An investigation of installation strategies to install next-generation offshore wind turbine generator components

Feedering vs. Shuttling, an efficient installation process for the future

Management of Technology - MSc Thesis

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Marine ingenuity

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Executive summary

Climate change is triggering, amongst others, a larger demand for offshore wind energy. This leads to many new developments of which larger next-generation Wind Turbine Generators (WTGs) is the most relevant. These next-generation WTGs create challenges for the carrying capacity of current-day installation jack-up vessels that work according to the conventional installation method (shuttling). These installation vessels can carry less or even nil of these WTGs per trip compared to the current-day WTGs. Fewer turbines per trip would still keep the larger current-day installation vessels to maintain their workflow. However, they endure more sailing time since more trips are required. This could even lead to a more inefficient process due to the increasing offshore distance of Offshore Wind Farms (OWFs). Another option - within the conventional method - is to build larger installation vessels that could carry more WTGs per trip.

Another installation method called feedering is a potential substitute for the conventional method. To date, only limited research has been made on feedering as well as on the practical implementation. The conventional method, however, has extensively been researched and is mostly used in practice today. The models in the literature compared two different feeder methods to the conventional method, called 'base port feeder' and 'feeder-ship' method. These models are generic and lack different strategies to investigate feedering on a deeper level. The feeder-ship method has the most potential to solve the aforementioned problems and is therefore the key focus for further investigation in order to find the best installation strategy - being either a conventional or feeder strategy - depending on the conditions.

First of all, the feeder-ship method is evaluated based on practical knowledge and adapted so a base port is used to temporarily store all components that come from the production port. The feeder sails back and forth between the base port and the installation site to supply the installation vessel with WTG components. The installation vessel will stay at the installation site to be as efficient as possible (the least amount of sailing time). This research only looks at the feeder and installation side and leaves the port elements out of the scope. Feeder strategies (within this method) differ in the number of feeder vessels/types and transfer options using either barges or Platform Support Vessels (PSV)s and being indirect (transfer components onto the installation vessel) or direct (install components from the feeder). The installation vessel for feedering is also looked into as being either a current-day or a special feeder purpose installation vessel. Different carrying capacities of the installation vessels are used to create different strategies for the conventional method.

A stochastic Discrete Event Simulation (DES) model is the most suited research method to evaluate the strategies. The output of the DES simulation is the P50 (50^{th} percentile) project duration per sailing distance and strategy. The costs for this duration is calculated in a cost model, both from the perspective of the contractor as well as the developer. Besides duration and costs (based on the European market), the strategies are also evaluated on fuel consumption since emissions are an increasingly important element in the industry. The results of the initial input parameters show that the PSVs are more competitive than barges due to the higher workability and short cycle time. Additionally, the indirect strategy is most suited at sailing 'shorter' distances using one PSV while the direct method is better at 'larger' distances using two PSVs. Using more PSVs would not be beneficial.

A sensitivity analysis is performed to understand the impact of three critical input parameters; the number of tower segments for a full tower, environmental sailing limits of the feeder and transfer limits of the nacelle and tower segments. The blade rack transfer is not taken into account because current market developments do not indicate solutions for increased limits yet. The key results of the sensitivity analysis on the feeder strategies are;

- The model is most susceptible to the number of segments the tower is transferred in.
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- Increasing the transfer limits of the tower segments and nacelle show minimal impact on the process. The blade rack transfer becomes a bottleneck when the environmental limits of the aforementioned components are increased and the blade rack not. This bottleneck needs to be (technically) solved in order to increase the workability of the system when using Platform Support Vessels as feeders.
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- The OWF size must be large enough not to have dominant fixed costs to make feedering interesting
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- Feeder strategies consume more fuel and thus have (potentially) more CO_2 emissions than the conventional strategies in most cases.

These results bring about new technical challenges which need to be solved first before feedering can be used competitively in the European market. For example, designing a fast feeder with high stability to increase workability. Pending next level solution to be developed, a large (four WTGs) carrying capacity conventional strategy is overall the most suited installation strategy with the least amount of risks.

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Marius Smorenberg
Delft, September 2021

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Acronyms

DES Discrete Event Simulation. i, 3, 7, 23, 25–27, 29, 30, 55, 56, 59–61, 64, 65

DP Dynamic Positioning. 5, 15, 17, 18, 21, 32, 56, 64

KPI Key Performance Indicator. 10

nm nautical miles. 18, 29, 31, 34, 35, 37, 38, 43–45, 49–53, 56–58, 62

OWF Offshore Wind Farm. i, 1, 2, 4, 7, 13, 21–24, 29, 31, 34, 35, 37–39, 42–46, 55–58, 62, 64

OWTs Offshore Wind Turbines. 1, 7

PSV Platform Support Vessel. i, ii, vii, 5, 15–18, 27, 29, 31–39, 41, 42, 51, 52, 55–59, 63, 65

RAO Response Amplitude Operator. 24

RFD Research Flow Diagram. 14, 15, 23, 31

WoW Waiting on Weather. 11, 13, 25, 31, 50, 59

WTG Wind Turbine Generator. i, ii, vii, 1, 2, 5–16, 18–23, 27–31, 33, 35, 37–39, 41, 42, 44, 45, 48, 49, 51–61, 63–65, A-I

WW Weather Window. 11, 20, 21, 23, 25, 26, 30, 31, 34, 37, 38, 41, 42, 44–46, 50, 56, 57, 59–63

deze aan als het niet werkt

Nomenclature

day-rate The costs a service would take for one day. 2, 4, 10, 13, 26–29, 34, 52

heave A motion along the vertical axis (up and down). 5

hub The component that holds the rotor blades together and connects the rotational movement to the drive train in the nacelle. 1, 10, 13, 16, 17, 41

jack-up vessel A vessel that can be elevated above the waves using legs when in position so it will not interact with the waves. 1, 5, 10, 13, 15–18, 29, 31, 55

nacelle The housing for the drive train of the wind turbine. i, ii, 10, 13, 16–18, 41, 43, 52, 55, 57, 58, 61

pitch A motion where a vessel tilts to the port or starboard side or goes back and forth. 5, 24, 48

roll A motion where a vessel's bow moves up and the stern down or the other way around goes back and forth. 5, 24, 48

rotor blade The component that harnesses wind energy and creates the rotational movement. vii, 10, 13, 14, 17, 61

tower The vertical component that holds the other components at the correct height. i, ii, 10, 13, 14, 16–18, 24, 29, 41–44, 46–53, 55–65

workability The percentage of time a vessel can operate under environmental conditions depending on its workable limits. 2, 11, 29, 34, 50, 56–58

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Chapter 1: Introduction

Climate change has become a major issue on a global scale (UNCCC, 2020) and throughout the years, several initiatives have been promoted with the goal of reducing CO_2 emissions. For example, the 2015 Paris Agreement triggered a large demand for renewable energy. To cope with such growth, the renewable energy sector has been growing and developing over the years more and more wind energy projects, especially offshore, due to its higher capabilities in terms of efficiency and energy production and the limited visual and noise pollution (IEA, 2018). However, new developments are necessary to drive the costs per Megawatt (MW) installed down, among which the most relevant is the installation of larger Offshore Wind Turbines (OWTs), leading to a higher power output for a similar size Offshore Wind Farm (OWF) (IRENA, 2019).

Currently, the largest OWTs used are 10MW which have a hub height and rotor diameter of respectively 105 and 164 meters (MHI Vestas Offshore Wind, 2020). The next-generation 12 MW offshore wind turbines are expected to be ready for commercial projects in 2022 (GE renewable energy, 2020). These turbines will have a hub height and rotor diameter of respectively 150 and 220 meters. Even larger OWTs with ratings of 15 MW are already announced for the next decade and extensions to 20 MW are expected for the future (IRENA, 2019). The market standard for installing Wind Turbine Generator (WTG) components is the conventional method, also known as 'shuttling', which is shown in Figure 1.1 and Appendix A.1 (Ait Alla et al., 2017). Large transport vessels, as shown in Appendix B, are loaded with WTG components at the production port. Next, they are transported to a base port where they will be unloaded and temporarily stored. An installation jack-up vessel sails back-and-forth between the base port and installation field where it will respectively load components and install them. However, as larger turbines are entering the market, there will be two major problems with this installation process. First, the current midsize jack-up vessels do not have the carrying capacity to transport the next-generation WTG components when fitted with a new larger crane. Crane upgrades are required due to the increased installation height and component weights. The second problem is for the larger installation jack-up vessels. Although they can install WTG components with the current or upgraded cranes, they only have the carrying capacity for two to three 15 MW WTG sets, whereas the 10 MW allows for four to five sets. Therefore, when adopting the conventional method for next-generation WTGs, the expensive jack-up vessel needs to sail more often and thus will be less efficient in time and costs. Additionally, offshore wind projects are moving further offshore; increasing the sailing time itself even more (IRENA, 2020).

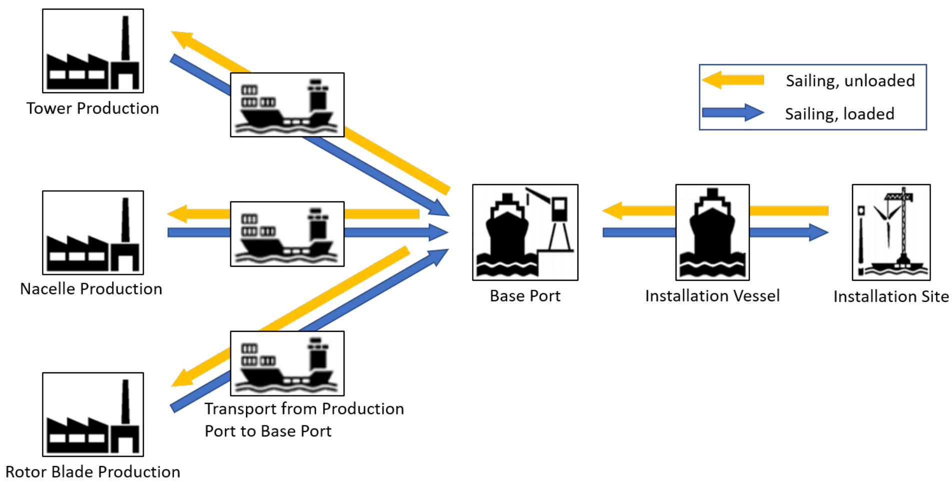


Figure 1.1: The conventional method visualised based on Ait Alla et al. (2017)

Building an extremely large installation vessel and maintain the conventional method could be a solution for the future. However, this is a large investment with a high day-rate and risks since these vessels could be outdated by new market developments if not designed properly. According to the literature, the installation method called ‘feedering’ could be a potential game-changer to replace the conventional method (Ait Alla et al., 2017). A relatively low-cost feeder vessel receives WTG components at the (production) port. Next, it will sail to a ‘sheltered area’ near the installation field or to the installation field itself and ‘feed’ (supply) the components **directly** to the expensive installation vessel. The installation vessel will have shorter or no WTG components transportation operations and could potentially be more efficient on both costs and time. However, the system must be tuned properly since it is challenging to find the best feeder strategy. In particular, the strategy includes, the number of feeders required, feeder types, number of turbines to be installed and the workability for feeder activities. Finally, its performance strongly depends on the sailing distance and environmental limits. The larger the sailing distance and the lower the limits, the more costly a strategy becomes.

In the literature, two different feeder strategies have been studied; the base port and the feeder-ship method. Although these methods have great potential, they have not been investigated exhaustively according to Oelker et al. (2018). For example, the literature lacks an analysis between different strategies (e.g. using different vessels) within a method as well as not explaining which process steps are most critical (Rippel et al., 2019b). Most logistical models that have been created, are using the conventional method and consider the entire installation process of an OWF (Barlow et al., 2014b, 2015, 2016, 2018). Therefore, these have insufficient focus on the installation of WTGs and the potential different strategies such as feedering.

In this research, we will analyse the performance of both the conventional and the feeder method for the next-generation WTG components and get a better understanding of the influence of the change in critical parameters on different installation steps. We do this by developing a simulation framework that considers relevant aspects such as workability and different types of vessels and will investigate the main trade-offs, aiming to provide a solid answer for this strategic choice. The process of the problem will be extracted from the current literature and insights from a relevant contractor operating in the industry, namely, Van Oord. The costs and time of installing WTG components are important parameters in this study. The time element will be analysed independently as well as combined with the cost elements since certain cost elements are time-dependent. The total costs are viewed from two perspectives, the marine contractor (such as Van Oord) and the developer (owner of the OWF) and are based on the European market. The former has expenses such as vessel/tools costs (per day) and would prefer to have a short project duration with as few vessels/tools as possible to remain cost-competitive. The latter pays daily costs per day on top of the contractor costs during the entire installation project and would therefore especially benefit from a short installation procedure. The lowest cost strategy in combination with a time-efficient process (being either the feeder or the conventional method) will be the best strategy for a particular scenario. In addition, the fuel consumption per strategy is also looked into because environmentally friendly installation processes are becoming increasingly important since tenders are nowadays also won by having the lowest emissions. The focus of this thesis can be translated to the main research question:

What is the best installation strategy for installing next-generation offshore Wind Turbine Generator components within the feeder-ship and conventional methods and under which conditions?

The approach of this entire thesis follows a mixed-method approach and contains three different methods (Sekaran and Bougie, 2016). The literature review and secondary data analysis are used in a qualitative manner (in the form of words). They are used to describe the main research question and to simplify the problem respectively. To answer this main research question, a quantitative method is more suited since data in the form of numbers is gathered and utilised. The best quantitative approach is simulation modelling. Within simulation modelling, stochastic Discrete Event Simulation (DES) modelling is the most suitable method because it recreates stepwise real-world events spread over time with varying weather without the high costs and risks (Sekaran and Bougie, 2016; Shull et al., 2008). What happens within each step will not be looked upon since only the start and the end of a step is important in the problem definition.

This thesis is structured as follows. Chapter 2 is the literature review that explains the existing literature, knowledge gap and research question. This will be followed by the problem description in Chapter 3. Next, the methodology of how to solve/model the problem is explained in Chapter 4. The results of the model are provided in Chapter 5. Lastly, conclusions are drawn and the method, results, managerial recommendations and future research are discussed in Chapter 6.

Chapter 2: Literature review

This Chapter contains the literature review about the history of the offshore wind installation market, feeder methods and installation process models. The literature has been found using the following search query in Google Scholar from 2012 until 2020.

- "feeder" AND "vessel" AND ("barge" OR "barges") AND "wind" AND "offshore" AND "turbine" AND ("installation" OR "install")

The over 140 papers in the query have been filtered on title, abstract and conclusion. Roughly 20 papers remained and have been fully read to narrow the list further. This narrowed the list even further down to the literature which is useful for this research. Additional researches have been found using citations from the already chosen papers. Next, a knowledge gap is described based on the literature review. This is then used for the formulation of the goal, the main research question and sub-questions of this thesis.

2.1 OWF installation history

The book of Kaiser and Snyder (2012) broadly explains the installation of an Offshore Wind Farm (OWF) including the conventional as well as the feeder method briefly. They explain that the installation of an OWF contains four major steps; foundation, cable, turbine and substation installations. The first offshore wind turbines (200 kW) were installed in 1990 (Dedecca et al., 2016). The vessels which performed these first installations came from the oil and gas industry. These vessels were in high demand and therefore had high day-rates while their capacity exceeded the requirements (Barlow et al., 2015). Later around 2002, the offshore wind market started its own developments for these installation vessels, decreasing the contributions of the oil and gas industry (Dedecca et al., 2016). This led to the first specialised vessels which had the purpose to install offshore wind turbines.

According to Barlow et al. (2015), it is important to have vessels that can fulfil the specific role they are designed for. The trend of these vessels is that they are becoming larger as the turbine sizes increase (Barlow et al., 2015; Kaldellis and Kapsali, 2012). This is due to the carrying capacity that an installation vessel requires when installing via the conventional method (Higgins and Foley, 2014). Over time, the dominant standard for such an installation vessel became the jack-up vessel as shown in Figure 2.1, and typically uses the conventional method.

Other innovative vessel designs and methods were proposed to potentially change the installation process (Barlow et al., 2015). However, the industry was not backing these innovations and the market was not ready for them. Nowadays, the market has changed. Innovative concepts and methods, such as the wind turbine shuttle of Huisman and the feeder method are more accepted and being developed (Huisman Equipment, 2020; Ait Alla et al., 2017).

Figure 2.1: The Aeolus installation jack-up vessel of Van Oord installing WTG components

2.2 Feedering

Researches that deepen information on the performance of the feeder method when installing Wind Turbine Generator (WTG) components and/or comparing this to the conventional is very scarce. Ait Alla et al. (2017) were the first to make such a comparison as stated by Oelker et al. (2018). They explain that there are two different feeder methods possible within the feeder process. In this section, firstly, the vessel types for a feeder process will be discussed. This will be followed by an explanation of the different feeder methods.

2.2.1 Types of feeder vessels

According to Kaiser and Snyder (2012), the feeder vessel is often referred to as a barge that requires towing. An example of this is depicted in Figure 2.2a. However, due to the instability of the floating barge, offshore transfers are risky and could potentially delay the installation process. Instead, they advise using jack-up vessels/barges, so-called liftboats, to overcome the wave climate during these offshore transfers as shown in Figure 2.2b. This jack-up feeder still has environmental limitations for the jacking-up process which again could delay the entire installation process (Vartdal, 2017).

Another suggestion is to use a Dynamic Positioning (DP) vessel (as a feeder) which can hold its geographical position in environmental conditions by means of thrusters (Haselsteiner et al., 2019). However, the other degrees of freedom (heave, roll and pitch) are not controlled by this system, allowing the components to move with the ship. This could potentially delay the process if not controlled properly. The DP system is not only limited by the waves and wind but also by the current. A Platform Support Vessel (PSV) is such a DP vessel and an example is shown in Figure 2.2c. This vessel option is barely used as a feeder solution in the literature.

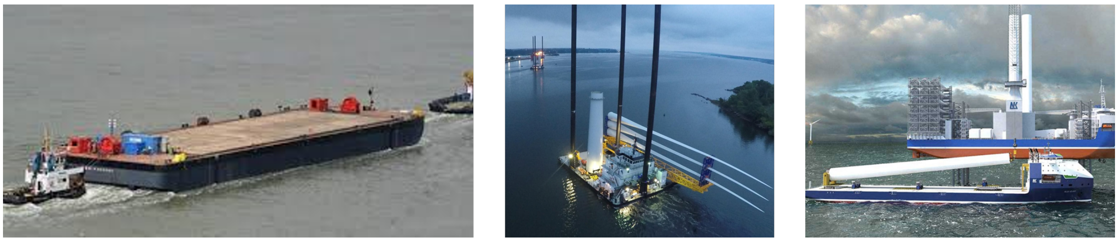


Figure 2.2: (a) An example of a (feeder) barge (Van Loon Maritime Services B.V., 2020), (b) An example of a jack-up feeder (Rochas, 2018), (c) An example of a DP feeder vessel (Blenkey, 2019)

2.2.2 Feeder methods

According to Ait Alla et al. (2017), the first method is the base port feeder as shown in Figure 2.3 and Appendix A.2. A feeder vessel will be loaded with a WTG component at a production port. The loaded feeder will then sail to the next production ports to receive all components until a full set is on board. Depending on the carrying capacity of the feeder and installation jack-up vessel, one or multiple components (of that specific type), are loaded at the ports.

Next, the feeder will sail to a ‘safe/sheltered area’ with favourable lifting conditions. Here it will meet and supply the installation jack-up vessel with the components **directly**. No storage port is needed in this method. This ‘safe/sheltered area’ is called a base port and can be man or nature-made. The feeder will only need to travel between the production and base port, while the installation jack-up vessel travels between the installation site (to install) and the base port (to pick up). The risks during an offshore lift are significantly reduced due to the improved conditions at the base port. However, the installation jack-up vessel still requires to have a large enough carrying capacity to transport WTG components. This will therefore not solve some of the issues described in Chapter 1.

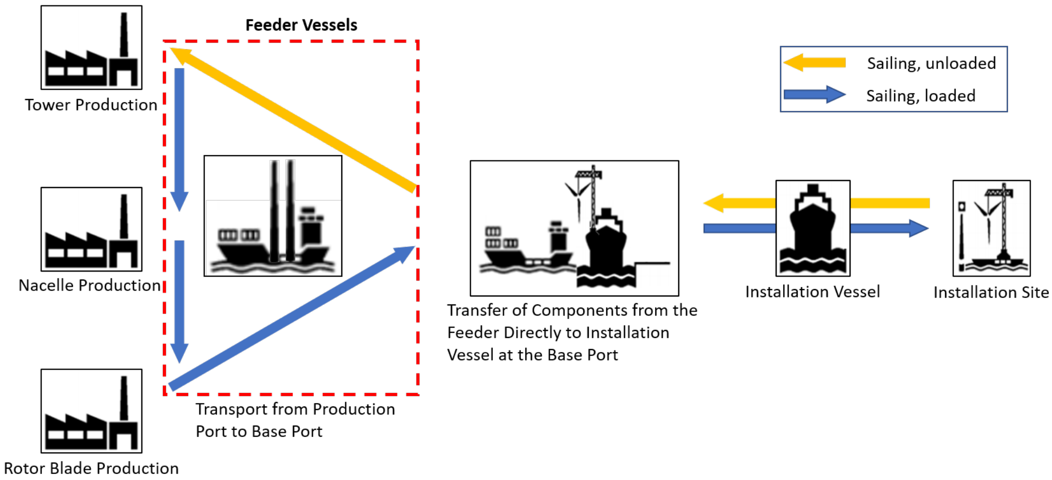


Figure 2.3: The base port feeder method visualised base on Ait Alla et al. (2017)

The second method is the offshore feeder-ship method as shown in Figure 2.4 and Appendix A.3. A feeder vessel will collect the WTG components from the production ports in the same manner as in the base port feeder method by sailing to all the production ports first. The loaded feeder will then sail to the installation site. Here, the installation vessel is ready (jacked up) at the installation site and respectively unloads and installs one set of WTG components. As stated by Haselsteiner et al. (2019), this offshore lift from the feeder to the installation vessel contains high risks. In their paper, they reviewed the current solutions and remaining problems of a floating offshore lift by investigating the available (lifting) tools in the market. They concluded that the lift can only be performed when the conditions are favourable, potentially delaying the entire installation project. The right (compensation) tools could decrease the potential delays

The feeder will sail back to the production port to restart the cycle when it has no more WTG components on board. If the feeder carries another WTG set, it will stay offshore and wait at the next installation site. This method compared to the conventional and base port feeder method has a more efficient installation vessel since it will only install components instead of transferring them to the installation site. This method could potentially solve the problems described in Chapter 1.

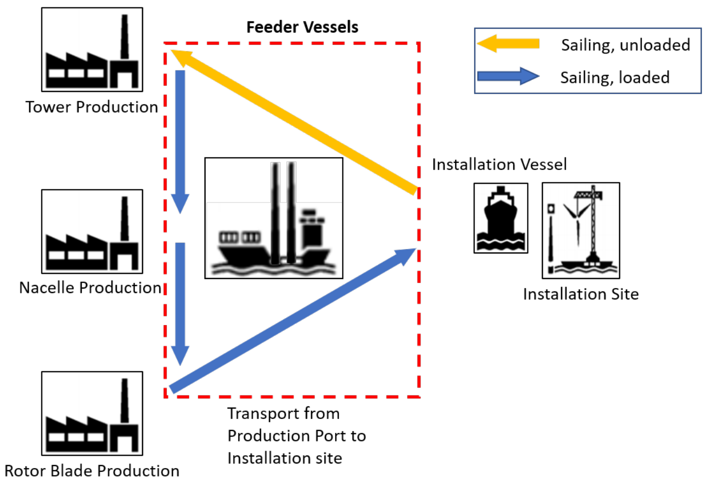


Figure 2.4: The offshore feeder-ship method visualised based on Ait Alla et al. (2017)

2.3 Installation process models

In the literature review, most papers focus on analysing the installation process of an entire OWF by using the conventional method. Scholz-Reiter et al. (2010) studied the conventional method to determine the best logistical solution through a mathematical mixed-integer linear programming (MILP) model. They used categorised weather limits and historical environmental data in their model. They concluded that bad weather could cause 'extensive project delays of several months'. Ait Alla et al. (2013) also used the MILP model to shape the installation process for an entire OWF by the conventional method. They stress that improving the logistical process could significantly decrease the installation costs of an OWF. They used different numbers of installation vessels to determine the best cost strategy. They concluded that using two installation vessels (one for foundation and one for WTG installations) is the best strategy.

The following models are improvements to the logistical process. As reported by Barlow et al. (2014a), a MILP approach is not accurate enough. The Discrete Event Simulation (DES) model developed by Barlow et al. (2014b) 'provides a more realistic representation of the conventional installation process' of an entire OWF using a 'synthetic hourly weather time-series model generated from real data'. According to Barlow et al. (2015), this model 'provides an accurate representation of a large-scale installation project in terms of the duration and costs which would be realised. Therefore, it is a means to obtain a realistic assessment of the benefits gained through a given operational or technological development, and is the method employed to explore potential innovative developments'. The research of Barlow et al. (2015) uses the same logistical model as Barlow et al. (2014b), but implements a syntactical time series based on autoregression for weather patterns of historical data and Monte Carlo simulations to predict the weather. They conclude that the installation process of an entire OWF is most sensitive to weather delays. These delays can be overcome by 'simply employing vessels with increased operating capacity'.

Barlow et al. (2016) created a new DES model after developments in the offshore wind market. They again used autoregression and Monte Carlo simulations to syntactically create weather predictions. They extended the model with a robust optimisation model to create a more realistic understanding of the logistical decision-making process. The model can be used as a tool to support 'OWF developers with logistical installation decisions at the planning or bidding phase of an installation project'. They concluded that it optimises the costs and duration by means of improved vessel utilisation. Tezcaner Öztürk et al. (2017) also used a robust optimisation modelling method for the conventional method of the entire OWF to find in their first model the shortest project duration or lowest costs. In their second model, they found 'the worst possible project duration for a percentage of deviating tasks'. However, this paper is still in progress and did not provide any clear conclusions. The research of Barlow et al. (2018) used a mixed-method framework to 'exploit the complementary strengths' of the DES and robust optimisation models used in Barlow et al. (2016) and Tezcaner Öztürk et al. (2017). They concluded that their model can be used as a 'support for developers, to ensure that operations are planned as efficiently as possible and that the vast installation costs are streamlined where possible'.

With concern to the feeder installation methods, the first attempt is the recent work from Ait Alla et al. (2017). They model the conventional as well as the base port method only for the installation of WTGs, as described in Subsection 2.2.2. They use a DES model for the logistics. They used historical weather data (of multiple years) as environmental input. They averaged the results of all the years to conclude 'that the base port feeder method outperforms the conventional method in the case when the installation duration covers the period in which the weather availability is good'. On the other hand, 'if the OWF is located far away from shore, the number of Offshore Wind Turbines (OWTs) is high, and the weather availability is poor, the installation duration can spread over a long period, and the conventional method remains in this context the best concept strategy'.

Oelker et al. (2018) continued on this study and investigated the offshore feeder-ship method using the same methodology, but provided insight into the usage of multiple feeders instead of using only one. When using one feeder vessel, they came to the same conclusion as the base port feeder method. However, when using two feeders, this method can become more interesting at larger distances, depending on the accompanying weather windows. The installation vessel can then potentially have a continuous supply of WTG components for optimum efficiency. However, They did not investigate any other feeder possibilities in their research. Therefore, they did not find a best installation strategy.

Rippel et al. (2019b) share this remark and states that the models created by Ait Alla et al. (2017) and Oelker et al. (2018) only create 'a plan after the simulation finished, they do not include an optimisation component to evaluate different plans or configurations', as for example in Barlow et al. (2018). Rippel et al. (2019a) continued by stating that the 'just in time' principle of supplying WTG components exactly at the right time is highly important for both feeder methods to ensure a high efficiency of the expensive installation vessel. They mean that the installation vessel is constantly busy (continuous supply) while the feeder/feeders are busy supplying the components or waiting to sail out (as a buffer system).

The research of Vartdal (2017) is similar to Oelker et al. (2018), but focuses on the logistically different foundation installation. They concluded that the installation vessel is more time-efficient when using two feeders at larger distances when installing jacket foundations. Moreover, the research by Shields and Nunemaker (2019) to install monopiles foundations using feeder barges provided the results that feedering will be less efficient when using more than two feeders (in their case study).

All in all, we can conclude, that the research on the conventional method is quite substantial, whereas data and fundamental research on feedering are relatively recent as much more needs to be investigated. The works of Ait Alla et al. (2017) and Oelker et al. (2018) are the only two who explored the feeder WTG installation process. However, they do not look into the different types of feeder vessels and do not explain which steps in the process are most critical. From their conclusions, it is unclear at what point a feeder method would be better than the conventional method. In this paper, we aim to fill this gap.

2.4 Main research question

The literature review in the previous sections explains that the base port feeder method is not ideal to solve the problems described in Chapter 1. Therefore, this feeder method will not be discussed further in this thesis. The feeder-ship method shows great potential since it can be used for short and potentially long feeder distances depending on the number of feeders. However, only one model has been created to compare the feeder-ship method with the conventional method for installing WTG components (Oelker et al., 2018). This model lacks precision and 'optimisations' (Rippel et al., 2019b). They only provide a plan according to their one simulation. Different strategies within the feeder-ship method are not being discussed upon. Other feeder-ship method models are coming from the foundation installation process. The cost aspects are not often taken into account while this is a highly important element of the decision-making process.

The literature only provides the results and do not go in-depth which steps in the installation process are most critical. Highlighting and improving those critical steps of the feeder method could potentially make feedering a more preferred method. Additionally, feeder models, which install WTG components and foundations, do not consider/include the different types of feeders or installation vessels which potentially could make a strategy more appealing. They also did not look into the emissions of an installation project since this is a more important present-day topic in the industry.

