine and install it. However, the installation cost is the highest of the three floating types.

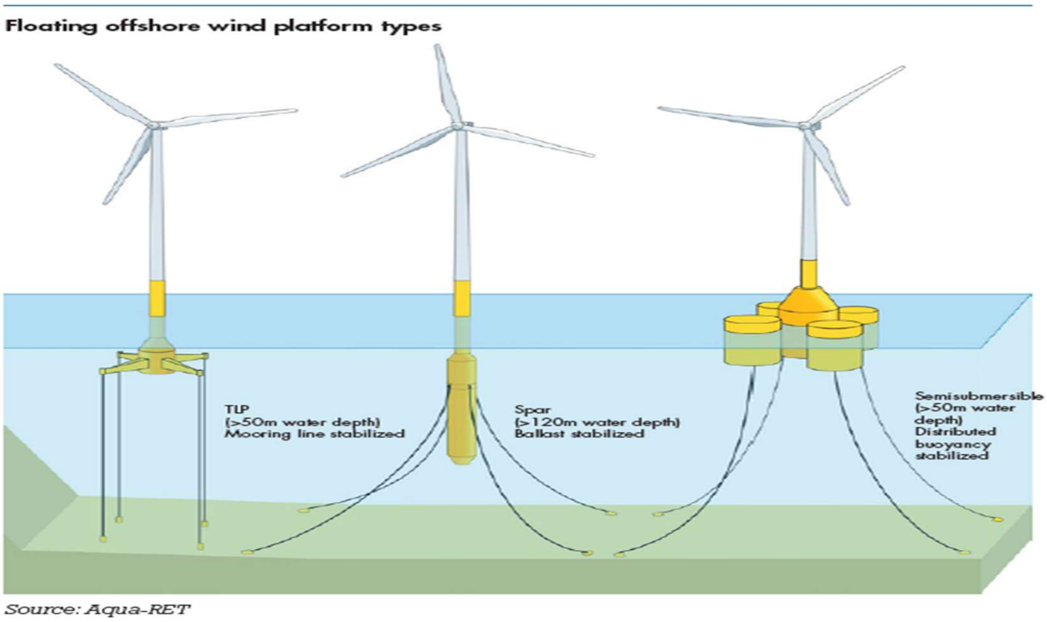

Figure 2-4: Floating offshore wind platform types (Global Wind Energy Council, 2020)

2.1.2. Wind turbine (Nacelle and rotor)

Wind energy means the electrical energy is generated by converting the kinetic energy of moving the air (Wiser & A. Zervos, 2011). So, a wind turbine is an essential part of making a conversion on the wind farm. Theoretically, the more electrical energy can be extracted from kinetic energy in the wind as the more wind speed increases. However, the turbine has a limit to extract a portion of the available energy.

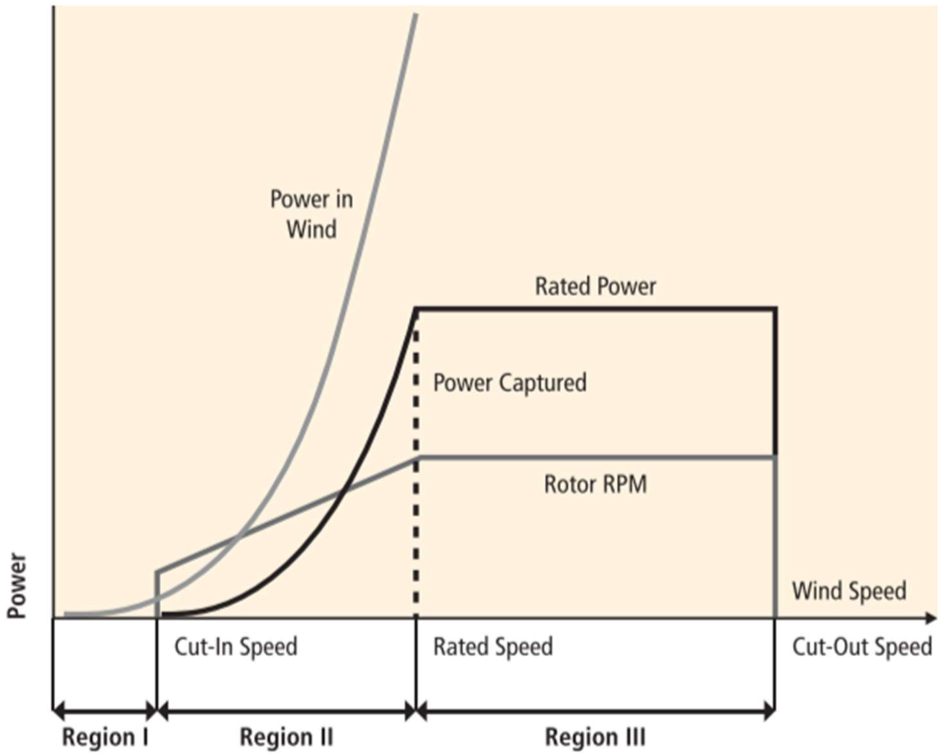

Figure 2-5: Conceptual power curve for a modern variable-speed wind turbine (Wiser & A. Zervos, 2011)

The engineering of a wind turbine focuses on maximizing energy capture over the range of wind speed (Region III) with minimizing the cost of wind energy. One way to maximize the energy captured is to increase the rotor's diameters for a given generator capacity, which is defined as the energy capture at rated power in Figure 2-3. Larger rotor size makes the wind speed rated power achieved reduced. It means lower wind speed at which rated power achieved and smaller region II in Figure 2-5 so taller tower gives more efficiency over variable wind speed in the wind farm operation.

Based on maximizing energy capture or efficiency over variable wind speed, the rotor size or the tower's height and rated generator capacity is increased as the wind turbine technology is developed, and the cost of wind turbine development is reduced.

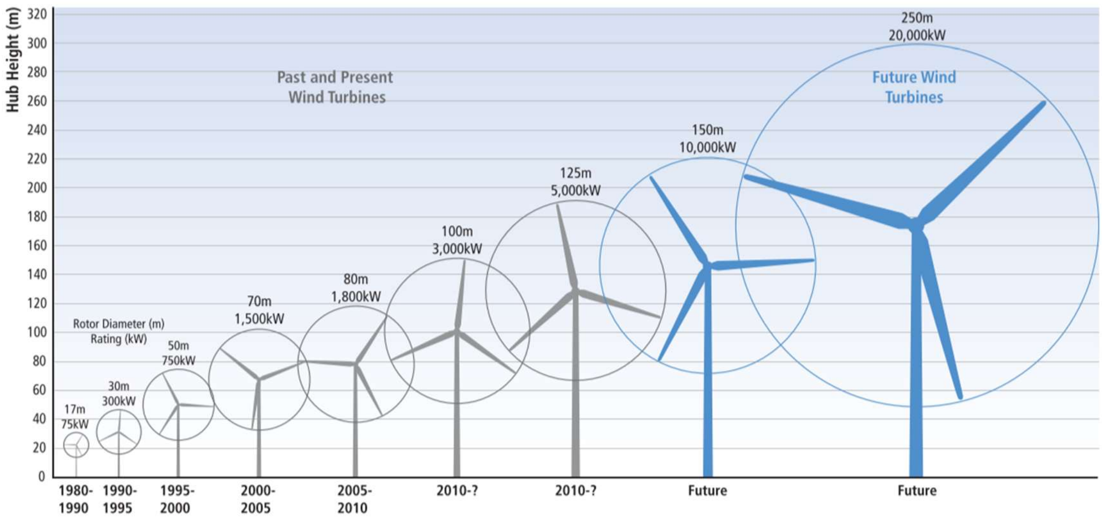

Figure 2-6: Growth in size of typical commercial wind turbine (Wiser & A. Zervos, 2011)

As mentioned in Figure 2-6, a 5MW-nameplate wind turbine typically has over 100m diameter of the rotor.

Another reason to increase the size of the rotor can be found in turbine design. The equation can determine the output of the turbine:

$$P = \frac{1}{2} \rho A v^3 C_p$$

Where P = power output, ρ = air density (kg/m^3), A = swept area (m^2), v = wind speed (m/s) and C_p = power coefficient. Swept area is defined as the area through which the turbine blades spin.

The rotor's size can be the same as the swept area, and the bigger size of the rotor can generate more power output; and this rotor size will be a critical factor in deciding offshore logistics and installation methods, which will be discussed in Chapter 3.

2.1.3. The project development process in an offshore wind farm

According to PMI (Project_Management_Institute, 2013), a project can be defined as "A project is temporary in that it has a defined beginning and end in time, and therefore defined scope and resources" Different characteristics and unique environmental conditions should be considered in the planning stage to succeed.

This chapter will introduce the general phases for project development related to wind farm-specific (Crown_Estate, 2019). All periods for the wind farm development project can be identified in Figure 2-7.

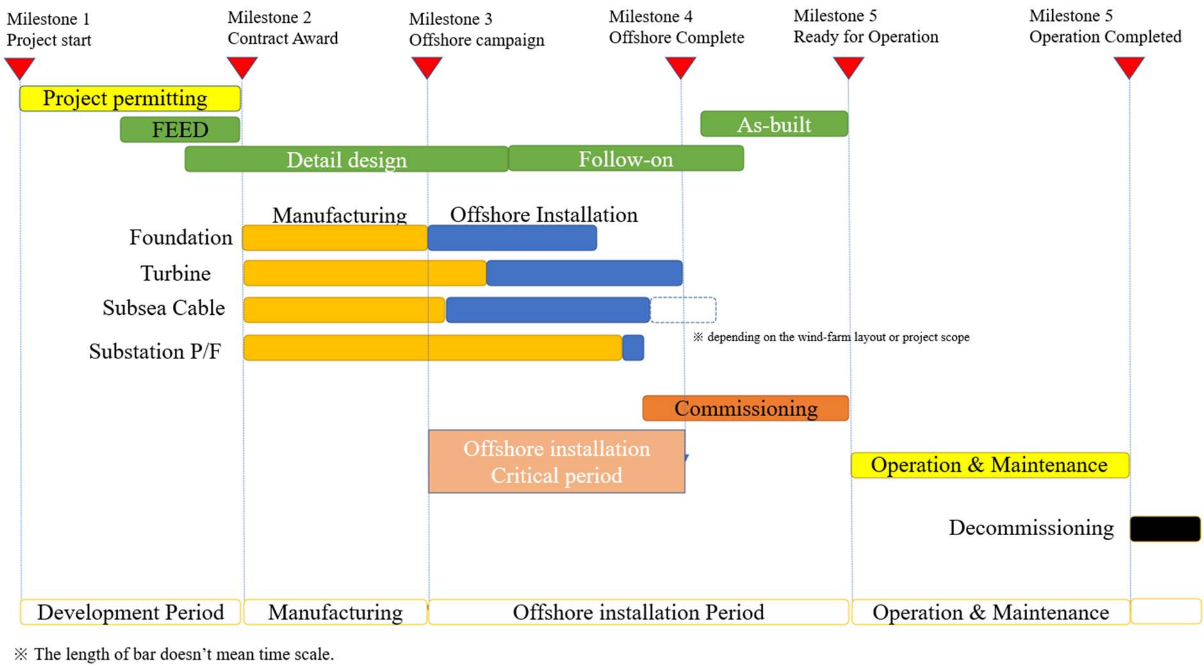

Figure 2-7: Overall life cycle for wind farm development project

Since subsea cable operation and installation of the substation can be done before or after the completion of the foundation and turbine installed, based on project characteristics, the offshore installation critical period can be defined as the total duration of the installation of foundations and turbines (Muhabie, 2018).

In this master thesis, the offshore installation will be handled at the offshore installation critical period to fit the research purpose and minimize the complexity of the total installation steps offshore.

Development (Planning) phase

During this phase, project developers will perform data collection and permit applications. Data collection means to gather project-related data such as geotechnical or marine and Environmental impact assessments should be carried out according to European Legislation (Crown_Estate, 2019). Most concept of design and profit model can be decided during this phase, so assessing the uncertainty of the project and proper estimation can reduce the total cost of project development

Manufacturing

Typically, the project wind farm design is completed during the permit approval period, and significant contracts have a tender process with a permitting period, such as substructure and turbine. For shareholders to reduce manufacturing costs, early involvement from the vendors of substructure or turbine or standardization of the design can be implemented. Generally, it takes three years to take up for this period (ATKINS, 2019).

Offshore Installation

One of the most critical and cost-saving periods in the wind farm development is preparation, installation of foundation, turbine, substation, and final testing and commissioning. All delivery time from manufacturing should be decided by offshore installation timing, and the start date of the manufacturing should be calculated backward. Inter array cable, export cable work, and substation installation can be overlapped with installing the substructure or turbine (ATKINS, 2019).

Operation & maintenance

Most North Sea projects have an operational life of up to 25 years without any upgrade. A local onshore base manages most O&M activities near a wind farm, and preventive maintenance and condition-based maintenance are used as a general maintenance strategy. Because most wind farm has the operation target as 97% or above so O&M strategy is essential. Additionally, since all O&M activities should be carried out offshore, predictive, and environment forest is the most critical point in building O&M strategy.

Decommissioning

The decommissioning will happen based on the permit conditions for the project.

2.2. **Offshore wind installation concept**

The installation of an offshore wind turbine and foundation is the most critical phase in project development. This installation process can be defined as a critical period because it contains a wide range of scope from onshore to offshore and from many steel structures to various vessels, as described in Figure 2-7.

Even though there are many natural hazards such as a seabed condition, dust, or the fossil fuel in seabed surface, during submarine cabling and rock dumping, wind turbine and foundation installation can be focused to simplify the installation modeling in the thesis too.

The offshore wind critical period should consider each turbine parts' logistics, port availability, and installation vessel specs such as vessel speed, crane lifting capacity, and loading capacity. (Thomsen, 2014).

First, there is a summary of the foundation and turbines' installation method in the bottom-fixed-foundation wind farm. This summary is listed from most projects carried out in European offshore wind farm construction (Kaiser & Snyder, 2010).

2.2.1. Substructure installation (Bottom-fixed)

Monopiles installation

Monopiles can be transported from the fabrication facility to offshore wind location by installation vessel, barge, or feeder vessel. The towing method can be decided by the monopile's size and weight, deck availability of installation vessel, and crane capacity of installation vessel, the distance to shore, and the towing route's environmental condition.

After arrival at the site, by crane, the monopile is lifted in a vertical position and holding the position by a specialized pile gripper. The top of the monopile is impacted by a hydraulic hammer and penetrating the seabed until predetermined depth. This operation can be variable based on the seabed condition.

After the monopile is fixed in the seabed, a transition piece is installed by bolting. The tolerance between a transition piece and monopile is also a critical point like soil condition for offshore installation (Habakurama & Joseph, 2016).

Jacket and Tripods installation

Jackets and tripods also can be transported by barge or installation vessel. However, due to the heavyweight of the jacket or tripod (generally from 500 to 800 ton), sometimes the newbuild jack-up installation vessel need for transportation and installation. Piling work is more uncomplicated than monopile because the jacket and tripod have 3 or 4 piling positions and the size of each pile is smaller than the monopile itself. So, soil condition is less critical than monopile.

The tripod or jacket's size and weight can decide the number of traveling of installation vessels, and this can also decide the total installation time. The most remarkable environmental factors are significant wave height (H_s) and Spectral peak period (T_p) than wind speed (Zhu, Li, & Ong, 2017).

2.2.2. Offshore wind turbine installation

Components of a wind turbine can be transported one by one or assembled. The pre-assembled scope can be decided by factors such as the deck's size and load in the installation vessel, the usage of feeder vessel, the distance to onshore, and space availability in port (Sarker & Faiz, 2017).

An offshore wind turbine installation strategy can be selected to optimize the offshore critical installation duration based on these factors based on the coordination of these factors according to the project specification. The scope of pre-assembled in a component can reduce the number of offshore lifting and duration; meanwhile, it can limit the installation vessel's selection.

Based on the degree of pre-assembled onshore, there are various installation strategies in Figure 2-8, and Among these installation strategies, No 1,3,4 are current preferred methods (Crown_Estate, 2019).

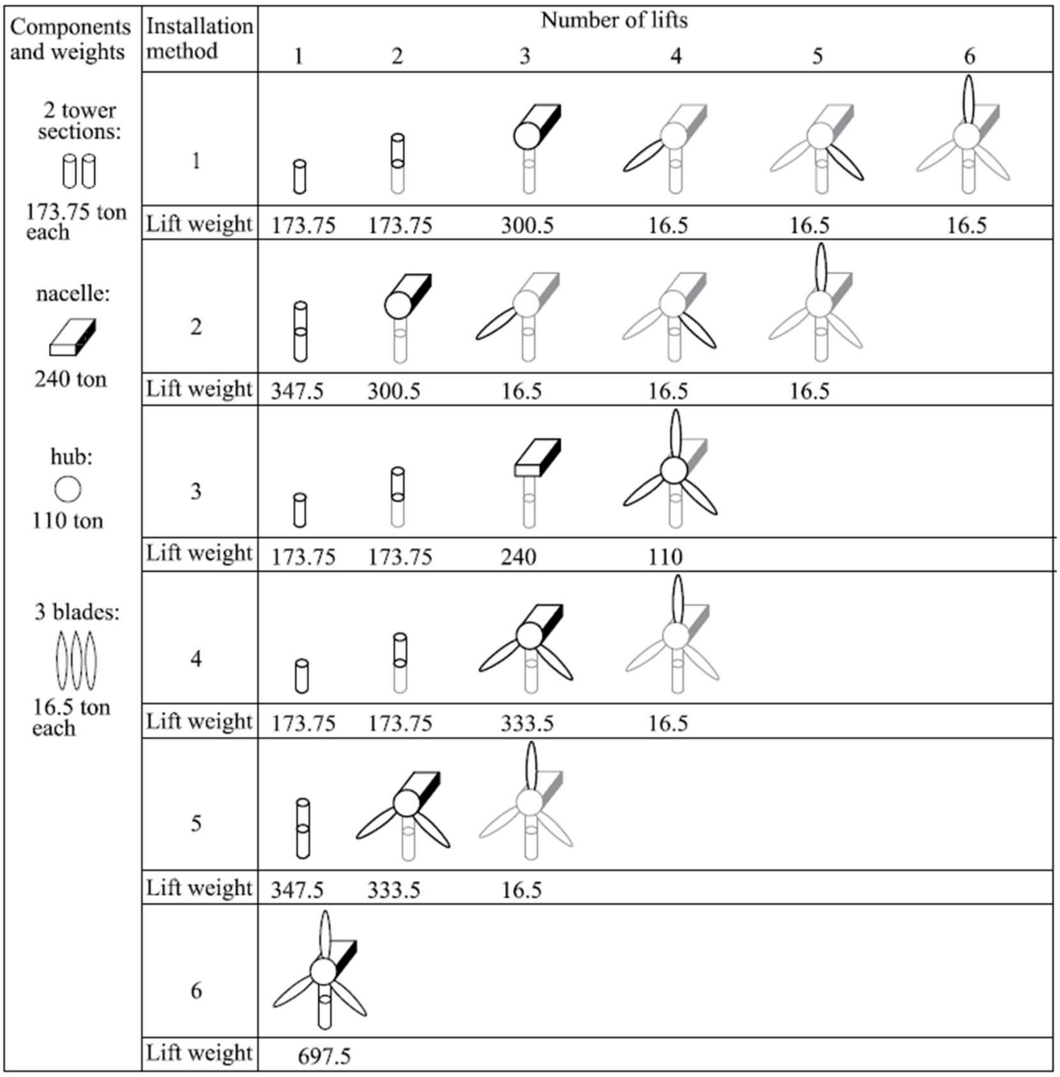

Figure 2-8: Wind turbine installation methods (Li, 2016)

1. Nacelle and hub joined onshore (NHJ): This method has an advantage in the long distance between the port and the offshore site. The efficiency of deck space in the installation vessel can be maximized, and a greater number of turbine set can be transported per one trial than other strategies
2. Tower assembled onshore (NHJ-1): basically, this is similar to method 1, and the difference is an assembly of the tower.
3. Rotor and hub assembled onshore (RHA): 3 blades and hub are assembled onshore and lifted one time offshore. This method allows the distribution of weight for each offshore lifting.