The above-mentioned elements led to the goal of this research to find the best strategy for the installation process of next-generation WTG components by analysing the feeder-ship as well as the conventional method. The installation process duration, total costs and fuel consumption are used to compare the feeder strategies to each other and the conventional method. This research can lead to further process improvements and technical developments in future research. This goal can be translated into the following main research question;

What is the best installation strategy for installing next-generation offshore Wind Turbine Generator components within the feeder-ship and conventional methods and under which conditions?

Sub-questions have been developed to answer the main research question. These sub-questions are listed below:

1. What are the possible installation strategies within the feeder-ship and conventional method?
2. What is the most suited research method?
3. How is the research method implemented?
4. What are the parameters of the processes?
5. What are the results of these parameters?
6. Which parameters are critical to the feeder installation process?
7. What is the effect of changing the critical parameters on the results?

Chapter 3: Problem description

In this chapter, we first give a high-level overview of the problem. Next, we describe the elements of different strategies that are a Key Performance Indicator (KPI). Finally, the general assumptions are discussed to specify the scope of the overall problem.

3.1 General problem framework

We tackle the problem of installing next-generation Wind Turbine Generator (WTG) components by comparing different strategies. Here, we will discuss the overarching problem elements of all strategies. These are the installation activities, delaying factors and costs.

3.1.1 Installation activities

The port is required to have a port crane to assemble and/or transfer the components onto a vessel (in case of feedering). One full set of WTG components contains one nacelle-hub assembly, three rotor blades (combined in one blade rack) and multiple tower segments (separate or already combined to a full tower). The components need to be seafastened once they are loaded on the vessel. Besides the components, additional equipment/supplies need to be transferred (e.g. by a container).

The duration of a sailing activity depends on the sailing speed of a vessel and the distance it has to travel. As an example, the distance between the port and a single installation site differs for every installation cycle. Additionally, the sailing speed might also change depending on if the vessel is loaded or empty. These factors lead to an ever-changing sailing duration for a repeated sailing activity.

The installation vessel needs to be fitted/upgraded with a large crane that is high and strong enough to install the next-generation WTG components. The crane of the company Tetrahedron as depicted in Figure 3.1a, is an innovative example of such a crane that can install next-generation WTGs. Upgrading the crane would increase the day-rate of the installation jack-up vessel. The rotor blades will always be transferred in a blade rack to reduce the number of lifts. The blades can easily be installed one by one, after being lifted out of the rack. Such a blade rack is shown in Figure 3.1b. Each component has a special lifting tool that needs to be equipped onto the crane hook before any lift operation.

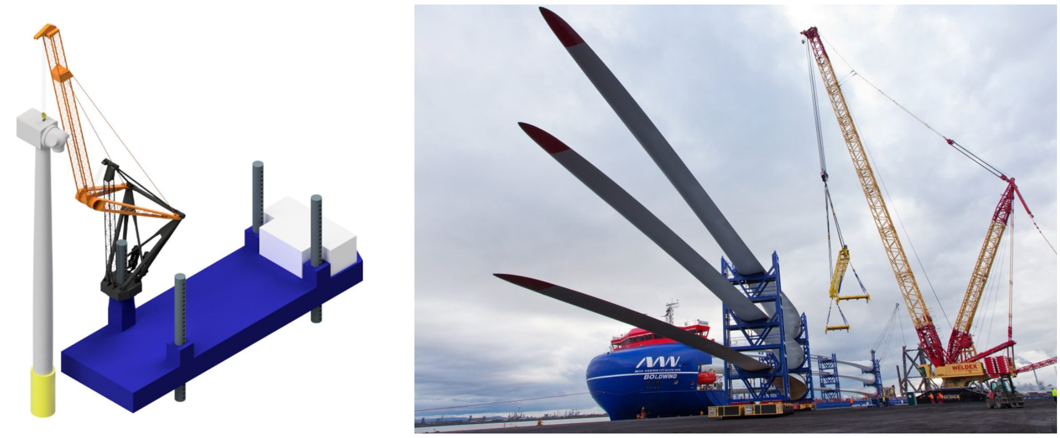


Figure 3.1: (a) Tetrahedron innovative crane concept (Tetrahedron, 2021), (b) WTG rotor blades in a blade rack (Durakovic, 2020)

3.1.2 Delaying factors

Understanding the delaying factors of an installation project is crucial since the project duration is a key element to determine the best installation strategy. All operations are affected by the environmental conditions of the wind (speed), waves (height, period and directionality) and/or current (speed). Each operation will have a duration and a required Weather Window (WW) (DNV-OS, 2011). The required WW is often longer than the duration due to environmental uncertainties. This also allows for a later 'no point of return' and flexibility in the operation.

An operation cannot start if the environmental conditions are above the workable limits within the WW. This is called, Waiting on Weather (WoW). Workability is the percentage of time a task will be performed relative to the entire operation duration (working and WoW combined). Each operation has a different workability depending on its workable limits. The lower the workability, the longer the start of an operation is delayed, leading to an extended project duration. Another important problem element for the environmental conditions are the overarching WWs that are used so vessels can follow the 'safe to safe' principle. This means that multiple activities need to fall under one WW in order to ensure a safe activity sequence and reduce the risk of damages to for example the WTG components. The overarching WW is taken before its first activity of the sequence, and could therefore hold up the entire process. The other WWs (of the activities) within the overarching WW are still required since the limits of these activities might be different from the main (overarching) limits. A visualisation of how this works is shown in Figure 3.2. These overarching WWs are later specified for the problem.

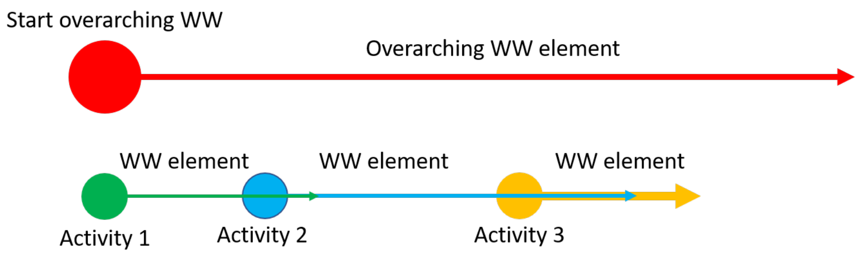


Figure 3.2: Overarching WW in this research versus reality

Logistical models of Ait Alla et al. (2017) and Oelker et al. (2018) noticed that the workability changes over time depending on the environmental climate (seasons). For example, the workability in the winter season is low compared to the high workability in the summer. The start date of a project is therefore important as well. The workability of an operation can be increased by motion compensation tools as shown in Appendix C. Besides shortening the overall project time, these tools reduce the risks of damages during lifts and/or transportation (Kaiser and Snyder, 2012; Haselsteiner et al., 2019). However, they introduce additional expenses creating a trade-off between, risks, costs and time.

Besides environmental delays, mechanical downtimes of vessels or equipment could also hamper the installation process. On the flip side, the installation process could also speed up. Learning effects may occur since the installation of WTGs is a repetitive operation (Schilling, 2013). With every repetition, the operators learn how to be more efficient which enables them to reduces the installation time and therefore costs. This learning effect is not linear but normally follows the form of $y = ax^{-b}$, where y is the labour hours required to 'produce the nth unit', a is the number of hours to produce the first unit, x is the nth unit and b is the learning rate. A representation of this formula is shown in Figure 3.3. With the first units, a lot can be learned so the process speeds up quickly. The more units are done, the less is there to be learned which is the reason why the curve flattens. In reality, this would not be a smooth curve. It might take multiple units to find an improvement in the process. The line is more likely to go down in steps where each step is a new 'improvement' and at the end of the step, the line will be more smooth due to (minor) updates. This learning effect takes place within, for example, a WTG installation project. The process will also improve over multiple projects as will be explained next.

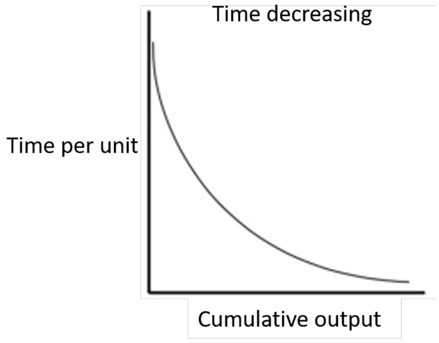


Figure 3.3: A representation of a learning curve, based on (Schilling, 2013)

When applying a new technology in a market such as feedering for the installation of WTGs, the technology is not yet at its best performance. In the early stages, the fundamentals of the technology need to be understood more properly, especially how it works in practice. Therefore, the performance will improve slowly. Next, more research and experience and adjustments of the technology lead to a better understanding and an acceleration of the performance. This better understanding leads to finding the critical elements where the 'greatest improvement per unit of effort' can be made. The technology then begins to 'diminish its returns on effort' as it starting to reach its limit. This process follows an S-curve and is depicted in Figure 3.4. The learning effects, as explained before, take place within each improvement of the technology. In practice, the S-curve does not follow a smooth line as shown in the figure. Each technological improvement will create a step in performance, the steps do follow the pattern of the line. When a step has been taken, the performance of that step can be slightly increased due to (minor) changes in the existing technology. Reaching the limit of a feeder technology takes many projects, where for example, the delivery of a new installation or feeder vessel is a step in performance.

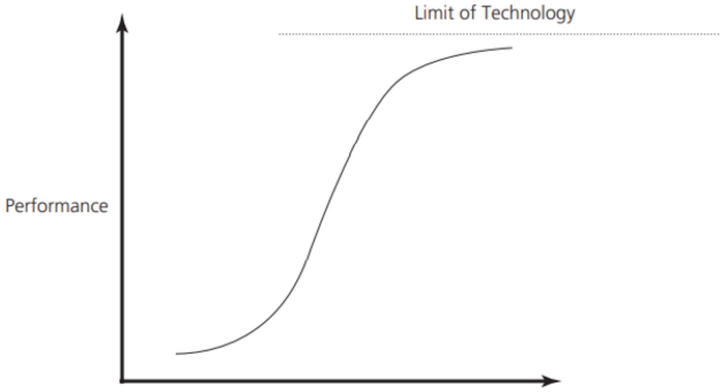


Figure 3.4: A representation of an S-curve (Schilling, 2013)

3.1.3 Costs

The project costs are one of the most critical elements to determine the best installation strategy. The strategy (using the feeder or conventional method) with the lowest costs could be the most interesting for that particular scenario. There are two perspectives to look at the costs;

1. The contractor's perspective
2. The developer's perspective

The cost elements of the problem for the contractor's perspective are the cost of the vessels, tools, port, fuel and vessel (de)mobilisation. Van Oord is such a specialised offshore marine contractor and has a lot of experience with installing Offshore Wind Farms (OWFs) in Europe. The developer, as owner of the OWF, has the same costs as the contractor but has the so-called developer costs as an additional day-rate. Therefore, the shorter the duration, the lower the total costs of the developer are. This perspective gives strategies with a short duration a bonus to be more attractive for the developer and potentially an advantage to win a WTG installation contract for the contractor. Both cost perspectives are based on the European market.

The day-rates are fixed prices per vessel or tool and are often required for the entire duration of the project. The total installation duration is not only dependent on the required time of operations (including WoW) but also the number of WTGs to be installed and the number of (feeder) vessels to be used for example. The required storage size of a base/production port (including port cranes) and port fees when entering a port, introduce the total port costs. Fuel usage is a problem element that is becoming increasingly important since certain projects are even awarded due to lower emissions than competitors. The fuel usage mainly depends on the operation (e.g. sailing, working of idle) and the type of vessel. Besides the dependency on vessel type and operation, the fuel price may also fluctuate over time. The vessel (de)mobilisation costs are the only expense that is not time-dependent in the problem.

3.2 Conventional method strategy

The conventional method as explained in Chapter 1 and shown in Appendix A.1 is an essential aspect of the problem. It functions as a base case to which the feeder strategies can compare. First, all WTG components are transferred from the production ports to a base port by large transport vessels. Examples of these vessels are shown in Appendix B. At the base port, the WTG components are temporarily stored as shown in Figure 3.5. The tower segments will be stacked at the port so they form one full tower. The installation jack-up vessel will be jacked up or moored at the base port and loaded with multiple sets of WTG components depending on the vessel's carrying capacity (by the crane of the installation vessel itself). A larger carrying capacity increases the day-rate of the vessel.

Figure 3.5: The Eemshaven as an example of a base port (WindEurope, 2020)

The installation vessel can sail to the installation site once all components (seafastened), equipment and consumables are loaded. There it will be jacked up and install the components. First, the tower will be installed in a single lift. This will be followed by the nacelle-hub assembly. Lastly, the rotor blades are installed one by one as shown in Figure 3.6.

Figure 3.6: Rotor blade installation of 4 MW WTGs for the Gemini project (Van Oord, 2016)

Motion compensation tools for waves are not required since all lifting operations are only wind limited. After installing one full WTG, the installation vessel will jack down and sail to the next installation site. This will be repeated until all sets on deck are installed. Next, it will sail back to the base port to collect new components and restart the cycle. This process is visualised in a simplified Research Flow Diagram (RFD) in Figure 3.7. A more detailed RFD can be found in Appendix D.

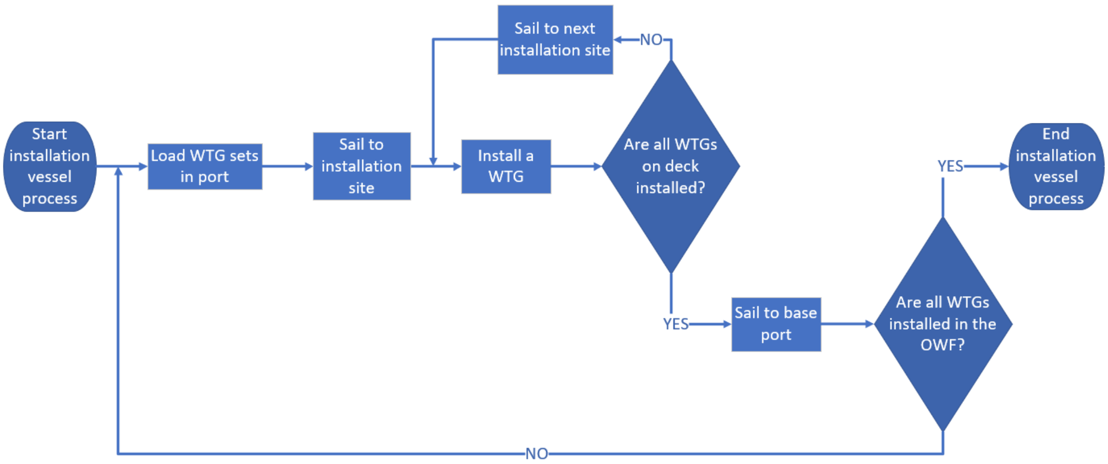


Figure 3.7: Simplified RFD of the installation vessel process for the conventional method

3.3 Feeder strategy

In this section, the feeder vessel follows the feeder-ship method as described in Subsection 2.2.2 and shown in Appendix A.3. The strategy within this method could differ considering different feeder types and the number of feeders used. The different feeder types are explained in Subsection 2.2.1. For example, the sailing speed would be different per feeder vessel type (Van Oord, 2020). The feeder(s) will pick up one or multiple full sets of components and equipment/supplies at the (production) port(s) depending on the carrying capacity. The separate tower segments are stacked in the port to the desired number of transportable segments (if not already). Examples of loaded feeders are shown in Figure 3.8.

The feeder will directly sail to the installing site once fully loaded by the crane in the port. At the site, all feeder types need to be positioned next to the installation vessel and horizontal movements are minimised for the offshore transfer. A barge requires a mooring system while the PSV can use its Dynamic Positioning (DP) system and lift boats are jacked-up above the water.

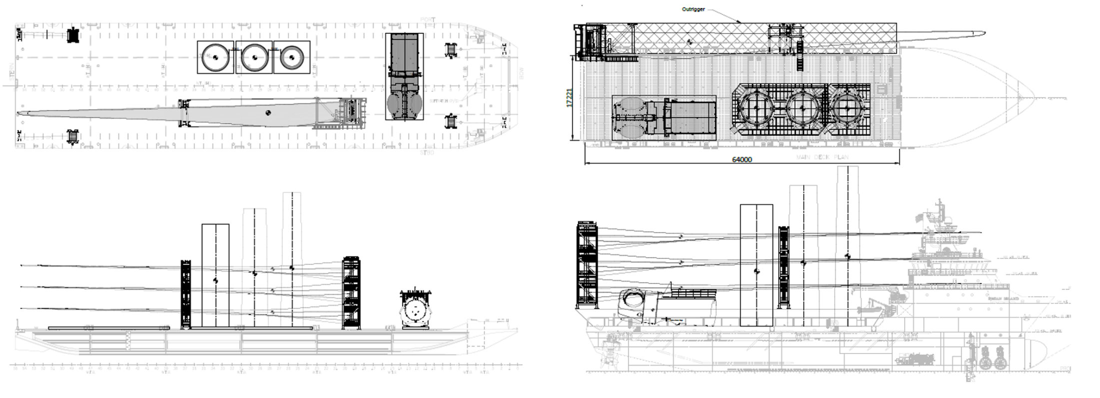


Figure 3.8: (a) Example of a feeder barge layout for a 12 MW WTG (b) Example of a feeder PSV layout for a 12 MW WTG (Van Oord, 2020)

Potentially, a supply PSV (non-feeder type) is required to refuel and resupply consumables to the installation jack-up vessel, since it does not go back into the port during the project (Van Oord, 2020). It is expected that the installation vessel would only go to port when it has to go into shelter due to bad weather. The supply PSV delivers every three weeks and is added to the costs for the time it is used. This could potentially also be done by the feeder itself if the carrying capacity allows it.

The feeder barge requires a towing vessel (tug) to be moved from one location to another. At the installation site, an additional tug is required to position the feeder barge next to the installation vessel and secure the mooring lines that connect the feeder barge to the installation vessel. This additional tug will always stay offshore while the other sails back and forth to tow the barge(s). When using multiple feeders, it is logistically easy to use one towing tug per feeder barge. However, it is more economical to use as few towing tugs as possible. Multiple towing tugs must only be used in cases when the towing tug (at sea) is not back at the port yet, but another feeder barge (at the port) has to leave to be on time at the installation field. This is not a problem element for self-propelled vessels since tugs are not required.

To have a continuous supply to the installation vessel, the feeder should arrive at the same time or just before the installation jack-up vessel is done jacking up. This allows the feeder to directly be positioned next to the installation vessel (where the crane of the installation vessel can reach). The following aspect of the problem is the offshore transfer and installation process. A quick-release seafastening and motion compensation tools as shown in Appendix C are highly recommended to reduce the risk during offshore transfer operations (Kaiser and Snyder, 2012; Haselsteiner et al., 2019). After transferring the WTG components, the feeder will sail to the next installation site and wait for the installation jack-up vessel to arrive if multiple WTG sets were loaded onto the feeder. If the feeder is empty, it will sail back to the port to restart the cycle. A simplified RFD for the feeder in this process in cases for a single WTG per feeder is shown in Figure 3.9 and more detailed in Appendix D. The offshore transfer process has two different options:

1. Install from the installation vessel ('indirect installation')
2. Install directly from the feeder ('direct installation')

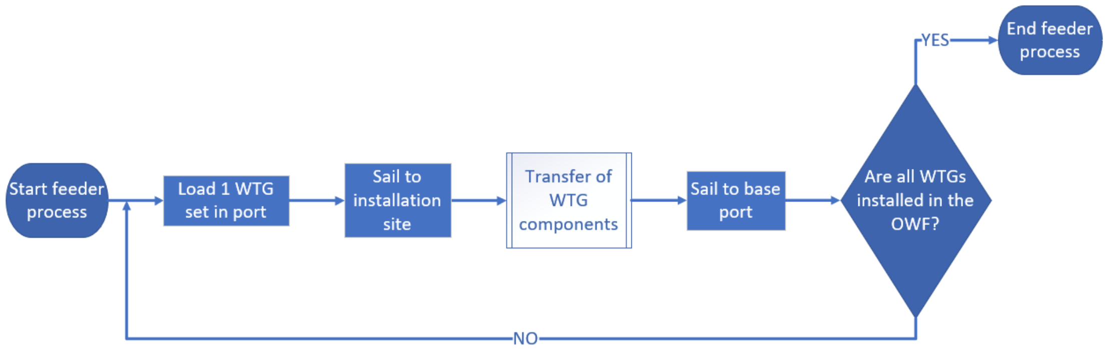


Figure 3.9: Simplified RFD of the feeder vessel process for the feeder method

1. Install from installation vessel

In the cases of using a feeder barge, a 'bullbar' could be temporarily mounted next to the installation jack-up vessel when it is jacked up just above the waves to a so-called lifting height. This reduces the loads on the legs of the installation vessel (by having a short moment arm) when the feeder pushes or pulls on the 'bullbar'. A PSV does not require such a system and the installation vessel will be fully jacked up (at installation height) during the offshore transfer. The crane of the installation jack-up vessel will lift the WTG components as well as the equipment/supply containers one by one from the feeder onto the deck of the installation jack-up vessel. A motion compensation tool in the crane hook and/or at the feeder vessel side will be used to increase the wave height limit for the offshore transfer. Other tools can also be used.

The deck of the installation vessel should have a large enough capacity and space to place the tower segments as well as the nacelle-hub assembly. The blade rack could be located on deck or supported next to the installation vessel. The empty lifting rack (from a previous installation) and containers/tools are then placed back on the feeder. Less deck space is required compared to the conventional method where multiple WTGs are on deck. This could potentially lead to smaller and more specialised installation jack-up vessels than the current-day installation vessels. However, the installation vessel still needs to be large enough to be stable in the water with a large crane and 1 set of WTGs on deck because of safety reasons.

When all components/containers are loaded/unloaded, the feeder can move away (and sail back to the port) and the installation vessel can be jacked up to the correct installation height (if not already) and start installing. It will jack down and sail to the next installation site when all components are installed. There it will jack up again to restart the cycle of the installation vessel. With this option, each component is moved two times and lifting equipment for the crane is changed multiple times as well. This handling is time-consuming for the installation vessel. However, the feeder vessel can sail back to port as soon as everything is transferred, having a short as possible offshore time of the feeder itself. This could lead to using a single feeder at even larger distances offshore while continuously supplying the installation vessel. The simplified process for the installation vessel in this option is depicted in Figure 3.10 and more detailed in Appendix D.

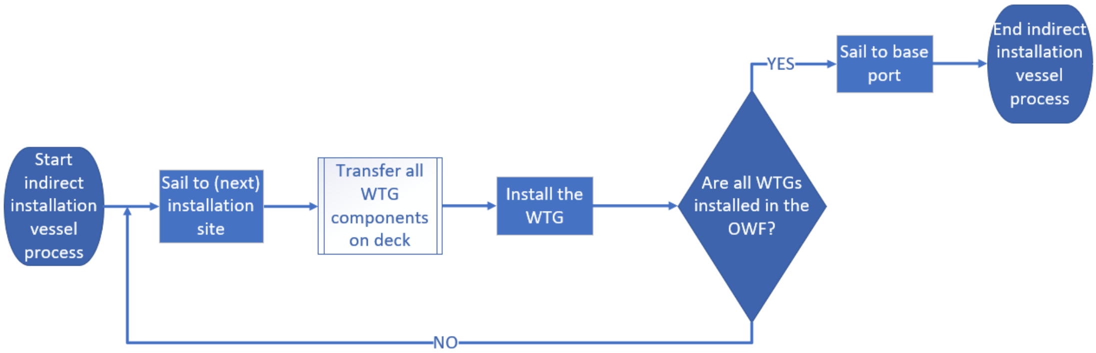


Figure 3.10: Simplified RFD of the installation vessel process for the indirect option

2. Install from feeder vessel

In this option, the installation jack-up vessel is jacked up to the installation height when a feeder is positioning. A 'bullbar' as described above could be used for the feeder barges but the forces might be too high for the jacked-up vessel. Further technical research should investigate this. Again, the PSV will be on DP and motion compensation tools are required. However, for this option, a more specialised (more costly) tool at the crane side is expected to be required according to the engineers of Van Oord since the lifted component will directly be installed as well.

The crane of the installation jack-up vessel will lift the first tower segment from the feeder and directly installs it. This will be repeated with all tower segments and the nacelle-hub assembly. The blade rack will be transferred onto the installation vessel because of the precise (risky) lift when a rotor blade is lifted from the blade rack. The empty blade rack will be placed back on the next feeder that arrives. Compared to option 1, this option should have a quicker installation process since the tower segments and the nacelle-hub assembly are moved only once. Additionally, the lifting equipment of the crane needs to be changed less frequently. However, this option requires the feeder vessel to be offshore (next to the installation vessel) for a longer period. This larger cycle time could potentially lead to additional feeders (more costs) for the same scenario as in option 1. The process of the installation vessel for this option is shown in Figure 3.11 and more detailed in Appendix D.

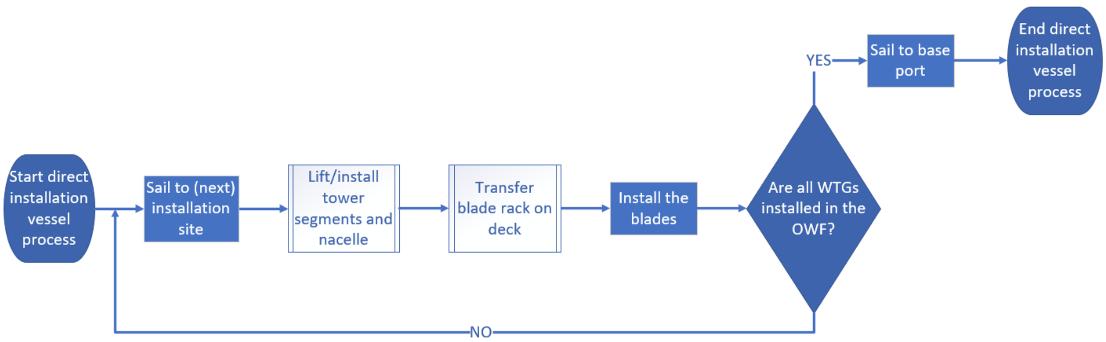


Figure 3.11: Simplified RFD of the installation vessel process for the direct option

3.4 Assumptions of the problem

Multiple assumptions are made to set and reduce the scope of the problem as described above. These assumptions are described below for the feeder/conventional method and overall elements.

3.4.1 Conventional strategy assumptions

The conventional method is used as a base case to which the feeder strategies can compare. There are also different strategies within the conventional method possible that can be compared to each other as well. Two strategies are used in this research and the main difference is the size of the installation jack-up vessel. The first strategy uses an installation vessel that has a carrying capacity of two WTGs. The other strategy uses a larger installation vessel with a carrying capacity of four WTGs.

A larger carrying capacity vessel is expected to have a shorter installation process compared to the smaller one. However, it also has a higher day and fuel consumption rate compared to the smaller one causing a trade-off. The Aeolus is the largest installation jack-up vessel of Van Oord and can be used for installing foundations as well as WTGs. The specifics of this installation jack-up vessel are used for both strategies. The conventional method will not make use of any additional (motion compensation) tools in this research.

3.4.2 Feeder strategy assumptions

The installation vessel of the feeder strategy is also based on the specification of the Aeolus of Van Oord since this vessel is large enough to be stable with an upgraded crane and has sufficient available deck space/capacity. As explained before, a smaller/cheaper more specialised installation jack-up vessel will also be used. The downside of such a specialised vessel is that it might be too specialised for other projects (such as foundation installation) and can not be used.

Van Oord investigated the different available types of feeder vessels for one of their future projects. They created a list of pros & cons for each feeder type for that specific project. This list can be found in Figure 3.12. The Platform Support Vessel (PSV) is a DP vessel and a lift boat is a jack-up feeder as described in Subsection 2.2.1. Lift boats are not desired as explained in the list. Larger lift boats are too expensive as feeder vessels, especially when multiple are required and towing vessels are added. Therefore, this research will only investigate feeder barges and PSV feeder vessels. For both types, it is assumed that only one full set of WTG components can be loaded per feeder. Additionally, the port can only load components/equipment onto one feeder at a time since it is assumed that only one port crane is available.

Van Oord does not follow the feeder-ship method as suggested by Ait Alla et al. (2017) and Oelker et al. (2018) in their potential future feeder projects since there is a difference between theories and practice. In practice, the different production ports might be spread over multiple countries with potentially large distances between them. Additionally, the installation field might also be at a distant location from these ports. The sailing duration of the feeder vessel could therefore be extremely long (potentially multiple days) if the feeder-ship method is applied accordingly. This long duration could most likely lead to considerable delays of the entire project due to the many times the feeder should wait in port or go into shelters along the route (because of potential bad weather conditions). This makes it difficult to keep the continuous supply to the installation vessel. As an example, the tower segments can be produced in the port of Le Harve, France. The blades, nacelle and hub production sites are located at the port of Esbjerg, Denmark. If a feeder vessel follows the steps of Oelker et al. (2018), it will have to sail (loaded with components) roughly 480 nautical miles (nm) to reach the other production port to pick up the next component(s). From here on, it still has to sail to the installation site. Van Oord states that 'installing offshore WTGs should be seen as a production line with as little delays as possible'. Besides the large transport duration, contracts may also require the usage of a base port making it impossible to exactly follow the feeder-ship method.

Figure has been remove due to confidential information

Figure 3.12: Feeder vessel trade-off per feeder type (Van Oord, 2020)

With this knowledge, a more practical version of the feeder-ship method can be created and used in the problem. This version makes use of a base port to temporarily store the WTG components that come from the production ports. The transportation will be done by large transportation vessels as explained for the conventional method. The feeder vessel(s) will only sail from the base port to the installation site and back to supply the installation vessel with WTG components. This new strategy within the feeder-ship method will be referred to as the 'practical feeder-ship method' and is depicted in Figure 3.13 and Appendix A.4. It is a combination of the conventional and feeder-ship method of Oelker et al. (2018). This method can be split up into two segments, 'large transportation' and 'feedering'. It is also possible that all components are produced at one production site. This could potentially leave out the base port and directly feeder from the production port. However, this is contract and production facility dependent. The supply vessel that potentially needs to be used to supply consumables to the installation vessel is not taken into account in this research since this could also be done by the feeder itself. The practical feeder-ship method will be the feeder method used for the rest of this research.

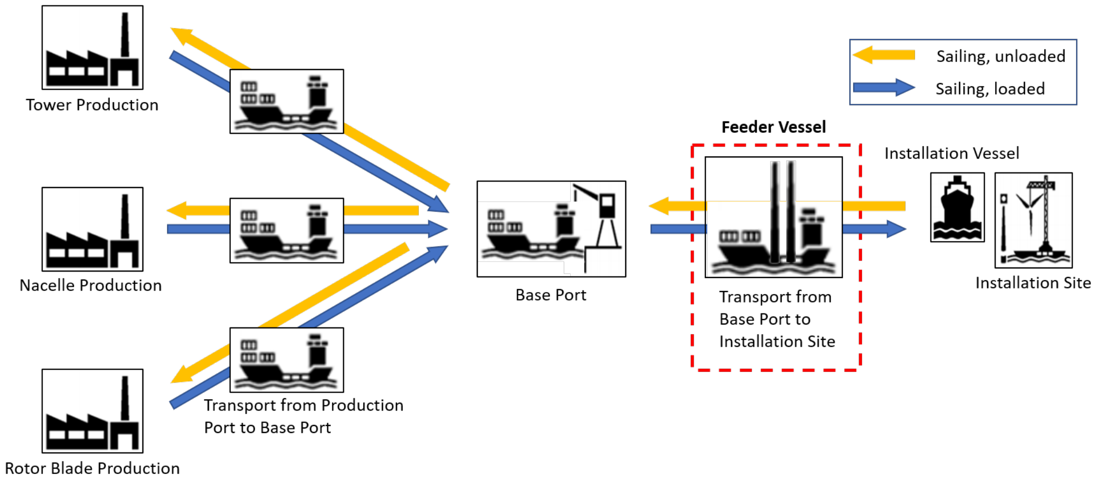


Figure 3.13: The practical feeder-ship method visualised

3.4.3 General problem assumptions

The scope needs to be narrowed down in order to simplify the problem and focus on the feeder elements and the actual installation of the WTG components. The (production) port and large transport elements for both the conventional as the feeder method are out of the scope because they are assumed to be (highly) similar. All port costs and large transportation vessel costs will not be taken into account. It is assumed that all WTG components arrive at the storage on time so it will never be empty during the project. Therefore, the scope of the problem begins when the feeder or installation vessel picks up components at the base port for the first time. The scope ends when all the WTGs are installed and the vessels are back at the base port.

Both the conventional as feeder methods have overarching WWs in their process. For this problem there are four different overarching WWs that include the following activities where all environmental limits are set by the sailing limits for that particular vessel;

1. The installer sailing from the port to the installation site and jacking up.
2. The installer jacking down, sailing to the next site and jacking up.
3. The installer jacking down and sailing from the site to the port.
4. The feeder sailing from the port to the site and transferring all components.

Overarching WWs are also used in real-life projects, but the sailing distance could be split up into smaller segments by having shelter areas along the route. This means that the WW for sailing can be divided into smaller durations where only the last stage will have the overarching WW of sailing and transferring in case of feedering. However, this is highly project-specific. Therefore, in this research, it is assumed that the feeder(s) and installation vessel will sail directly from the port to the installation site and shelter areas along the sailing route are not available or present. Therefore, the results (of this research) are expected to be more conservative (mainly for the large distances) since the overarching WW are long compared to the overarching WW when shelter areas are used. This is further explained in the results of Section 5.6. A visual differentiation between real-life projects and this research concerning the combination of shelter areas and overarching WW is depicted in Figure 3.14 as an example with two shelter areas along the route.

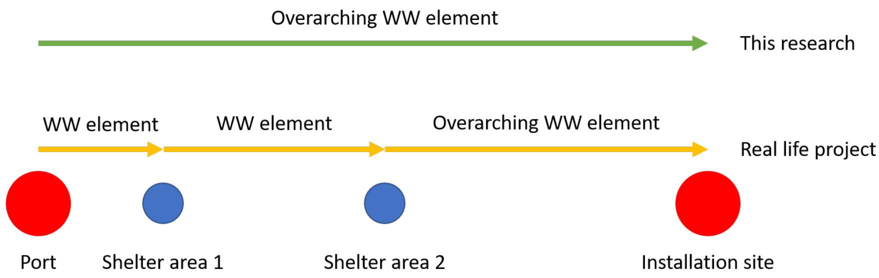


Figure 3.14: Overarching WW differentiation example between real life and this research

The mechanical downtimes and learning curves for any of the vessels and operations as described in the problem are being neglected in the simulation. The sailing distance is assumed to be constant at the average sailing distance between two points if this changes over time. For example, this means a constant sailing distance between the port and installation site as well as the distance between different installation sites. Additionally, the sailing speed for loaded and unloaded operations are assumed to be the same. The fuel usage per unit of time will be different for each activity and vessel type to make the fuel consumption more realistic such a sailing and DP activities. The fuel costs are assumed to be constant over the duration of the project. The emissions are directly linked to fuel consumption. This is not entirely correct. It could be that a new vessel has lower emissions than older ones. For now, it is assumed correct to make this comparison.

The different sizes of next-generation WTGs are not specified. It is assumed that the differences in these sizes do not affect the outcome of the project durations. The costs, however, are affected since potentially larger feeder vessels are required. This is later discussed in the discussion.

All these assumptions lead to a list of components that are within and outside of the scope of this research. These are the main elements that are within the scope;

- The process starts with the mobilisation and loading of the feeder/installation vessel and ends when all WTGs are installed and the vessels are demobilised
- Different transfer/installation combination strategies are used (direct/indirect)
- Practical knowledge is used to improve theoretical strategies
- Different feeder types and installation vessel sizes are used
- Environmental conditions and (overarching) WWs are used
- Different cost perspectives are taken (contractor and developer)
- Different OWF sizes and sailing distances are used

The main elements that are out of the scope are:

- Production and base port logistics/costs
- Other special installation strategies within feedering besides the ones described in the literature (e.g. hybrid feedering)
- Shelter areas to decrease the (overarching) WWs
- Learning effects and breakdowns
- Specifications of next-generation WTGs

Chapter 4: Methodology

First, the most appropriate research strategy will be determined to solve the described problem and to answer the main research question. Next, the best research method within the strategy is chosen. Lastly, the method is explained in more detail how it solves the problem including additional assumptions and the outputs it provides.

4.1 Research strategies

The problem as described in Chapter 3 is bounded by numbers such as activity duration, costs and workability. Therefore, to solve the problem, a quantitative study is most suited. The research strategies available to solve the problem while using a quantitative research are; case studies, observations and experimental designs (Sekaran and Bougie, 2016).

Case studies collect information about specific matters such as 'events' within an operation (Sekaran and Bougie, 2016). These events must be based on a real-life situation and need to be examined from multiple perspectives. 'Events' must already have happened to use this research strategy and to collect data. The problem describes a new installation method that has not been applied yet. Therefore, case study research cannot be used to solve the problem.

Sekaran and Bougie (2016) explain that an 'observation concerns the planned watching, recording, analysis, and interpretation of behaviour, actions, or events'. The 'event' should take place during the observation. However, the installation process of installing WTGs is an expensive process that should be executed with high efficiency. A lot of money will be misspent when observations are used to find the best process due to the many variable parameters in the problem. It could also take years to find the best solution which does not give a competitive advantage to the marine contractor. Therefore the observations as a research strategy to solve the problem is not the most appropriate. Although, it could be used to fine-tune the installation process when the best installation method is chosen by another strategy.

In experimental designs, the focus is on finding the cause and effect relationships (Sekaran and Bougie, 2016). This strategy would fit the problem since many variable parameters need to be taken into account and to understand the effect. Additionally, the goal is to understand which installation method would be the best fit for the different parameter combinations. An experiment can take place in three different forms; field experiments, lab experiments and simulations.

Field experiments take place in the natural environment. These are difficult for this problem due to the Offshore Wind Farm (OWF) size and costs of an installation project. This is similar to the observatory strategy. Lab experiments take place in a controlled environment. This strategy has the same difficulties as the field experiments despite the possibility of creating a small scale project.

'Simulations use model-building techniques to determine the effects of changes' (Sekaran and Bougie, 2016). Simulations are often not too far from 'reality' while still being in control. Control is changing or eliminating a variable parameter to better understand the cause and effect relationship. However, it could be too difficult to simulate certain parameters realistically. A Simulation is also beneficial because large multi-variable parameter experiments can be run in a matter of hours instead of what normally would take months in real life as for the problem in this research. This makes the research itself also cost-efficient compared to other research strategies. For these reasons, simulations are the most appropriate research strategy for this problem.

4.2 Simulation methods

According to Shull et al. (2008), simulation models can be divided into four categories. One of the four categories is quantitative versus qualitative simulations. This is already discussed in Section 4.1. The three other categories are discussed are; deterministic versus stochastic, static versus dynamic and continuous Versus event-driven simulations. From the outcome, the best simulation method (or combination) is chosen based on the problem description.

Stochastic simulations contain a probabilistic element. 'The output parameter values may vary depending on the stochastic variation of the values of input parameters or intermediate (internal) model variables' (Shull et al., 2008). Simulations without a probabilistic element are deterministic. These use a fixed set of parameters. 'For a fixed set of input parameter values, the resulting output parameter values will always be the same for simulation runs'. Static simulations only take a snapshot in time of the variation of the model parameters (Shull et al., 2008). Dynamic simulations take the changing behaviour of the model into account spread over a period of time.

Continuous simulations keep the variable parameters up-to-date during the run-time of the model. This makes the variable parameters time-dependent. This required possibly complex 'time-dependent linear differential equations of first or higher order' which need to be solved using a numerical integration Shull et al. (2008). On the other hand, event-driven simulations 'update the values of the model variables as new events occur'. The most frequently used event driving simulation is the Discrete Event Simulation (DES). DES 'models are typically represented by a network of activities and items that flow through this network'. Events can be triggered by other starting or ending events or items that moved from one point to another. Other event-driven simulation types have been less popular according to Shull et al. (2008).

To solve the problem described in Chapter 3, it is not interesting to know what happens within an activity. Therefore, the best approach is the DES. Each activity in the problem can be seen as an event and the items that are moved in the model are the WTG components. The parameter of vessels and the OWF in the problem are deterministic since all of them are fixed. However, the weather from hindcast data as an input for the model is seen as a stochastic approach since this contains a varying element. The next section, among others, explains how the weather is taken into account in the model. The problem does not require going into the dynamic behaviour of the installation activities over time since all input parameters are deterministic. For these reasons, using a stochastic Discrete Event Simulation model is the most fitting simulation method.

4.3 DES and cost model

First is described how the problem is implemented in the DES. This is followed by the description of the separate cost model. Lastly, the outputs of both models are explained.

4.3.1 DES model

At the beginning of the simulation, all vessels will be mobilised at the port. The mobilisation is the preparation of the vessel for the project by among other things adding seafastening and other equipment. After the mobilisation, the installation process start and all vessel will do their first activity. In the case of feedering, the installation vessel will sail to the installation site and the first feeder will start the loading process. The feeder will stay moored along the quayside when it is done loading but cannot sail out due to the weather or the installation vessel that is delayed and not ready. The other feeder (in cases of multi-feeder strategies) can now start loading (if in the port) since the port crane is available. This is the same in the real world as in the simulation if only one port crane is available. The simulations follow the activity sequence as described in the problem description and are visualised in a detailed RFD in Appendix D.

Each activity has its duration, environmental limits and WW linked to the environmental data location. In an ideal simulation, multiple years of real-life environmental (hindcast) data should be collected from all WTG installation locations, multiple points along the sailing route and the port. However, processing all this data is computationally intensive, so the data locations used in this research are at the port and the centre of the OWF. Multiple years of data are required so the simulation can be repeated with the same start date for each year. All these simulations will also be repeated at different distances between the port and the OWF since this is an important element in the problem. As an example, if there are ten years of environmental data and four different distances are used, then the simulation will have to run forty times per installation strategy. How the results of multiple years and distances are used is explained in Section 4.3.3.

The activities in the port will only be wind limited since the port is assumed to be wave 'sheltered'. The offshore activities (including sailing) encounter wind as well as waves based on the OWF environmental data. The environmental current speed limitations are excluded from the simulation.

The collected environmental data are significant wave height (H_{m0}), peak wave period (T_p) and wind speed at 10 (U10), 60 (U60) and 160 (U160) meter height. The significant wave height is the average of the highest one-third recorded waves for a period (Holthuijsen, 2010). The significant wave height value is a very close representation of visually estimated wave heights in experiments. The peak period is the period corresponding to the most energetic waves in the spectrum. Waves are created by the energy that passed through the water creating a circular motion of water particles. The energy is provided by the friction between the surface and the wind. Two types of wind-generated waves are defined; wind waves and swell waves. Wind waves are waves that are generated in a wind field and located in that same wind field where they are created. These waves tend to have a small peak period. Swell waves are waves that have moved out of the wind field where they were created. They tend to have longer peak periods as wind waves. A simplified visualisation is provided in Figure 4.1.

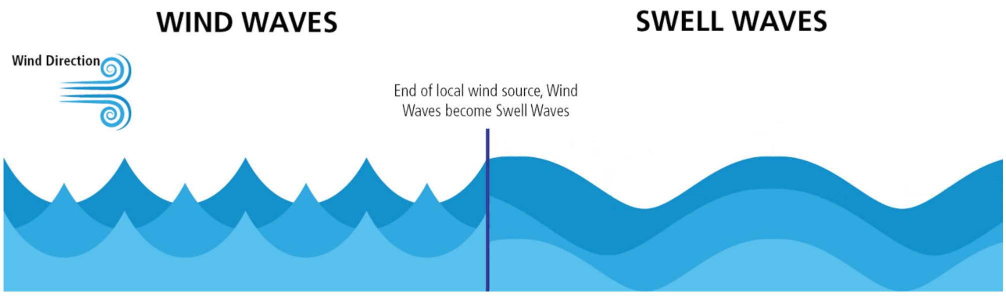


Figure 4.1: wind waves versus swell waves, based on Mazarakis (2019)

The combination of significant wave height and peak period is of importance since certain activities are more affected by long or short waves. This could lead to a lower wave limit for that activity for different peak periods. Short waves periods have a smaller effect on a vessel in for example pitch and roll motions because the waves hit the vessel too soon after each other and the mass of the ship is more dominant (Journee et al., 2015). At longer periods, the ship tends to move more with the waves creating more motions. The response characteristic of a vessel due to waves is a Response Amplitude Operator (RAO). The RAO is the motion response of the vessel per wave height at a certain frequency. The period is the frequency divided by one (long periods are low frequencies). Figure 4.2 shows to RAOs of roll and pitch of a container vessel. Long periods tend to move with the waves because the RAO is (close to) one (left side of the plot). The spike in the plots is the natural frequency of the vessel. Here, the motion is amplified. At shorter periods, the RAO moves to zero meaning the response of the vessel becomes smaller allowing for a higher wave limit than with a larger response. In this research, a distinction has been made between 'long' and 'short' waves. The period where the difference is set is provided in Section 5.1.

The wind speeds at different heights are required because the activities take place at different heights. For example, the installation of the nacelle, blades and tower (in segments and full tower) are assumed to be at 160m height. On the other hand, the offshore transfer and/or loading (in port) will be at 60m height (except for full tower loading with the conventional method). Sailing, positioning, preparing and jacking activities are limited to the wind measured at 10m height.

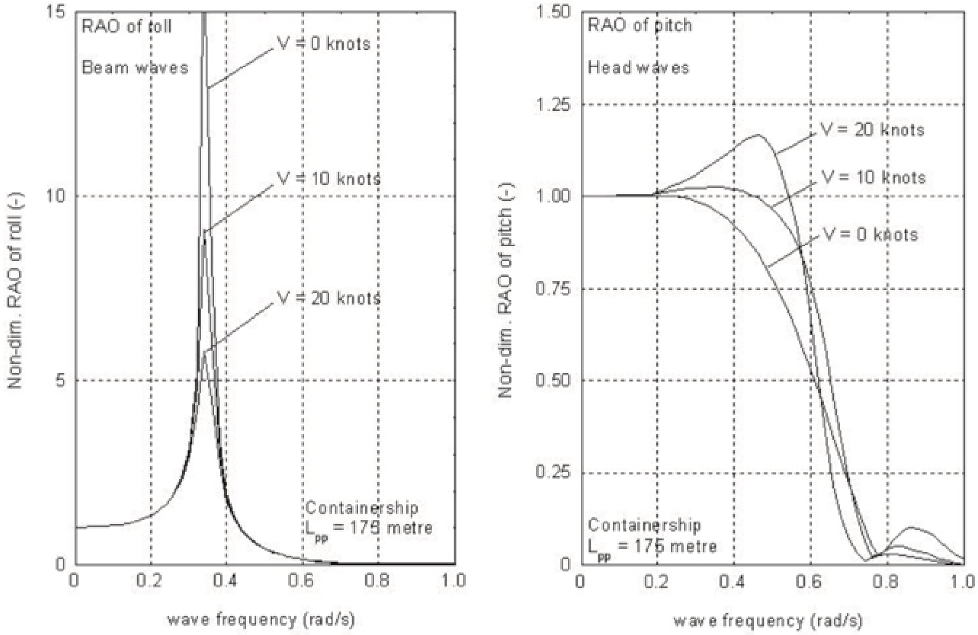


Figure 4.2: Example of containership roll and pitch RAO Journee et al. (2015)

As explained before, an activity can only start if the environmental conditions within the WW and/or overarching WW are below the wave and wind limits. The steps the simulation takes for an activity in the DES are as follows, a 'triggered' activity will start and retrieve its input parameters at time T1. Next, the environmental data of the specific location data set is used to find the first possible WW where the environment is below the limits. The time will move to the beginning of this available WW called T2. This could also be the same as T1 in case the available WW starts at T1. The time difference between T1 and T2 is the so-called Waiting on Weather (WoW). Following, the activity is executed and the next activity or activities are 'triggered' for the same and possibly other vessels. Now, the initial activity is finished, the time moves to T3 and the new activity/activities can start. This simulation process is visualised in Figure 4.3. The overarching WW follows the same steps but does not have an activity duration since it only acts as a trigger for the sequential activities within. The DES models or both installation methods are also shown in IDEF0 (Integrated Definition for Function modelling) diagram in Appendix E for more clarity. The IDEF0 is a technique to analyse systems and design systems of what the constraints, in and outputs and the physical aspects are (Presley and Liles, 1998).

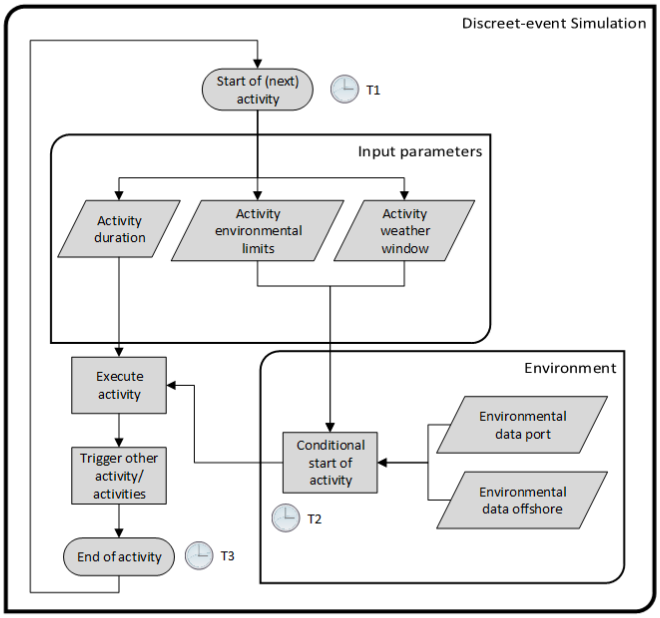


Figure 4.3: DES model steps

The simulation sequence for the conventional method is straightforward since there is only one vessel that has to follow the steps of its process. The simulation for the feeder strategies is more complicated because the feeder and the installation vessel have to communicate with each other when to start the sailing activity for the feeder from the port to the installation vessel. To maintain a continuous supply to the installation vessel, the feeder must start its positioning activity at the same time the installation vessel is done jacking up. This positioning activity falls within the aforementioned fourth overarching WW from section 3.4. There is a chance that the feeder will have to wait for a very long time at sea if it directly sails out when it is loaded in the port. In the worst case, it could be that some activities fall outside of the overarching WW due to the long waiting period for the installer to be ready. This is a potential risk for the operation. Therefore, the feeder must know the point in time it can start sailing to the installation site. It could be the case that the feeder must wait at the port if the installer is not ready in the future when the feeder will arrive. However, one of the problems of DES modelling is that one cannot look into the future to know when certain activities for other entities (vessels in this research) are finished due to the random (weather) input. To work around this problem without any complicated mathematical solution, a code has been added to the feeder simulation so it will arrive at the installation vessel at the correct moment when the process is simulated without any weather delays. When the weather is taken into account, the installation vessel might encounter delays that are not known to the feeder when it already started sailing. Then, the feeder might have to wait offshore but for a shorter duration than when 'no waiting in port' is used. This reduces the risk of the feedering process. Another downside is that the feeder receives the 'go' signal from the installation but will firstly search for an available overarching WW which could also delay the process. In real life, the approach would be the same, but weather forecasts in combination with communications between vessels are added to be more precise.

In the simulation, the vessels will be demobilised when the project is finished and all vessels are back in the port. All vessel costs (day-rates) will continue until the very last day of the project. In the real world, this can be different, especially for the feeders. A feeder will return to port for the last time if it does not need to transport any new components. From that point, the demobilisation can start for that particular feeder and its costs will be finalised. The installation vessel will be the last vessel to arrive at the port and start its demobilisation. This difference leads to a very slightly overestimates of the total costs of the simulation compared to the real world.

4.3.2 Cost model

The costs are calculated using a different script so the time-intensive DES is not required to be run again when the costs need to be adjusted for example. The cost model uses the output being the project duration (as discussed in detail in the next section) of the DES as an input to calculate time-dependent fuel, vessel and developer's costs.

The fuel consumption rates (ton/day) for sailing, working or idle activities are used to compute the total fuel costs. The installation vessel is either sailing or working, whereas the feeder vessels that use fuel (PSVs and towing vessels) on the other hand encounters all three fuel consumption types. The installation vessel uses the input of the sailing activity and total project duration to determine how much time is spend on sailing and working (total duration minus sailing duration). The same is done for the feeders/tugs to determine the combined working and idle duration. The distribution of working and being idle for this combined duration is assumed to be 50/50.

The vessel costs are easily calculated by multiplying the total project duration with the day-rate of that specific vessel. The (low) day-rate of the specialised smaller installation vessel is not precisely known while the current-day installation vessel day-rate is. Therefore, a value has been estimated for this lower day-rate. This value and the current-day installation vessel day-rate are then used as a bandwidth input for the installation vessel to provide a more specialised installation vessel.

A sensitivity analysis for the feeder strategies for some of the critical parameters is performed to understand their impact on the process duration. In real life, the costs of a vessel or tool might increase with these changes of the parameters since certain aspects/tools need to be more specialised or added. This increase in costs is hard to estimate. Therefore, the cost input parameters are kept the same for all scenarios and the available costs per day of that feeder strategy to just be competitive are calculated. This is done by taking the difference in costs between a feeder and a conventional strategy and dividing this by the installation days of that feeder strategy.

4.3.3 Outputs

The output from the DES simulation is the date a WTG is installed and the installation vessel is jacked down. Figure 4.4 is an example of the outputs of multiple years of data for one distance offshore where the weather is taken into account in the model. Each line represents a starting date (the same day) for a different year. The y-axis indicates the nth WTG installed. The x-axis can be used to find the date any nth WTG is installed. This can then be used to determine the project duration. The difference between summer (steep lines) and winter (less steep) is clearly visible. The weather causes the results to vary. The results in the plot are the same and linear for every year if the weather would be excluded. The total installation duration per year for a distance can be determined by the difference between the starting and ending date and added the (final) sailing to port activity duration of the installation vessel.

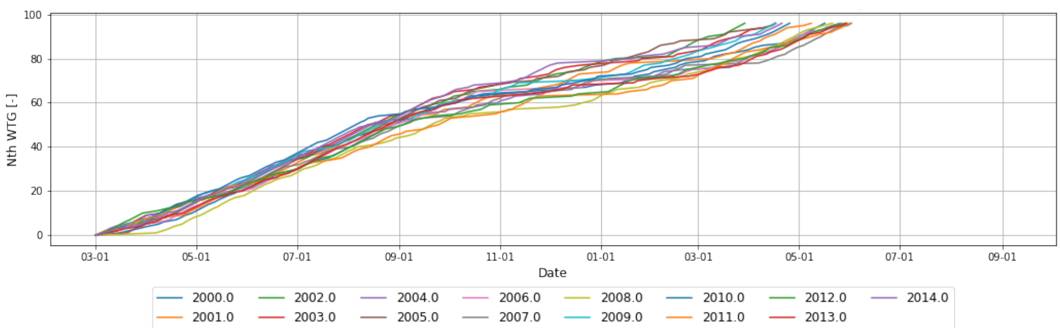


Figure 4.4: DES output example results that include the weather for a single OWF distance

There are two types of duration results used in this research, the P0 and P50, also known as the 0^{th} and 50^{th} percentile, and are common in the industry. The P0 indicates that 0% of the project duration estimations are lower than the P0 value itself for each distance that is simulated. This is the most optimal case and can only be reached when the weather is excluded from the simulation (only one simulation is required). These results are used to understand the process and potentially filter out feeder strategies that will not likely be a best installation strategy.

The P50 indicates that 50% of the duration results (as described above) are lower or equal to the P50 value itself for each distance that is simulated. An example of the P50 to a normal distribution is shown in Figure 4.5 where eight out of the fifteen 'estimates' are lower than or equal to the P50 'estimate'. In this research, the weather needs to be taken into account to determine the P50 duration value which is read from the green line in the figure. The more simulation runs for one project (one distance and rerunning multiple years), the better the estimation of the P50 for that specific distance will be. However, this also means a longer simulation time. These results are used to determine the best installation strategy. Other P-values, such as the P70 and P90 are dependent on the variance and could also be used to have more confidence in the simulation durations of the project compared to the potential reality and for the contractor to justify potential delays to the client (the developer). Therefore, for projects, other P-values can be used, but for this research, the P50 is sufficient to provide a good overview of the different strategies. The variance of the results will be analysed to provide insight into the effect of using other P-values.

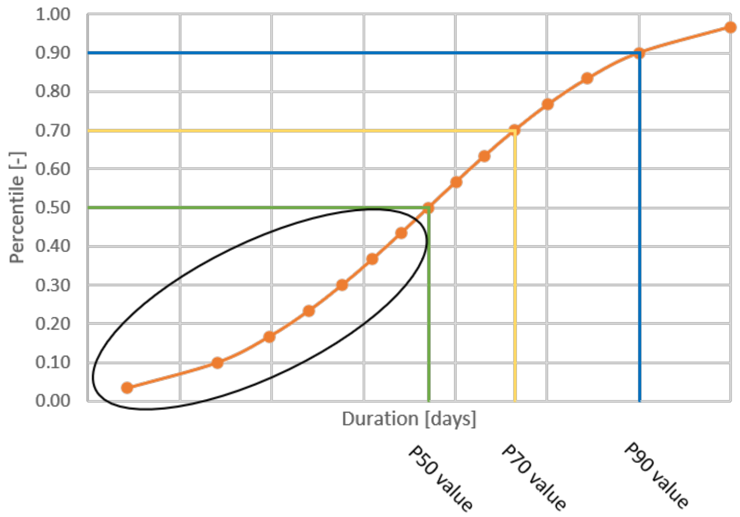


Figure 4.5: P-value visualisation for normal distribution

The cost model provides the output of the total costs made out of the fuel, vessel, (de-)mobilisation costs and developer's costs (depending on the perspective). The total costs for the feeder strategies are in the form of a bandwidth due to the uncertainty of the installation vessel day-rate; where the lower bound uses a specialised installation vessel and the upper bound a current-day installation vessel. Besides the total costs, the cost model also provides insight into the available day costs for a feeder strategy compared to the conventional ones. If the value is negative, the feeder solution needs to be cheaper. On the other hand, if the available day costs are positive, the feeder strategy has the potential to increase the costs per day while remaining competitive up to a point where the available costs are zero. This increase can be seen as the available amount per day to upgrade the (feeder) vessel and/or tools for potential larger next-generation WTGs. These results again have a bandwidth due to the installation vessel day-rates where the lower bound is the current-day installation vessel and the upper bound the specialised installation vessel. The fuel cost outputs per strategy are evaluated separately from the other costs to compare the fuel consumption.

Chapter 5: Results

In this chapter, we first introduce the parameters for the simulation and the model validity. Next, the P0 and P50 results of the initial cases are analysed. Thereafter, different scenarios for the sensitivity analysis are explained and the results analysed or the duration, costs and fuel consumption. The Discrete Event Simulation (DES) model is built using Python and makes use of the OpenCLSim package that is specially created for complex logistical simulations.

5.1 Model parameters

The duration of each activity for the conventional method is provided by Van Oord based on their experiences and documents. The durations for the feeder methods are also based on the experiences of engineers and upcoming projects since feedering has not been performed in real life by Van Oord. The activity durations are found in Appendix F.