4. 2-blades and nacelle in the bunny ear (BEJ): two parts of the turbine can be transported. The nacelle, rotor, hub, and two blades are joined in onshore and installed one time. The third blade is installed separately. In this case, lifting weight for the nacelle, rotor, hub, and two blades should be checked compared with crane capacity.
5. The same method as no 4 (BEJ-1) with tower assembled onshore.
6. Entire turbine assembled onshore (EAJ): all turbine parts are assembled onshore and installed one time. Therefore, the workspace in port, heavy lifting vessel, and the crane's assess height are critical to making this method feasible.

2.3. **Marine operation and model uncertainty**

2.3.1. Weather window analysis and Metocean parameters

Weather restricted operations

According to the DNV-OS-H101, weather restricted operations can be defined as the marine operation with a reference period (T_R) less than 96 hours and a planned operation time (T_{POP}) less than 72 hours (DNV, 2011). A reference period can be described as the summation of operational time and an estimated contingency time, and T_C should be taken as the same is T_{POP} as maximum. The starting of weather restricted operations can be determined based on the last weather forecast.

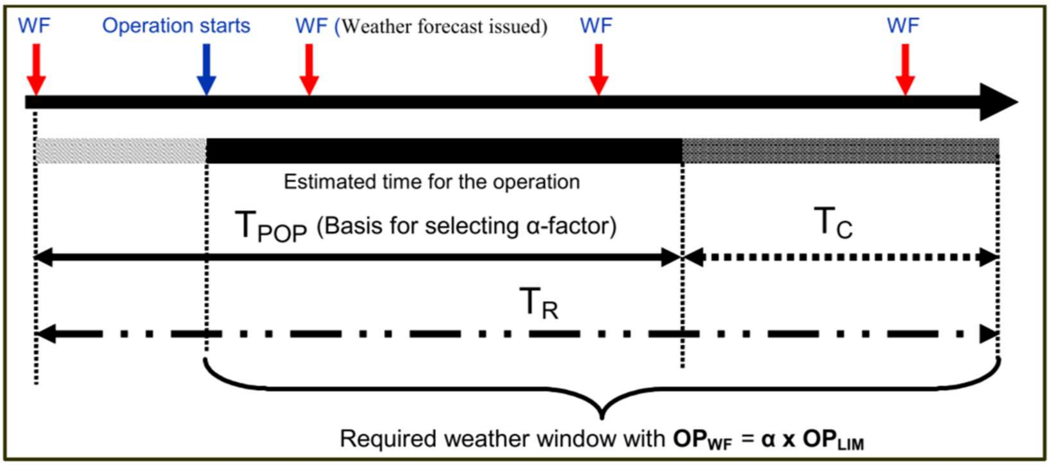

Figure 2-9: Operation periods (DNV, 2011)

Operation limit can be applied under the ALARP principle, and it means the costs are in gross disproportion to the benefits gained (Aven, 2014). ALARP principle can allow the progression of the tasks. Additionally, it is widely accepted that each step of the operations can be specified if the object handled has been taken from one safe condition to another.

Originally, DNV-OS-H1010 has been issued for the oil and gas industry. However, weather window analysis can be utilized for wind farm installation based on ALARP and the specific safe condition for each step. So, there are generally marine operation steps specified for the wind farm installation per one sea trial as below

- Loading the Wind Turbine or foundation in port
- Transportation from port to site
- Installation of the WT or foundation
- The transition from site to port

Like Figure 2-9, continuous weather forecast can make these operations as weather restricted adequately. During T_R, the operational limit can be compared with the weather forecast, and the weather window can be determined. If the whole of the steps in one sea trial or operations surpasses 96 hours, it should be handled as unrestricted operations. The necessary process can be identified in standard as a process map in Figure 2-10.

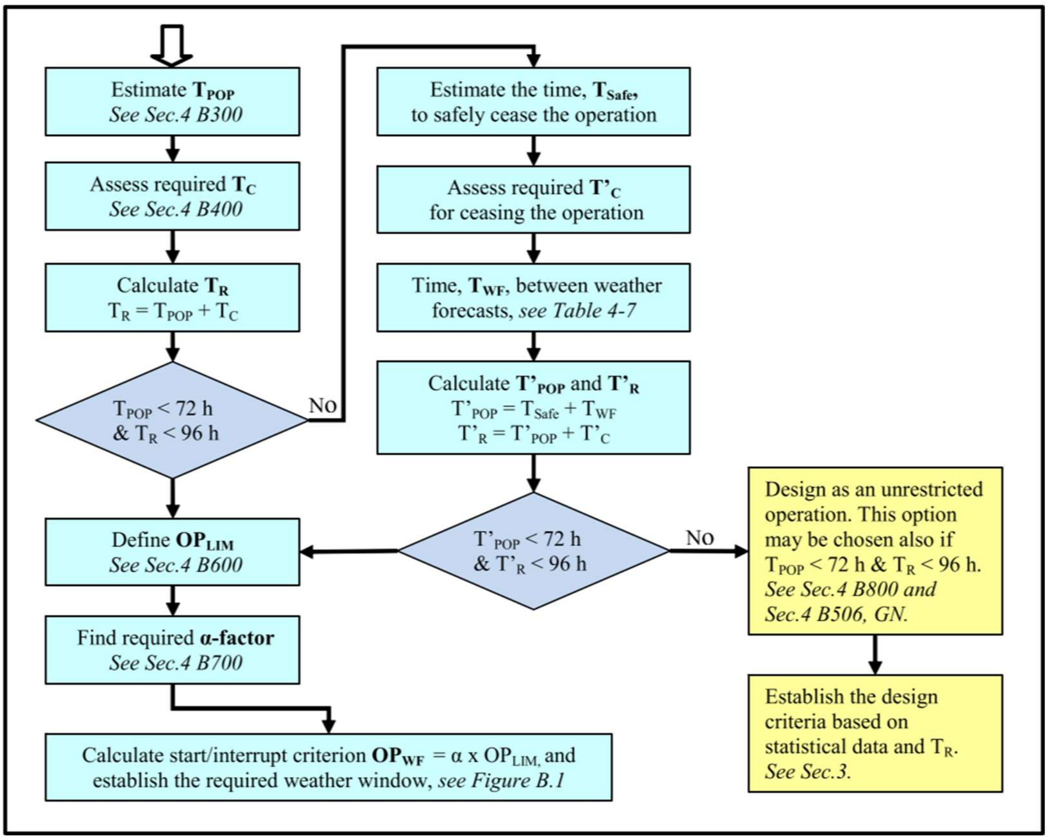

Figure 2-10: Restricted or unrestricted operation (DNV, 2011)

Operational limiting Criteria can be denoted as OP_{LIM}, and it shall not be greater than the environmental design criteria such as WSP or Hs. The OP_{LIM} can be determined by considering safe working conditions for equipment, diving system, and objective handling system. In this research, most OP_{LIM}s are referred from other articles related to the installation of wind farms. However, the OP_{LIM} for the foundation installation can be derived based on the simulated modeling mentioned in APPENDIX 2.

Alpha Factor

DNVGL recommends that forecasted operational criteria (OP_{WF}) be developed from OPLIM multiplied by α because there is uncertainty in the monitoring and forecasting of the weather. The α factor can be selected as minimum time input between weather forecasts and time to safely halt the operation. In DNV-OS-H101, there are comprehensive tables for choosing the α factor for waves in the North and Norwegian seas (DNV, 2011). However, there is no consideration of the uncertainty from the wave period.

Weather Unrestricted operations

If a marine operation has T_{POP} over 72 hours or T_R over 96 hours, any analysis for weather window should be completed considering extreme value statistics. Characteristic wave conditions for unrestricted operations shall be based on long-term statistical data, and unrestricted operations may contain one or more restricted operations as a sequence of restricted operations with different operation limits. Therefore, the type of operation should be defined early in the planning process for weather window analysis.

Parameters for Metocean data

The sea condition parameters and related statistics parameters are generally used for feasibility study or FEED (Front End Engineering and Design). These parameters will generalize the overall field condition to be compared to each other.

Parameter	Description	Definition
H_s	Significant wave height	The average of the highest one-third of wave height or four times the standard deviation of the sea surface elevation
T_p	Spectral peak period	The inverse of the frequency at which the spectral density function of the elevation time series is maximum
Std Θ_m	The standard deviation of the mean wave direction	The standard deviation of the mean direction in which waves are traveling
U U_{th}	Mean wind speed Mean wind speed at the height of the turbine	The mean of the speed of the air particles over 10m
Std Φ	The standard deviation of the mean wind direction	The standard deviation of the mean direction from which the wind is blowing
Δ_m	Mean difference btw wave & wind direction	The mean value of the difference between wind and wave direction
100-year Return value H_s, T_p, U	The 100-year return value from GEV distribution	GEV distribution provides a condensed representation of all data.

Table 2-2: Metocean modeling parameters

In some research (Bailey, Filippelli, & Baker, 2015) and (Monbet, Ailliot, & Prevosto, 2007), there are many parameters related to atmospheric, water surface subsurface. However, parameters should be prioritized to make a model based on simpleness, relevance to engineering, and representatives.

For the research purpose of parameterizing ocean data to project uncertainty, here is the list of our significant parameters to be used in the next simulation.

2.3.2. The uncertainty and risk

There are many cases to mixture risk and uncertainties for risk analysis. Risk can be described by specifying the events or consequences and that these consequences are unknown (Aven, 2014). If a specific thing affects the project without knowing those who carry out the risk analysis, it can be considered a risk.

Unlike the risk, uncertainty can be defined as the variation of a consequence of the event or the degree of not knowing the real value of an event (Aven, 2014) or the future consequence of a marine operation. The uncertainty can happen from imperfect or incomplete information about the hypothesis, a quantity, or the occurrence of lifting operations. Uncertainty can be divided into two groups

Aleatory uncertainties (Inherent nature):

This case is of inherent random nature, and it can be reflecting variation in defined populations represented by the numerical model.

Epistemic uncertainties (Epistemic nature):

This uncertainty can be classified by introducing the lack of knowledge about an observed phenomenon or parameter.

On the other hand, according to (Aven, 2014), we can use the terminology of the uncertainty related to the simulation model as below;

Model error: the difference between the model and real future value

Model output uncertainty: the magnitude of model error, which can be epistemic uncertainty about the model error

Model output also can be divided into two components:

Structural model uncertainty: the conditional uncertainty associated with the model error, given the true value

Input quantity uncertainty: the uncertainty associated with the true value of the input quantity

Usually, we need to express the inherent uncertainty using the probabilistic model. However, the parameters of the probability model are derived from limited data. This limited data or observed information can make the magnitude of the uncertain with epistemic nature. This epistemic uncertainty can be decreasing as more observation or data are available.

Based on the model output uncertainty, this study can obtain the uncertainty band of the total duration for WT installation operation to express the magnitude of uncertainty derived from the model error.

There is another uncertainty from the methodology for analysis. According to the (Vanem, 2015), we can also recognize the general sources of uncertainty when the extreme value analysis of wave statistics as below.

- The extrapolation of estimates of the tail area of the fitted model.

- Most of the data to fit the model will be located near the model of the distribution

- The assumption of the asymptotic of the extreme value is iid (independent and identically distributed), and real symptoms can follow the non-stationary process

- Small amount of data can only generate a much smaller set of extreme value

These sources of uncertainty can be checked during the parameterization of the hindcast data.

Chapter 3. Methodology and simulation model

In this chapter, it will be introduced that the methodology finds out the optimized parameter for offshore critical installation in Figure 2-7, and the parameterization of the hindcast data among H_s, T_p, and WPS estimates the total duration. The simulated model will be established with a similar project, the Global Tech 1 wind farm project; however, some of the simulating areas is assumed per research purpose, such as the installation vessel specification.

3.1. Statistical review of hindcast data

To implement the methodology described in Chapter 3.2. three different locations hindcast data can be randomly selected and utilized for the simulation. All hindcast data are from NORA10. Before reviewing the hindcast data across all three sites, it needs to interpolate the wind speed and calibrate T_p. For H_s, the duration of each step in installation models uses an hour as a unit for analysis, so the interval of each data sample needs to be converted from 3 hours to 1 hour.

The wind speed as an average value was observed at 10m of altitude as a reference in two perpendicular directions and every 10 min. Because the hub location of the wind turbine is 100m from sea level as mentioned in Figure 2-6, to get the correct simulation data, WSP should be interpolated at 100m according to the wind profile power law relation (Peterson & Hennessey Jr, 1978).

When U_r is the known wind speed at a reference height Z_r, Equ (1) is used to estimate the wind speed U at height z. the exponent α is an empirically derived coefficient that varies depending on the stability of the atmosphere. In the case of the open sea, this value is equal to 0.1. (Manwell, McGowan, & Rogers, 2010)

$$U = U_r \left(\frac{z}{z_r}\right)^{\alpha} \qquad \text{Equ (1)}$$

The original T_p^* in NORA10 is too low for moderate and large peak periods due to constant resolution in ln (T_p) (Haver, 2018). The problem is that all original T_p^* value in NORA10 has no one decimal place. When the original T_p^* value is compared with the operational limit for a tripod with one decimal level in Figure 3-11, the simulation value for the duration can be distorted. There is the calibration method in Equ (2) (Haver, 2018).

For future simulation, original T_p^* are post-processed by Equ (2) to generate T_p.

$$T_p = 3.244\, exp\, \{0.09525\, (i - 0.5 - rnd)\} \qquad \text{Equ (2)}$$

Where and is uniform distributed in the range 0 ~ 1, and i is from Equ (2-1)

$$i = ROUND\left[1 + \frac{\ln(T_{p^*} / 3.244)}{0.09525}\right] \qquad \text{Equ (2-1)}$$

Figure 3-1 shows the change of scatter diagram for H_s and T_p after correction

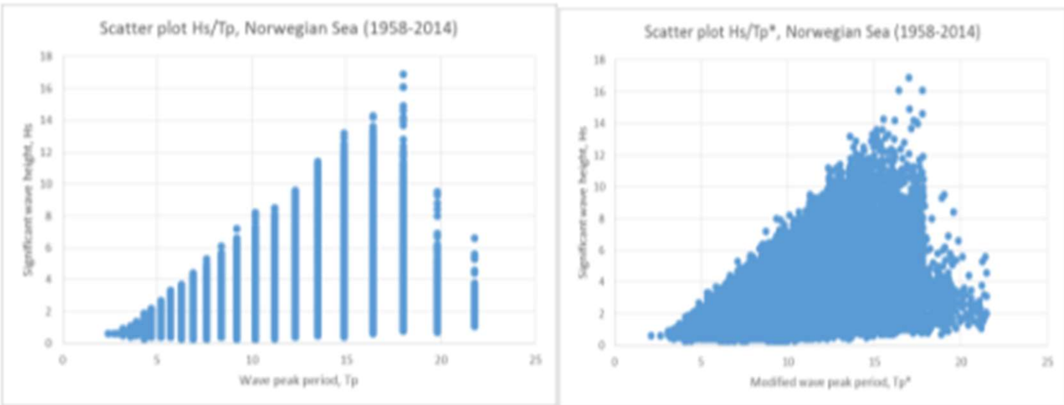

Figure 3-1: Scatter diagram for Hs and Tp before and after correction of Tp (from Kvamme (2015))

Utsira, Belwind, and FINO3 near the Global Tech1 wind farm site are selected in three different locations. Figure 3-2 shows each of the geometrical locations. Hindcast data from NORA10 and the period contains from 1958-01-01 00:00 to 2019-01-01 00:00, a total of 60 years. Because NORA10 has a value per 3 hours, an interpolated one-hour occurrence, 550,767 ea, of all parameters such as H_s, T_p, and WSP is used for the simulation.

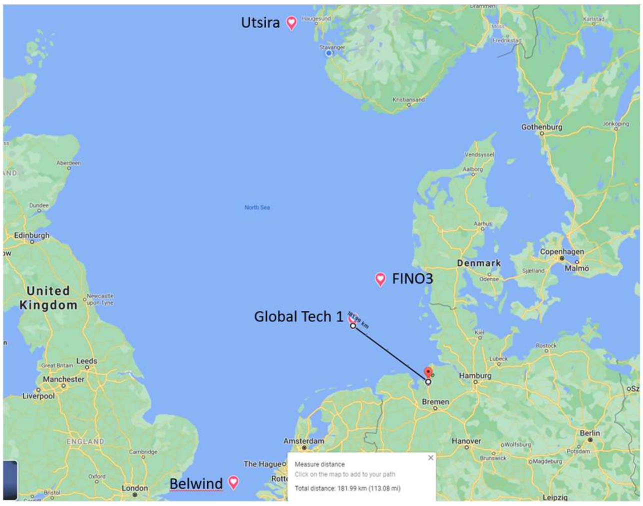

Figure 3-2: 3 Locations for analysis and cast study windfarm location (google map)

	Belwind1			FINO3			Utsira		
	H_s (m)	T_p (s)	WSP100 (m/s)	H_s (m)	T_p (s)	WSP100 (m/s)	H_s (m)	T_p (s)	WSP100 (m/s)
Jan	1.6	6.3	12.3	2.2	7.4	12.9	3.1	10.1	13.1
Feb	1.5	6.2	11.3	1.9	7.2	12.0	2.7	10.0	11.8
Mar	1.3	6.2	10.3	1.7	7.0	11.3	2.5	9.8	11.2
Apr	1.1	6.2	9.0	1.3	6.6	9.4	1.9	9.1	9.4
May	1.0	6.0	8.6	1.1	6.2	8.6	1.5	8.1	8.6
Jun	1.0	5.8	8.2	1.2	6.1	8.7	1.4	7.6	8.4
July	0.9	5.7	8.2	1.2	6.0	8.7	1.3	7.2	8.2
Aug	0.9	5.6	8.5	1.2	6.1	9.0	1.4	7.5	8.5
Sep	1.1	5.9	9.4	1.5	6.7	10.4	2.0	8.5	10.2
Oct	1.3	6.0	10.7	1.8	7.0	11.8	2.4	9.3	11.4
Nov	1.6	6.2	11.9	2.1	7.4	12.6	2.7	9.8	12.1
Dec	1.7	6.3	12.3	2.2	7.6	12.8	3.0	10.1	12.6

Table 3-1: Average for Hs, Tp, and WSP100 for all sites

Table 3-1 compares the mean metocean value across all three locations. For all sites, there is calm weather from April to September. Based on these values, it can be concluded that it is beneficial to start and perform the offshore installation from April; however, due to the short project duration of wind farm construction generally, the offshore campaign has to be carried out regardless of any specific month (Habakurama & Joseph, 2016).

It can be shown that Utsira has a harsh environment and is in the most north among the sites; meanwhile, Belwind1 has the lowest calm weather and is located in the most south.