The two base cases are given by the conventional method that uses respectively two and four WTG deck capacity installation jack-up vessels. The feeder method is initially simulated for the indirect and direct strategy using 1, 2 or 3 feeder barges and PSVs. The number of towing vessels for the barges are dynamically changed so the least amount of towing vessels are used while still remaining a constant supply to the installation vessel. This has a lower total cost compared to the strategy where every barge has its own towing vessel. The feeder method initially transports the tower in four segments. The day-rates and the estimated fuel consumption per day of the installation and feeder vessels can be found in Appendix F. The price per ton of fuel is estimated to be 450 Euro.

The distance between the port and the Offshore Wind Farm (OWF) is an important parameter since it provides inside into when a certain installation method outperforms the others on duration and/or costs. The distances used in this research range from 20 nm to 300 nm in six equal steps (every 56 nm). According to Van Oord, OWFs further than 200 nm rarely occur. However, distances up to 300 nm are used since this could happen in the future. The size of the OWF is a crucial parameter because with larger projects, the chance of working throughout the winter season or even two increases. The winter season is known for its rough environmental conditions leading to a lower workability, and therefore more project delays. Three different OWF sizes are initially used in the simulations to create an understanding of this parameter as well as the seasonal effects. These sizes are 48, 96 and 192 WTGs. These numbers are chosen based on the experiences of Van Oord and the capability of the model. The installation vessel has a sailing speed of 12 knots, the PSV sails at 15 knots and the towed barge at 6 knots.

The P0 simulations do not require environmental data, whereas the P50 simulations do. In this research, the data from the port and OWF are respectively from the Maasvalkte (52°N, 4°E) and the Hollandse Kust-NW OWF (52.9°N, 3.6°E) as shown in Figure 5.1 (DHI Group, 2021). As an indication, the distance between these points is roughly 54 nm (100 km).

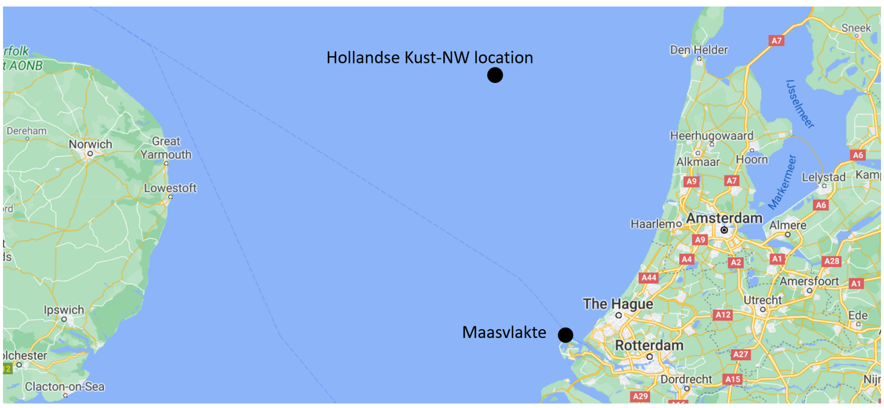


Figure 5.1: Port and OWF location for environmental data

The data has been gathered for the period between the 15^{th} of January 1979 until the 31^{st} of December 2019. This data has hourly intervals. The interval step size has been decreased by linear interpolation to 15 minutes for more accurate results.

The environmental data allows the simulation to be rerun 39 times (having the same start date but for a different year) to lead to a P50 value. However, this amount of runs would take too much time, and therefore, due to time constraints of the research, the number has been reduced. In this research, each installation project starts on the 1^{st} of March at 8 am for the years 2000 until 2014 (15 simulation runs per distance). The results of the 15 simulation runs provide a distribution that is close to a normal distribution as shown in Appendix G. It provides rigorous results with a reduced simulation time. From here on, the P50 can be calculated by taking the mean of project duration for that case.

The limiting wind speeds Van Oord provided are at 10, 50 and 100 m height above the waterline. To scale the wind limits to the correct height, a logarithmic wind speed conversion formula is applied since the wind speed profile follows a logarithmic scale (DNV, 2010). This formula is shown in Equation 5.1. The wind limits for each activity can be found in Appendix F.

$$U(z) = U(H) \cdot \left(1 + \frac{ln\left(\frac{z}{H}\right)}{ln\left(\frac{H}{z_0}\right)}\right) \tag{5.1}$$

Where:

H	is the reference height	[m]
$U(H)$	is the wind speed at reference height	[m/s]
$U(z)$	is the wind speed at the new height	[m/s]
z	is the new height	[m]
z_0	is the terrain roughness parameter (open sea or port)	[m]

The wave limits are also based on the data and experiences of Van Oord. As explained in Section 4.3, the height of the wave limit could be affected by the peak period. The 'short' waves are defined for peak periods up to 8 seconds while the 'long' waves are above 8 seconds. This boundary at 8 seconds has been defined by hydrodynamics engineers of Van Oord. The wave limits with their accompanying wave period for the activities are shown in Appendix F.

5.2 Validation and verification

Most parameters have been retrieved from the documents of Van Oord. The other parameters that are not exactly known are based on similar values and/or experiences. The Discrete Event Simulation (DES) model assumptions, as well as the parameter values, are firstly validated by discussions with experienced engineers of Van Oord. Most of their remarks were about the costs which have been changed to more realistic values. The mobilisation costs for the direct feeder method remains a discussion. Some engineers say these can be significantly lower because only the blade rack will be taken on deck of the installation vessel (less seafastening required), while others agree that because of safety reasons, seafastening for one WTG should always be installed. It is assumed correct to follow the safer method. The effect of potential lower mobilisation costs will be discussed later in the results.

Another remark by the engineers is about the overarching Weather Window (WW) for the large distances since shelter areas along the sailing route are not used in this research. They agreed that shelter areas (and their locations) are highly project-specific and the feeder is required to follow the 'safe to safe' principle so it has an opportunity to safely transfer the components and potentially sailing back to the port while still having WTG components on deck in case of breakdowns of for example the lifting equipment. Therefore, they accepted this assumption but felt the need to place this remark.

To check whether the P0 simulation is working according to the RFDs in Appendix D, an analytical excel simulation is created (also based on the RFD that uses the deterministic parameters of activity durations for one WTG installation cycle. This cycle is then multiplied by the number of WTGs in the OWF to result in the total installation time. The results of the P0 and Excel simulation must be exactly the same in cases where the feeder can maintain a continuous supply to the installation vessel (mainly the short distances). All of the duration results are the same, proving that the P0 simulation works accordingly. In addition, the conventional method P0 has also been checked with another simulation tool built by Van Oord in Excel. The difference between these results is roughly 1% and is therefore neglectable. Another deterministic Excel sheet is created to check whether the costs are calculated correctly in the cost simulation. This resulted in marginal differences. These can be explained because the fuel costs are not taken into account in the Excel sheet. The total costs are the same again when the fuel costs from the simulation are added to the Excel file, proving that the cost calculations are correct.

The Waiting on Weather (WoW) durations of the P50 are checked by dummy simulations. Multiple random WoW segments have been taken and the start and end of each the WoW segment are noted including the WW and the environmental limits for that specific activity. The environmental data were used to confirm each WoW segment. All these WoW durations are in line with the data.

5.3 P0 Results

The P0 simulations consider the feeder method as well as the conventional method. The initial input parameters as described above and in Appendix F are used in the simulations. First, the project durations are discussed. This will be followed by a subsection about the costs for the contractor and the developer.

5.3.1 P0 Project duration results

The P0 duration results for an Offshore Wind Farm (OWF) with 96 WTGs are shown in Figure 5.2. The y-axis is the total installation duration in days and the x-axis is the distance between the port and the OWF. All axes have respectively the same scale. The P0 duration results of the other OWF sizes can be found in Appendix H, but share a similar pattern as the one provided here (but on a different scale). The plots can be used to find the project duration (in days) for a specific distance. The base cases are the yellow and black lines that represent the conventional strategies. The blue, red and green lines represent the feeder strategies. The different strategies can be compared to each other. The lowest line for a specific distance is the fasted strategy (not necessarily the cheapest). Therefore, for feedering, it is ideal to be lower than the conventional strategy lines, mainly the lowest (yellow) one.

The first thing that stands out are the (green and red) lines that are relatively horizontal for all distances for the cases that use a PSV, except for two PSVs - direct feedering from roughly 240 nm. This means that the installation has a continuous supply of WTG components. However, the supply is not continuous anymore when these lines break off from their horizontal such as for the red lines in the cases where barges are used at roughly 75 nm for direct and 130 nm for indirect feedering. The blue line does rarely indicates a continuous supply, meaning that the single feeder option cannot keep up with the pace of the installation vessel and is not a best strategy considering the duration. It is only continuous for indirect feedering with one PSV up to roughly 75 nm and one barge at 20 nm.

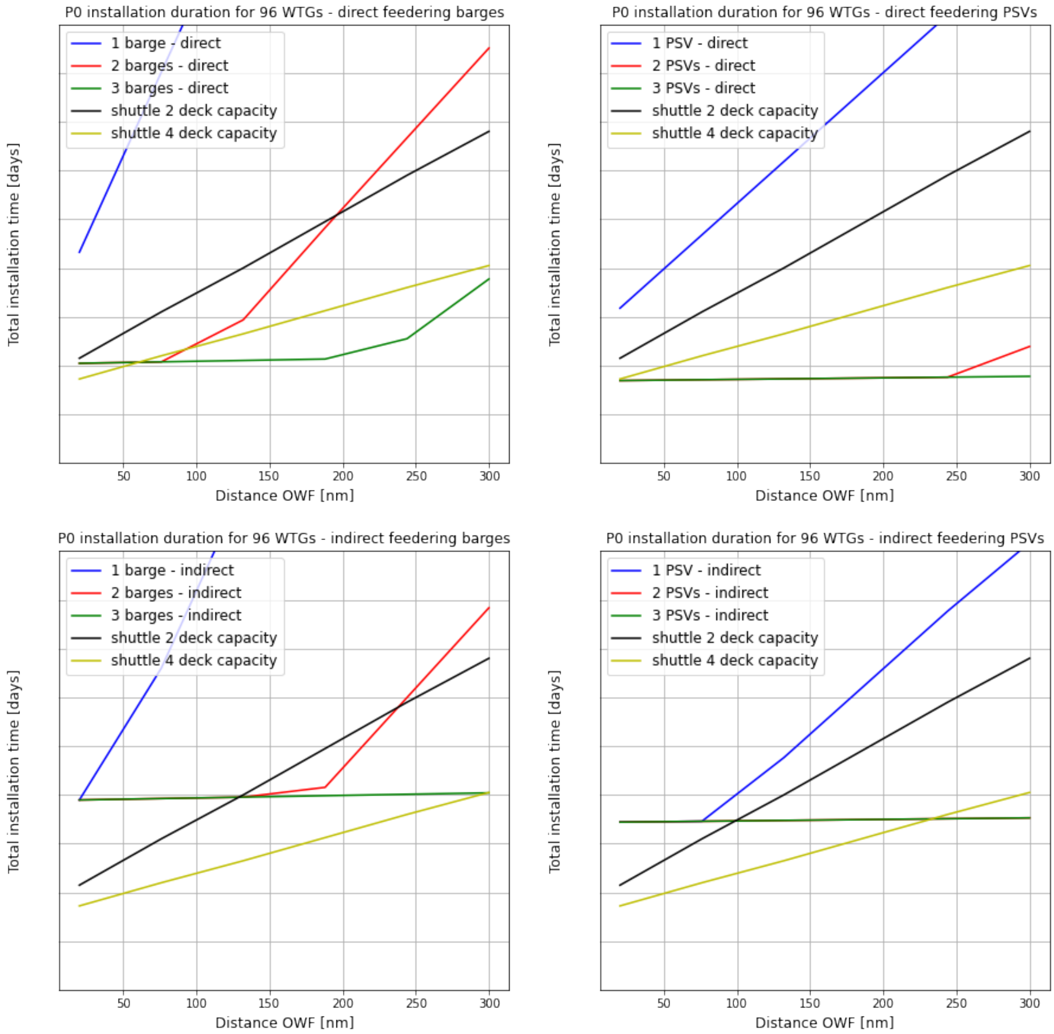


Figure 5.2: P0 duration plot for 96 WTGs with 4 tower segments

The second element that sticks out is the difference between barges and PSVs. The total duration when using barges is always higher than for PSVs. This is because of the difference in cycle times due to the (de)positioning activity. The PSV can be positioned using its Dynamic Positioning (DP) system while the barge requires a more time-intensive mooring system. Additionally, the break-off point (for a continuous supply) for barges is at much shorter distances. This is due to the difference in the sailing speed of the feeder. A PSV is 2.5 times faster than a barge and could therefore maintain a continuous supply of components to the installation vessel at large distances.

The P0 duration results also show the direct installation method is much quicker than the indirect method. This can be explained by the additional handling time of the WTG components for the indirect method since the components first need to be transferred onto the installation vessel and then be installed. The direct method merges these two steps and installs the components straight from the feeder (except for the blades that are the same as for indirect due to risk of damages) to have a shorter cycle time of 'transferring' (lifting) and installing. This is clearly visible in Figure 5.3 when comparing the direct and indirect strategies. The bar plot shows the cycle time of the different installation steps for installing one WTG (sailing excluded). This figure also shows that the conventional installation process is much faster than the transfer and installation for feedering. Combining figures 5.2 and 5.3 shows that the supply speed (the continuous supply) of the components is the key reason for a feeder strategy to be faster than a conventional strategy. Overall, the P0 duration results show that it is possible for a feeder strategy (mainly the direct method and PSVs) to be faster than both of the conventional strategies. However, this could change when the weather is taken into account.

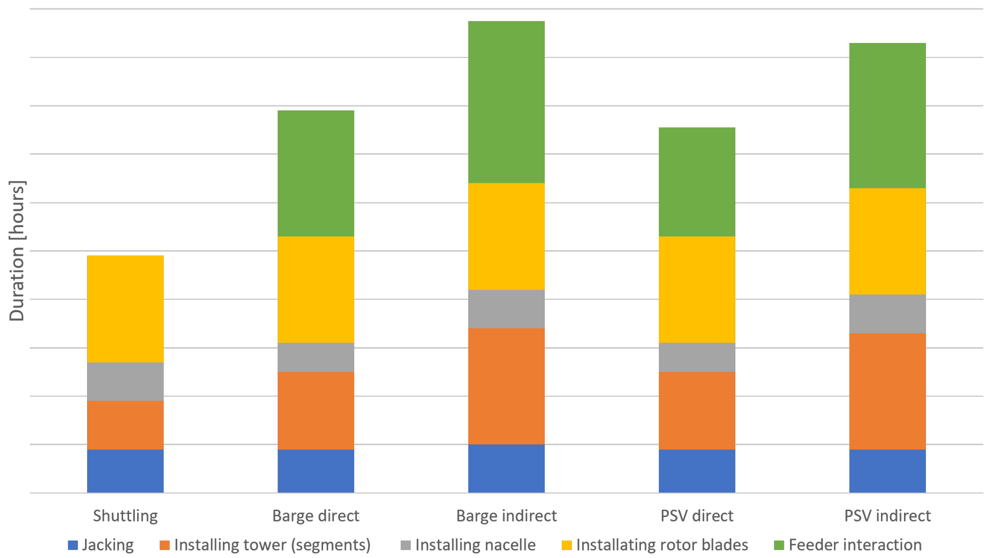


Figure 5.3: P0 single WTG installation and transfer duration breakdown for all strategies (with 4 tower segments)

5.3.2 P0 Cost results

The P0 contractor costs are derived from the P0 duration results and are depicted in Figure 5.4. The duration for each distance as shown in Figure 5.2 is multiplied by the day-rates of all used vessels in that strategy. The fixed and fuel costs are added to derive the total costs per strategy per distance. The different cost components can be found in Appendix F.

The y-axis is the total installation costs for the contractor in million Euros and the x-axis is the distance between the port and the OWF. All axes have respectively the same scale. The cost plot can be used to find the project costs for a specific distance per strategy. The yellow and black lines are the base cases and represent the conventional strategies. Each feeder strategy has a lower and upper bound. The lower bound is a feeder strategy in combination with a specialised installation vessel. The upper bound is that same feeder strategy but with a current-day installation vessel (that is more expensive). The marked area in between the bounds is the difference in installation vessel day costs to indicate the potential of creating a special purpose installation vessel. The overall lowest line indicates the lowest cost strategy at a specific distance. A feeder strategy with a specialised installation vessel would be the cheapest solution (for a specific distance) if the lowest line is the lower bound of the feeder strategy. However, ideally for feedering, the upper bound would be lower than the lowest conventional line. This means that current day installation vessels can cost-wise competitively be used in feeder strategies. No investments are required for a new installation vessel. Any adjustment to the existing installation vessel that lowers the day-rate makes the feeder strategy more competitive. On the other side, feedering is not cost-competitive when the lower bound is higher than the conventional strategy (for a specific distance) as in the left plot of Figure 5.4. The P0 contractor costs of the other OWF sizes slightly differ in pattern due to marginally different duration patterns and the significant difference in duration scale. These plots can be found in Appendix H.

It is clear that the conventional method compared to the indirect feeder method has lower project costs and therefore would be a potential best installation strategy. However, the direct feeder method while using two PSVs can be cheaper than the conventional method from roughly 150nm and more. To have lower costs, the installation vessel costs for this feeder method should be as low as possible.

The strategies of barges and PSVs are compared to potentially rule-out feeder strategies. It clearly shows that the PSVs have lower costs when the direct and indirect options are compared separately. Barges are only competitive at very short distances (20 nm). Feedering by one PSV indirect for short distances and feedering by two PSVs for longer distances would be the preferred feeder option if the feeder types and the transfer options (indirect/direct) are compared at the same time. However, the decisions to use direct or indirect on a certain distance and the number of feeders can change when implementing the weather.

The result that the barges are more costly is expected not to change when taking the weather into account. This is because the environmental limits of the barge are only slightly higher than the limits of the PSV while having a much longer overarching WW due to its significantly slower sailing speed. This leads to a lower workability while the feeder strategy should have high as possible workability to be competitive with the conventional method. Therefore, PSVs have the most potential and the barges can be ruled out for now for the contractor.

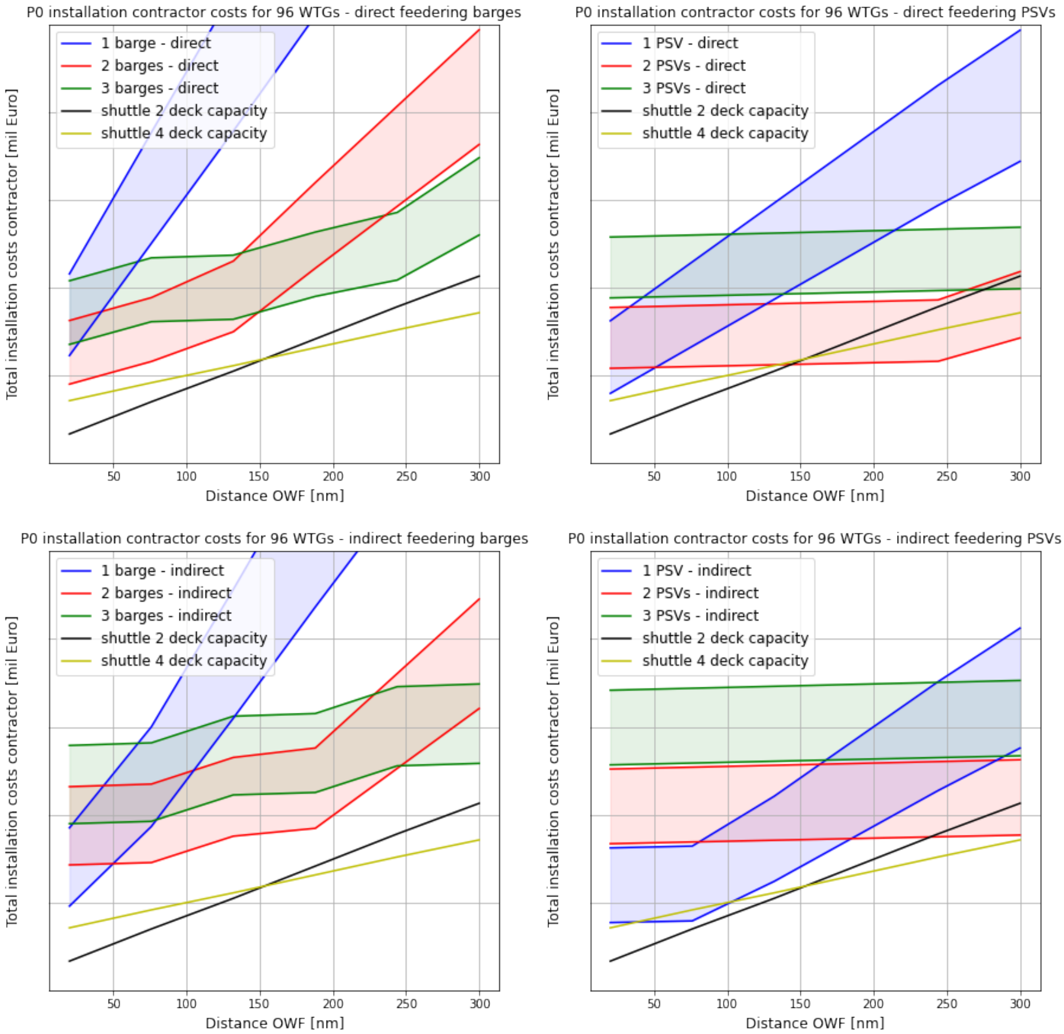


Figure 5.4: P0 contractor cost plot for 96 WTGs with 4 tower segments

The developer cost results for the OWF with 96 WTGs is shown in Figure 5.5. The other OWF sizes are depicted in Appendix H. The developer costs plots are read in the same manner as the contractor cost plots. The costs for the developer shows a similar outcome as for the contractor costs. Although the values increased, the decision to rule out the barges still holds.

The results clearly show the effect of the additional cost per day as a bonus for fast strategies and a penalty for the slower ones. For instance, the strategies that use one feeder are slower compared to both strategies of the conventional method. Therefore, the relative gap between the results becomes larger in comparison with the results of the contractor in Figure 5.4. On the other hand, the results of the two and three feeder strategies become more interesting since these are faster than the conventional method. One thing that stands out is the direct feeder method with two PSVs. Here, from roughly 200-300 nm, the estimated 'most expensive' installation vessel in this method would suffice as a potential best strategy if the weather is not taken into account. However, projects at these distances are expected to occur rarely.

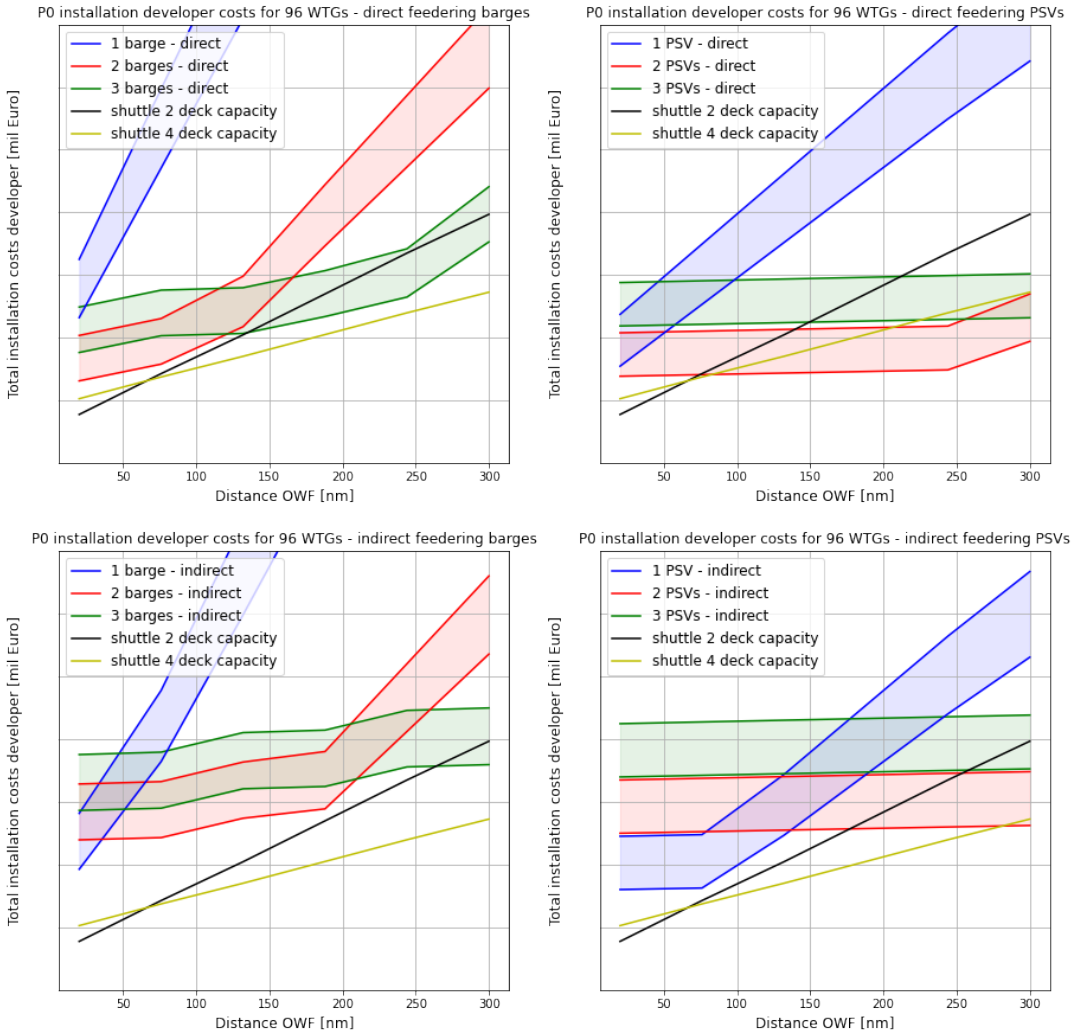


Figure 5.5: P0 developer cost plot for 96 WTGs with 4 tower segments

5.4 P50 Results

The P0 results provide a best installation strategy decision between the feeder types. However, it did not allow a choice between the indirect and direct feeder option, the number of feeder vessels required and at which distance any strategy is better since the weather can have a significant impact. Therefore, in this section, the weather is taken into account to provide the P50 results for feedering with a PSV as well as the conventional method. All environmental limits and costs used are the initial values shown in Appendix F. First, the duration plots are discussed. This is followed by the cost plots for the contractor as well as the developer. These plots are read in the same manner as explained in Section 5.3.

5.4.1 P50 Project duration results

The duration plot for the P50 results is given in Figure 5.6. The first thing that stands out is that not any of the PSV feeder strategies is faster than any strategy of the conventional method for a 96 WTG OWF. The other sizes in Appendix I show that the direct feeder method with two PSVs can be faster than the conventional method with a deck capacity of two WTGs at larger distances that range from 150 to 250 nm. However, the conventional method that has an installation vessel with a deck capacity of four WTGs is the fasted for all distances and all OWF sizes. The two-deck carrying capacity conventional strategy is slower since it has to sail more often and therefore also encounters more delays due to the loaded sailing overarching WW. This is mainly noticeable when a project enters the winter season since the wave limits of the installation vessel for sailing are relatively high.

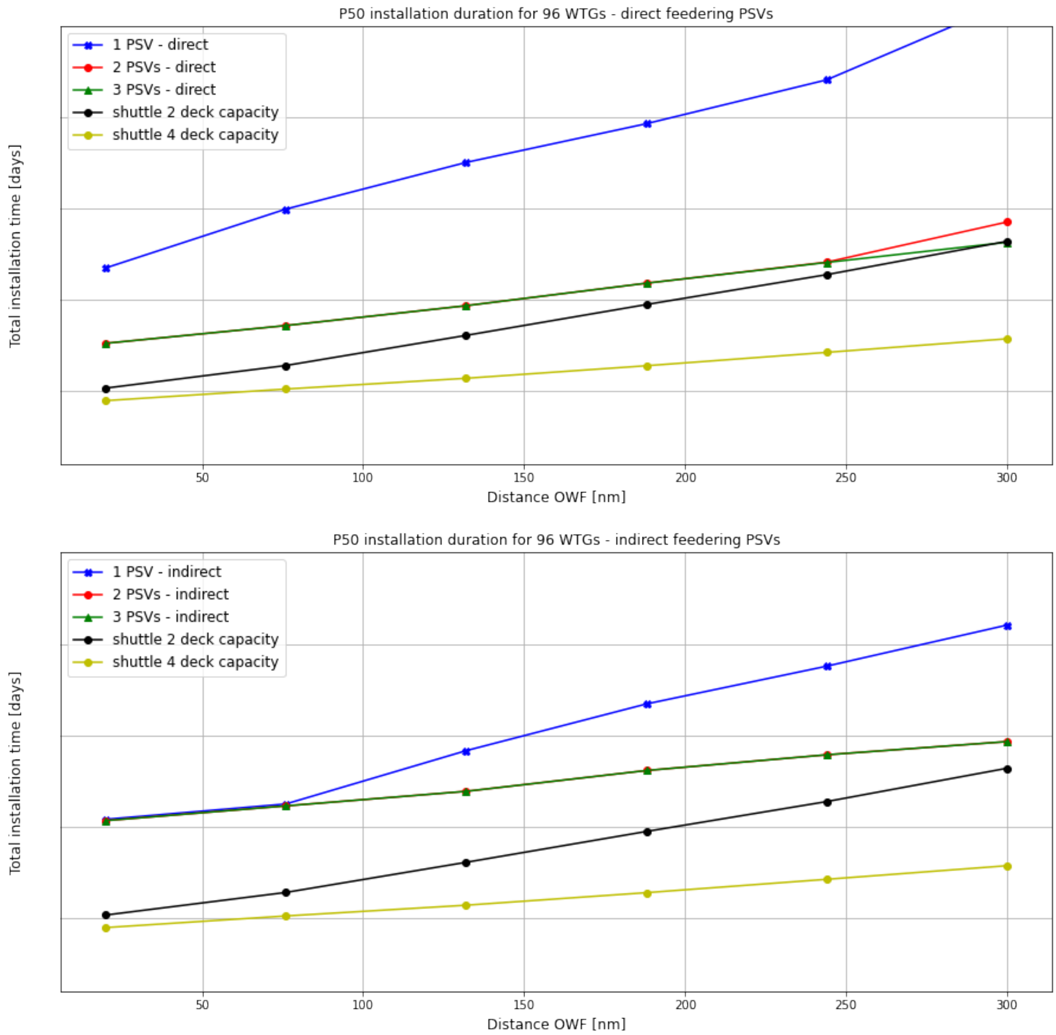


Figure 5.6: P50 duration plot for 96 WTGs with 4 tower segments

A very interesting result is provided for the two and three PSVs for both direct as indirect. The lines are (for most of the distance) exactly the same. This indicates that a three feeder installation process would not be any faster than using two feeders. This is caused by weather that does not allow the feeder to sail out (due to the overarching WW) as well as the installation vessel that is not ready to receive new WTG components due to installation delays. The same holds for the other OWF sizes. From these plots, it can be stated that the direct feeder method using two or three PSVs is faster than the indirect method with the same amount of feeders.