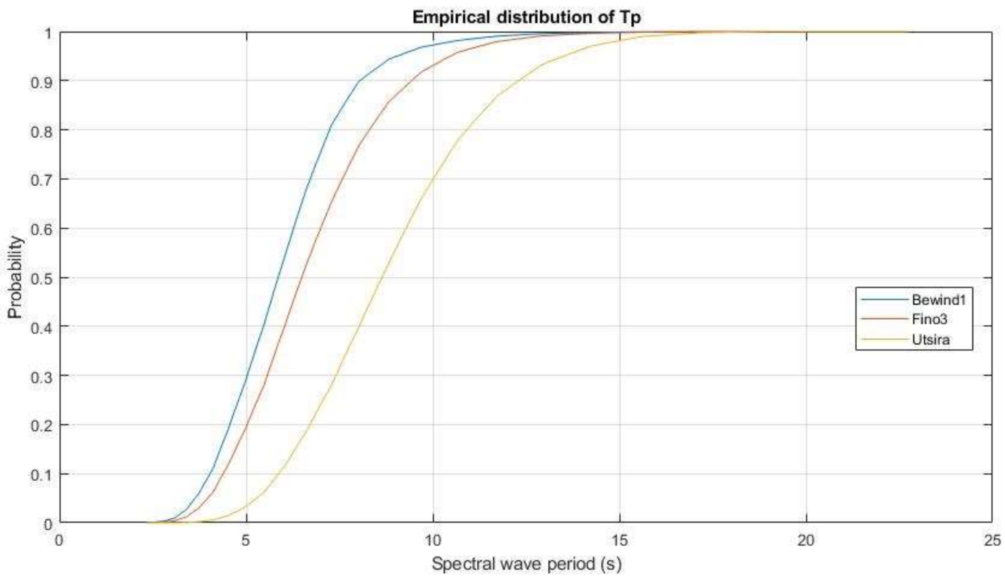

Figure 3-3: Empirical distribution of Tp for all sites

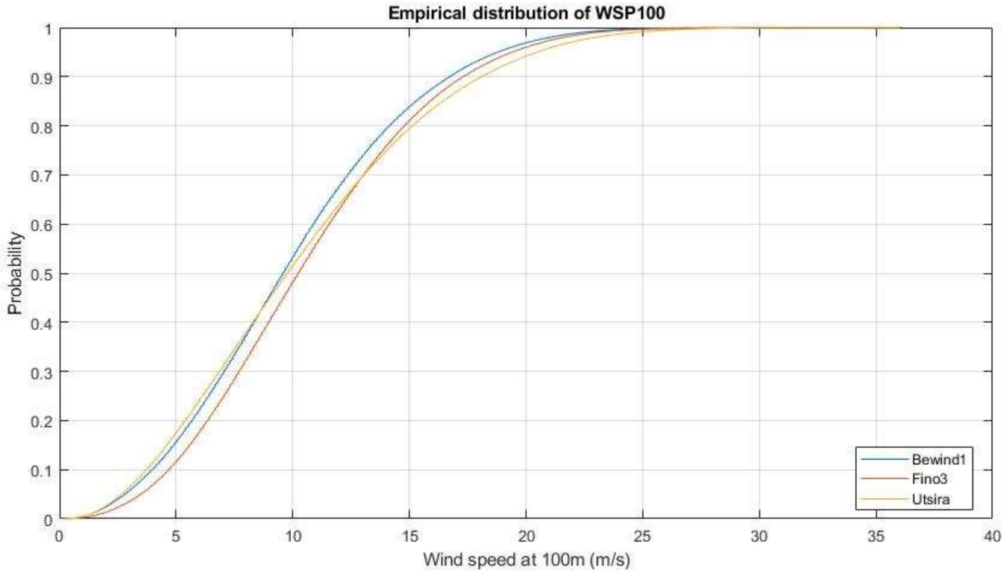

Figure 3-4: Empirical distribution of WSP 100 for all sites

Figure 3-4 presents that the wind speed at 100m does not significantly differ among all sites. It means WSP100 is hard to use the parameter to match the simulated installation duration.

In the case of T_p, Figure 3-3 shows a similar result to Table 3-1; however, the variance of the value in Utsira is more extensive than those of others.

As shown in Figure 3-5, Hs has a similar distribution for all sites with different values per each probability. Hs can be a positive parameter for future analysis.

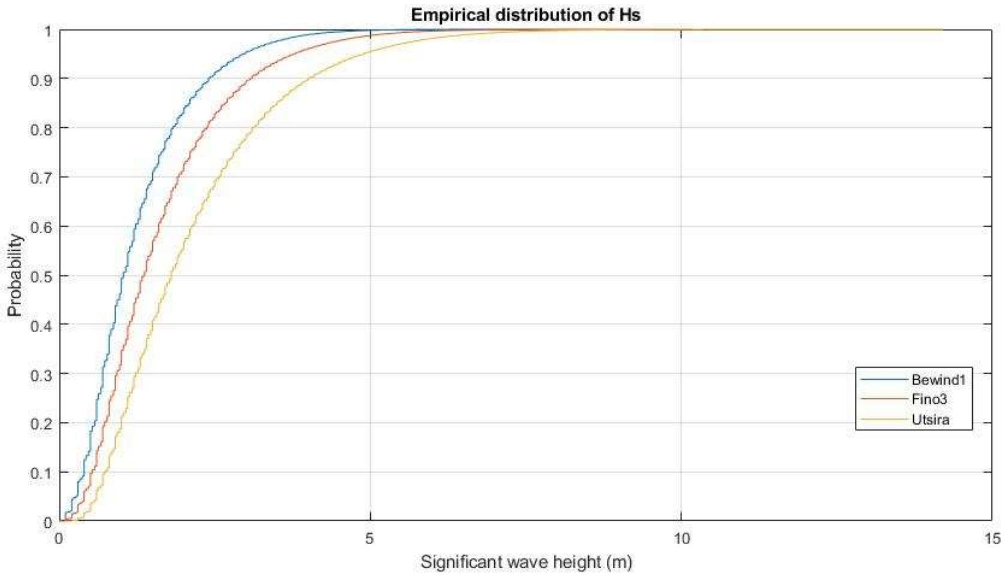

Figure 3-5: Empirical distribution of Hs for all sites

Weather window assessment

This section presents the results for a weather window analysis based on Hs for all sites. By considering an operational limit of Hs, 1.4m, which will be mentioned in 3.3.2. the weather window analysis will be counted based on 2 hours from 2 hours to 24 hours.

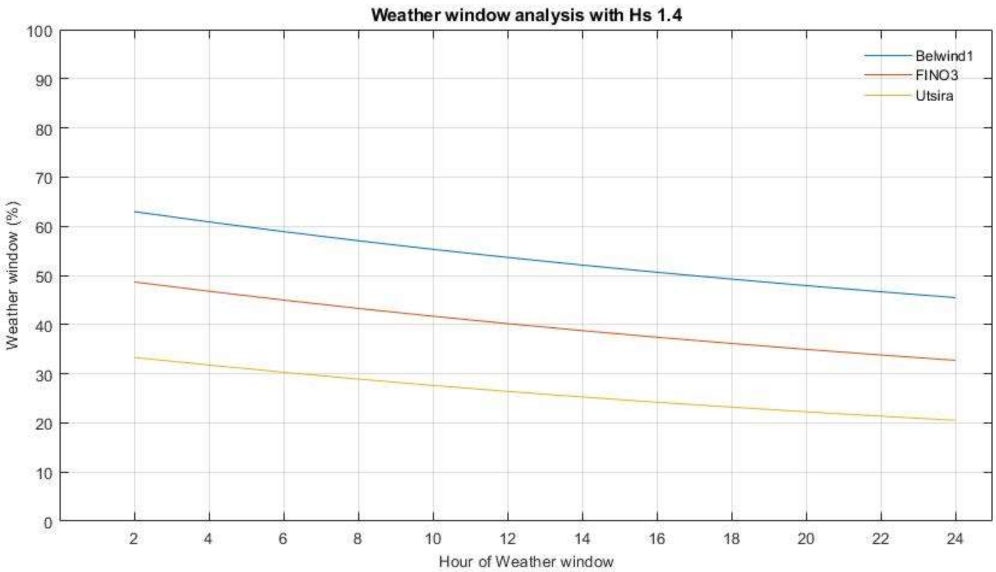

Figure 3-6: The percentage of each hours weather window in the total number of wave occurrence

Figure 3-6 represents the percentage of the weather window from two hours until 24 hours per 2 hours cumulative with H_s 1.4m, based on the total wave occurrence. As shown in the previous section, Utsira has the lowest weather window for every weather window, and Belwind1 has the highest weather window.

Because the percentage of the weather window with H_s 1.4m has linearity for each period and regular interval for each field, this value can be utilized to estimate the total duration, which will be presented in Chapter 0as nominated in $P_{12hww,\ 1.4m\ Hs.}$

For example, $P_{12hww,\ 1.4m\ Hs}$ means the probability of the number of 12 hours weather window above the operational limit, 1.4m Hs.

3.2. General methodology and model for the parameterization

Parameterization methodology

The methodology to derive the optimized parameters from using different locations hindcast data will be introduced to estimate total duration during the project permitting period. This methodology is updated from the existing schedule method with more elaboration parts necessary for offshore wind farms and available installation vessels. These are significant considerations for this methodology, such as defining the scope boundary with the assumption, logical linking between each activity, and the project's required duration based on the economic review. Uncertainty and risk must be distinguished in the plan, according to Chapter 2.3.2.

The scope boundary can be defined generally by the contract, specification for the project, or business case. However, it is significant to assume the project and sub-work boundary in the project permitting phase and divide the sub-work scope mutually exclusive.

During the concept study of the project, typical oil and gas construction project plans were developed based on previous records with similar production capacity or a similar field. Risk analysis can be carried out using various the duration for the critical path, which can be defined as the series of activities that can delay the project end if these activities are delayed.

For offshore wind installation case, the historical record can be used to determine the sub-work scope and activity duration like oil and gas project. However, uncertainty should be analyzed based on the Metocean data of its field data because most construction and equipment for construction are utilized offshore, compared with oil and gas platform construction.

As below, specific factors should be considered in the planning stage in a wind farm to decide the onshore scope of work for the wind turbine components (Ostachowicz et al., 2016).

◦ Available space in the port
◦ Distance to shore from the windfarm
◦ Vessel deck capacity compared with a rotor size

For example, in the rotor and hub pre-assembled, this assembled component's total weight is almost 110ton, and the size is over 100m diameters. Over 10,000m2 - reinforced area to support the weight is needed in the commercial port near wind farm location to proper assembly work. The reinforced area in the quay has to be rented over the installation period. It will be another concern to increase CAPEX.

Distance from shore needs to be analyzed by a vessel speed and number of loading WT or foundation per one sea trial. The distance can be spin-off by the introduction of the feeder barge. A reasonable number of feeder barges can be simulated based on the number of turbine and installation methods (Oelker et al., 2018). However, feeder barge simulation is out of this thesis.

Vessel deck capacity can represent the number of loading WT or foundation with selected WT installation methods described in Figure 2-8. Deck capacity is direct connected with deck load configuration in Figure 3-7.

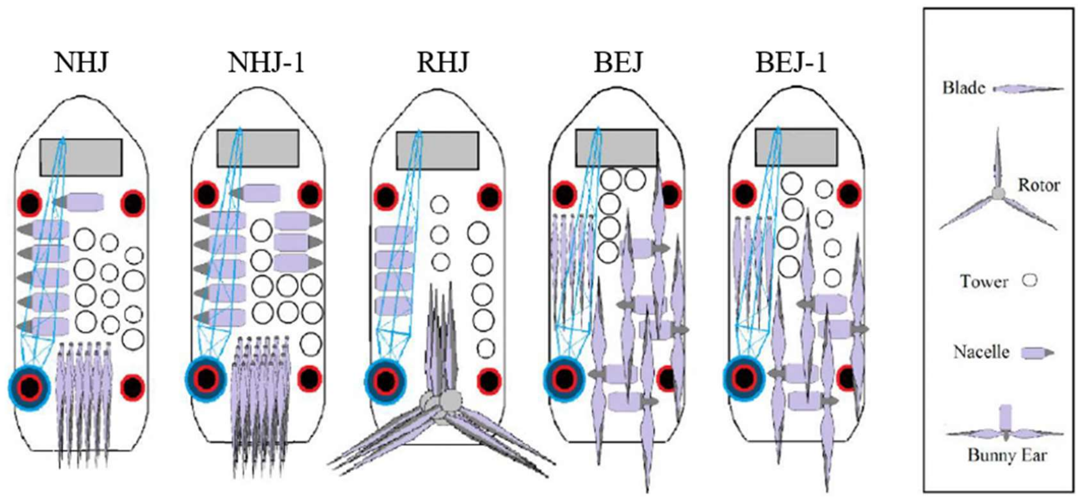

Figure 3-7: Deck configuration of each installation method (Figure 2-8) (Uraz, 2011)

Here is the elaborated methodology to parameterize the hindcast data to installation duration offshore.

1. Defining a scope boundary with the assumption
2. Reviewing the significant factors for the installation
3. Estimate each activity duration and operational limit
4. Defining the critical step and developing a numerical model to find acceptance criteria
5. Executing simulation and statistical review
6. Select the optimized installation method and logistics plan
7. Calculating total duration and extracting extremes of total duration per each year
8. Finding the uncertainty band from Monte Carlos simulation for different fields
9. Repeat no 7 and 8 for each field
10. Matching parameters from hindcast and uncertainty band of the duration
11. Fitting and selecting the parameter to estimate the duration.

A simulation model for installation

There are two simulation models for offshore wind farm installation: the foundation installation and the other for the wind turbine installation. The model can consist of essential activities with the operational limit of H_s, T_p, or WPS, and the duration consisted of an hour as a unit. Each model will be considered based on the availability of the installation vessel and the loaded number of wind turbines or the foundation (Rippel et al., 2019).

For the foundation installation model, lowering operation into the sea can be critical (Zhu et al., 2017). The physical acceptance criteria can be determined based on lifting wire tension. The detailed simulation process and the results are summarized in Appendix 2 section. Activities for the installation tripod can consist of loading a foundation, transportation, preparation, lifting & installation, and back to the port. Moreover, this set of activities is repeated until achieving all tripod is installed.

For the wind turbine installation model, the primary purpose of this model is to find out an optimized method among methods in Figure 2-8. The pre-assemble scope of the wind turbine can be changeable according to the port's available space and deck space of the installation vessel (Sarker & Faiz, 2017). Moreover, the optimization of the wind turbine's installation schedule can be achieved by significant consideration factors as below:

◦ Transportation - The number of WT sets on-board and the area size for pre-assembled in port.
◦ Limited weather window – The percentage of the offshore duration in the total WT installation duration according to each installation method.
◦ Planning – The number of the total steps for WT installation.

Activities for the installation WT can also contain loading a WT, transportation, preparation, lifting & installation, and back to the port. Like foundation, this set of activities is repeated until achieving all WT is installed.

Parameterization of hindcast data to the uncertainty band of the total duration

After selecting the best offshore installation method for tripod and WT installation, there will be a simulation for the total critical period during offshore installation in Figure 2-7. The installation of foundations and turbines can be overlapped (Kerkhove & Vanhoucke, 2017).

For the total duration of the critical period, each year's max value can be utilized to get parameters for GEV (General Extreme Value) distribution for the estimation.

Selection of model according to the shape parameter (ξ)	
$\xi = 0$	Gumbel
$\xi > 0$	Fréchet
$\xi < 0$	Weibull

Table 3-2: Summary of the interpretation of the shape parameter to select the model

Fitted distribution model can be identified by the visual check in probability plot and empirical distribution, and shape parameter in maximum simulated duration data, based on Table 3-2, according to (Coles, Bawa, Trenner, & Dorazio, 2001). The parameters in the fitted distribution model can be found out by the moment of method.

Using the Monto Carlos simulation, 1000 sets of the sample size of 50 maximum duration can be generated randomly, generating return value probability.

With the 50-percentile value in generated maximum duration, an uncertainty band from 30% to 80% can be derived from 50 years' data. It can be plotted, the uncertainty band with the parameters of T_p, H_s, WSP, and WSP100. Based on the plots, there is some relationship between parameters and total duration's uncertainty band.

Finally, using the same method in this chapter, simulation can be carried out for three different fields in chapter 3.1. to get the relationship with the parameters of T_p, H_s, WSP, and WSP100 and the total duration's uncertainty band of the critical installation.

Parameter	Description	Definition
Avg H_s	Significant wave height	The average of the highest one-third of wave height or four times the standard deviation of the sea surface elevation per day or a year
Avg T_p	Spectral peak period	The inverse of the frequency at which the spectral density function of the elevation time series is maximum per day or a year
Avg WSP100	Mean interpolated wind speed at the height of the turbine	The mean of the interpolated wind speed at the height of the turbine hub from the sea surface per day or a year
$P_{12hww, para}$	Workability of 12-hour weather window with parameters Hs, Tp, or wind speed	Defined the ratio of no. workable 12-hour weather window with min value with parameters Hs, Tp, or wind speed into the whole observed period in one field
$P_{above\_occu, para}$	Percentage of wave occurrence above the operational limit with parameters Hs, Tp, or wind speed	Defined the ratio of no. wave occurrence above the operational limit with parameters Hs, Tp, or wind speed during a specific period

Table 3-3: The list of parameters for future analysis

We can determine the relationship between parameters in hindcast data and max duration based on the plots between parameters in Table 3-3 and the uncertainty band of random sample max duration.

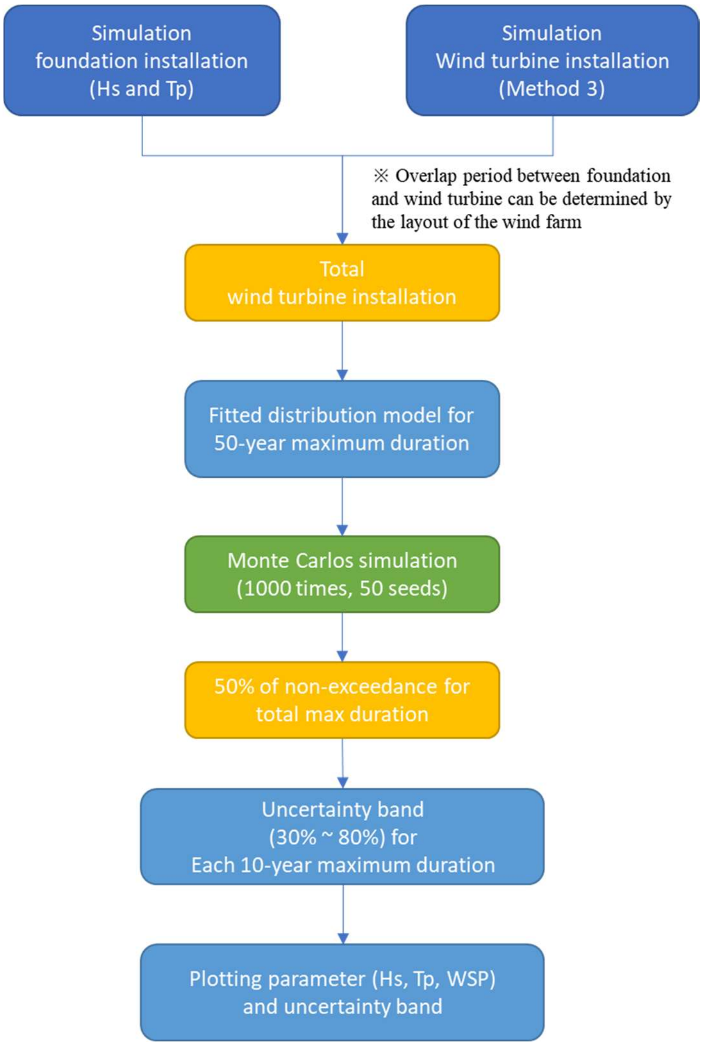

Figure 3-8: Simulation flow for the parameterization

In the next chapter, the methodology and model will be developed specifically with a detailed project record of the case study, and a simulation model is introduced.

3.3. **Case study; Global Tech 1 Wind Farm**

Global Tech 1 is in the Germain Exclusive Economic Zone in the southern North Sea (Wikipedia, 2020b). The project was approved formally by BSH on May 24, 2006. Offshore installation activity started from 09.09.2012 with tripod transportation (Lacal-Arántegui et al., 2018) and the official start of operation is on Sep.02.2015. the first project phase comprised 80ea Areva Multibrid M5000 wind turbines with a nameplate of 5MW. The total capacity of the wind farm is 400MW.