Using one or multiple PSVs for the indirect option at distances up to roughly 75 nm provides the same duration results. This is mainly due to the continuous supply, short feeder cycle time of the indirect method and the relatively short overarching WW at the short distances. This does not hold for the direct method since the single feeder cannot keep a continuous supply to the installation vessel.

The lines of the two and three feeders as well as the conventional method are slightly curved. The single feeder methods show a more visible curve. These curves are caused by the seasonal impact of the weather. The slope of the lines is larger when an installation project is finishing in the winter season as one can clearly see for the single PSV with the direct method at the short distances. Next, the slope decreases when the installation project finishes in the following summer season. At the larger distances (around 240 nm) for that same line, the slope increases again due to the second winter season the project is going through. The seasonal impact of the multi feeder methods is much less since these all finish around or in the first encountered winter season in this plot. The same holds for the conventional method. The larger OWF size OWF (192 WTGs) in Appendix I also clearly shows this seasonal effect since the projects go through multiple summers (and winters). The smaller OWF size shows an installation process that can be finished before or just at the start of the winter season.

5.4.2 P50 Cost results

The contractor cost plots for 96 WTGs based on the P50 duration are shown in Figure 5.7. These costs when using any feeder strategy for this size as well as the costs for other OWF sizes in Appendix I, are not lower than the costs of any of the conventional method strategies. The conventional method, in this plot, shows a turning point for the size of the installation vessel (two or four-deck capacity) at roughly 100 nm. This turning point changes depending on the OWF size and therefore also on the winter season(s) the installation process encounters.

Figure 5.7 shows that the feeder method with three PSVs is not the cheapest feeder method for the contractor. This is because the duration is (almost) the same as the method with two PSVs but additional costs are made. This holds for the direct as well as the indirect option. Therefore, feedering by three PSVs is ruled out in further simulations.

When comparing the plots of the direct and indirect for the one and two PSVs, the results show that feeder with two PSVs is the better feeder method for large distances (from roughly 150 nm) while feedering with one PSV is better at shorter distances. Although the single feeder - indirect is slower than two feeders - direct, the costs per day are low enough to compensate for the additional time. This effect increases for the small OWF at short and medium distances since the project ends before the winter season.

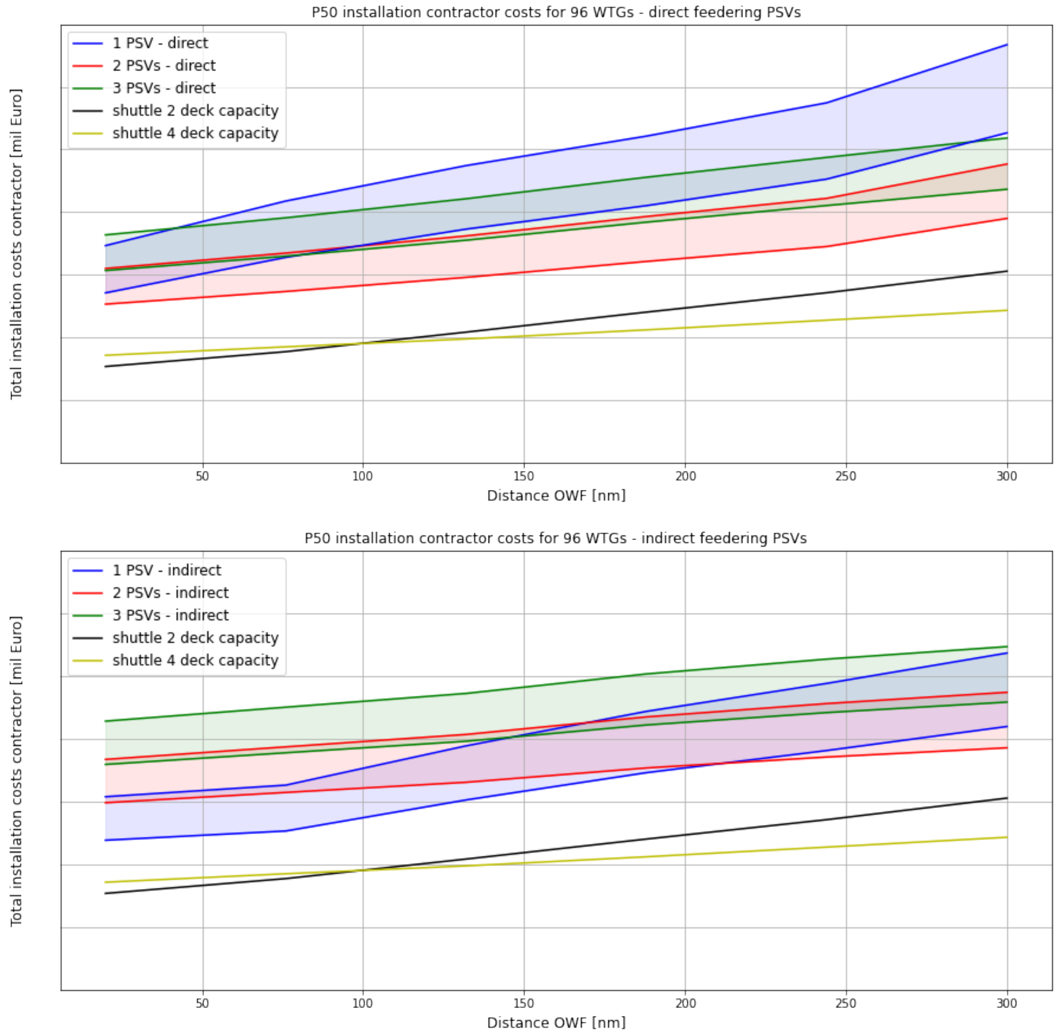


Figure 5.7: P50 contractor cost plot for 96 WTGs with 4 tower segments

The bar plot in Figure 5.8 shows the breakdown of the costs for the single PSV - indirect and two PSV - direct strategies for 96 WTGs. Appendix I provides the other OWF sizes. The costs are divided into (de)mobilisation, fuel and day costs, respectively from bottom to top, to get a better understanding of their influence. Each modelled distance has two main bars, one for each feeder strategy. The total day costs per strategy are divided into two separate bars where the difference lies in the costs of the installation vessel, being either current day or specialised.

From these bars can be stated that the fuel costs are relatively little compared to the other cost elements. The daily cost has two bars per feeder strategy because the installation vessel costs can be low or high depending on how specialised it is. The (de)mobilisation costs do have a significant impact on the total costs. As discussed before, the mobilisation costs of the installation vessel could be lowered to less than half the current amount for direct feedering. This would mean that the direct method with two PSVs potentially becomes more interesting. The effect of this decreased mobilisation cost becomes weaker for OWFs since the fixed costs are spread over more turbines. The opposite occurs for smaller OWFs.

The outcome for the perspective of the developer in Appendix I does not change the aforementioned statements about the installation methods. Therefore, the initial input values and other assumptions for the feeder method can not provide any competitive feeder installation strategy compared to the conventional method for the initial input values. This research will continue with a sensitivity analysis based on the aforementioned results.

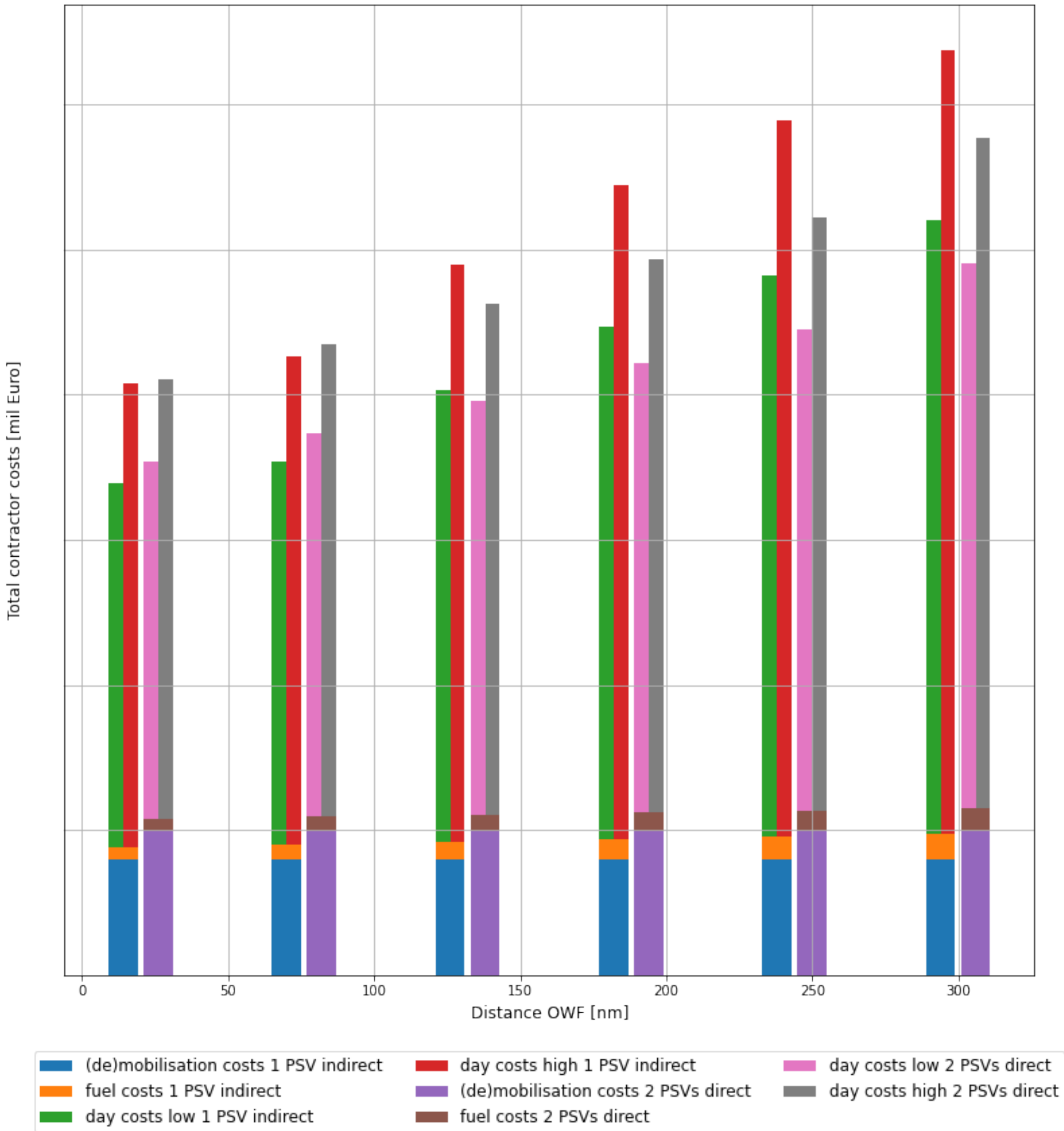


Figure 5.8: P50 contractor cost breakdown for 96 WTGs by feeders

5.5 P50 Sensitivity analysis

In this section, first, the critical parameters are discussed to create different scenarios. The results of these scenarios are then analysed to provide insight into what is required to have a competitive feeder strategy and an understanding of the impact of the critical parameters.

5.5.1 Critical simulation parameters

Many parameters can be used for this sensitivity analysis for this research. However, due to time constraints, only a few parameters have been selected to create different scenarios for the simulations. These parameters have been chosen based on the critical path (bottleneck) of the installation project or current developments in the market. The results of the previous sections are used, so the simulations are only run for a single PSV - indirect and two PSVs - direct. The parameters of the installation vessel are known/given by Van Oord and will not be used in the sensitivity analysis. Therefore, the parameters of the feeder are the ones used.

The first parameter is the environmental limit of the sailing activity of the feeder, and therefore also the overarching WW for feedering. The overarching WW withholds the feeder from sailing to the installation vessel under certain conditions. Therefore, it can cut off the supply of WTG components. It is expected that if these limits set by the wind and waves are raised, the project duration will decrease. These limits could be changed by for example building a more stable feeder vessel. First, the impact of the wind and wave data is investigated by analysing the environmental data. Both or only one of the limits will be changed in the simulation scenarios depending on the outcome of the initial weather data analysis. The limit(s) will be raised in small steps to understand the impact on the total costs and project duration. It is expected that the overarching WW will create significant delays in the winter season when rougher seas are anticipated. Therefore, the understating of this effect is critical.

The second parameter is the transfer limit of the tower segments and the nacelle-hub assembly. Since the wave limits are relatively low, it is expected that these could potentially be a bottleneck for the installation project. The wind limits of the transfer will not be looked into since these are limited by the crane of the installation vessel. Additionally, at this moment, the market is showing interest in developing specialised feeder vessels with increased wave limits for the offshore transfer (Ampelmann, 2021; Huisman Equipment, 2021; GustoMSC, 2021). The new designs include motion compensation systems so the aforementioned components can be held stable at larger wave heights during preparations and the transfer. One of these designs is shown in Figure 5.9. The motion compensation systems will not be used for the transfer of the blade rack and the back lift of tools and other equipment. This could potentially lead to a bottleneck while having a more specialised feeder vessel.

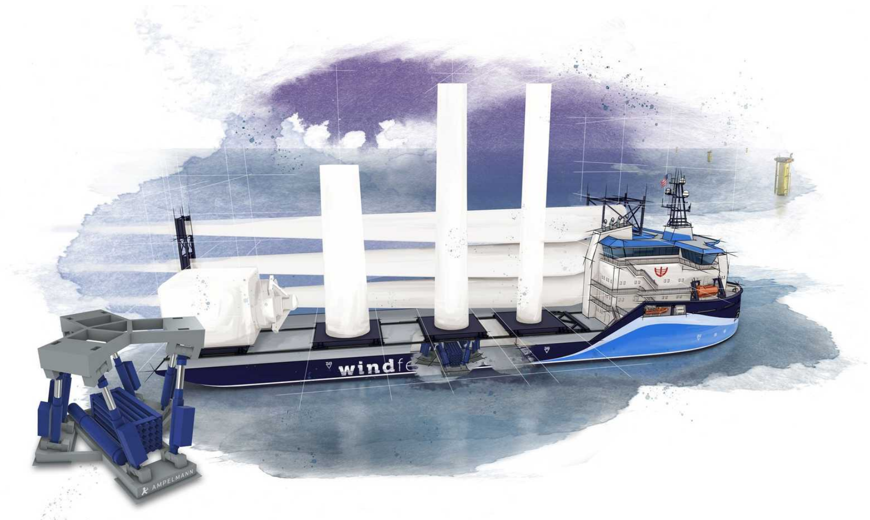


Figure 5.9: Example of a new PSV feeder by C-job and Ampelmann (Ampelmann, 2021)

The third parameter is the number of tower segments that are loaded onto the feeder to combine into one full tower. Changing this number of segments changes the cycle time of the feeder. A significant amount of time could be reduced since transferring and installing multiple tower segments is a dominant factor according to Figure 5.3. This potentially provides insight into how many segments are required to make feedering an interesting installation strategy. It is also useful knowledge for the design of the vessel for, for example, the size and stability. Fewer tower segments mean more available deck space (compared to more tower segments), but also means higher tower segments. This leads to a higher centre of gravity and potentially to an unstable feeder vessel in the even calm seas.

5.5.2 Simulation scenarios

The first parameter in the scenarios is the sailing limit of the wind speed and the significant wave height of the feeder. The environmental data are used to get an overview of the impact of the wind and waves on this activity alone. This is done by extending an Excel sheet with the data and checking how many data points are lower than the limits of the sailing activity. First, the initial values (for a PSV) are used to set the baseline. Next, the values are slightly increased to check the change of the number of data points below the limit. In addition, a dummy WW is used to make sure the outcome does not differ too much. The results of the checks are shown in Table 5.1.

Table 5.1: PSV sailing operability based on the environmental data

H_{m0} [m]	**U10 [m/s]**	**Data points under the limit, excl. WW [%]**	**Data points under the limit, incl. 20h WW [%]**
2	14	77.62	64.05
2	15	77.75	64.22
2	16	77.75	64.22
2.25	14	82.48	70.03
2.25	15	82.84	70.68
2.25	16	82.92	70.78
2.5	14	85.90	73.97
2.5	15	86.75	75.64
2.5	16	87.00	76.09

The table shows that increasing the wind speed barely affects the total data points that are under these limits. On the other hand, the impact of the increasing significant wave height is of significance. Although the percentage drops, these results do not change when a WW is included.

The OWF sizes in this analysis are 48 and 96 WTGs. The 192 WTG OWF is excluded since the outcome of the initial P50 results are highly similar to the other OWF sizes. The effect of the winter season on the feeder solution can be taken from the 96 WTG size. Additionally, this reduction in simulation, reduces the simulation time significantly, allowing for more simulations in a shorter period.

The initial values (scenario 1) for the limits is the baseline for the sensitivity analysis. As described above, the sailing limit will first slightly be changed. Next, the transfer limit of the tower segments and the nacelle are stepwise increased (looking at market developments) to understand this effect. This process is repeated for each number of tower segments. The exact values for the environmental limits as well as the number of tower segments for all scenarios are provided in Table 5.2. The table has been altered due to confidential information. The duration results of the scenarios are provided in the same table where scenario 1 is used as a baseline at where the distance offshore is 132 nm. The other scenarios are a percentage of the baseline of the specific strategy and OWF size. The results per scenario are analysed and the outcome determines if it is required to run additional or even skip subsequent scenarios where the outcome can easily be predicted, such as the results of the indirect strategy of scenarios 7-9, which will almost have the same result as scenario 3. This example is based on the outcome of scenarios 2, 4-6 that have a similar pattern in the input. The duration results of this table are used in the next subsection for a quick numerical overview to compare the different scenarios within their respective strategies.

Table 5.2: List of scenarios and duration results at 132 nm, with scenario 1 as a baseline

	Sailing	**Transferring**		**Tower**	**Duration - 132 nm [%]**			
	H_{m0} [m]	H_{m0} [m]		**segments**	2 PSVs direct		1 PSV Indirect	
Scenario #	All T_p	$T_p \leq 8$s	$T_p > 8$s	# [-]	48 WTGs	96 WTGs	48 WTGs	96 WTGs
1 (baseline)								
2								
3								
4								
5								
6								
7							-	-
8							-	-
9							-	-
10								
11								
12								
13								
14								
15								
16							-	-
17							-	-
18							-	-
19								
20								
21								
22								
23								
24								
25							-	-
26							-	-
27							-	-

5.5.3 P50 Sensitivity analysis results

This subsection discusses the effect of the change of different parameters. The first parameter that is being discussed is the wave limit for the sailing activity. This is followed by the wave height parameter for the transfer of the WTG components. Lastly, the effect of reducing the number of tower segments is explained. The costs for the developer are not discussed in this subsection since the effects are already explained in Section 5.4. The manner to read the duration and cost plots in this section is explained in Section 5.3. The input values for the simulations are found in Appendix F.

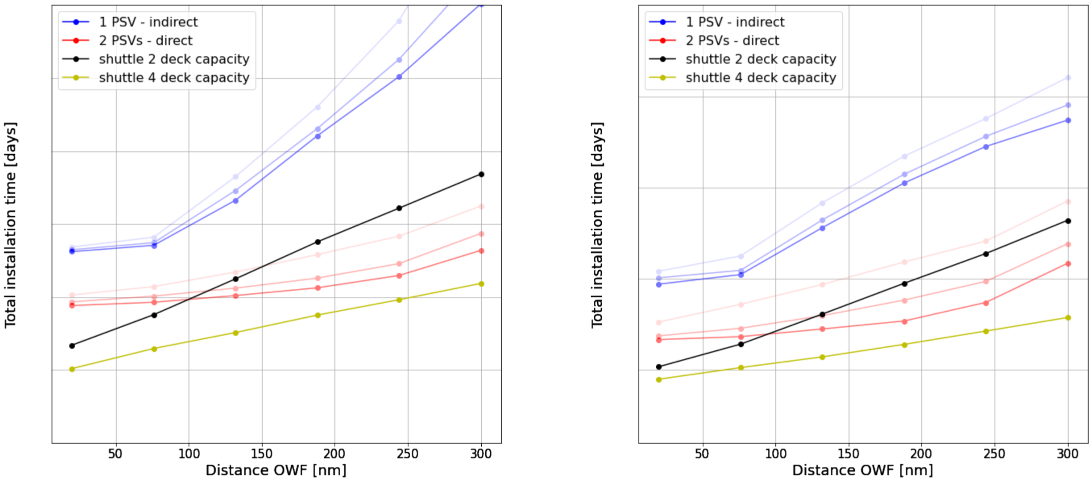
Sailing limits

The three scenarios couples 1-3, 10-12 and 19-21 are used to develop an understanding of the change of the sailing limits. All of the plots of these scenarios are shown in Appendix J. The outcome for the effect (which is discussed below) is highly similar for all three scenario couples. Therefore, only one couple (scenarios 1-3) is shown and used to explain the effects.

The P50 duration results of scenarios 1-3 are plotted in Figure 5.10a for 48 WTGs and 5.10b for 96 WTGs. The y-axes have different scales since the project duration is significantly different due to the different OWF sizes. The least clear line for the feeder strategies is scenario 1 and the clearest line is scenario 3. The plot clearly shows a decrease in project duration when moving from scenarios 1 to 2. The step size decreases by roughly a half for scenario 3, meaning that increasing the sailing limit any further might not be of significance anymore. This is firstly caused by the environment itself since high waves occur less frequent which Table 5.1 confirms. Secondly, other activities are that still limited (with other wave limits) such as the transfer lift create a potential bottleneck in the system. This is further investigated in the transfer analysis. The sailing limit is important for the design of the feeder vessel since designing a more stable vessel possibly meaning a more expensive one.

Another thing that stands out is that the duration reduction is not equal across all distances. At short distances up to roughly 75 - 100 nm, the effect of increasing the sailing limit is less effective than for larger distances. This hold for both OWF sizes and is caused by the length of the overarching WW. Smaller WWs occur more often than the larger ones allowing for relatively fewer new available WWs when the limits are increased.

The two feeder strategy is more affected by the change in sailing limits than the single feeder strategy, meaning, the decrease is more significant. This is due to the waiting time of the installation vessel. As explained before, the single feeder vessel has a significant increasing waiting time at larger distances from roughly 75 nm due to the lack of continuous supply, making this effect more dominant. Going back to the remark of Section 5.2 about the possible shelter areas along the route and the long overarching WW, it is expected that the outcome (lines) are more horizontal and somewhat lower when using the shelter areas due to shorter WWs for sailing. This potentially makes feedering more interesting for the shorter as well as the larger distances.



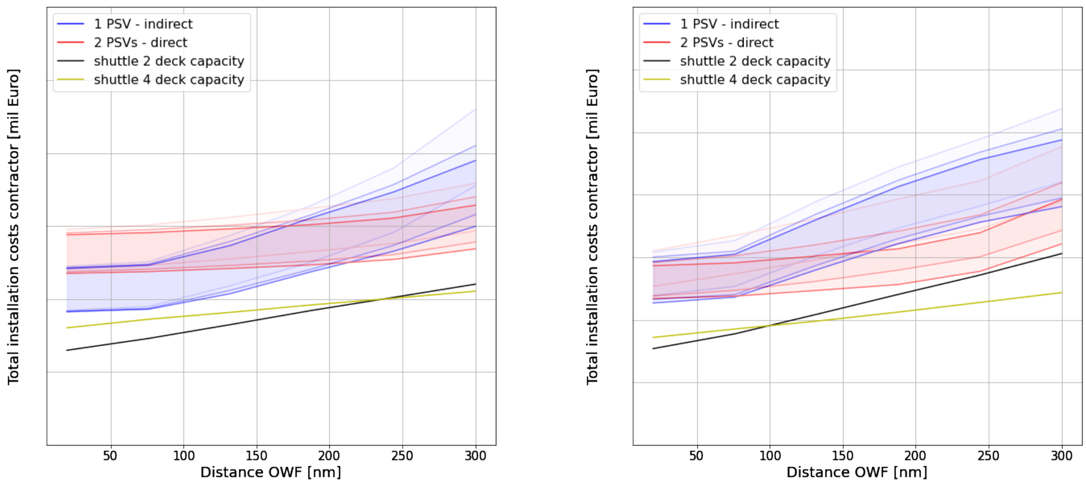
(a) 48 WTGs

(b) 96 WTGs

Figure 5.10: Scenarios 1-3, P50 duration plots

The costs for the contractor follows the same pattern as the duration plot as shown in Figure 5.11. The single feeder with the indirect method is of importance for the shorter (and medium) distances as stated in the initial P50 results and clearly visible for the 48 WTG OWF. The low impact of the different scenarios at the short distances (below 75-100 nm) is also noticeable in the costs. At the larger distances, one can see that the costs for the two feeder - direct strategy are lowered significantly. This is highly beneficial for this strategy since this is exactly where this strategy matters.

The single feeder - indirect strategy for 48 WTGs is more appealing to the contractor at 'short and medium' distances. When this strategy reaches the winter season, the duration and therefore the costs go up significantly and a two feeder strategy becomes more attractive. The two feeder - direct strategy for the other OWF size is more interesting for the contractor since both feeder strategies finish in or after the winter. Using two feeders according to the direct strategy in the winter allows for a better-utilised WW due to the faster process.



(a) 48 WTGs

(b) 96 WTGs

Figure 5.11: Scenarios 1-3, P50 contractor cost plots

Transfer limits

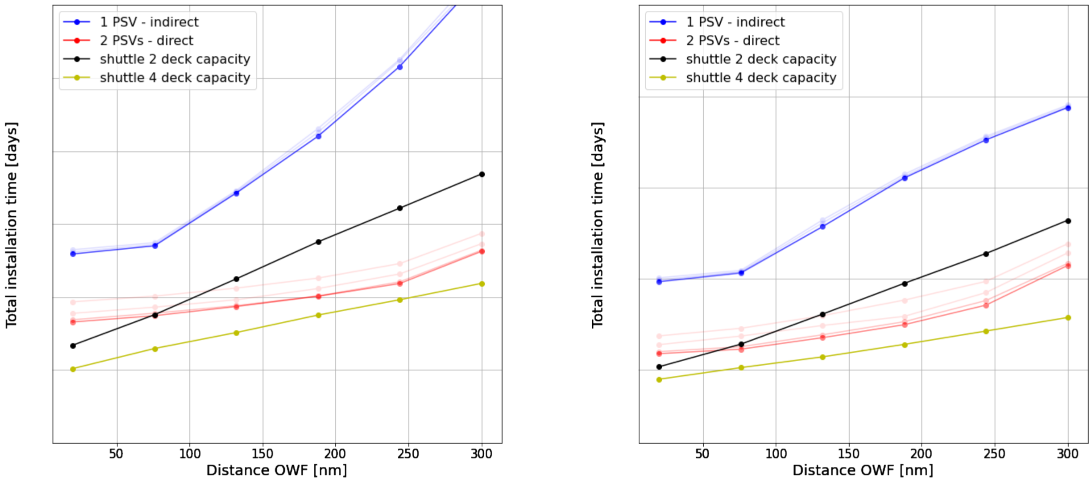
The scenarios couples that are used to compare the transfer limits are split up into groups for sailing limits at 2.25 m and 2.5 m. This is done to check whether the increased sailing limits have an influence since the overarching wave limit is higher than the transfer limits. The scenarios at 2.25 m sailing limits are scenarios 4-6, 13-15 and 22-24. Scenarios 7-9, 16-18 and 25-27 are used for the other sailing limit. Again, all scenarios of both groups have a similar pattern in their outcome with only a small difference which will is explained below. Therefore, only scenarios 4-6 are used to explain the outcome of this analysis. Additional, the baseline (scenario 2) of these scenarios is added to clearly show the effects.

The P50 duration results of scenarios 2, 4-6 are plotted in Figure 5.12. The lowest (and most clear) feeder strategy line is scenario 6. The higher the line the lower the scenario number with scenario 2 as the highest (and most vague). The other scenarios are provided in Appendix J. The first thing that stands out is that scenarios 4-6 are (almost) the same as scenario 2 for the single feeder - indirect strategy. This can firstly be explained by other lifting operations (the blade rack and the back lift of equipment) that still have the initial transfer limits. The second reason is that the feeder vessel has another limiting factor that is the overarching WW. Since only one feeder is used, the overarching WW is more limiting for the project duration than the transfer limit.

The two feeder - direct strategy shows a step towards scenario 4 and significantly smaller steps further to scenarios 5 and 6. These steps are explained by two phenomena, first, two feeders are used so the supply to the installation vessel is more continuous and allows for a faster installation process. Second, as well as for the single feeder, other lifting/preparing activities (the blade rack and the back lift of equipment) still have the initial wave limits and causes a bottleneck in the system causing the steps to decrease with increasing limits.

The environmental wind data has been checked to understand if changing the wind limits changes the results. The data shows that when increasing the wind limit for any wave limit, the amount of data points merely increase (not even 1%). Therefore, increasing the wind limits will not have a significant effect on the outcome at this OWF location.

The other scenarios in the group use fewer tower segments, meaning fewer tower segments need to be transferred. This leads to smaller steps between the scenarios in that group. Therefore, reducing the number of segments causes a smaller effect on reducing the installation process duration. The effect of having larger waves in the overarching WW of 2.5 m (the second group) instead of 2.25 m (the first group) is barely noticeable for the difference in transfer limits because these higher waves occur less frequent as stated before. These scenarios (at 2.5 m) are only simulated for the two feeder - direct strategy since the single feeder hardly encounters any change when increasing the transfer limit.

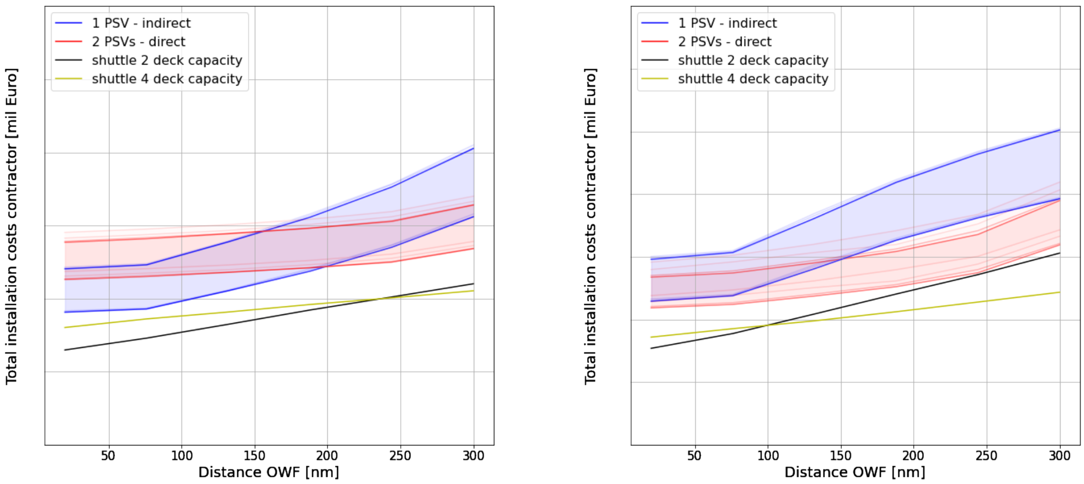


(a) 48 WTGs

(b) 96 WTGs

Figure 5.12: Scenarios 2 & 4-6, P50 duration plots

The cost plots of the single feeder - indirect strategy do not differ from the plots of scenario 2 in Figure 5.11. The cost plots for the two feeder strategy are just slightly lower than scenario 2. These contractor costs for scenarios 2, 4-6 are depicted in Figure 5.13 in the same manner as for the duration plot. Overall the cost plots follow the same steps downwards compared to the duration plots. These plots make clear that the duration requires a larger reduction to have an impact on the costs for the contractor. This holds as well for the perspective of the developer.



(a) 48 WTGs

(b) 96 WTGs

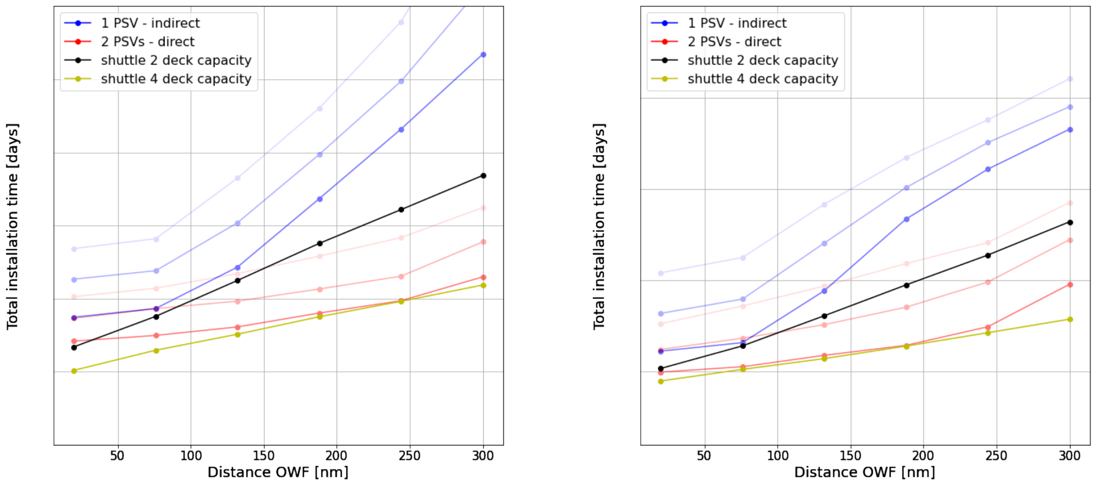
Figure 5.13: Scenarios 2 & 4-6, P50 contractor cost plots

Tower segments

The effect of reducing the tower segments has been briefly addressed above. For a more detailed analysis, all comparable scenarios that only differ in the number of tower segments form a couple and are analysed separately. As an example, scenario 1 can be compared to scenarios 10 and 19 while scenario 2 can be compared to scenarios 11 and 20. All these couples show comparable results. Therefore, only the couple with scenarios 1, 10 and 19 are used to understand the effects to keep in line with the previous plots.

Reducing the number of tower segments decreases the total loading, transferring and installation time of the process. In other words, the total installation cycle duration of installing a single WTG goes down. The duration plots for these scenarios are depicted in Figure 5.14 where the clearest feeder line is scenario 19 and the most faded line scenario 1.

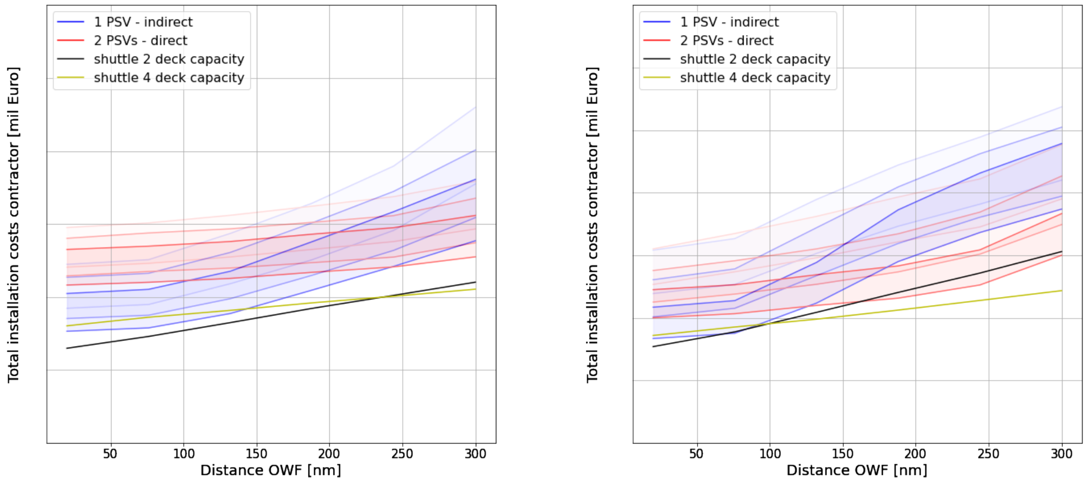
The plot with 48 WTGs shows (almost) equal steps downwards (roughly % decrease) for every tower segment that is reduced for both feeder strategies. This is caused by the constant reduction of cycle time while the project starts and finishes in the summer season. The plot for 96 WTGs with the two feeder - direct strategy also has equal steps for when the feeder can maintain a continuous supply to the installation vessel. The lines slowly converge when the strategy cannot maintain a continuous supply and a winter season is entered. This is clearly visible for the single feeder - indirect strategy. Therefore, it can be stated that if the project reaches the winter season and the strategy cannot keep up with the continuous supply, the effect of reducing the number of segments becomes less.



(a) 48 WTGs (b) 96 WTGs

Figure 5.14: Scenarios 1, 10 & 19, P50 duration plots

The stepwise reduction is also clearly visible in the cost plots for the contractor in Figure 5.15. It is economically best to use as few as possible tower segments for a feeder strategy. Feedering a full tower would be the most ideal solution. However, transporting longer segments (or a full tower) brings technical challenges. The centre point of gravity becomes higher, potentially causing stability issues. Another possible challenge is a more advanced (and expensive) compensation system that is required due to the larger weight and displacement of the segment when only slightly moving with a rolling or pitching vessel.



(a) 48 WTGs (b) 96 WTGs

Figure 5.15: Scenarios 1, 10 & 19, P50 contractor cost plots

All in all, the feeder installation process simulation shows to be most susceptible to changes in the number of the tower segments as well as increasing sailing limits up to a certain point that is not reached in this research (higher than 2.5 m). The simulation is much less affected by changes in the transfer limits for the two feeder - direct strategy and even barely affected for the single feeder - indirect strategy. The limit would be at roughly 1.75 m for direct feedering. This is mainly caused by other transfer operations that are not subjected to the change of the limits and become a bottleneck in the system. It is expected that the effect would be more significant if these other operations also increase the limits.

5.6 Best installation strategy

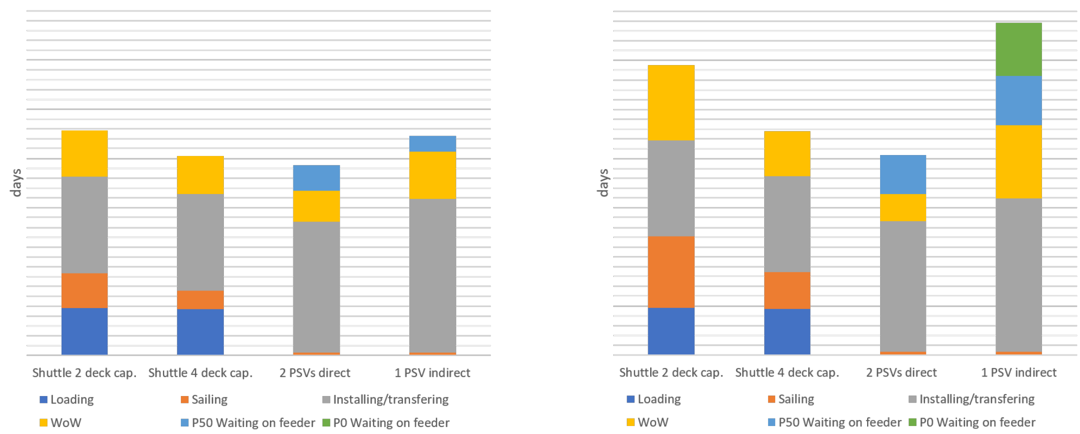
This section will analyse the feeder results of the different scenarios and provide an answer to the questions of how and if feedering can become a best installation strategy. The best installation strategy decision can be divided into three main topics; project duration, costs and fuel consumption. The project duration also provides a short analysis of what the feeder system could potentially be improved upon.

5.6.1 Project duration

Based on all scenarios it can be stated that the two feeder - direct strategy is the fasted feeder strategy. For 48 WTGs, this strategy just outcompetes the fasted conventional method (with a deck carrying capacity of four WTGs) for distances from roughly 115 nm when using tower segments and increased sailing (m) as well as transfer limits (m). When using tower segments, having limits of m for sailing and m transferring is enough to be the fasted strategy for all distances. The difference with shuttling is roughy % at 20 nm and increases with the distance up to roughly %. The same holds for the 96 WTG size (but for percentages roughly twice as large). All other strategies with increased limits and/or fewer tower segments are even faster.

The activities durations of the installation vessel are broken down and analysed since the installation vessel is the most expensive vessel and therefore critical to the costs of a project. This provides an understanding of which installation vessel activities are critical to the project duration what is possible to be even faster. Figure 5.16 shows the number of days each activity takes. The activities are divided into loading (only for the conventional method), sailing, installing/transferring, Waiting on Weather (WoW) and ‘P50 waiting on the feeder’. The single feeder also has a ‘waiting on feeder from P0’ since the continuous supply cannot be maintained for that distance. The yellow, light blue and green bars combined is the total waiting time for the installation vessel. Ideally, these bars are barely visible in the plot, indicating a high workability for the installation vessel. The WoW (yellow) bar is the number of days the installation vessel cannot transfer/install due to exceeded weather limits. The time the installation vessel has to wait for the feeder to arrive (light blue) is highly interesting since this is mainly caused by the feeder that cannot sail out due to exceeded limits within its overarching WW.

The first two things that stand out is that the installation vessel for the feeder strategy has very little sailing and zero loading days. More time is spent transferring and installing the components. This is a potential element to reduce the time and or costs further. The tower segments are an important parameter in this element since this affects the installation time significantly. The scenario in the plot already uses tower segments. The WoW bar is larger for the indirect method since all components are lifted twice. The bar plots show that the P50 waiting period for a feeder to arrive at the installation vessel is roughly % for 76 nm and % for 188 nm of the total project duration. This percentage growth at larger distances is caused by longer sailing durations, leading to longer overarching WWs. Increasing the sailing limits within the overarching WW is already applied to understand the time it could safe. Shelter areas along the sailing route as discussed before are the solution to chop up and decrease the overarching WW for the feeder. It is expected that this would reduce the percentage of ‘P50 waiting on feeder’ not completely but by a significant amount.

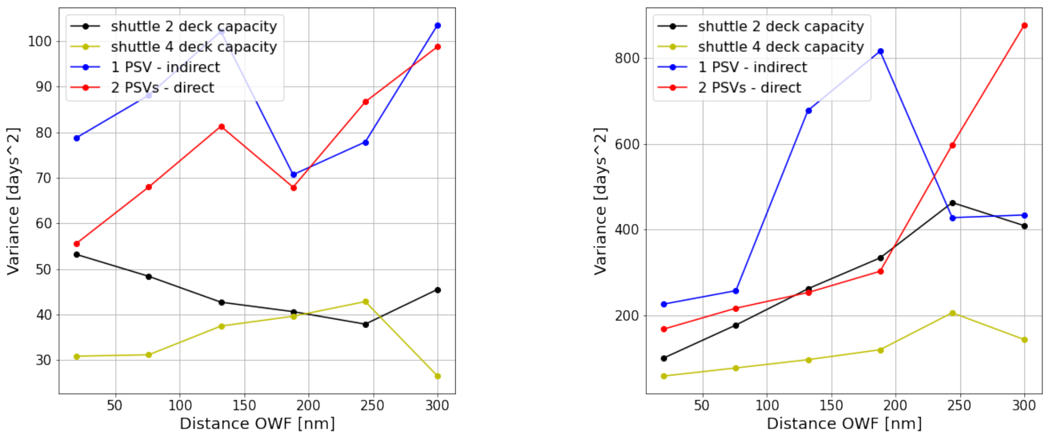


(a) 96 WTGs at 76 nm

(b) 96 WTGs at 188 mn

Figure 5.16: Scenario 22, installation vessel activity breakdown

Section 4.3.3 explains why the P50 is chosen in this research and that the other P-values are dependent on the variance of the duration simulation results. The variance per strategy for scenario 22 (same as scenario as above) is plotted depending on the sailing distance in figure 5.17. The lower the variance the closer the other P-values are to the P50 results. If the variance is high, the other P-values will deviate more from the P50 results. The figure of 48 WTGs shows that the feeder methods have a higher variance than the conventional method. All strategies finish in the summer meaning that the feeder strategies are more susceptible to environmental conditions. This is also visible in the 96 WTG plot. Here the winter comes into play. The two-deck carrying capacity conventional method is more susceptible to the harsher environmental conditions during the winter than the four-deck strategy. This is caused by the double amount of trips the former strategy has to take.



(a) 48 WTGs

(b) 96 WTGs

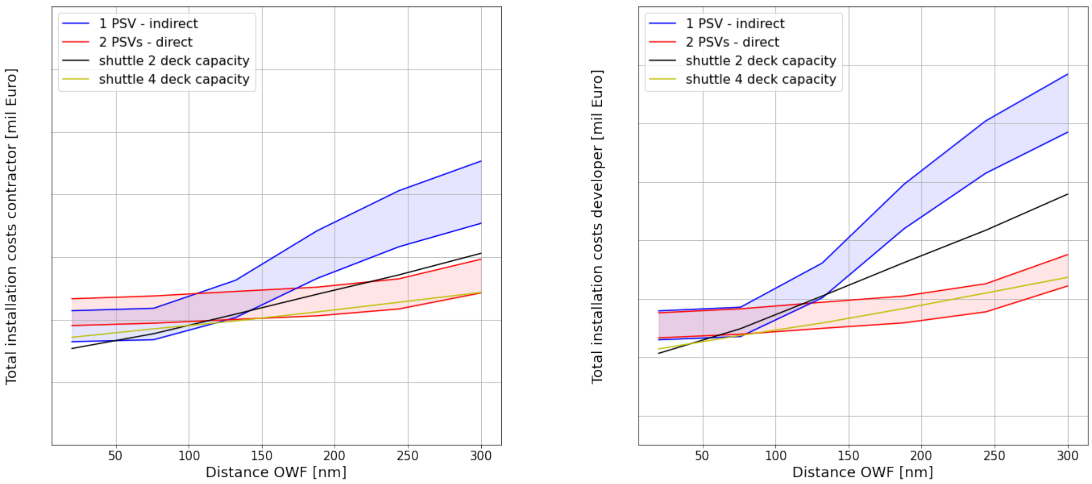
Figure 5.17: Scenario 22, variance of simulation results

5.6.2 Project costs

The costs are taken from two different perspectives, namely, the contractor and the developer. The outcome is highly similar despite the daily costs for the developer on top of the contractor costs. First of all, the conventional method for 48 WTGs is fast enough to be the cheapest solution on all distances having either a two or four-deck capacity. For the contractor, the two-deck strategy would be the best up to 240 nm while for the developer this would be up to 110 nm. The higher fixed (mobilisation/demobilisation) costs of the feeder strategies are the main reason why they are not cheaper. This is proven by the 96 WTG size since the project duration is relatively long and the daily costs are more of importance. Here, feedering is becoming the cheaper solution but mainly for the lower boundary (using a special feeder purpose installation vessel). The feeder strategies (from the contractor's perspective), both direct (from roughly 125 nm) and indirect (between 50 and 125 nm), are required to carry the tower in segments and have at least m sailing and m transfer limits to become merely cheaper than the cheapest conventional strategy as shown in Figure 5.18. The two-deck conventional strategy is still the cheapest at distances up to 50 nm since the sailing distances are short. Despite a larger margin, the developer has the same requirements for the feeder strategies as the developer to become cheaper. The difference of the perspectives lies in the distance (and margin). Direct feedering with two PSVs becomes attractive at a shorter distance of 80 nm.

As mentioned before, feedering only becomes attractive when using a specialised installation vessel. Building such a specialised installation vessel can be interesting but the downside is that it will be hard to utilise in other projects, particularly outside of its specialisation. More time and/or money needs to be reduced to make less specialised installation vessels interesting for feedering as well. One option is to feeder with a fully assembled tower. This would reduce the installation time significantly that follows the pattern as in Figure 5.14. Feedering a full tower has its downsides since it is more difficult to transfer the tower since movements at the tip becomes larger when the height of the tower increases (when transported vertically). It is also more difficult to keep the feeder stable while sailing since the centre of gravity of the tower is high.

The costs can be reduced by lowering the day-rates of the vessels. The installation vessel has the highest day-rate and has, therefore, the most potential to reduce. Another cost component that can be reduced is the mobilisation costs of the installation vessel for the direct method only as described in Section 5.2. This reduction is done by reducing the amount of seafastening on the installation vessel since the tower and nacelle are not transferred on deck of the installation vessel. Figure 5.8 roughly shows the potential of how much the mobilisation costs can be reduced.



(a) Scenario 22, 96 WTGs contractor costs

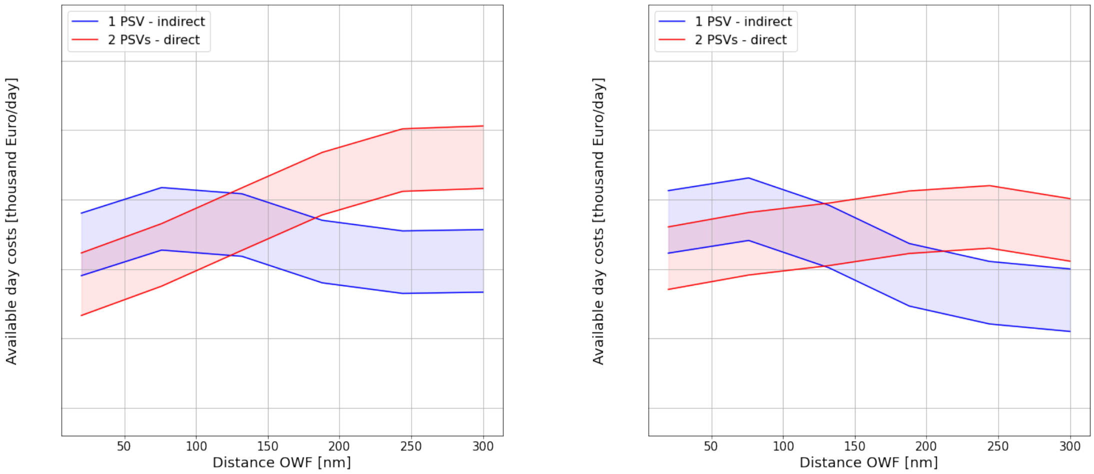
(b) Scenario 22, 96 WTGs developer costs

Figure 5.18: Scenario from when feedering becomes economically competitive

As explained in Section 4.3, the available costs per day would determine how much per day the costs can be increased by having advanced/larger feeder vessels/tools to maintain a competitive feeder solution compared to the conventional strategies. Figure 5.19 shows these available day costs for 96 WTGs for scenario 22 from Figure 5.18. Only the perspective of the contractor is used since they would be the ones who would invest in a feeder vessel. Both plots have the same scales. The upper line of a feeder strategy uses a specialised installation vessel and the lower line is a current day (less feeder specialised) installation vessel. A line of a strategy must be above zero (positive) to have available daily costs on top of the costs in Appendix F. The zero lines means that the costs are the same as the conventional strategy for that plot. Having the lower line above zero would be ideal since current installation vessels can be used and more money (if necessary) can be spent on the feeders or tools until the line reaches zero. This is the case in Figure 5.19 a from roughly 225 nm for two PSVs - direct. The opposite occurs when the upper line remains negative and money needs to 'saved' to be competitive with that conventional strategy.

It is clear that feedering compared to the conventional strategy with a deck capacity of two WTGs has a lot of available costs per day starting from 150 nm, allowing for advanced feeders or more margin. For shorter distances, this amount decreases significantly even to a point it becomes negative when using a specialised installation vessel. Feedering compared to the four-deck carrying capacity conventional strategy is just slightly over the zero-line for a specialised installation vessel. This would allow for a slightly more advanced feeder/tools. The available day costs of the other scenarios are provided in Appendix J.

It is uncertain how much the improved limits would cost on a daily basis. Therefore, potentially more time needs to be reduced to allow for a feeder that is advanced enough to meet the required limits. The costs of the installation vessel have a significant impact on the opportunity of investing in a more advanced feeder vessel. As described above, having a specialised installation vessel would be best for any feeder strategy, although less specialised installation vessels also show potential by reducing the number of tower segments to one for example (full-tower feedering).



(a) 2 deck capacity conventional strategy

(b) 4 deck capacity conventional strategy

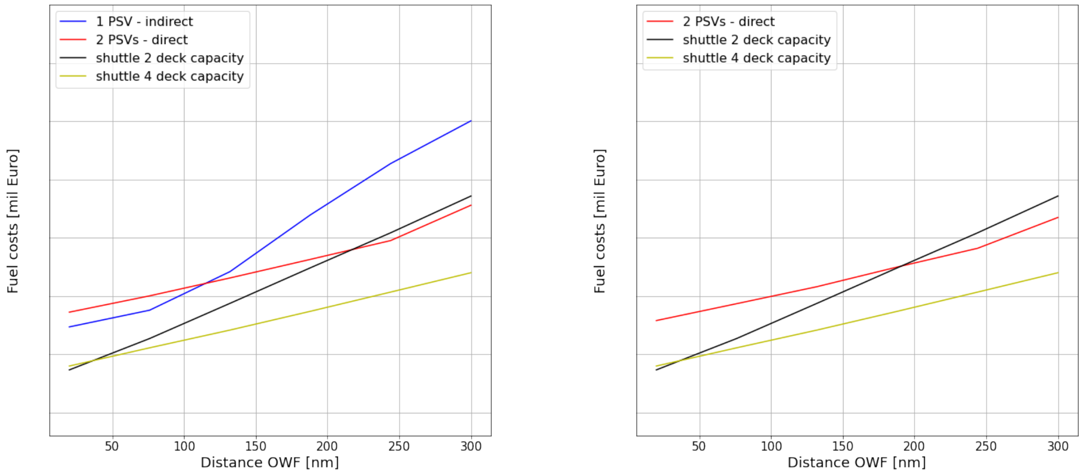
Figure 5.19: Scenario 22, available day costs for feedering compared to shuttling with 96 WTGs

5.6.3 Fuel

The fuel costs per strategy are plotted in Figure 5.20. The y-axes have the same scale and show the fuel costs. The fuel costs per strategy per specific distance can be read from the graph. The lowest line has the lowest fuel costs and therefore consumes the least amount of fuel. The fuel costs line of the feeder strategies should be lower than the conventional strategies to be fuel consumption and environmentally (CO_2 emission) competitive.

The cost plots are used for the fuel consumption since the fuel price is assumed constant and are provided in Appendix F. Both conventional methods use less fuel for 48 WTGs for all scenarios. Therefore, only the plot for 96 WTGs is shown. The fuel consumption for any scenario with the single feeder - indirect strategies is not competitive compared to any of the conventional methods. The two feeder - direct method becomes competitive compared to the two-deck capacity conventional method from scenario 21 and onward for distances starting at roughly 200-220 nm. This is mainly caused by the shorter project duration at these distances.

As one can see, the conventional method with a deck capacity of four WTGs consumes the least amount of fuel. This is because of two reasons, first, the project duration is shorter than the two-deck capacity method. This already causes a lower fuel demand. The second reason is the amount of sailing the installation vessel has to do to install all WTGs. This four-deck capacity installation vessel has to sail 24 times back and forth between the port and the installation site, while the two-deck capacity sails 48 times back and forth and therefore consuming more fuel, leading to higher CO_2 emissions. This difference is also visible in the bar plot of Figure 5.16.



(a) Scenario 21 for 96 WTGs

(b) Scenario 27 for 96 WTGs

Figure 5.20: Fuel cost comparison between the strategies

Chapter 6: Answers and discussion

Firstly in this chapter, the answers to the research questions are given and explained. Next, in the discussion, the research methods, as well as the results, additions to the literature, managerial recommendations and future research, are discussed.

6.1 Answers to the research questions

This research investigated the possibilities of the conventional method to install next-generation WTGs as well as an unexplored practical and theoretical installation method called feedering. The problem with the conventional method is that the current-day large installation jack-up vessels are required to be upgraded with larger cranes but have a limited carrying capacity which allows them the transfer just a few (two) turbines which are relatively little. Besides the carrying capacity, the distances between the shore and the OWF increases leading to longer sailing durations and a less efficient installation vessel. Feedering might solve these problems but has other problems such as the offshore transfer of components and the unknown number/type of feeder vessels required to be competitive. First, the sub-questions as posed in Section 2.4 are answered. They lead to the answer of the main research question as stated in that same section.

SQ1: What are the possible installation strategies within the feeder-ship and conventional method?
The conventional method follows the installation steps as described in Chapter 1. The first strategy for the conventional method is to use a current-day installation jack-up vessel (with an upgraded crane) that can only carry two full sets of next-generation WTG components. Another strategy is to build a new, larger and more expensive installation jack-up vessel to increase the carrying capacity to multiple WTGs (four or more) per trip.

Feeder strategies in the literature are the base port and feeder-ship 'methods', where the base port method is not the best fit to solve the problem. The feeder-ship method as stated in Section 2.2 where a feeder sails to all production ports (to pick up components) and then to the installation field where the installation vessel waits is not the most practical solution either. A more practical version of this strategy has been created where a base port is supplied from the production port(s) by supply vessels. The components are temporarily stored and a feeder vessel picks up a full set of WTG components. The installation vessel remains at the installation site to receive the components.

Within this strategy, multiple 'sub-strategies' have been investigated. Firstly, different feeder vessels can be used, namely, barges, lift boats and PSVs. The lift boats are ruled out because of the number of lift boats required and/or the high costs of such a vessel. The other types are possible to use as feeder vessels. Besides the types, the number of feeders used is also important because of the timing the components are supplied to the installation vessel and the costs that comes with multiple vessels. The last 'sub-strategy' is the sequence to transfer the components onto the installation vessel and to install them. The first strategy is the indirect option where all components are first transfer from the feeder to the installation vessel and then installed. The other strategy is the direct option where the tower segments and nacelle are lifted and installed one by one straight from the feeder. The blades still need to be taken onto the installation vessel due to the risk of damages.