This wind farm's meaning was the longest-located wind farm from onshore when it started the offshore campaign. The reason why the Global Tech 1 wind farm is selected as the mother case of the simulation is that the foundation type is the same as the tripod, and the longest distance from the port can minimize the effect of the transportation time when different location hindcast data are used in the simulation.

Summary information can be reviewed in APPENDIX 3

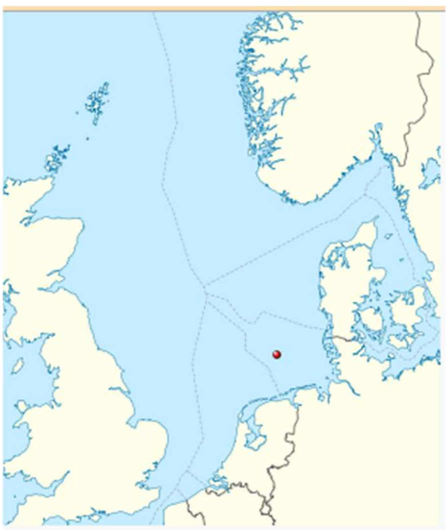

Figure 3-9: Location of Global Tech 1 wind farm (Wikipedia, 2020b)

3.3.1. The tailoring methodology for the case study

1. Boundary and assumption of the case project

The methodology described in this chapter focuses on the critical installation period in Figure 2-7 as the boundary scope. Based on the case project data and records (Wikipedia, 2020b), the case's brief specification can be summarized in Table 3-4.

Item	Description
Nameplate	400MW windfarm, 5MW wind turbine 80ea,
Location & Sea depth	Coordinate: 54 ° 30 ′ 0 ″ N , 6 ° 21 ′ 30 ″ E, up to 40m
Distance	180km from Bremerhaven in Germany
Foundation	Tripod (bottom size: 28 X 28, Height : 68m)
Wind Turbine	Manufacturer: AREVA Wind GmbH, Model: Multibrid M5000
Installation vessel for a tripod	The floating vessel, similar spec with HGO INNOVATION One trial contains three tripods
Installation vessel for a WT	Wind turbine installation jack-up vessel similar spec with crane jack-up vessels Brave Tern and Bold Tern
Height of WT	around 125m from sea level
Weight of components	Nacelle 235 tonnes Tower section Lower 90 tonnes Tower section Top 90 tonnes Hub 64 tonnes Blade (3-blade rotor) 17 tonnes x 3

Table 3-4: Brief specification for a simulation project

The detailed assumptions for this methodology are listed below.

◦ Environment conditions for loading in port can use the hindcast data of the wind farm location; however, 10m for H_s can be applied as operational criteria because the impact of the wave has a little impact on lifting activity in the mooring of the quay.

◦ The duration of each activity will be the same during the offshore campaign.

◦ Foundation and turbine are delivered when the installation vessel is ready to load at the port.

◦ Any delay from soil condition can be treated as a risk, out of the schedule.

◦ The weight of foundation or WT loaded in the installation vessel is evenly distributed on the installation vessel's deck.

2. Reviewing the significant factors for the critical installation

One of the essential factors in the critical installation is selecting an available vessel and the loading number of foundation or WT per sea trial.

For the installation of the tripod, in this case, the HGO INNOVATION jack-up installation vessel was used, and the open deck size of the vessel is 3,400 m^2 (DEME, 2020). Considering the floor area of the tripod is 784 m^2, three tripods can be loaded as maximum with the consideration of buffer space. For the simulation purpose, a floating installation vessel with the same deck size as HGO INNOVATION is assumed.

In WT installation, Brave Tern or Bold Tern jack-up wind turbine vessel is assumed to be used. The deck space is 3200 $m^{2,}$ and typically, 8ea of 3.6MW or 4ea of 8MW WT can be loaded (Fred. Olsen Windcarrier, 2020). For the simulation, max 6ea of 5MW WT can be loaded based on the NHJ method, and max 4ea of 5MW WT can be transported based on the RHJ method, mentioned in Figure 2-8.

RHJ method mentioned in Figure 2-8 needs port space to assemble three rotors and hub. Port reinforced space is assumed as the Global Tech 1 project record.

The last consideration point is the overall layout of each WT. Figure 3-10 shows each WT location (Schneemann, Rott, Dörenkämper, Steinfeld, & Kühn, 2020). Approximate 500m is the distance between each turbine, and the first row in North has 8 WTs. The installation of the tripod and WT can be carried out at the same time. Furthermore, based on the layout, it is assumed that after 30ea tripods are installed, WT installation can start to get buffer.

In a real project environment, the starting point of WT installation can be considered based on the delivery date and logistics condition of WT and environment conditions. However, the 30ea tripods can be determined to get enough buffer to carry out the WT installation campaign continuously with minimum risk in this case study.

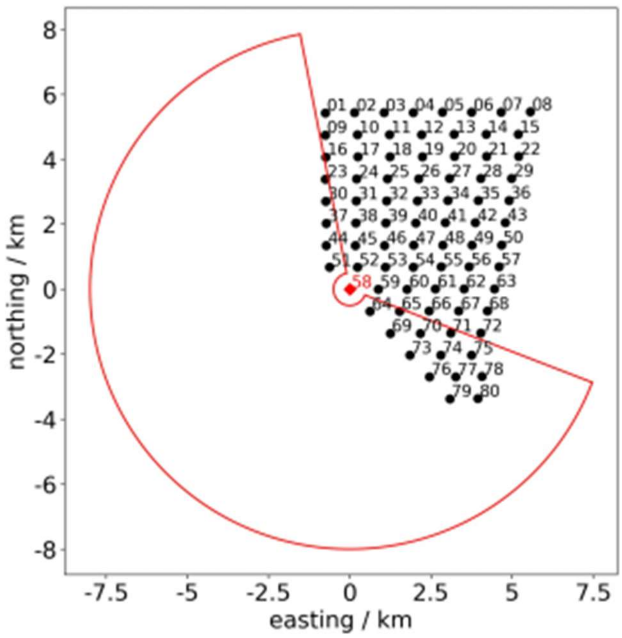

Figure 3-10: Global Tech 1 wind farm layout, (Schneemann et al., 2020)

3.3.2. The installation model for tripod and WT

Tripod Installation model

The total duration of 80ea-tripod installation can be estimated with the assumption that a floating installation vessel is used for installation, then T_p can be a significant parameter for the operational limit (Zhu et al., 2017).

For the actual record for installation of the tripod in Global Tech 1, the HGO INNOVATION jack-up installation vessel was used, and it took 6.14 days to install one tripod from actual data (Lacal-Arántegui et al., 2018). The critical information among the vessel specifications related to the offshore installation is the draft, deadweight, open deck area, crane capacity, and speed. It is vital for planning purposes to check how many foundations can be loaded in one sea trial based on the foundation size and open deck space.

Based on the vessel specification, open deck space, and the tripod's size, as mentioned in Chapter 3.3.1. Three tripods can be loaded at one trial, and in the different from the real installation, a floating heavy lifting vessel is assumed to be used for tripod installation.

Generally, tripod installation is less impacted by wind than the turbine (Thomsen, 2014), so significant wave height (H_s) and spectral peak period (T_p) are more important than wind speed in floating case.

In the Tripod case described in Table 3-5, this operational limit can be derived from numerical modeling analysis using SIMA described in APPENDIX 2, related to lowering the tripod case. The result of the numerical analysis of the lowering step is shown in Figure 3-11. And each duration of the step in Table 3-5 was assumed based on the ECN Install tool (Savenije, Asgarpour, & Dewan, 2015).

Step	Description	WPS	Hs	Tp	Dur
1	Loading 3 foundations and 9 60m-poles for installation	17	10		10
2	Traveling to the wind farm	17	4		10
3	Installation of 3 foundations (Floating HLV) including moving next location of the foundation	17	Figure 3-11		54
4	travel back to the offshore harbor	17	4		10

Table 3-5: Tripod case: installation steps for the tripod per one sea trial of the vessel (in case of a Floating vessel)

Even though operational limit has uncertainty band by Monte Carlos simulation, 50% of uncertainty band in Figure 3-11 will be used for future analysis.

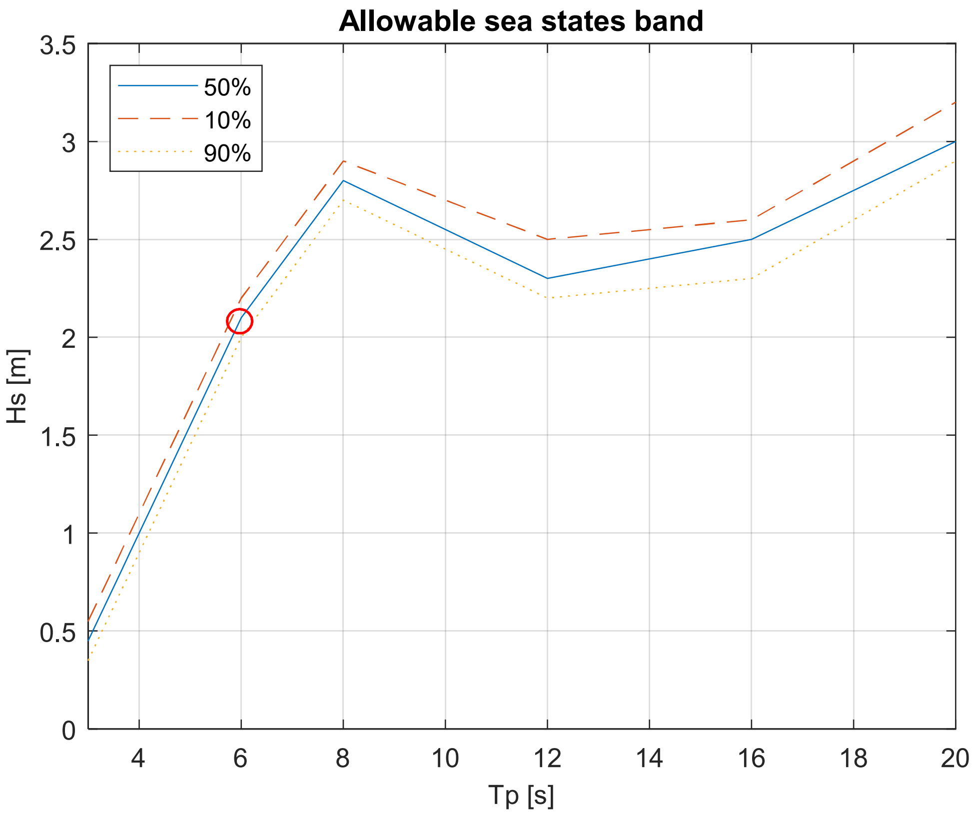

Figure 3-11: Operational limit and uncertainty band

Wind turbine installation model

The simulation model, the installation method, NHJ (Nacelle and Hub Joined onshore), and RHA (Rotor and Hub Assembled onshore) for the turbine, described in Figure 2-8, will be compared because WT method NHJ-4 has the greatest number of lifting operations offshore. RHA needed the largest size for assembling and transportation and was the used method in the case project.

Method	Loading WT (ea)	Loading Time at port (hour)	Total duration (hour)	Total duration offshore (hour)	Trial to complete (ea)
NHJ-4	4	16	3280	2960	20
NHJ-6	6	24	3160	2841	14
RHA-2	2	12	3280	2800	40
RHA-4	4	24	2880	2400	20

Table 3-6: The summary of the models for installation of WT

Table 3-6 shows a summary of the simulation models for the installation of WT, and total duration means the pure installation time without considering waiting time due to ocean state. The total duration offshore is derived from the deduction of loading time at the port from the total duration. Total duration offshore can be impacted directly by metocean status.

Like tripod installation simulation, each operational limit and duration of the step was assumed based on the ECN Install tool (Savenije et al., 2015).

The method NHJ in Figure 2-8 is that all turbine components will be lifted offshore with no pre-assembled scope onshore. It means the onshore port is only for storage before shipping. Per one offshore trial, a total of 164 hours will be consumed to install four turbines. Therefore, it takes 3280 hours to complete 80ea turbines. Net offshore working hours are 2960 hours, 90% of total duration, which is derived from excluding loading time in the port per each trial. Table 3-7 shows each activity per sea trial with operational limit and duration.

Step	Description	WPS	Hs	Dur
1	Loading 4 turbines (4 tower assemblies bottom, four-tower assemblies top, 12 blades) to the vessel	17	10	16
2	Traveling to the offshore wind farm	17	3.5	10
3	Jack up vessel	14	1.4	4
4	Upending tower bottom and bolting to TP	17	2	3
5	Upending tower top and bolting to TP	17	2	3
6	Installing nacelle	17	2	5
7	Installing 3 blades	17	2	12
8	Jack down vessel	14	1.4	4
9	Travel to the next turbine site	17	4	1
10	travel back to the offshore harbor	17	4	10

Table 3-7: NHJ method, Installation steps for all turbine parts in offshore

Installation of the turbine, method RHA in Figure 2-8, contains the actual Global Tech 1 wind farm case and analyzes the pre-assembled impact to various total duration.

Compared with method NHJ, the RHA method has turbine sets consisting of tower bottom, tower top, pre-assembled rotor, and hub. The one trial's duration is 82 hours, and there are 40 trials and 3280 hours as total duration without consideration of sea states to install 80 turbines. Table 3-8 shows each activity per sea trial with operational limit and duration.

2800 hours can be carried out offshore; it is 85% of the installation's total duration.

For this simulation, one Jack-up WTIVs are considered to have the specification to load two turbine sets, including two completed assembled turbines. A total of 40 times trials will be executed by one installation vessel.

Step	Description	Wind	Hs	Due
1	Loading two turbines (2 tower assemblies bottom, two-tower assemblies top, two completed rotor, and hub)	17	10	12
2	Traveling to the offshore wind farm	17	4	10
3	Jack up vessel	14	1.4	4
4	Upending tower bottom and bolting to TP	17	2	3
5	Upending tower top and bolting to TP	17	2	3
6	Installing nacelle	17	2	5
7	Installing assembled rotors and hub	17	2	5
8	Jack down vessel	14	1.4	4
9	Travel to the next turbine site	17	4	1
10	travel back to the offshore harbor	17	4	10

Table 3-8: RHA, Installation steps for wind turbine except for rotor and hub per 1 trial of the vessel (Jack-up type)

each operational limit and duration of the step was assumed based on the ECN Install tool (Savenije et al., 2015).

The total duration of critical installation

After finding the optimized results from the tripod installation, and installation method for WT, it is assumed that after 30ea foundations are installed, turbine installation can start offshore considering the volume of transportation for the turbine per trial as mentioned in chapter 3.3.1.

By extracting the extreme result per each year from 1960 to 2010, the uncertainty band for the total duration can be derived from Extreme Value Theory with a fitted probability plot.

The methodology and model for parameterization explained in chapter 3.3.1. , and 3.3.2. is repeated for three different field locations in Figure 3-2Figure 3-2: 3 Locations for analysis and cast study windfarm location (google map).

Chapter 4. Result and discussion

The simulation was performed based on hindcast data from FINO-3 location, and the period contains from 1958-01-01 00:00 to 2019-01-01 00:00, a total of 60 years for the simulation described in chapter 3.3.1. and 3.3.2. There is 550,767 of one-hour wave occurrence data compared with installation duration and the simulations' operational limit for tripod and selecting optimized WT method.

The tripod and WT installation models were simulated, considering every day at 6 AM as the starting point of the operation. Environmental data such as WSP, T_p, and H_s is average value for one day when each simulation starts in every result.

Chapter 4.1. presents a simulation result for tripod installation with the T_p and H_s in the floating wind installation vessel. And chapter 4.2. shows optimal installation method for a wind turbine and the sensitivity result of various activity duration in APPENDIX 1.

Finally, chapter 0presents the relation graph between parameters from hindcast data and the total duration of the critical installation period

4.1. **Results assessing installation of the tripod**

The planning schedule model of the tripod in chapter 3.3.2. was applied to assess the impact of the floating installation vessel on an offshore installation. The simulation was for different sets of time series (1h), considering every 6 AM per each day as the operation's starting time.

In Figure 4-1, this empirical distribution can estimate the duration of a tripod installation based on the probability. Generally, during the concept selection phase or FEED phase, duration and cost can be considered in ±30%. In practice, the P20 and P80 percentile of empirical distribution can be used for decision support. When observed time series are considered, the P20 and P80 interval of the duration may range from 123 days to 193 days to install 80ea tripods.

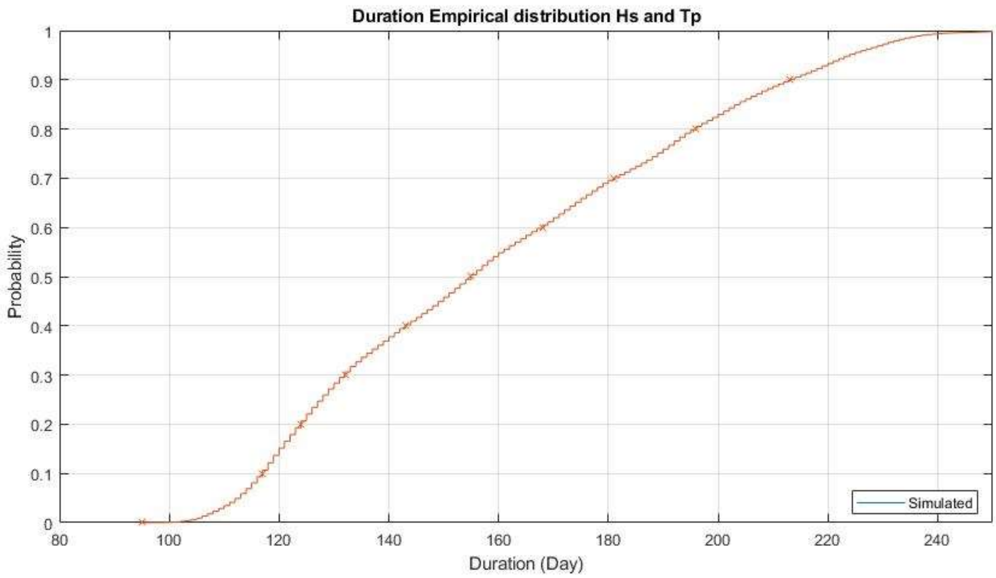

Figure 4-1: Empirical distribution of total duration in tripod simulation

There is also a summary value in Table 4-1, and downtime is calculated as the remaining value deducted by the necessary duration, 91 days, without environmental consideration from the simulation result.

Unit: day	Average	Standard deviation	Maximum value
Total duration	148.6	35.0	245.8
Weather downtime	57.6		154.8

Table 4-1: The overall result of the simulation in the tripod case

In the tripod simulation, the operational limit is derived from the hydrodynamic model by SIMA, as shown in Figure 3-11. There is a variation of H_s, according to T_p.

If H_s 2.5m is fixed for lowering operation, 82.8% of the whole wave occurs during 60 years of hindcast data are covered. Meanwhile, the operational limit from the simulated case contains 83.5% of the total wave occurrence during 60 years of hindcast data. It means that the operational limit of H_s given by T_p does not make a big difference in a simple comparison of all Hs in hindcast data. Moreover, Figure 4-2 shows a visual comparison between two operational limits in the scatter diagram of H_s and T_p. The yellow area covers the operational limit for fixed H_s, 2.5m, and the red area covers various H_s' operational limits in the tripod case.