SQ2: What is the most suited research method?
The first sub-question uses a qualitative research method to develop different strategies. To find the best installation strategy as stated in the main research question, a quantitative research method is more appropriate. Within this quantitative approach, a simulation method called a stochastic Discrete Event Simulation (DES) is the most suitable as described in Section 4.2. Here, events (activities) are stepwise simulated in sequence or parallel. A DES models only the start and the end of an event (not the activities within an event such as sailing) and triggers other events to start. The stochastic element in this method is the environment which is random over time and could prevent events from starting due to environmental limits that are exceeded.

SQ3: How is the research method implemented?
The scope of the problem is narrowed down to put focus on the feeder elements and the installation process of WTG components. Therefore, the production and base port logistics (and costs) are taken out and the problem starts with the mobilisation of the vessels and loading of the components in the base port. The process ends when all WTGs are installed and the vessels are demobilised. Problem elements such as learning effects, breakdowns and shelter areas are also left out of the scope as explained in Section 3.4

The DES model is built using an open-source Python DES package called OpenCLSim. Each strategy has its own model that follows the corresponding installation steps and event triggers as realistic as possible as explained in Section 4.3. An event is triggered by the start or the end of another event by the same or another vessel. The weather is implemented where Weather Window (WW)s per activity are created with corresponding environmental limits. Certain activities need to be combined due to risk-avoiding reasons. This is done by overarching WWs.

The outputs of the DES model are installation process durations. Each simulation per strategy contains six different sailing distances (ranging from 20-300 nm). Each simulation is repeated for two to three Offshore Wind Farm (OWF) sizes (48, 96 and 192 WTGs). Every simulation also is rerun 15 times with the same starting date but for a different year. Every output is different because the weather is different per year. The mean of the simulation outputs per strategy and OWF size is the P50 value and is used to calculated the costs that are that time-dependent. The cost model is a separate model and contains fixed costs (demobilisation and mobilisation costs), daily costs (vessel and time-dependent) and fuel costs (vessel and time-dependent). The costs are taken from the perspective of the contractor and the developer where the latter has an additional daily cost element.

SQ4: What are the parameters of the processes?
The installation process has many parameters. The cost parameters are vessel costs per day, fuel consumption rates and costs, (de)mobilisation costs and developer costs in cases from the perspective of the developer. Each activity in the process has a certain duration with a corresponding (overarching) WW. The environmental limits for and activity are based on experiences and documents of Van Oord. Not all limits are exactly known and have been estimated using in collaboration with experts. The limits are based on wind speed at different heights (depending on the activity), significant wave height and peak period as explained in Section 4.3 and 5.1. The location for the environmental data in this research is taken from the Hollandse Kust-NW (OWF) and the Maasvlakte (port) to create a more realistic difference between the environmental data locations. Other parameters have been mentioned in the previous sub-questions such as the different sailing distance, number of tower segments to form a full tower (four segments initially) and OWF sizes.

SQ5: What are the results of these parameters?
The process is firstly simulated without the weather creating the ideal installation scenario. This is called the P0 results. They are used to rule out any strategy that does not indicate to become a potential best strategy. As explained in Section 5.3, the P0 results allow for the conclusion that feedering by barges has a longer cycle time compared to the PSVs, leading to longer project durations and higher total costs. This is mainly caused by the (de)positioning activity the barges have (connecting the mooring system), while a PSV can use its DP system. It is expected that the barges have a lower workability since the sailing/overarching WW is longer due to the lower sailing speed. Because of these reasons, the PSVs are the chosen feeder vessels to investigate further.

Next, the P50 for the PSV strategies are simulated for more realistic results that include the weather as explained in Section 5.4. From these P50 results that use the 'initial' input parameters is firstly concluded that the conventional method having a four WTG deck carrying capacity is the fasted installation strategy overall. None of the feeder strategies would be the fasted strategy compared to shuttling. A comparison between the feeder strategies concludes that using two PSVs according to the direct strategy outcompetes all other PSV feeder strategies at all distances on project duration except for extremely large distances (over 240 nm). Using three PSVs - direct would be faster at these extreme distances. However, these distances hardly occur in projects.

The conventional method is the least expensive where the two-deck carrying capacity strategy is the cheapest at distances up to 240 (for 48 WTGs), 100 (for 96 WTGs) and 140 (for 192 WTGs) nm, taken from the perspective of the contractor. At larger distances, the four-deck carrying capacity installation vessel would be cheaper. The costs of the feeder strategies are more difficult to draw concrete conclusions from since the distance a strategy becomes more attractive depends on OWF size, perspective (contractor of developer) and the bandwidth of the results. However, the first thing that is concluded is that using three feeders is more expensive than any strategy while not installing any faster. The second thing is that feeder strategies are most cost-efficient when using a single feeder - indirect or two feeders - direct. The two feeder - direct strategy becomes less expensive than the single feeder - indirect at increased distances. These exact distances are discussed later since feedering is not the cheapest solution with these input parameters.

Conclusions about the seasonal effects are first that the four-deck carrying capacity conventional strategy is less affected by the winter season than the two-deck carrying capacity strategy since it has to sail less often. Secondly, Feedering (with the 'initial' parameters) has a lower workability than shuttling (in summer and winter). Therefore, it encounters a lot of weather downtime (especially in the winter) and becomes much less competitive to the four-deck carrying capacity conventional strategy. The feeder strategies need to increase the workability or reduce cycle time to become competitive on both duration and costs.

SQ6: Which parameters are critical to the feeder installation process?
Three parameters have been chosen to be investigated further in a sensitivity analysis as explained in Section 5.5. The first parameter is the significant wave height limit of the feeder's sailing activity. This is potentially critical because having a higher limit would allow the feeder to have a higher workability on the sailing activity and also the overarching WW. The second parameter is the transfer limit of the tower segments and the nacelle. These two components are chosen based on current market development where multiple companies show interest in building a new PSV. The transfer lift of the aforementioned components have increased environmental limits by motion compensation tools. The transfer limits are initially relatively low and could be a bottleneck in the system when the sailing limits are increased too. The blade rack transfer remains at the initial limits. The final parameter is the number of tower segments in which a tower is transported. Reducing the number means that the cycle time of installing a single WTG is decreased and could be key to make feedering competitive to the conventional strategies.

SQ7: What is the effect of changing the critical parameters on the results?
The sensitivity analysis performed for the two feeder strategies as explained above and in Section 5.5 shows that out of the three investigated (critical) parameters, the simulation is most sensitive to changes (reducing) in the number of tower segments because the cycle time for installing a single WTG is changed (reduced). The duration is reduced by roughly % per reduced segment. However, this percentage decreases when the continuous supply cannot be maintained and the winter season is encountered. The simulation is also sensitive to changes (increasing) of the feeder sailing limits. However, this effect levels out, meaning, there is a limit to increasing the wave height limit. The step from 2.25 m wave height to 2.5 m is roughly half the duration reduction of the step from 2 m to 2.25 m. The next step to 2.75 m would be a marginal decrease in duration. The simulation is least sensitive to changes in the transfer (lift) limit of the tower segments and nacelle. These (transfer) lifts are chosen based on current-day market developments. Increasing the limits higher than 1.75 m wave height shows neglectable changes in the results. This is mainly caused because the blade rack lift and back-lift of equipment still have the initial input values creating a bottleneck in the systems. The limits of these components and tools should also be increased to remove this bottleneck.

From the results of the different scenarios is concluded that the indirect feeder strategy using one PSV is for non of the scenarios the fastest installation strategy. The single feeder - indirect strategy does not have a continuous supply to the installation vessel after a distance of roughly 75 nm, leading to larger delays when the distance further increases. It can be concluded that direct feedering by two PSVs can be the fastest strategy.

This strategy compared to the four-deck carrying capacity conventional strategy is merely the fasted from roughly 115 nm for 48 WTGs while having increased sailing (m) and transfer (m) limits as well as tower segments (for a full tower). This strategy becomes the fasted on all distances (by roughly % to % with increasing distances) when feedering with tower segments and sailing and transfer limits of respectively and m. The same holds for the 96 WTG OWF size (but the decrease is roughly twice as large percentage-wise). It is concluded that with these parameters, the workability of this system during the summer is higher compared to the shuttling. During the winter, the workability becomes lower again due to the many sailing trips required. This is also noticeable in the variance of the results. The conventional method (mainly the four-deck capacity strategy) has a lower variance in the summer and winter seasons. When a higher P-values is used/requested, the duration will increase less than results with a higher variance such a for the feeder strategies that are more affected by the environmental conditions.

It can be concluded that the mobilisation costs for feeder strategies are the main reason why the conventional strategies are still cheaper for the 48 WTG OWF. The fixed costs are too dominant for these small OWFs. The daily costs have more influence when installing more WTGs. For the 96 WTG OWF size can be concluded that, when changing the critical parameters, the two-deck carrying capacity conventional strategy would remain the cheapest solution for the contractor at distances up to 50 nm. The single feeder - indirect strategy with a specialised installation vessel would merely be the cheapest solution for distances from 50 to 125 nm. The two feeder - direct strategy with the same installation vessel is merely the cheapest for larger distances. The conditions for these feeder strategies to be merely cheaper are using tower segments and sailing and transfer limits of respectively and m. The perspective of the developer shares these conclusions with one important difference. The two feeder - direct strategy becomes more cost attractive from 80 nm instead of 125 nm than the single feeder - indirect because of its short project duration. Additional changes to limits will result as mentioned above. The fuel consumption of the feeder strategies is only competitive at roughly 200-220 nm offshore to the two-deck conventional strategy for the 96 OWF size. It is not competitive compared to the four-deck capacity conventional strategy.

MRQ: What is the best installation strategy for installing next-generation offshore Wind Turbine Generator components within the feeder-ship and conventional methods and under which conditions?
As described in Section 5.6, in order to make feedering (based on this research) the best installation strategy on project duration and costs, the number of tower segments should be reduced to two or even a full tower (has not been simulated). However, this brings new technical challenges and risks that are discussed in the discussion. The feeder should be fast (like a PSV) and be stable for waves of at least   m. Increasing the transfer limit is less important but would reduce risks during the lift. Besides the feeders, the installation vessel is important since this is the most expensive vessel and costs need to be saved by building a feeder purpose installation vessel. With such a special vessel the margin compared to shuttling still is marginal while transporting the tower in   segments with increased limits. This leaves little room for additional costs when a feeder project is performed. Feedering is also more susceptible (in the winter) to the environmental conditions than the conventional strategies (mainly the four-deck capacity).

The four-deck capacity conventional strategy is highly competitive on all levels and is also known in the industry as being more investigated and used. The two-deck strategy can be cheaper at ‘short’ distances (depending on the season) but is a lot slower when the distances increase (especially in the winter). Having a larger carrying capacity also allows the installation vessel to be used when even larger WTGs are developed in the future. This would be more difficult with a smaller carrying capacity installation vessel. Feedering is marginally better on costs with conditions that are not technically proven to be reachable yet. Therefore, the conventional strategy with a large carrying capacity installation vessel (four WTGs) would be the best if the feeder strategies cannot (technically) meet the requirements as explained before to reduce durations, costs, risks and fuel consumption.

6.2 Discussion

The discussion firstly discusses the methodology. Next, the results and the additions to the literature are discussed. Lastly, managerial recommendations and future research are explained.

6.2.1 Methods

The chosen methodology is the Discrete Event Simulation (DES). This method is ideal to investigate logistical processes like in this research to evaluate different strategies. The simulation looks at the start and the end of an activity. The large steps of the installation process are correctly simulated but these could be made up out of smaller steps or steps that are performed parallel. Simulating these smaller steps would give more accurate results but would also be too detailed for a study such as this.

The DES model uses a go/no go function based on environmental limits, (stochastic) environmental data series and communication between entities (vessels) to start or hold an activity as would be in the real world. However, looking at the environmental limits, this go/no go function has a drawback due to the strict limits causing Waiting on Weather (WoW). For example, if the waves in a potential WW just exceed the limits for only a short period (e.g. 2 cm exceedance for 15 minutes), the activity is put on hold till after this period and a WW is available. The simulation works with zeros and ones, while in the real world, more lenient and tailored decisions are made for these situations. For these cases, an ‘if’ statement for these scenarios could be added in the simulation to be more realistic.

The communication between the installation vessel and the feeder(s) is key to have a safe as possible and continuous operation. The feeder should get a signal when it should start sailing to the installation vessel. As discussed in Chapter 4, the DES is not made, when using stochastic inputs, to look into the future to determine when activities (of other entities in this case) are done. This problem is partially solved but could be more accurate by means of a more complex mathematical model to estimate the future. Although this would solve the problem, it is uncertain how much accuracy is gained by adding such a complex model and if this would change the results. It is expected that this would increase the accuracy only with a mere percentage of the outcome since the timing problem is already partially solved.

6.2.2 Results

The conclusion so far looked at the duration, costs and fuel separately or as a whole. What is not mentioned is the importance of the vessel occupation. In an ideal world, the vessel would never be in a port or anchorage waiting between projects. Therefore, sometimes it is preferred by the contractor to have a long project duration (because of a large project) to stay occupied before the next project. This could also be the other way around in case multiple projects have to be executed in a short period. Here, the advantage of having a faster but possibly slightly more expensive solution would be more suited since more projects can be done.

The results provide a clear overview of under which conditions the feeder strategy can outperform the conventional method based on the P50 project duration and costs. Other percentiles such as the P70 and P90 are not looked into but are important to discuss. While the P50 is the mean of the results for a scenario (and specific distance), the other percentiles are more dependent on the variance of the results. The variance of the conventional strategies is smaller compared to the feeder strategies (especially when the winter season is encountered). This means that, if for example, the P70 values are used, the project duration of a conventional strategy will increase less than the feeder strategies. This potentially leads to the conventional four-deck capacity strategy to outcompete the feeder strategies even with fewer tower segments and increased environmental limits. However, this is not investigated in this research.

The P50 duration (and costs) results are also location-specific, meaning that when using a different location in the world with different environmental states, the environmental-based conclusions and potentially the overall conclusion could be different. The statements about the increased sailing and transfer limits are these susceptible conclusions. The number of feeder vessels required depends on the sailing speed of the feeder, sailing distance, the number of WTGs (seasonal effect) and specific strategy. The conclusions about the feeder sailing speed and reduced number of tower segments are generalizable since these respectively influence the WW and cycle time.

The duration results of all strategies might be (slightly) overestimated since the learning effects are assumed to be out of the scope. However, on the other side, potential breakdowns are also neglected. If a breakdown would occur of the installation vessel, both methods would be at a hold. For feedering, the feeder vessel could also break down where the strategy of a single feeder is most at risk since the supply chain is broken. When using two feeders, the other feeder can keep going. These risks of vessel breakdowns are relatively low according to Van Oord. On the other hand, equipment that is used is more sensitive to breakdowns. The feeder strategies used specialised equipment mainly for the offshore lift/transfer and are therefore more susceptible to these breakdowns. From this research is it hard to find the influence of the two assumptions. Future research with for example a breakdown probability and added learning curve is required to investigate this further.

A critical element in the simulation are the overarching WWs that are rather long and are the main reason for feeders to remain at the port. As mentioned before, shelter areas are used in real-life projects to reduce this overarching WW, leading to a more efficient installation vessel that has less waiting time on the feeder. However, the conventional strategies can possibly also use these shelter areas and could therefore reduce their project durations as well. According to Figure 5.16, the installation vessel is roughly waiting for % (depending on the sailing distance) of the total duration on the feeder vessel to arrive which is delayed due to the overarching WW. A shelter area (or multiple) along the sailing route could reduce this waiting time (but not completely). It is not possible to provide exact numbers for the conventional method but time would also be saved when shelter areas are implemented here. The DES model in this research is currently built to automatically simulate multiple sailing distances without shelter areas. To be more realistic, shelter areas should be added. The model is easily adjusted by dividing the sailing duration into multiple segments where the final segment is included the overarching WW as in Figure 3.14. However, this would remove the automatic run of multiple distances since every distance (project) is more specific.

Currently, there is a discussion about the installation timing of the tower, nacelle and blades. The wind could potentially be at or close to the natural period of the tower and nacelle when they are installed. This could firstly potentially damage the installed components and secondly make it more difficult to install the rotor blades since the nacelle would move too much (too large oscillating movements of the nacelle). This could lead to an installation process where (all) components are installed after each other, meaning, an additional overarching WW is required for the installation. However, this is still ongoing research by the turbines developers.

This research excluded the port elements since it is assumed that all strategies would have the same port costs. However, this is not entirely realistic because feedering could potentially have more port costs since a port crane is required to combine/transfer all components onto the feeder. The base port crane needs to be larger when the tower is transferred into fewer segments, causing higher base port crane costs. The storage size is also a factor in the base port costs that could be larger for feedering than for shuttling. Feedering could require a larger base port storage (larger buffer) since the components can potentially be installed more quickly. This brings another discussion because the production rate of WTG components should also be high enough to supply to the base port in time. In general, newer WTGs are not produced at many locations in the beginning, causing a potential bottleneck in the entire installation process. Another cost element that is left out of the research is the consumable supply vessel. Depending on the carrying capacity of the feeder, an additional supply vessel is required to provide consumables such as fuel to the installation vessel since it will not go into port. The port components (and the supply vessel) are elements that are important for the total package of the installation process and should be added to future research. As explained, it is expected that these costs when using a feeder strategy are higher than for a conventional strategy, meaning the feedering becomes less competitive.

The cost results are based on the European market. However, The U.S. market is also growing but has the Jones act. where only U.S. built, flagged and crewed vessels can transport components in U.S. waters. Therefore, the conventional method with European installation vessels cannot be used. Two solutions are possible, Firstly, built a new Jones act. compliant installation vessel in the U.S., which is far more expensive than in Asia. Secondly, use Jones act. compliant feeder vessels but with a European installation vessel. This could make feedering more interesting since the installation vessel costs, being the dominant cost factor, of a European vessel are lower compared to the U.S. built ones.

6.2.3 Literature

The literature of Ait Alla et al. (2017) and Oelker et al. (2018) provided two different feeder strategy models. They looked into different installation methods where feeders supply the installation vessel directly from the production port at a short distance from the OWF. They did not specify what type of feeder vessel is used and what the size is of the installation vessel for the feeder as well as the conventional method. The activities in the model are quite generic so certain important steps such as the preparation of the crane are missing.

This research adds practical knowledge of a contractor (Van Oord) to the literature. First of all, create a more practical and therefore, more realistic feeder-ship method. The practical knowledge explains that the production port might not be at the same location close to the OWF. Often, a base port is used because of these larger distances or even required due to contracts. Secondly, (overarching) WWs are used to follow the 'safe to safe' principle in order to reduce risks. Next, the activities in the problem are more detailed as in more detailed/accurate steps as well as realistic durations, limits and WWs. Fourth, this research investigates different strategies within an installation method where multiple feeder types and installation vessel sizes (for both methods) are discussed and analysed. Fifth, different cost perspectives (contractor and developer) are used in this research. The costs are estimated more realistic since the input of a contractor is used. Last, fuel consumption is looked into besides only the project costs and the duration. The fuel consumption is directly linked to the CO_2 emissions which is not entirely correct because each engine is different with its emissions. However, this provided an indication of what could be expected.

The simulations in the literature use two different distances where this research uses six distances to better understand the sailing distance as well as seasonal effects. The seasonal effects are also taken by using different OWF sizes. The sizes in this research as similar to the ones in the literature. Ait Alla et al. (2017) and Oelker et al. (2018) did not do a sensitivity analysis to understand what parameters could make feedering more or less interesting. This research uses three critical parameters (tower segments, sailing limits and transfer limits) to provide this understanding as well as looking to the possibilities of using a special feeder purpose installation vessel.

The results of this research agree with the literature that using two feeders at larger distances would be better duration and costs wise than using a single feeder since the installation vessel in the convectional method has to sail more. This research disagrees that feedering at short distances would be better. shuttling at distances up to 50 nm is still the cheapest solution. After 50 nm, the feeder strategies are more cost-competitive. However, the tower must the transferred in as little segments as possible as well as having increased sailing limits. All results are mostly dependent on these parameters. These conditions are missing in the literature.

6.2.4 Managerial recommendations

There still are a lot of technological and logistical unknowns for the contractor as well as the developer within feedering. This brings additional risks to the table compared to the conventional method which is a proven strategy. Therefore, the margin for feedering to be better than shuttling (duration and costs) should be significant in order to cope with these risks in a real project. The results of this research indicate that the feeder strategies costs are just lower than the cheapest conventional strategy when using a specialised installation vessel. This brings the first managerial recommendation that it would be preferred to use a special feeder purpose installation vessel to reduce costs in case feedering is the chosen installation method. This can be a new built or a converted (older) installation vessel. The risk of having an installation vessel that is too specialised is that it is more difficult to use for other projects outside of its expertise. The current-day installation vessels are too expensive to be competitive (for the European market).

The second managerial recommendation when using feedering is to use a feeder that is fast since this reduces the (overarching) WW and therefore increases the workability. Additionally, a single feeder could then potentially maintain a continuous supply to the installation vessel at larger distances where two feeders would be required when having a low sailing speed. The indirect method is recommended when using a single feeder. However, this is not the fasted solution. The direct method is a faster solution and requires two feeders. The feeder(s) should be able to carry a tower in   segments to marginally be competitive or as a whole to create more margin compared to the conventional method. It is important that the feeder would also be stable and has high environmental limits during the transit and positioning since this increases the chance of finding an available WW. The transfer limits are less critical and only have to be slightly increased to gain limited workability. Possibly, additional motion compensation tools are required to increase this. PSVs would fit the requirements of a fast vessel and are used in this research. However, it is not known if the carrying capacity is large enough to transport next-generation WTGs. Therefore, the availability of these types of feeder vessels should be looked into as well as the technical aspects mentioned before. Possibly, special feeders need to be new built that meet the requirements or existing feeders need to be adjusted. Both options should be carefully looked into since costs are critical.

Building new installation and/or feeder vessels would required investments. This research did not look into this. However, it is important to mention that the depreciation of this investment would flow back into the company of the contractor (who makes these investments). The costs lost during a project are called the out of pocket and are for example the personnel costs and port costs. A project is more interesting if it has a high Depreciation and Interest (D&I) v.s. out of pocket ratio since the most amount of money spend would flow back into the company of the contractor. However, a distinction between these elements is not made and no managerial recommendations on this can be made for now.

Another issue with feedering is the contractual point of where to stop the responsibility of the contractor and start the responsibility of the developer. For the conventional method, the contractor is often responsible for transporting and the developer for installing. For the indirect method, there would be a grey area (not transporting or installing) during the offshore transfer of which the responsibility must be clearly defined since this is a risky activity. This responsibility will be even harder to define for the direct strategy since the lift and the installation are done back to back.

The contractor should investigate the size of the installation vessel if they choose to use the conventional method. The size of the WTGs are increasing rapidly and a costly mistake would be made if the installation vessel is too small when the next-generation WTG increase even more. A market study of the future turbines is required as well as the current-day techniques such as larger cranes. The claim in the introduction that the conventional method is less efficient in time and costs than feedering is not entirely true. Feeder vessels have specific requirements as explained before to be faster and cheaper than shuttling. Therefore, this claim is only true when the requirements are met.

A contractor can use this research to decide on which installation strategy (used in this research) is the best fit. Although the port logistics/costs are not taken into account, the results provide a good general overview of the different strategies looking at installation vessel size for the conventional strategy and feeder and installation vessel types for the feeder strategies. The DES model created in this research can easily be adapted to different locations (OWF sites) and shelter areas can be added to be more realistic. The input parameters can be changed in the input list. A new model should be created (or adjusted) to implement other strategies which have different installation steps. This is more complex since activities are potentially linked to each other. Last, the OWF size(s), sailing distance (if not also taken in by the shelter areas) and the number of reruns (one run per year as explained in Section 4.3) should be set before the simulation can be started. The outputs are the duration per simulation and progress plot like in Figure 4.4. These results can then be run in the cost model (cost input parameters can be changed) to develop the cost results. This process is depicted in figure 6.1. As mentioned before, the port logistics can be added to the DES model which provides input on the storage level of the base port. This is now assumed to be full with all components for a project.

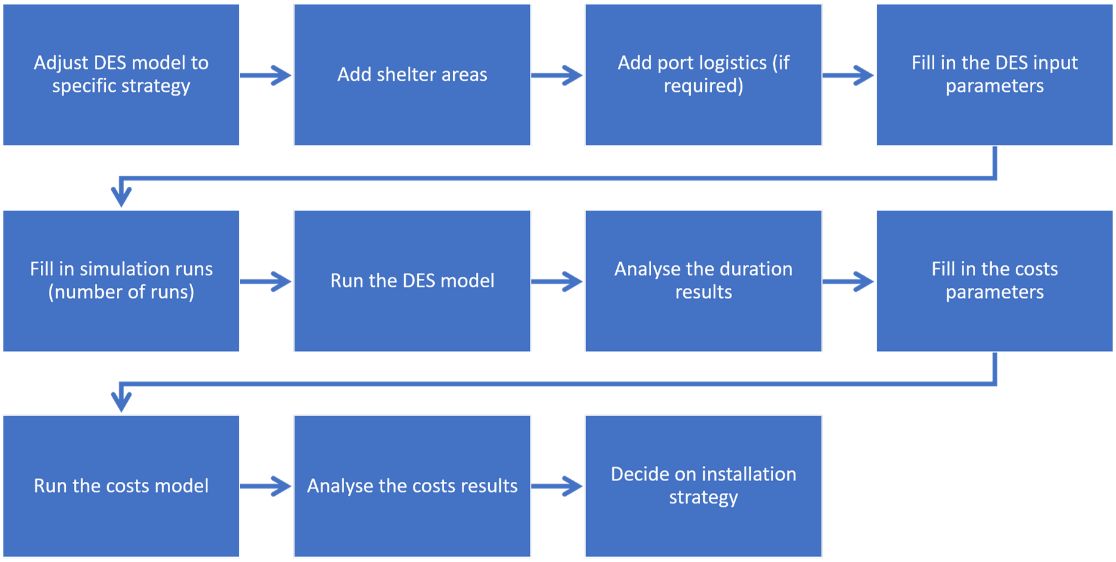


Figure 6.1: Process of how to adapt and run the DES and cost model.

6.2.5 Future research

This research and the model can be used to simulate the installation process starting at a base port. However, feedering would require more research to be implemented. The DES model built in this research can be used, adapted and/or extended for research and/or projects. First of all, there is still a lot of technical aspects unknown and need further research such as how a feeder can be stable with high environmental limits when carrying a full tower or in two segments. Also, it is unknown what the exact environmental limits would be for the transfer of WTG components of a feeder. This comes with another element to investigate what possibilities there are to increase the environmental limits without increasing the costs too much (especially when multiple feeders need to be used). This then requires more research in the specifics of the next-generation WTGs that will potentially be feedered. Additional research is also required to find a solution for the bottleneck of transferring the blade rack and the equipment back lift. Positioning the feeder on DP could be a possibility. However, other positioning methods such as mooring should be looked into as well.

Second, the model used in this research should be expanded. As mentioned before, shelter areas, possible breakdowns/learning curves and port elements should be added to be more complete and realistic. Another element that is left out of this research and could be added in later models to improve the reality is that all vessels will go into a shelter in case of severe weather. This could lead to additional delays mainly for the feeder method. Other percentiles (e.g. P70 and P90), as well as more parameters in the sensitivity analysis, should be analysed for an even better understanding of the results. To provide more generalizable results, the simulation should be run for multiple locations around the world. It would even be more realistic if the actual potential base and production ports are used to start a project at.

The strategies within this research as well as additional strategies can also be further investigated. For example, besides PSVs, barges and jack-up barges (lift-boats) can be used to fully show their potential. A new barge concept called BargeRack by Friede & Goldman has emerged where the barge is lifted out of the water by a rack mounted onto the installation vessel. (Friede & Goldman, 2021). This takes away the environmental waves limits during the lift, potentially creating a more interesting solution using barges because of a higher workability. Other strategies besides the ones in this research should also be further investigated. The strategies from the literature could be improved with sensitivity analysis and more realistic values. Another strategy could possibly be a hybrid feeder solution. Here, the installation vessel follows the conventional method but a feeder is added to provide additional WTG(s). In other words, the installation vessel installs for example two WTGs by the conventional method and a feeder brings the third WTG so the installation vessel can install another one while still being relatively small.

Due to the Jones act., feedering is a highly interesting option in the U.S. Currently, projects are being developed with this method. The PSVs in the U.S. have a limited deck space and are unstable when loaded with WTG components. Therefore, barges are planned to be used despite not being the better option according to this research. The current PSVs in the U.S. can be adjusted or new ones can be built with a new design in order to make PSVs viable feeder vessels. This is the main focus of the second thesis for this double degree. The thesis will dive into the technical aspects (stability) of the PSVs where multiple concepts are developed and evaluated. The best concept will be chosen and analysed on a deeper level by means of hydrodynamic simulation tools such as ANSYS AQWA and OrcaFlex. The DES model of this research can be used to access the outcome of the design duration and cost-wise.

All in all, can be stated that this research shows the potential of feedering and is a push to investigate feedering on a deeper and technical level. This research concludes that the conventional method with a large installation vessel in Europe is the best installation strategy for now. However, more simulations at different locations need to be performed to provide a more overall picture. The feeder possibilities need to be investigated more, especially on the technical aspects. In order to become competitive, a feeder should be fast with relatively high environmental sailing limits (overall stable vessel) when carrying a full tower in segments while using a special purpose installation vessel. More innovative feeder strategies with or without (motion compensation) tools are being developed leading to a potential change in the European market in the future. However, markets such as in the U.S. currently demand the use of feeder vessels and greatly pushes these researches since large Jones act. compliant installation vessels are just starting to be developed and the first one is expected in 2023 (Skopljak, 2020). Most likely, current or older installation vessels need to be upgraded to special feeder purpose installation vessels in combination with Jones act. compliant feeder vessels to be competitive with the upcoming Jones act. compliant installation vessels.