3	0	0	0	0	0	1	589	1754	2537	913	252	79	25	8	13	7	0	1	0	0	6179
2.9	0	0	0	0	0	2	809	2024	2594	890	253	66	39	28	13	7	2	0	2	0	6729
2.8	0	0	0	0	0	4	1110	2397	2472	744	274	64	29	27	8	6	1	0	1	0	7137
2.7	0	0	0	0	0	9	1428	2851	2492	733	198	67	42	26	11	10	0	2	2	0	7871
2.6	0	0	0	0	0	30	1886	3222	2430	646	248	95	37	27	23	11	4	0	0	0	8659
2.5	0	0	0	0	0	58	2526	3618	2248	675	234	106	62	41	28	11	4	0	0	0	9614
2.4	0	0	0	0	0	140	3053	4016	2084	633	258	104	63	38	22	13	6	0	1	0	10432
2.3	0	0	0	0	1	305	3724	4140	2011	622	240	122	69	35	25	15	6	0	1	0	11316
2.2	0	0	0	0	3	772	4211	4235	1842	523	210	116	62	46	26	16	0	2	0	0	12064
2.1	0	0	0	0	6	1430	4596	4370	1834	558	239	115	84	39	29	20	5	3	1	0	13329
2	0	0	0	0	18	2252	5115	4401	1599	551	221	122	77	75	25	17	6	2	1	0	14482
1.9	0	0	0	0	48	3466	5221	4198	1528	546	232	137	133	67	26	15	7	3	3	0	15630
1.8	0	0	0	0	106	4627	5538	4003	1482	568	202	148	119	66	20	15	6	0	0	0	16900
1.7	0	0	0	0	245	5829	5999	4145	1540	600	236	162	140	66	37	18	8	2	0	0	19027
1.6	0	0	0	1	512	7164	6022	4128	1514	552	289	207	189	64	29	12	4	4	1	0	20692
1.5	0	0	0	3	1133	7982	6265	4119	1390	489	239	235	189	58	15	17	21	0	0	0	22155
1.4	0	0	0	5	2271	8372	6143	4005	1463	470	311	245	155	58	32	22	11	2	0	0	23565
1.3	0	0	0	20	3982	7878	6179	3890	1364	505	359	280	131	54	32	21	4	3	0	0	24702
1.2	0	0	0	99	5926	7234	6443	3850	1092	514	432	361	167	59	28	21	9	3	0	0	26238
1.1	0	0	0	245	7432	6386	6822	3424	916	581	504	307	145	44	30	19	11	2	0	0	26868
1	0	0	1	611	8298	6524	6940	3173	953	706	511	265	119	47	44	38	27	7	4	0	28268
0.9	0	0	2	1401	8380	6847	6224	2482	932	693	472	223	102	32	32	33	25	4	4	0	27888
0.8	0	0	4	2433	8719	6857	5605	1955	1007	743	404	172	90	51	33	23	22	12	6	0	28136
0.7	0	0	37	4150	8152	7010	4627	1466	932	530	268	159	92	100	41	21	12	6	8	0	27611
0.6	0	0	179	5253	6909	6896	2992	1182	731	332	256	166	112	65	45	45	27	11	11	8	25222
0.5	0	0	374	4614	5180	5601	1676	915	453	264	222	136	113	70	48	49	20	16	10	9	19774
0.4	0	0	362	3200	4731	3226	1154	679	364	244	211	133	133	89	64	34	23	18	10	0	14678
0.3	0	0	253	2292	3768	1377	696	373	217	206	196	183	143	125	85	71	33	16	8	3	10051
0.2	0	0	244	1864	1634	469	339	226	181	168	103	96	74	46	29	22	9	3	2	0	5509
0.1	0	0	205	584	274	95	135	212	127	102	79	44	24	14	19	7	3	2	3	0	1929
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Sum
Sum	0	0	1661	26775	77728	108844	115164	91228	57800	33604	18813	9396	4899	2210	1248	769	367	138	84	20	Tp Hs

Figure 4-2: 50-year scatter diagram of Hs and Tp at FINO3 with operational limit coloring

There is a 0.7% wave occurrence difference between the hydrodynamic model's operational limit and fixed Hs 2.5m as the maximum value in an operational limit. However, this difference makes a longer installation duration and more significant uncertainty than the fixed operational limit, Hs, and It can be visualized in Figure 4-3.

The main reason for showing the more extensive range of the simulated case duration is that some of the Hs criteria given by Tp are lower than in case 1 in Figure 4-2. The average value of Hs is 2.27m even though higher Hs criteria are applied for simulation.

Because the operational limit from the hydrodynamic model is adjusted detailed for greater H_s given by T_p than the fixed operational limit given by T_p, there is a sharper installation duration. Therefore, It has beneficial to use the operational limit from the hydrodynamic model for the critical step.

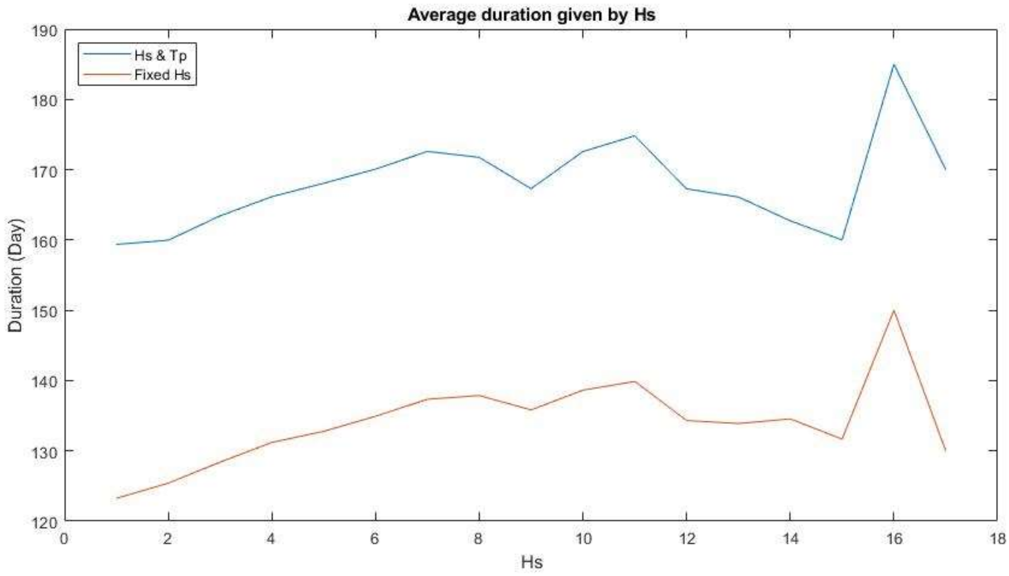

Figure 4-3: Average installation duration given by Hs

Additionally, above the Hs, 7m, the total duration of the 80ea-tripod has a downward trend because the Hs in Figure 4-3 is represented as the average Hs of every starting day. It means that when forecasting hindcast data within 24 hours shows H_s over 7m, the decision to go to install the tripod cannot be determined.

4.2. **The optimal installation method for wind turbine**

The simulation was carried out to compare method NHJ and RHA based on the net offshore working duration difference, and the net offshore working duration is taken by deducting total duration from the loading time of WTs in the port. If the CDF curve has a smaller duration than other methods, the smaller-duration method can be determined as the optimal solution considering environmental uncertainty.

Figure 4-4 shows all cases' empirical distribution of the simulated duration.

There is almost no difference in simulation results between method NHJ with four WT loading and RHA with two WT loading. It is generally accepted that pre-assembled of any parts onshore can save time offshore. However, two sets of rotor and hub loading per one trial cannot produce a useful result from pre-assembled in port. Over 5% discrepancy in offshore working duration between WT installation methods can develop pre-assembled value onshore.

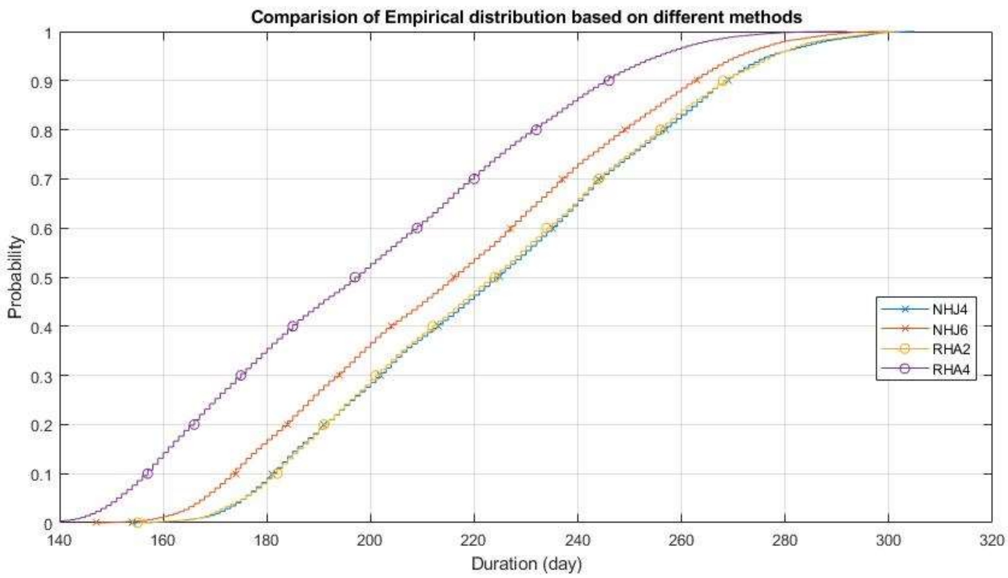

Figure 4-4: Comparison of all method cases with different loading WT based on CDF

The number of WT sets loaded in the vessel can be decided based on the size of the open deck space, deadweight, crane capacity of the installation vessel, space, and ground condition in port. Vice versa, the number of WT sets can be an indication for the selection of the vessel and the required area in the port. Based on the results, it is more beneficial that the vessel loading 4 WT in RHA can be selected in the planning stage of the project.

The influences of the number of WTs on board on the duration variation of each installation method are compared. An increase of 2 WT sets in loading from RHA2 to RHA4 can reduce the P50 duration from 227 days to 216 days, and P50 duration was decreased from 224 days to 197 days for NHJ4 and NHJ6. Therefore, method RHA has more sensitivity to the loading number of WT than method NHJ.

Based on the simulated result, if the project manager wants to expedite the installation progress, RHA has more flexibility and effectiveness when an additional installation vessel or a supply vessel is applied. Method RHA with 4 WT loading case (RHA4) has the minimum duration in Table 4-2, and it is the best-optimized option with environmental uncertainty, and it is a valuable decision to get the flexibility from the beginning stage in the project.

	Original duration	**Offshore duration**	**Mean**	**Max**	**P50**
NHJ4	137	123 (90.2%)	224.6	305	225
NHJ6	137	117 (85%)	224.2	302	224
RHJ2	132	118 (89.9%)	216.9	300	216
RHA4	120	100 (83.3%)	199.2	292	197

Table 4-2: Summary of the simulation result for each WT installation method

Table 4-3 presents simulation results from each month; March in a year is identified as the best month to start WT installation operation due to the lowest average duration considering the environmental factors. June and July are the calmest weather and very beneficial to minimize the uncertainty from wind and wave; however, a minimum 6-month duration of total installation needs to begin earlier than June.

Higher average WSP100 and H_s during the start date can not always show the higher duration of the operation.

	Average		Average (Day)			STD (day)		Max (Day)	
Month	WSP 100 (m/s)	Hs(m)	NHJ4	RHA4	Gap (1 - 2)	NHJ4	RHA4	NHJ4	RHA4
1	12.9	2.2	200.3	200.5	- 0.2	29.5	29.5	259.8	252.1
2	12.0	1.9	187.8	187.9	- 0.1	27.4	27.2	234.8	234.1
3	11.3	1.7	182.2	182.2	0.0	25.8	25.9	221.2	229.5
4	9.4	1.3	187.1	186.9	0.2	29.2	29.1	276.6	265.1
5	8.6	1.1	213.0	212.1	0.9	38.4	37.7	291.5	282.3
6	8.7	1.2	239.4	238.6	0.8	41.2	41.2	304.6	301.7
7	8.7	1.2	253.7	253.0	0.7	24.4	25.1	300.8	300.8
8	8.9	1.2	258.4	257.9	0.5	20.3	21.0	302.8	299.8
9	10.4	1.5	254.9	254.4	0.5	18.5	19.2	298.3	298.0
10	11.8	1.8	244.5	242.4	2.1	29.4	34.3	292.3	288.3
11	12.6	2.1	229.9	229.2	0.7	34.4	34.6	276.3	274.7
12	12.8	2.2	215.5	215.2	0.3	32.1	32.1	268.7	265.0

Table 4-3: Monthly simulation result for the duration (day)

In the real project execution phase, a short project total duration is essential to save the Capex, and the total project execution has the minimum duration in the beginning stage. Due to this reason, there is a consideration of all-year operation offshore for further simulation.

Additionally, each year's simulated duration results can be collected based on H_s, WSP100 of average data per day. Figure 4-5 and Figure 4-6 present that day-average Hs and WSP 100 when the simulation starts per day are compared with each simulated duration for 50 years. These figures show that a certain degree of the wave height and WSP100 tend to be lower as Hs and WSP100 increase. The simulated duration below 4 m in Hs and 23m/s in WSP100 can have the simulation’s validity based on the trend.

The value of P50 in CDF is more representative than the average value of all because the distributions given by Hs and WSP100 do not follow the normal distribution.

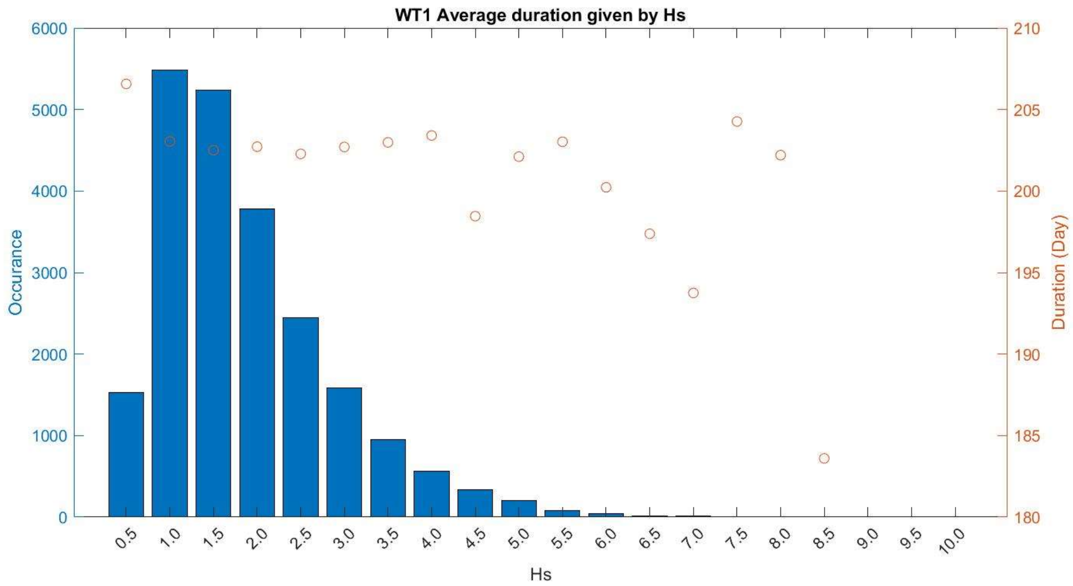

Figure 4-5: Average duration of WT installation (NHJ4) given by H_s

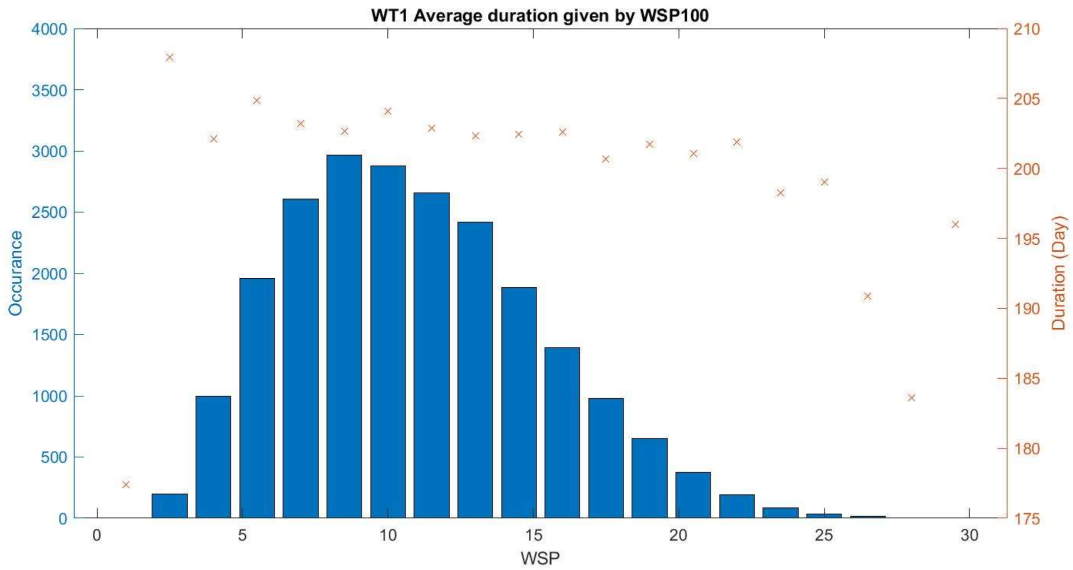

Figure 4-6: Average duration of WT installation (NHJ4) given by WSP100

4.3. **Parameterization to predict the installation duration**

Based on the results from Chapter 4.1. and 4.2. total installation duration can be calculated from the case, tripod with operational limit, T_p and H_s, and RHA4 in the WT installation case. Before simulation starts, the necessary total duration can be calculated on the 30ea tripod installation, 840 hours plus turbine installation, 2880 hours; so, total duration is 3,720hours (155 days) without considering environmental uncertainty. The simulation period is from 1960 to 2010, a total of 50 years. Final simulated data has 50ea of maximum total duration per each year.

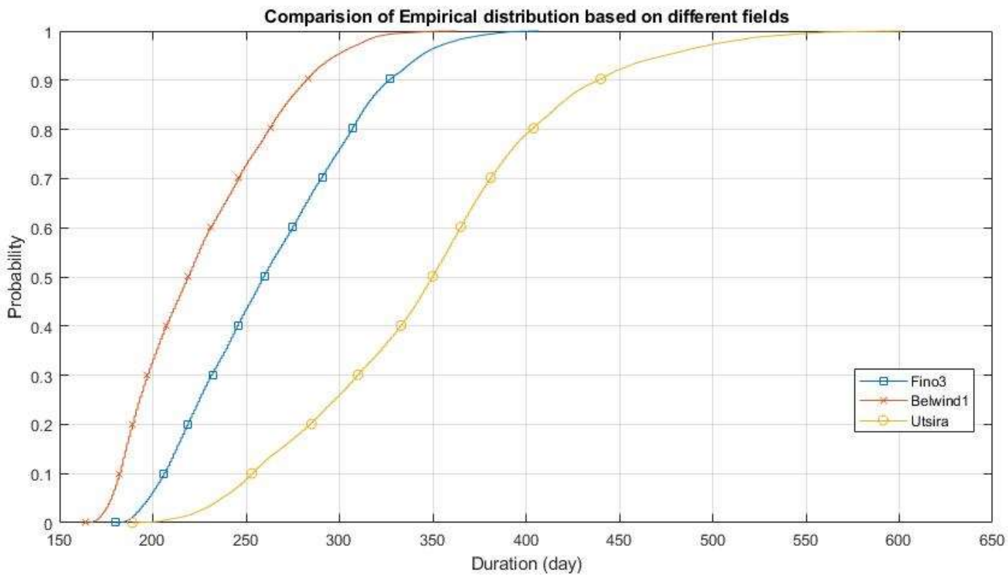

Figure 4-7: Comparison of the empirical distribution for the duration in all fields

Unit(days)	**P20**	**P50**	**P80**	**Mean**	**Max**
Belwind1	189	219	262	226	363
Fino3	219	259	307	264	407
Utsira	284	350	403	348	601

Table 4-4 and Figure 4-7 show the final simulation result for 80ea WTs installation, based on three locations' hindcast data. The harshest environment, Utsira, has the highest value of the critical installation duration, as mentioned in Chapter 3.1. and the broadest range between P30 and P80.

Compared with Figure 3-4, the maximum total duration increase as the average value of H_s, T_p, and WSP 100 increase except for wind speed, and it is hard to express the relationship between average H_s and T_p in 50 years and simulated total duration because there is only a difference of the average Hs in second decimal place between FINO3 and Global Tech 1 as target field.

Unit(days)	**P20**	**P50**	**P80**	**Mean**	**Max**
Belwind1	189	219	262	226	363
Fino3	219	259	307	264	407
Utsira	284	350	403	348	601

Table 4-4: Simulated results for the total duration based on hindcast data in Figure 3-2

The fitted distribution model for the maximum duration for uncertainty band

Each year's maximum total duration from 1960 to 2010 is extracted, and a total of 50 seed numbers of the max value will be analyzed using extreme value theory and Monte Carlo simulation to get the credibility of the uncertainty band by increasing the number of trials.

There are two ways to find out the fitted probability plot, as mentioned in Chapter 3.2. The shape parameter can select the fitted distribution plot in extreme value according to Table 3-2. Table 4-5 shows that the shape parameter of all fields' yearly max duration is less than 0; therefore, 3P Weibull distribution is decided for future analysis.

	Location	Scale	Shape
Belwind1	287.3	22.1	- 0.13
FINO3	329.9	30.0	- 0.25
Utsira	434.0	59.1	- 0.26

Table 4-5:Summary of GEV parameters in each field

For visual check, in plotting data through Figure 4-8, empirical data have been more fitted with the probability plot of 3P Weibull distribution than the Gumbel and 2P Weibull distribution. 3P Weibull distribution can reduce the uncertainty in the tail area, which is mentioned in chapter 2.3.2. Therefore, for future analysis, the 3P Weibull distribution can be determined as the most fitted distribution.

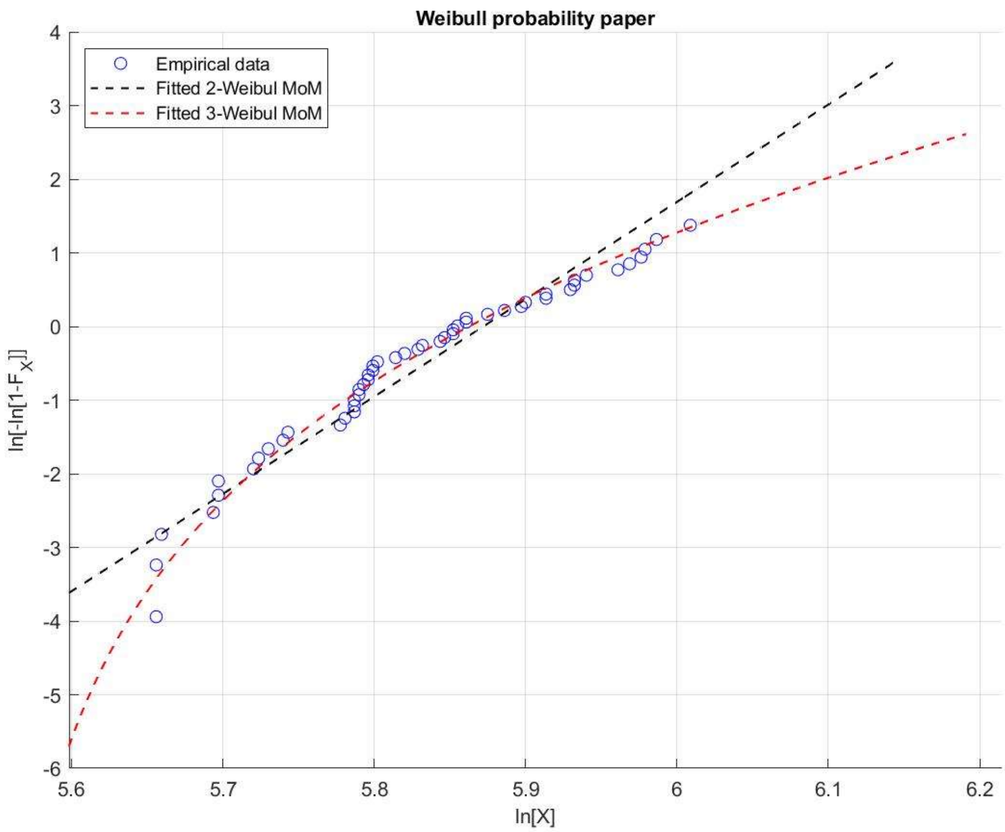

Figure 4-8: 2P, 3P Weibull probability plot with the empirical distribution

1000 times simulation by Monte Carlos simulation

Table 4-6 shows the parameters in the 3P Weibull distribution probability plot, and the 1000 random sample data have been generated by inputting the probability with these derived 3P Weibull parameters

	Scale (α)	Form (β)	Location (λ)
Belwind1	62.2	2.3	242.6
FINO3	95.4	2.9	256.3
Utsira	202.8	3.3	273.8

Table 4-6: Summary of 3P Weibull parameters in the fields

In Figure 4-9, the reliability of the data randomly generated can be checked. The green line is the original 3P Weibull distribution of 50 seeds, and blue circles mean empirical data of 50 seeds from each year's max duration in FINO3. All thin-different-color lines are the 3P Weibull probability plots by Monto Carlo simulation. Throughout the visual checking, original empirical data and probability plot are in the 3P Weibull probability plots by MC; therefore, MC's randomly generated data can be reliable.

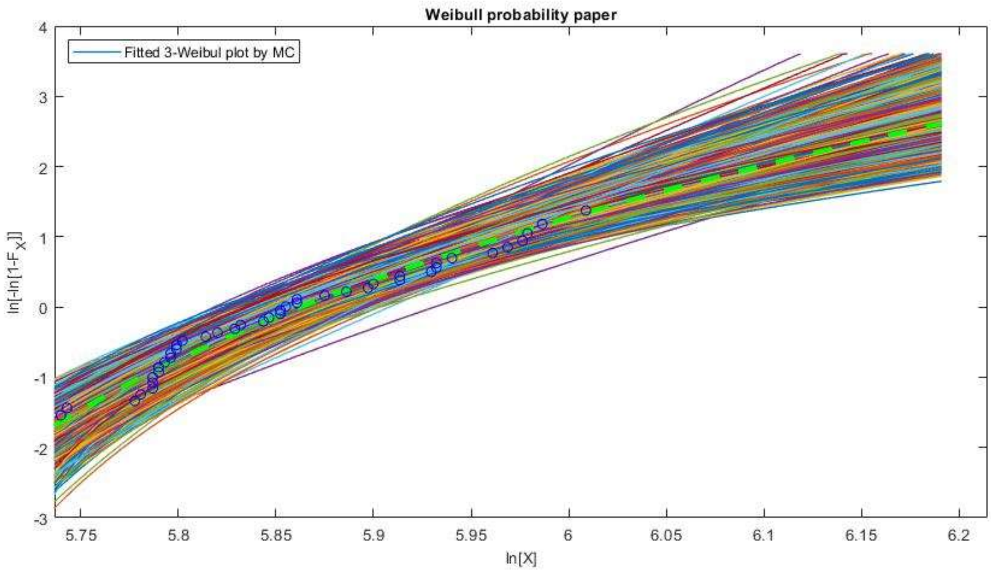

Figure 4-9: Comparison of original 3P Weibull and random generated 3P Weibull bu Monto Carlo

With 50 percentile of the maximum duration from 1000 times simulation, the uncertainty band from 20% to 80% can be derived. Table 4-7 shows the final summary of the uncertainty band of the maximum duration of each field, and comparing with Table 3-3, we can determine the relationship between one of the parameters in Table 3-3 and the uncertainty band in Table 4-7 to forecast maximum duration in the target field.

Field	**Uncertainty band of max duration by MC (Day)**			
	P20	P50	P80	Range (P80 – P20)
Belwind	292	296	299	7
Fino3	336	340	344	8
Utsira	447	455	463	16

Table 4-7: Uncertainty band of max duration from 1000 times Monte Carlo simulation

Parameterization of hindcast data to uncertainty band of max duration

The combination of Figure 3-3, Figure 3-4, Figure 3-5, and Table 4-7 shows the relationship between the parameters of the average H_s, T_p, WSP100, and max duration uncertainty, and It means that each year's simulated duration results can be compared with H_s or WSP100 of average data each year. Except for WSP 100, H_s and T_p's increasing values show an increase in max duration; however, the gap between all fields is under 1 meter or 1s. It is hard to represent the difference in max duration.

$P_{above\_occu,\ para}$ in Table 3-3 can be matched with the uncertainty band of the max duration. According to the case installation method, the minimum operational limit of H_s is 1.4m in Table 3-8. $P_{above\_occu,\ 1.4m}$ means the ratio of the number of wave occurrence above H_s, 1.4m with the total number of wave occurrence for each field.

Figure 4-10 shows the relationship $P_{above\_occu, 1.4m}$ from the hindcast data for each field and uncertainty band of the max duration. The circles, represented as simulated data in the figure, mean the corresponding P50 values in Table 4-7 with each field. If $P_{above\_occu, 1.4m}$ is zero, it can be considered no variation from the environment to the total duration. So the value in the y-axis is 155days. With 4 points of the simulated data from the result in Table 4-7, we can determine the proper function of the uncertainty band of the max duration, given by $P_{above\_occu, 1.4m}$. The non-linear fitting of the 4-degree polyfit function is applied to find out the relationship of max duration.

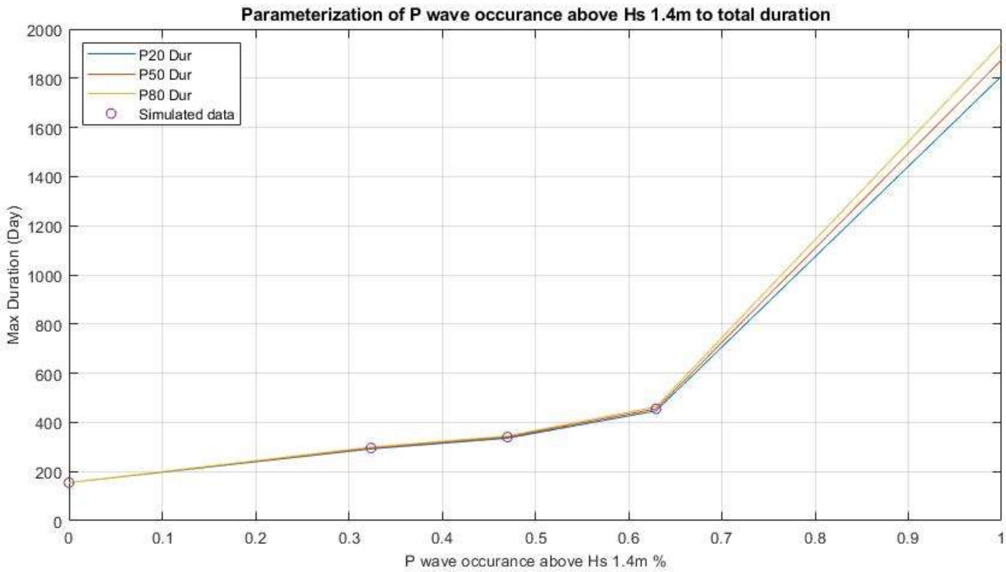

Figure 4-10: Parameterization of P above_ocurr, 1.4m to uncertainty band of max total duration.

If a specific target field has $P_{above\_occu, 1.4m\ Hs}$ over 64, we can determine that it has too considerable uncertainty from the environment to install the wind farm with RHA4 method and tripod installation with floating vessel without numerical simulation according to Figure 4-10.

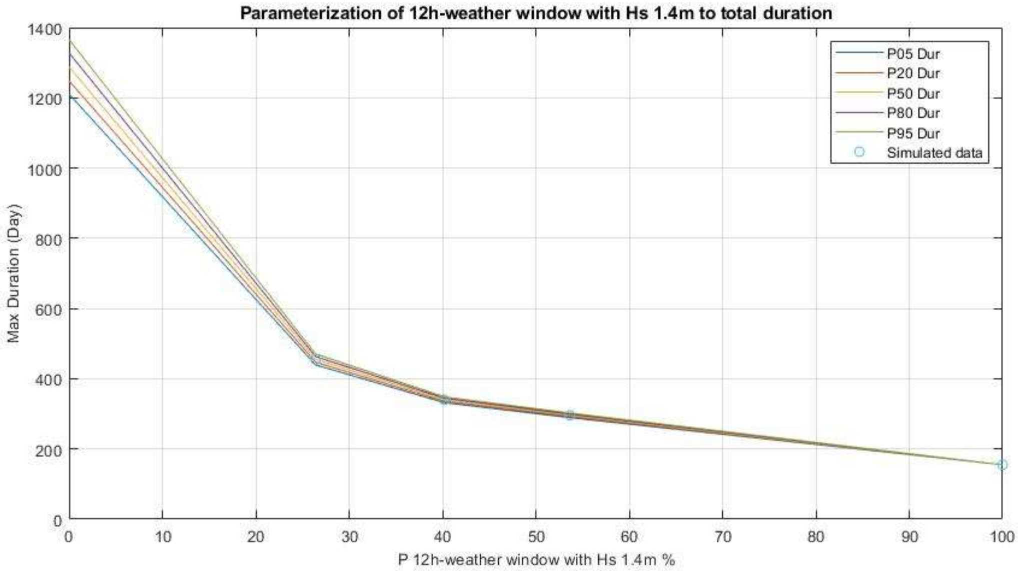

Figure 4-11: Parameterization of P 12h ww, Hs 1.4m to uncertainty band of the max total duration

Similar manner to $P_{above\_occu,\ 1.4m}$, $P_{12hww,\ 1.4m\ Hs}$ in Table 3-3 can also be parameterized; however, 100% of $P_{12hww,\ 1.4m}$ means no impact from wave or other factors from the sea, so the shape of the grape is opposite from right to the left side. The non-linear fitting of the 4-degree polyfit function is applied as the $P_{above\_occu,\ 1.4m}$ Parameterization with the same simulated max duration data in Table 4-7. Adding P05 and P95 values into the grape can cover the wider uncertainty band of max duration.

Based on Figure 4-11, if some candidate area for a wind farm has $P_{12hww,\ 1.4m}$ above 40%, this area can be considered a high possibility to be developed with the RHA4 method and tripod installation with a floating vessel in visual checking.

Testing Parameterization of $P_{above\_occu,\ 1.4m}$, and $P_{12hww,\ 1.4m}$

To check the credibility of the parametrization of the $P_{12hww,\ 1.4m}$, the numerical simulation with RHA4 and floating installation tripod in Chapter 3 was carried out by using the hindcast data of the Global tech1 field.

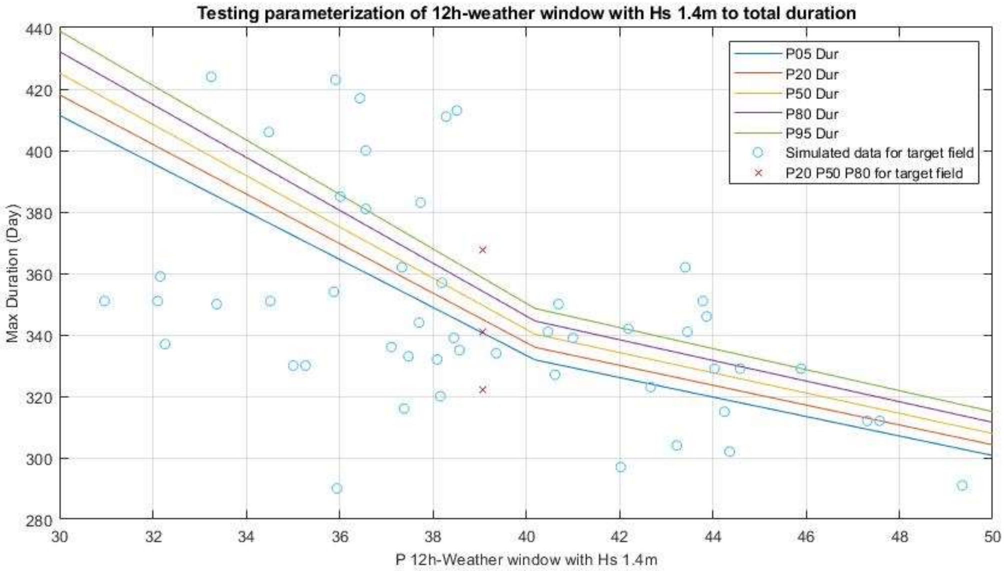

Figure 4-12: The testing result of Parameterization with Global Tech1 simulated data

Figure 4-12 presents the result by comparing the parameterization graph and simulation data from Global tech 1 field with "◦" in Figure 4-12, which represent year maximum duration for 50 years

Total 13 simulated results and P50 value in 50 results are located in uncertainty band, and it can be determined that the parameterization of $P_{12hww,\ 1.4m}$ has validity if the RHA4 WT installation method and tripod with floating vessel are used for any place in North sea with some uncertainty.

Chapter 5. Conclusion and future works

The concept study or planning stage of an offshore wind farm is the most critical phase during the project life cycle. Identifying the risk or uncertainty and considering many options in point of schedule and cost can guarantee the project's success. This study focuses on identifying the uncertainty band of the project schedule in the offshore campaign with the H_s parameter related to the weather window by using much metocean data.

The development of the wind farm in the execution phase contains the scope from the contract with BOP and WT to the connection of existed grid and commissioning. However, to reduce the complexity of a simulation model and identify the uncertainty from the offshore environment, the simulation scope is defined as the installation of a tripod and WT.

Firstly, CDF of the total duration to install 80ea tripods with the operational limit derived from numerical modeling for the tripod lifting operation. Even though most of the offshore installation period can be overlapped with the installation of WT, the analysis result presents that T_p and H_s are better applied for operational criteria than WSP when the floating vessel is employed.

Secondly, there are five general methods for WT installation. The best optimized WT installation method can be determined based on the project environment. This research compares NHJ and RHJ methods with different loading WT in an installation vessel per sea trial. RHJ with 4 WT loading case can be identified as the best-optimized solution without considering the cost. The result means minimizing offshore installation duration and maximizing the number of WT loading per one trial can diminish the uncertainty from weather and weather downtime.

Using simulation data from tripod installation and WT installation of the RHJ loading case, the total duration can be developed, if WT installation can begin after four-row tripods (30 tripods) are installed to prevent unnecessary delay due to the delivery of WT. The CDF of the total duration can be simulated for three locations, including location, near Norway in North Sea, where it has harsh environment condition. The result for simulated total duration has the highest value and broader gap between P30 and P80 values similar with analysis result of H_s, and T_p from hindcast data.

In detail, parameters from hindcast data of three different locations are compared with the total duration to determine the relationship. H_s and T_p's increasing values show an increase in max duration; however, all fields' gap is under 1 meter or 1s. It is hard to represent the difference in max duration.

As the most relevant parameter from hindcast data, $P_{12hww,\ 1.4m,}$ percentage of 12-hour weather window with Hs, 1.4m represents the relationship to total duration based on the RHA4 method and tripod installation with a floating vessel in visual checking. If a candidate field has $P_{12hww,\ 1.4m}$ below 40%, this area has a low possibility to be developed with the RHA4 method and tripod installation with a floating vessel in visual checking. Moreover, if the planned-developed location for the wind farm has 48% in $P_{12hww,\ 1.4m,}$ the max duration for the total offshore installation can be estimated as 318days with a 50% percentile. It means 163 days of downtime will be expected during the offshore installation period. Therefore, the total figure of the estimated duration can present the basis for the cost and schedule analysis easily.

Future work

To increase the credibility of the final parameterization of $P_{12hww,\ 1.4m}$, more hindcast data to be analyzed in the same manner because more samples reduce the bias of the result in the population. The durations and constraints for each modeling activities could be reconsidered to account for performance by the different installation vessel used.

This final simulation result in the parameterization of $P_{12hww,\ 1.4m\ Hs,}$ is derived from one specific WT method and an installation vessel in this study. There is a limitation for a different method or floating installation vessel used. For future work, simulation results for BEJ and NHJ are added with 2 or 4 loading cases.

Because the development of the wind farm is going deeper and deeper, utilizing the floating installation vessel for WT and foundation vessel should be considered a base case. Numerical modeling and simulation for WT installation onto the foundation by a floating installation vessel should be included to determine the operational criteria for installation activity for future work.

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APPENDIX 1: Uncertainty from activity duration

Sensitivity test for the number of steps for the total installation for the turbines

This sensitivity test can present the duration of activity and total simulation steps to the total duration result.

Method (80ea)	Loading Turbine (EA)	Loading Time at port (Hour)	Total duration (Hour)	Total duration in offshore (Hour)	Trial to complete (No. trial)	No of steps per one trial	Total Steps
NHJ-Plan	4	16	3280	2960 (90.2%)	20	23	460
RHA-Plan	2	12	3280	2800 (85%)	40	15	600

Table A1-1: Sensitivity test for the steps and duration of the activity

Table 3-7, the method NHJ, step 4,5,6,7 is combined into two steps, as described in

Table A1-2. The change makes the total simulation steps from 620 to 460.

Step	Description	WPS	Hs	Dur
4,5	Upending tower top & bottom and bolting to TP	17	2	6
6,7	Installing nacelle & 3 blades	17	2	17

Table A1-2: Modified installation steps for Method NHJ per one WT

From Table 3-8, the method RHA steps 4,5 are combined into one step as Upending tower top & bottom and bolting to TP with 6 hours duration. The change makes the total simulation steps from 680 to 600 to install 80ea WTs.

Sensitivity test of the number of steps in the schedule

For planning purposes, the suitable scope defined, and the critical activities' duration are essential to avoid overestimated results. It compared the influence of the duration of critical activities related to the installation of nacelle or blades to the variation of each installation method's duration.

	Total duration	Offshore duration	One trial steps	Mean (Day)	Max (Day)	P50 (Day)
NHJ (620 steps)	137	123 (90.2%)	31	224.6	305	225
NHJ-plan (460 steps)			17 (-50%)	227.0	307	227
RHA (680 steps)	137	117 (85%)	23	224.2	302	224
RHA-plan (600 steps)			15 (-30%)	224.4	302	224

Table A1-3: Summary of the result in the change of the number of steps

Figure A1-1 shows the increase of uncertainty in Method NHJ4 simulated duration compared with only different steps. However, there is not a difference in that in Method RHA2.

If one sea trial's duration is compressed less than 50% from the original to reduce the simulation time, there will be additional uncertainty in total installation duration.

In NHJ4 (460 steps), the activity, installing nacelle & 3 blades, has 17 hours duration modified from 5 or 12 hours of each installation of the nacelle and three blades. Due to the installation activity with the operational limit, Hs 2m, there is an additional waiting time to ensure the weather window for 17 hours, even though nacelle and blades do not need to be installed continuously.

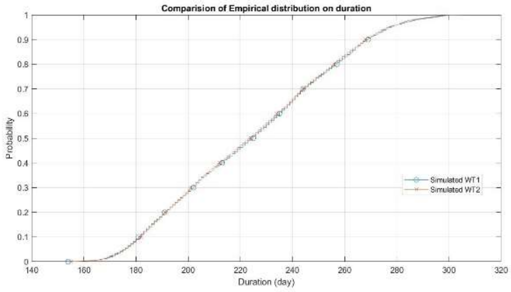


Figure 1: NHJ4 – 620 steps, Method 3 – 680 sets

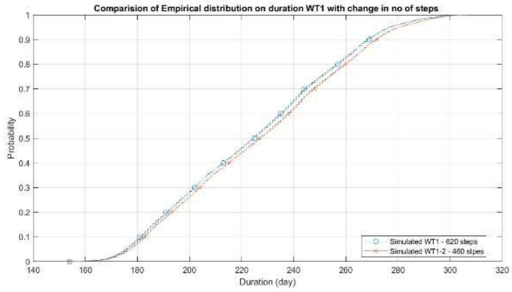


Figure 2: NHJ4 – from 620 to 480 steps

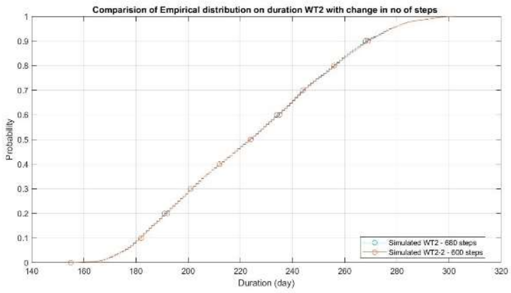


Figure 3: RHA2 – from 680 to 600 sets

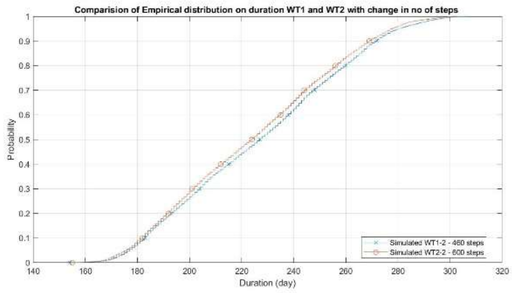


Figure 4: Final result

Figure A1-1: The result for sensitivity test related to the number of steps for each method

APPENDIX 2: Numerical simulation of tripod installation

Introduction

lifting operation of the tripod for wind turbine will be the model to be analyzed, and this project domain of the lifting operation is that the lifting down of the tripod from air to sea to find out the operational limit for critical installation activities for a tripod.

This study comprises five main areas: extreme value method, statistical inference, numerical modeling of the lifting operation, time-domain simulation with many seeds, and finding the uncertain band for allowable sea states with dynamic amplification factor in an offshore environment.

The uncertainty's primary analyzed data are the maximum tension values of lifting wire connecting the crane tip and tripod in each seed. Finally, the methodology and assessment process to assess the uncertainty band in allowable sea state will be the main subject to be discussed in this project because there is a relatively small variance of the maximum tension data.

Simulation model

Using the SIMO provided by MARINTEX, the environment and objective of simulation have been created in Figure A2-1. A construction vessel with lifting devices and tripod are modeled for this simulation. However, to reduce the heavy load of CPU in computer with max 200 seed number simulation, the model can be more detailed on crane and tripod then construction vessel. For other information, the length of the time-domain simulation is 35500s, and a tripod is lowering from air into seawater during the time.

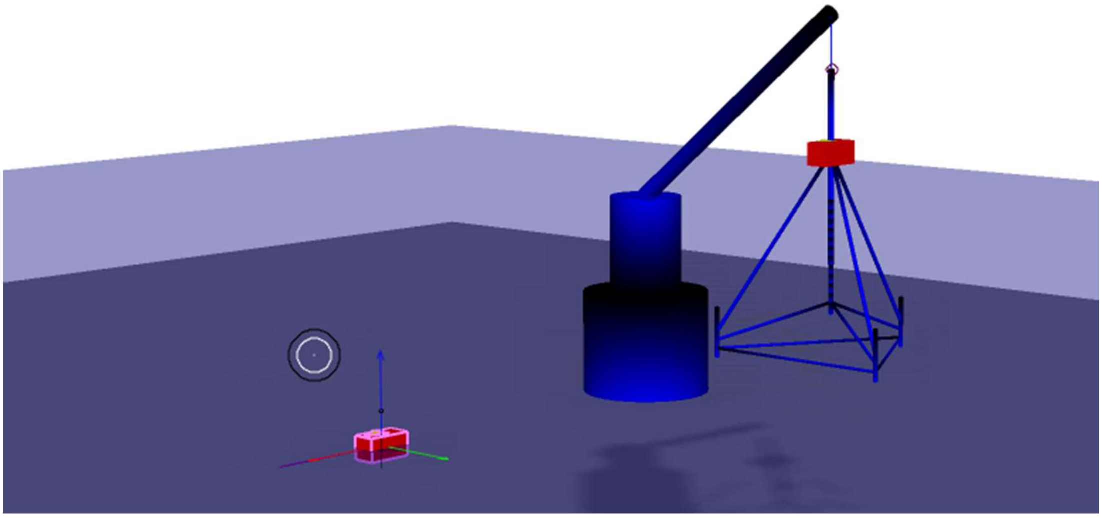


Figure A2-1 Modeling capture from SIMA

For the efficiency of this simulation, these assumptions can be applied related to the lifting environment.

1) Wave is the dominant factor for environmental condition

2) Mooring line of the lifting vessel can be considered to have a linear stiffness term in the surge, sway, and yaw motions

3) Ballasting water can be replaced with introducing the specified moment to compensate for the significant roll motion

4) The construction vessel model can be used as the default arrow box in SIMA with motion-related values

5) 165 degrees is considered a wave direction in this simulation

Methodology

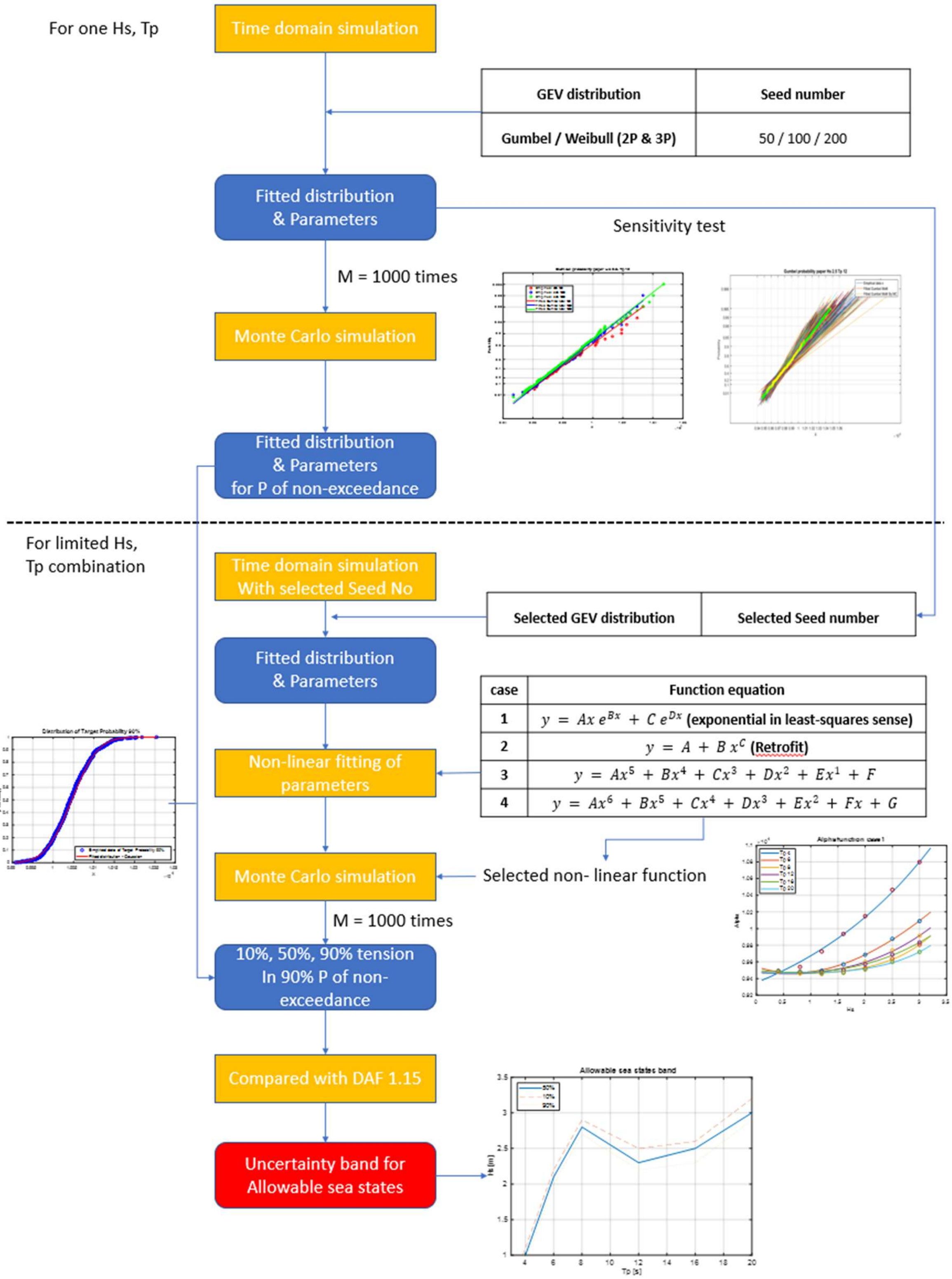


Figure A2-2: Method process chart for the uncertain band

Simulation

Figure A2-3 shows the example of the lift wire tension's time history during the lowering phase of the tripod in the given Hs, 2m, and Tp 6s. The trend of tension is down from the time, 15000s. It means that the tripod is contacted on the surface of seawater due to the buoyancy of the tripod. Furthermore, continuously the tension of the lifting wire is getting lower until all tripod is submerged. In the present study, the value of maximum lifting tension for each seed is gathered, and then, using the maximum value of each seed, the result of the fitted curve with empirical data can be analyzed to find outfitted distribution. The maximum tension value is 9,785N, pointing out a red circle. In the next chapter, the maximum tension value will be used to analyze the extreme value method.

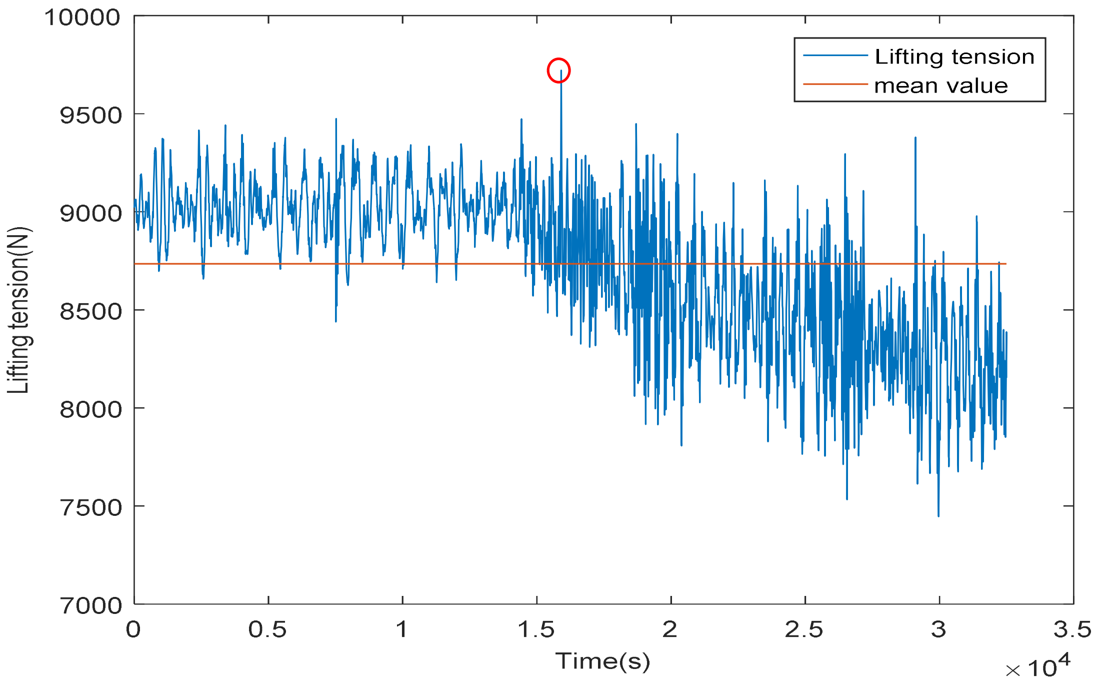


Figure A2-3: The time history of lowering tripod (Hs = 2.0m, Tp = 6s)

Even though the standard deviation does not have a big difference in parameters for each seed number, though the probability plot and the degree of alignment between empirical data and probability plot can be acceptable in any case of Gumbel distribution.

Because the value of σ/E is around 0.01, it is very similar to the trend of the fitted Gumbel probability plot with increasing seed no. Significantly, over n = 100, the inclination of the plots is almost the same. However, the beta parameter is getting smaller in increasing the seed no. Therefore, Gumbel distribution with 200 seed numbers can be the basement for the Monte Carlos simulation to determine the allowable sea state's uncertainty band.

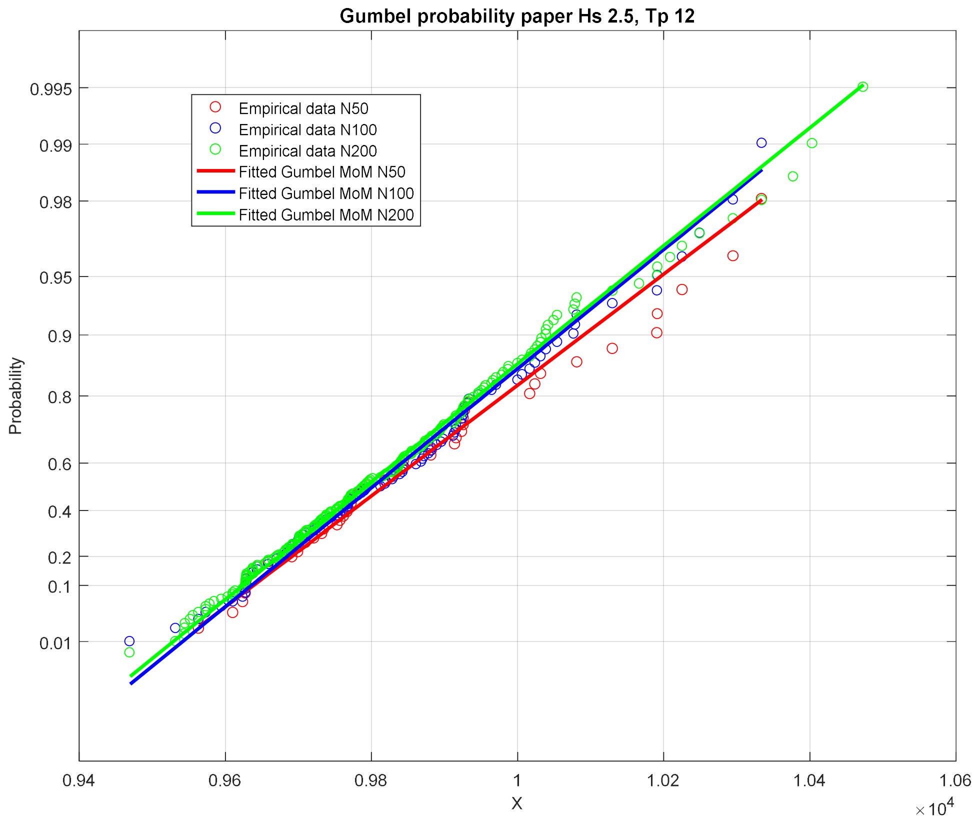


Figure A2-4: Comparison of Gumbel probability plot between Seed no 50, 100, and 200

We can check the reliability of the data randomly generated. The thick green line is the original Gumbel distribution of 200 seeds, and yellow circles mean empirical data of 200 seeds, and all thin-different-color lines are the Gumbel probability plots by MC. Original data of plot and empirical data are in the randomly-generated Gumbel probability plots. Therefore, we can understand that the data from MC can be reliable.

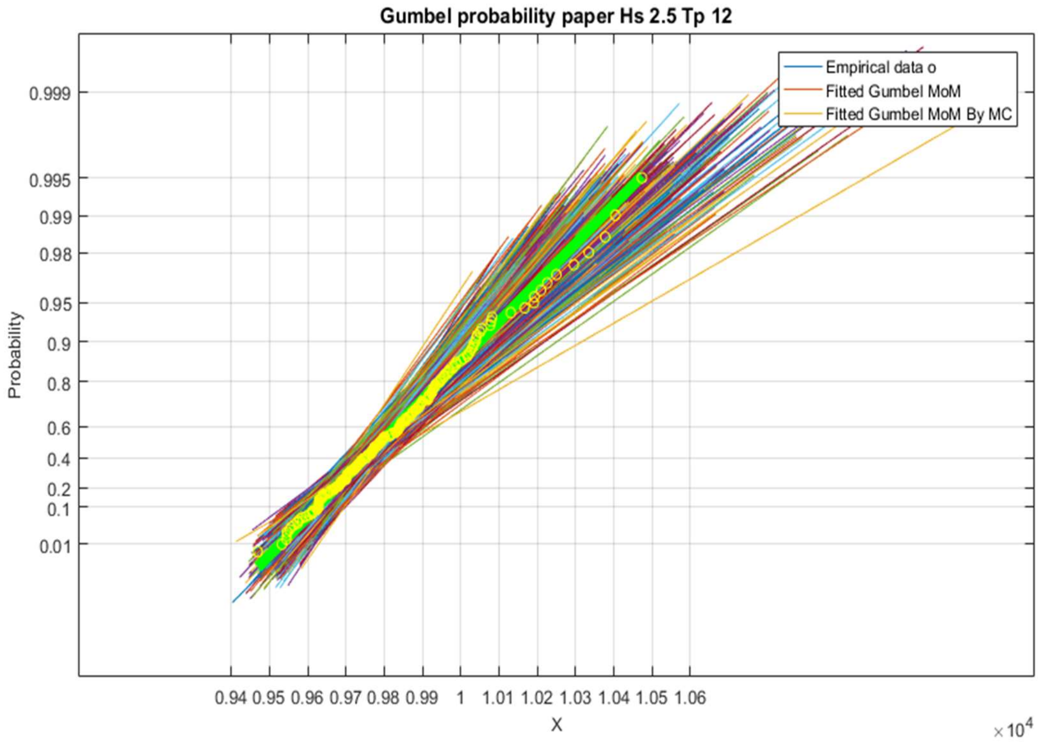


Figure A2-5: Comparison of original Gumbel and randomly generated numbers by MC

For example, for given Tp, 6s, through the MC technique again, 10%, 50%, and 90% of DAF value can be derived from the calculation of DAF with dynamic tension from the function parameter of case 1 for alpha case 4 for beta parameter in Gumbel.

There is an exploration of DAF value under 0.4m of Hs; the graph can draw the line up again according to the alpha parameter's function. Furthermore, due to the same reason, there is an uptrend before 0.4m in Hs. When we find out the Hs value on X-axis, corresponding to criteria, DAF 1.15 in the Y-axis, the Hs is 2.2m. these values matching with DAF 1.15 can be plotted in all sea states.

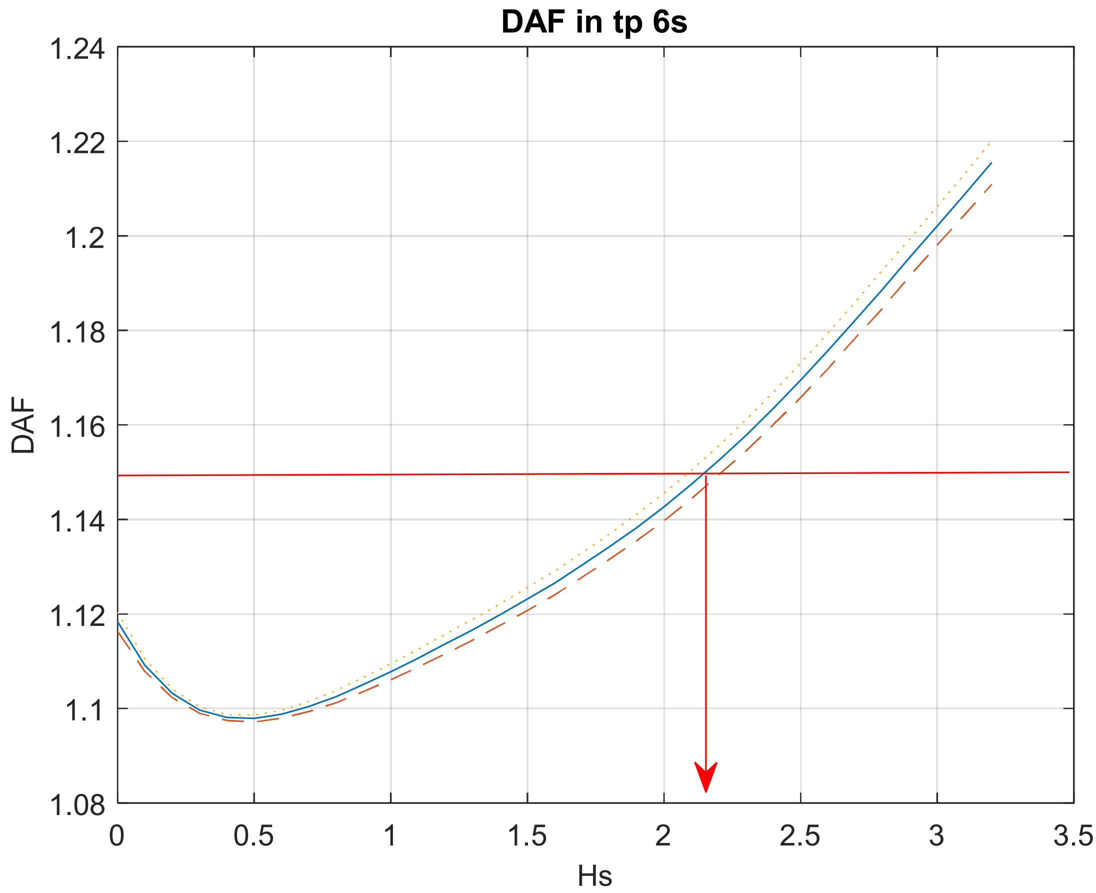


Figure A2-6: Uncertainty band of DAF value for given Tp, 6s

Result

When we check the 50% target probability of the DAF value in Tp 6s, Hs' same value in Figure A2-6 can be identified. To extend the given Tp to all sampled Hs data from the previous step, all corresponding DAF values of 10%, 50%, and 90% target probability of non-exceedance can be derived. Between the sampled Tp value, the value can be derived from linear interpolation.

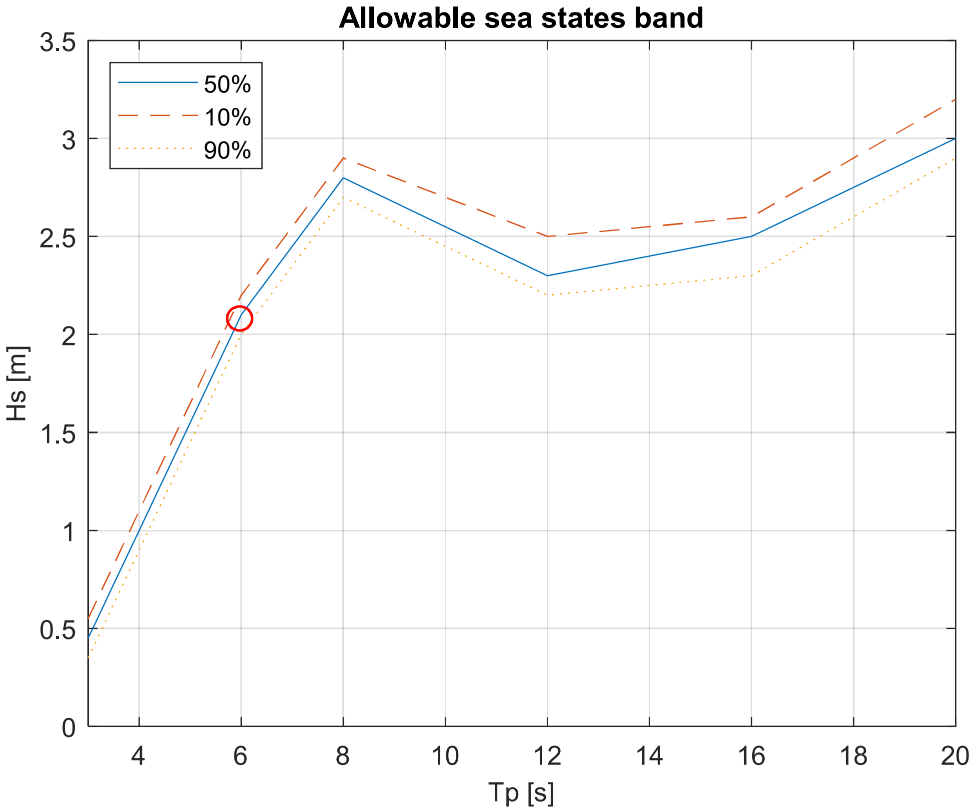


Figure A2-7: Uncertainty band for allowable sea state with DAF criteria

According to the eigenvalue of the coupled system, 12.61s of the eigenvalue in mode 6 (heave of the tripod) can impact increasing the lifting wire tension. Therefore, around Tp = 12s has the lowest allowable sea states after Tp is 8s, the maximum allowable sea state.

Conclusion

Many resources are needed within a limited working period with unexpected risks to proceed with marine operations such as lifting subsea equipment or installing the module. Especially lifting the tripod's operation can be defined as heavy-weighted operation, accurate risk assessment and conservative point to make the decision seem to be mandatory to make the success.

Risk assessment of lifting operation can be defined as assessing the uncertainty that can be divided into aleatory and epistemic. Because the aleatory uncertainty can be made from the model or observation itself, this study can identify the epistemic uncertainty with the Monto Carlo simulation. Maximum of the tension values of lifting wire have been analyzed with Extreme value model and fitted model with estimated parameters..

The lifting system's numerical modeling has majorly consisted of an installation vessel with corresponding hydrodynamic coefficient, a simple coupled system with a single wire, and a tripod model with a slender structure. Using numerical model simulation in SIMA, lifting wire's maximum tension value can get for each seed number. Two hundred seed numbers for each sea state have to be stored. Fitted distribution of maximum tension values in200 seed number can be concluded as Gumbel distribution by comparing empirical data and Gumbel probability plot and almost 0 value of the shape parameter in 200 sample data.

In 42 limited sea states in Hs and Tp, alpha and beta parameters using Gumbel distribution have been derived. For one specific Tp, we have found that the proper function for the alpha parameter is exponential non-linear, and for the beta parameter is the 6-degree poly function.

With Monte Carlo simulation, M = 1000, including 200 sets, we have obtained random-generated tension value, and to find out DAF value, these values have been divided by F_static. Finally, compared with operational criteria, DAF 1.15, the allowable sea states' uncertainty band can be acquired. Using 10%, 50%, 90% of the target probability of non-exceedance, the allowable sea state's uncertainty band can be identity.

APPENDIX 3: The Summary of Global Tech 1 wind farm

Global Tech 1 was planned by geologist Hans-Jurgen Kothe, and Windreich took over ownership to further develop the wind farm until commissioning. The wind farm location is 93 kilometers northwest of the island of Juist, with an area of 41 km^2 and a water depth of 39 to 41 meters.

The total investment is 1.8 billion euros, and there are ten shareholders as of July 31.2013. The general specification of the wind farm is summarized below table.

Item	Description
Location & Sea depth	Coordinate: 54 ° 30 ′ 0 ″ N , 6 ° 21 ′ 30 ″ E, & up to 40m
Distance from shore	180km from Bremerhaven in Germany
Wind Turbine	Manufacturer: AREVA Wind GmbH, Model: Multibrid M5000
Erection of tripod and vessel name	HOCHTIEF Solutions AG with the heavy-lift jack-up vessel INNOVATION
Erection of towers and nacelles and vessel name	Fred. Olsen Windcarrier with the two crane vessels Brave Tern and Bold Tern. Nearshore logistics is realized by BLG Logistics. Transporation on installation vessels at the offshore terminal ABC Peninsular of BLG at Bremerhaven
Rotor blade assembly and vessel name	Using: jack-up vessel Vidar of HOCHTIEF Solutions Transporation on installation vessel at JadeWeserPort in Wilhelmshaven The height of the turbine is around 100m from sea level
Weight of components	Nacelle 235 tonnes Tower section S3 180 tonnes Tower section S2 90 tonnes Tower section S1 90 tonnes Hub 64 tonnes Blade (3-blade rotor) 17 tonnes x 3

Table A3-1: Information on Global Tech 1 wind farm (GmbH, 2014)

Forty tripod steel foundation structures had been manufactured by ARGE Tripod Global Tech1 (a consortium of WeserWInd Gmbh and Erndtebrucker Eisenwerk). Because SIAG Nordseewerke had its insolvency, the rest of the construction volume was awarded to another consortium.

From September 2012, the jack-up installation vessel “Innovation” started to pick up the tripods from Bremerhaven, and all tripod installation was completed by September 2013.

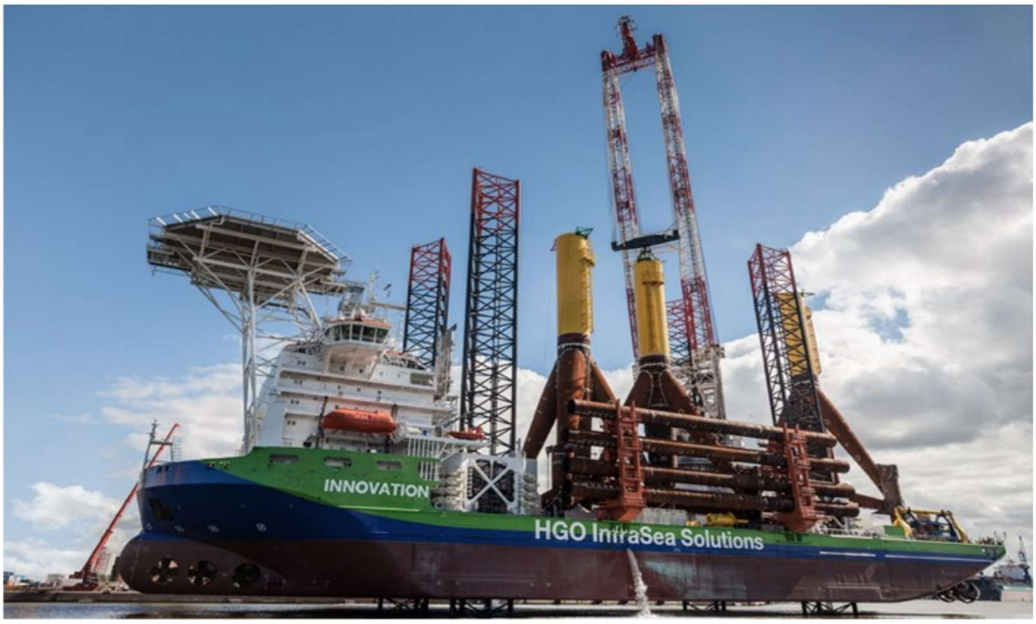
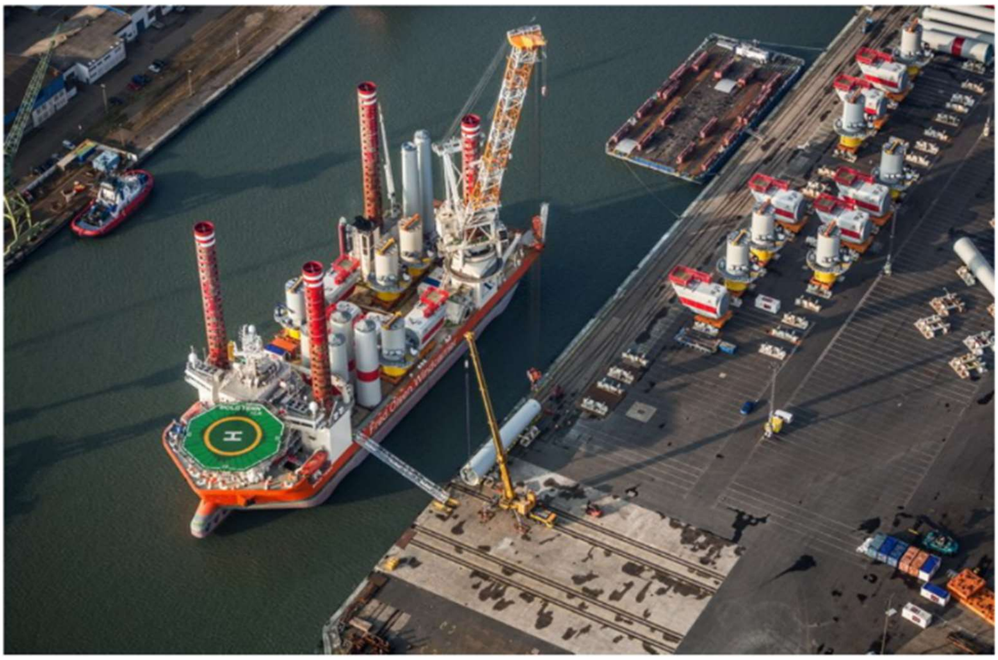


Figure A3-1: INNOVATION loading the 3ea tripod (Press lease from global tech 1)

The tower and Nacelle were installed in September 2013, and It took almost two years to mounted all Nacelle.

Bub and three blades were preassembled on the ground and installed by installation ships “Thor” and “Brave Tern.”. the total offshore was carried out for 359 days from 22.08.13 to 29.08.14.

The total duration of critical installation offshore was around 720 days from 09.09.12 to 29.08.14.



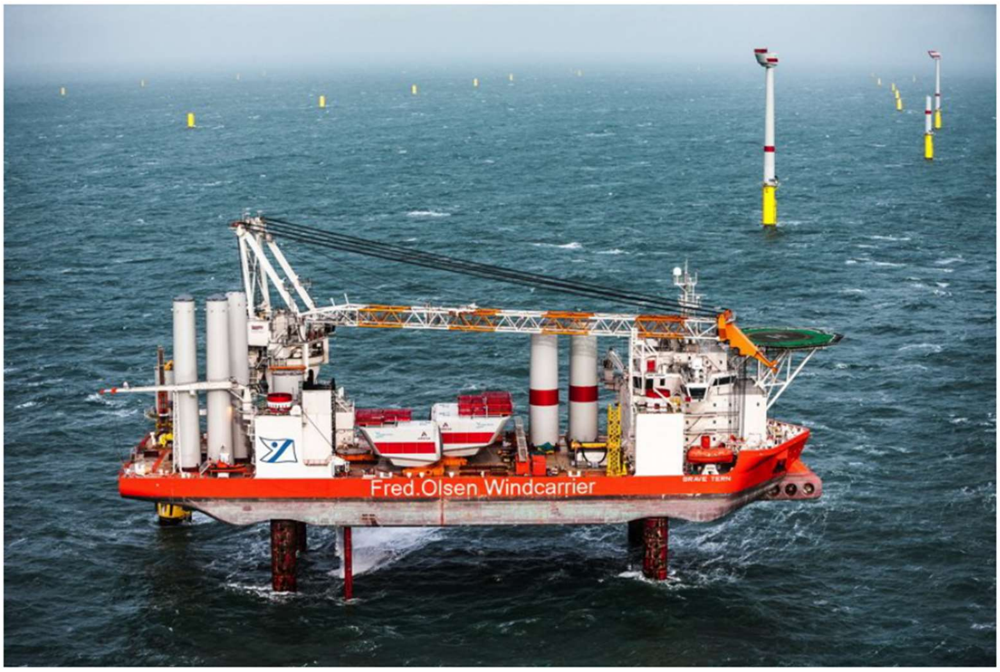


Figure A3-2: Loading and installing the tower and nacelle (Press lease from global tech 1)

Figure A3-3 : Loading pre-assembled rotor and hubs and installation. (Press lease from global tech 1)