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Appendices

Appendix A: General feeder method steps

A.1 Conventional method

Step 1: Transfer the WTG components from the production port to the base port by **large transport vessels**. (This step needs to be repeated to constantly supply the base port)

Step 2: Store the WTG components temporarily at the base port.

Step 3: Transfer multiple (as much as possible) full sets of WTG components from the storage to the installation vessel.

Step 4: Transfer the full sets to the installation site by the installation vessel.

Step 5: Install all the WTG components

Step 6: Sail back to the base port to pick up new WTG components.

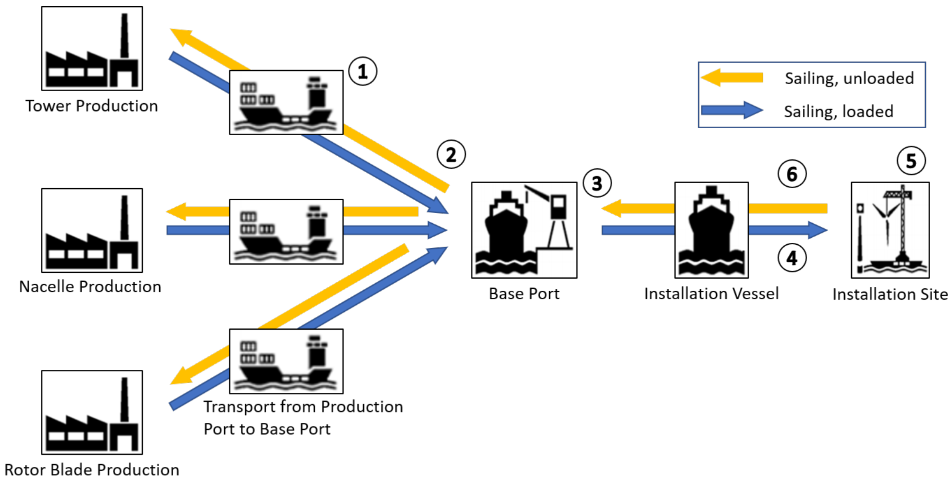


Figure A.1: The conventional method steps based on Ait Alla et al. (2017)

A.2 Base port feeder method

Step 1: Transfer the WTG components from the production ports to the base port by a **feeder vessel**. The feeder will first sail past all production ports to collect single or multiple full sets of WTG components. The feeder will sail to the base port when all components are loaded.

Step 2: Transfer all the WTG components **directly** to the installation vessel (at the base port).

Step 3: The feeder vessel(s) will sail back to the first production port to restart the feedering process.

Step 4: The installation vessel sails to the installation site and installs the WTG(s).

Step 5: The installation vessel sails back to the base port to receive new WTG components once all components are installed.

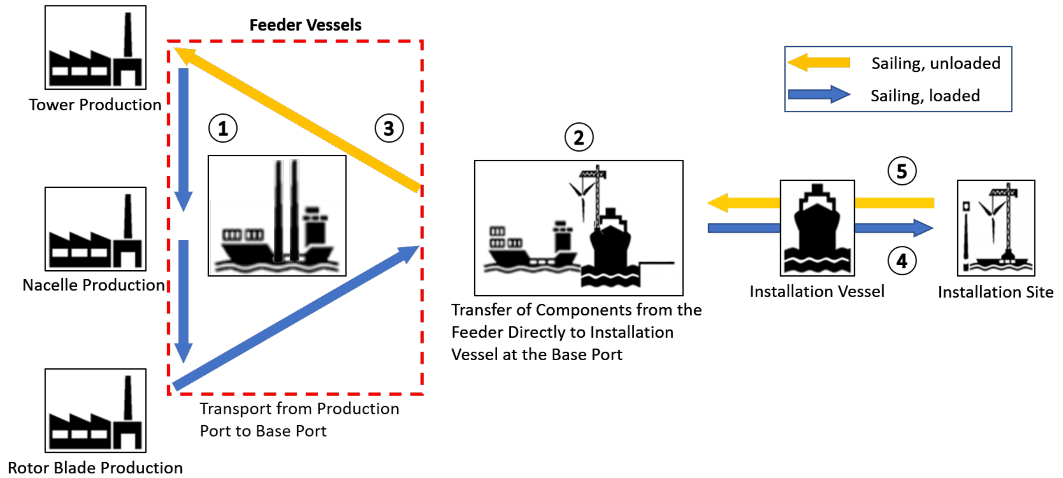


Figure A.2: The base port feeder method steps based on Ait Alla et al. (2017)

A.3 Feeder-ship method

Step 1: Transfer the WTG components from the production port to the installation site by **feeder vessels**. The feeder will first sail past all production ports to collect single or multiple full sets of WTG components. The feeder will sail to the installation site when all components are loaded.

Step 2: The transfer of 1 full set of WTG components directly to the installation vessel (at the installation site).

Step 3: The feeder vessel will sail back to the production port to pick up new WTG components only if the feeder is empty. If a feeder has components for 2 sets on board, it will stay offshore until all components are supplied to the installation vessel.

Step 4: The installation vessel installs the WTGs.

Step 5: The installation vessel sails to the next installation site where it will receive a new full set of WTG components.

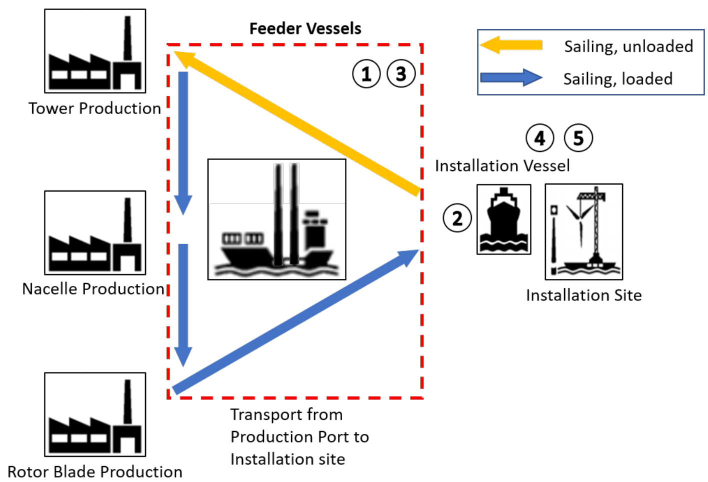


Figure A.3: The offshore feeder-ship method steps based on Ait Alla et al. (2017)

A.4 Practical feeder-ship method

Step 1: Transfer the WTG components from the production port to the base port by **large transport vessels**. (This step needs to be repeated to constantly supply the base port)

Step 2: Store the WTG components temporarily at the base port.

Step 3: Transfer the WTG components from the base port to the installation site by a **feeder vessel**. The number of components that need to be transferred depends on the maximum number of full WTG sets the feeder vessel can carry.

Step 4: Transfer 1 full set of WTG components directly to the installation vessel (at the installation site).

Step 5: The feeder vessel will sail back to the base port to pick up new WTG components only if the feeder is empty. If the feeder has multiple full sets on board. It will stay offshore until all components are supplied to the installation vessel.

Step 6: The installation vessel installs the WTG components.

Step 7: The installation vessel sails to the next installation site where it will receive a new WTG set.

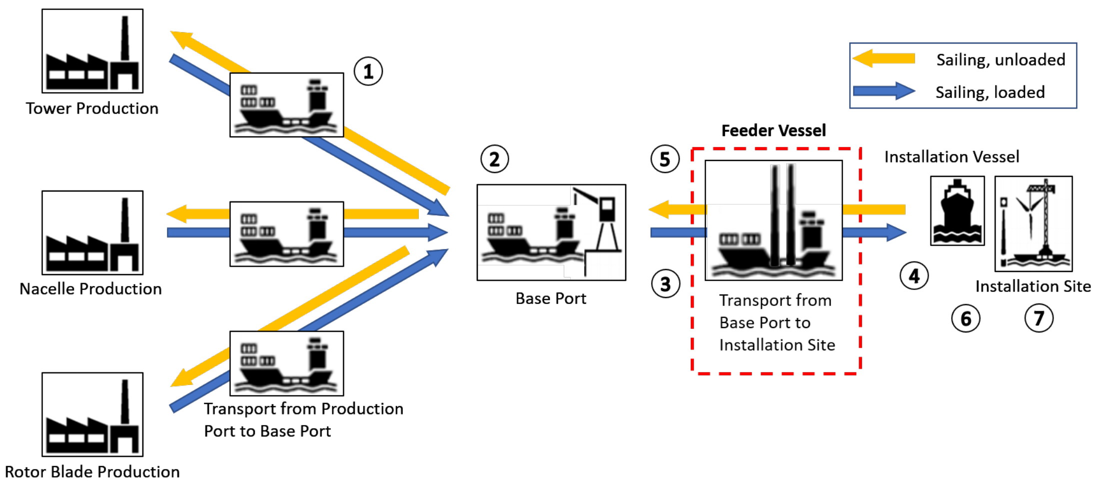


Figure A.4: The practical feeder-ship method steps

Appendix B: Large transport vessels & base port

These are examples of how the large transportation vessels and a base port looks like. The Larger transportation vessels are only used to transport the WTG components from the production port to the base port.

Figure B.1: Examples of large transport vessels (Froese, 2015; Pieffers, 2019)

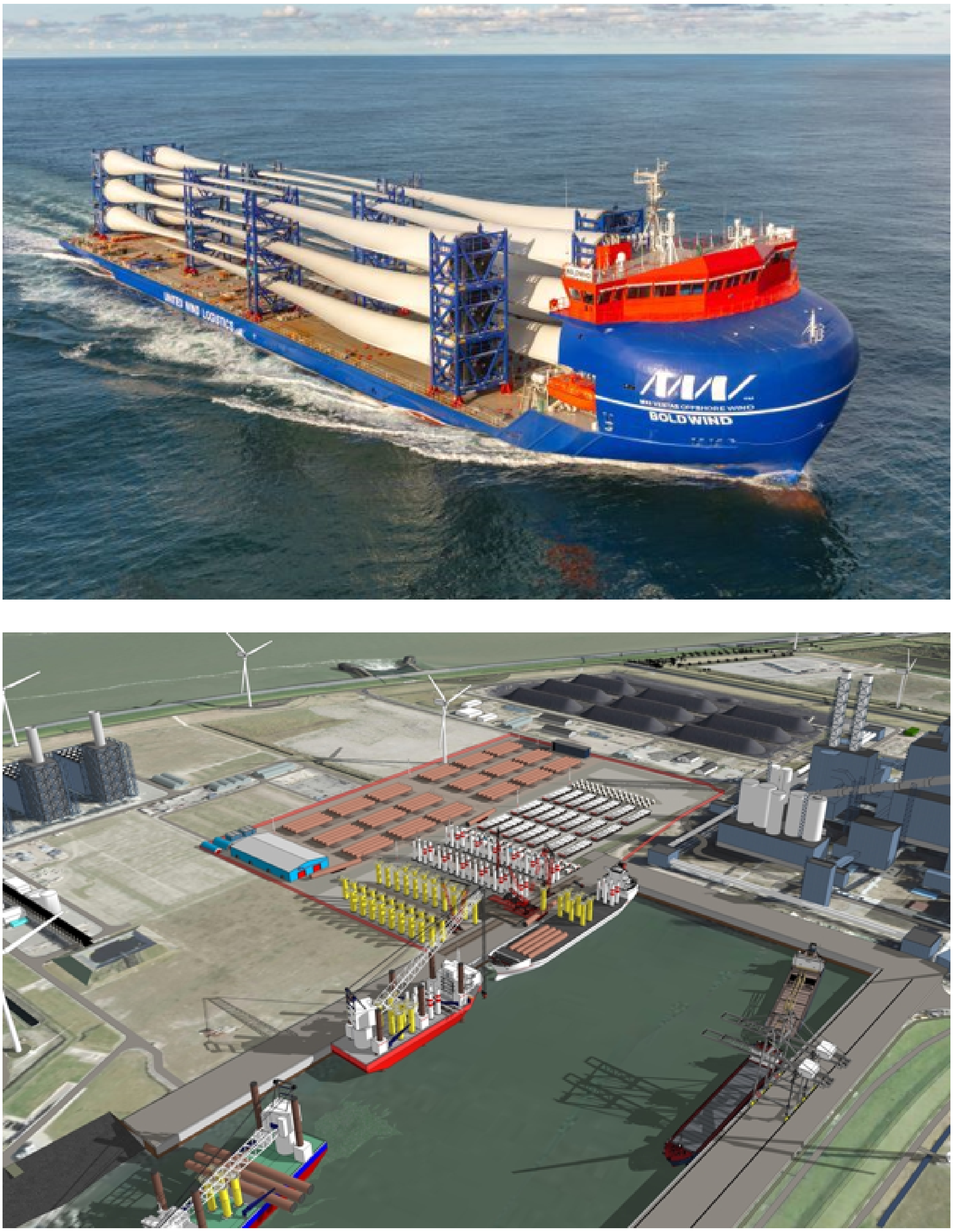


Figure B.2: Examples of large transport vessels and a base port for temporary storage (Wallis, 2020; Groningen seaports, 2019)

Appendix C: Tools

The Seaqualize is a tool to compensate for the heave motions at the side of the crane. It can also vertically move with the component on another moving vessel. The barge master is a tool to compensate for all the motions of a component on a moving vessel. These are two options for motion compensation tools. They are shown in the figures below.

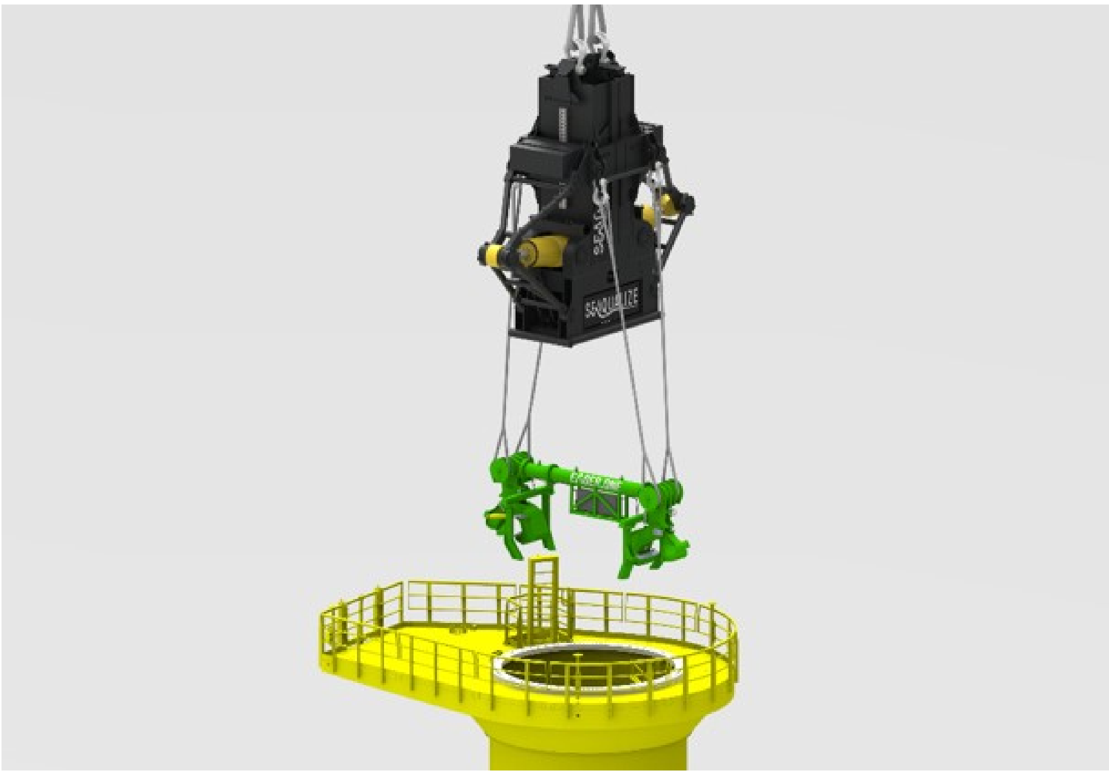


Figure C.1: Seaqualize motion compensation tool (Offshorewind.biz, 2021)

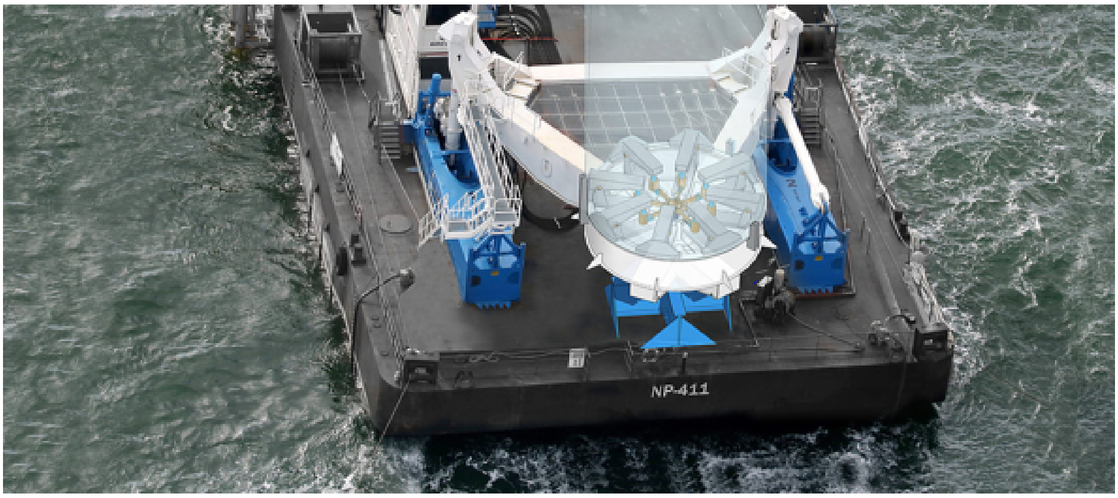
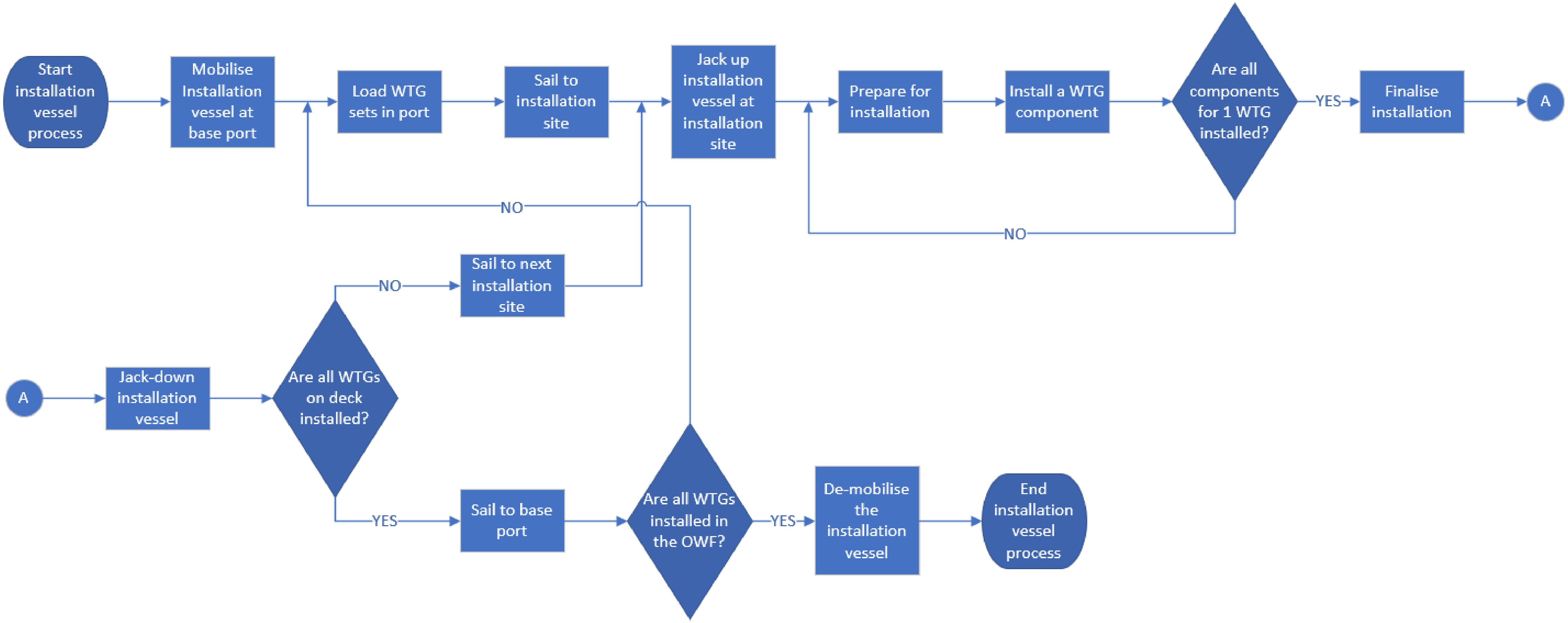


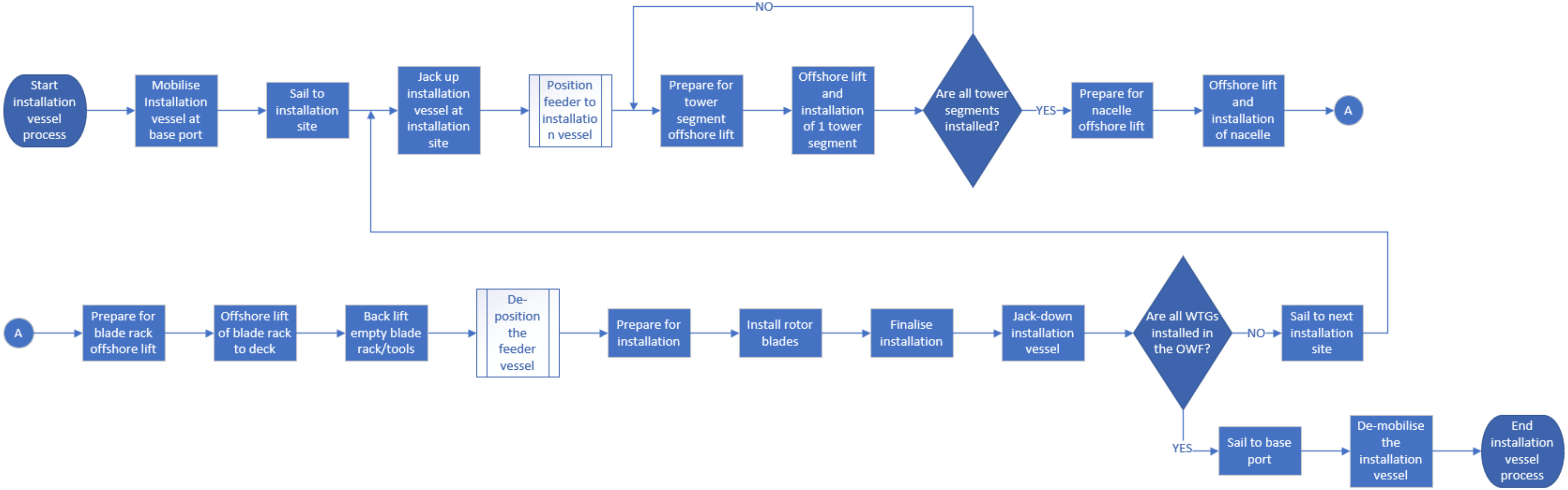
Figure C.2: Barge master motion compensation tool (Bare Master, 2021)

Appendix D: Problem Research Flow Diagram

D.1 RFD installation vessel - conventional method

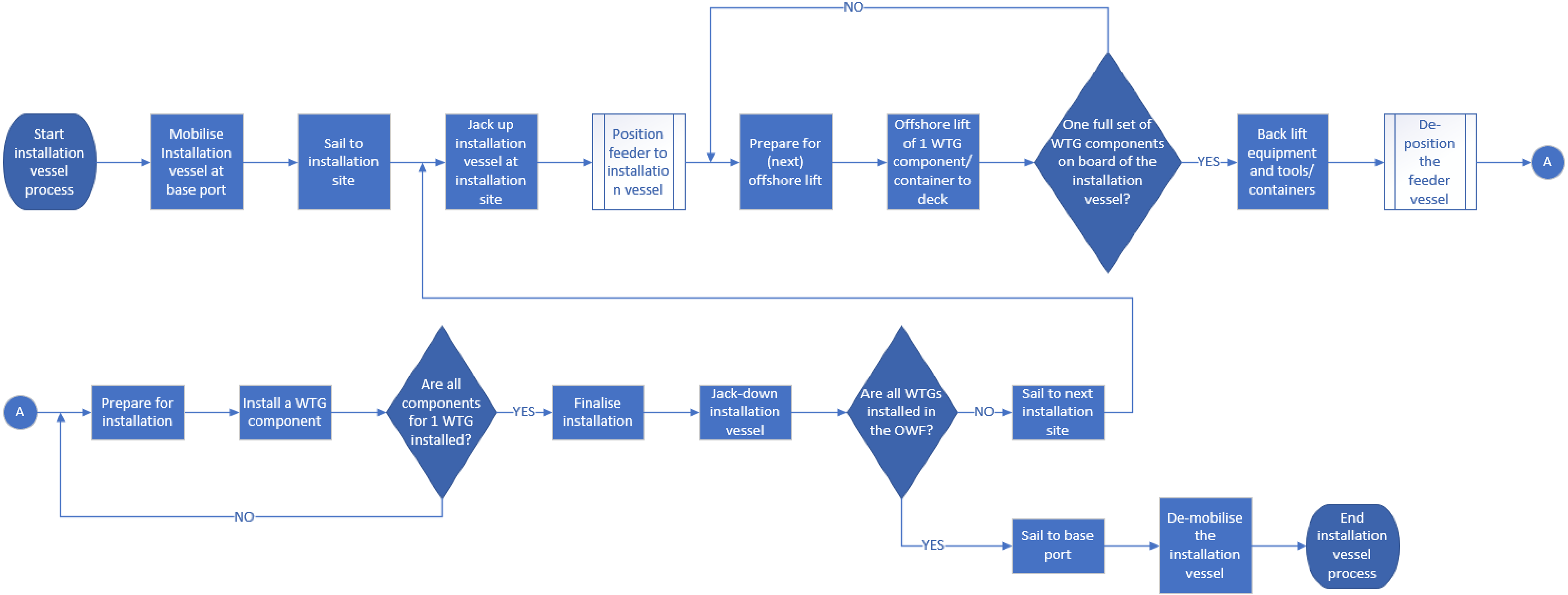

Start installation vessel process
Mobilise Installation vessel at base port
Load WTG sets in port
Sail to installation site
Jack up installation vessel at installation site
Prepare for installation
Install a WTG component
Are all components for 1 WTG installed?
YES
Finalise installation
A
NO
NO
Sail to next installation site
NO
A
Jack-down installation vessel
Are all WTGs on deck installed?
YES
Sail to base port
Are all WTGs installed in the OWF?
YES
De-mobilise the installation vessel
End installation vessel process

D.2 RFD installation vessel - direct feeder method



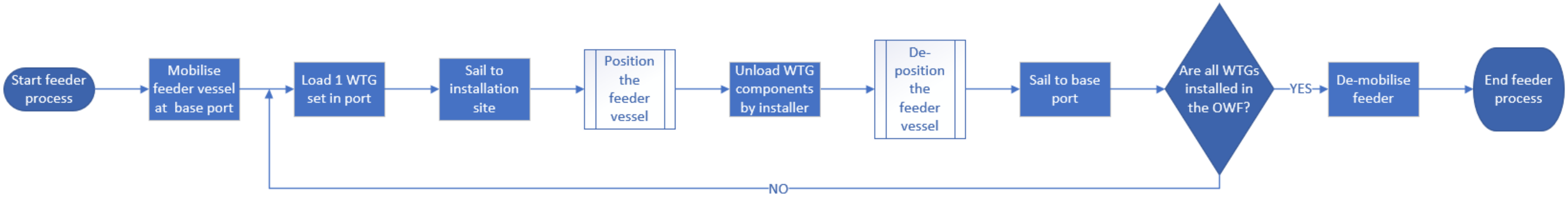
Start installation vessel process
Mobilise Installation vessel at base port
Sail to installation site
Jack up installation vessel at installation site
Position feeder to installatio n vessel
Prepare for tower segment offshore lift
Offshore lift and installation of 1 tower segment
Are all tower segments installed?
NO
YES
Prepare for nacelle offshore lift
Offshore lift and installation of nacelle
A
A
Prepare for blade rack offshore lift
Offshore lift of blade rack to deck
Back lift empty blade rack/tools
De-position the feeder vessel
Prepare for installation
Install rotor blades
Finalise installation
Jack-down installation vessel
Are all WTGs installed in the OWF?
NO
Sail to next installation site
YES
Sail to base port
De-mobilise the installation vessel
End installation vessel process

D.3 RFD installation vessel - indirect feeder method



Start installation vessel process
Mobilise Installation vessel at base port
Sail to installation site
Jack up installation vessel at installation site
Position feeder to installatio n vessel
Prepare for (next) offshore lift
Offshore lift of 1 WTG component/ container to deck
One full set of WTG components on board of the installation vessel?
NO
YES
Back lift equipment and tools/ containers
De-position the feeder vessel
A
A
Prepare for installation
Install a WTG component
Are all components for 1 WTG installed?
YES
NO
Finalise installation
Jack-down installation vessel
Are all WTGs installed in the OWF?
NO
Sail to next installation site
YES
Sail to base port
De-mobilise the installation vessel
End installation vessel process

D.4 RFD feeder vessel - feeder method


Start feeder process
Mobilise feeder vessel at base port
Load 1 WTG set in port
Sail to installation site
Position the feeder vessel
Unload WTG components by installer
De-position the feeder vessel
Sail to base port
Are all WTGs installed in the OWF?
YES
NO
De-mobilise feeder
End feeder process

Appendix E: IDEF0

E.1 Conventional method IDEF0

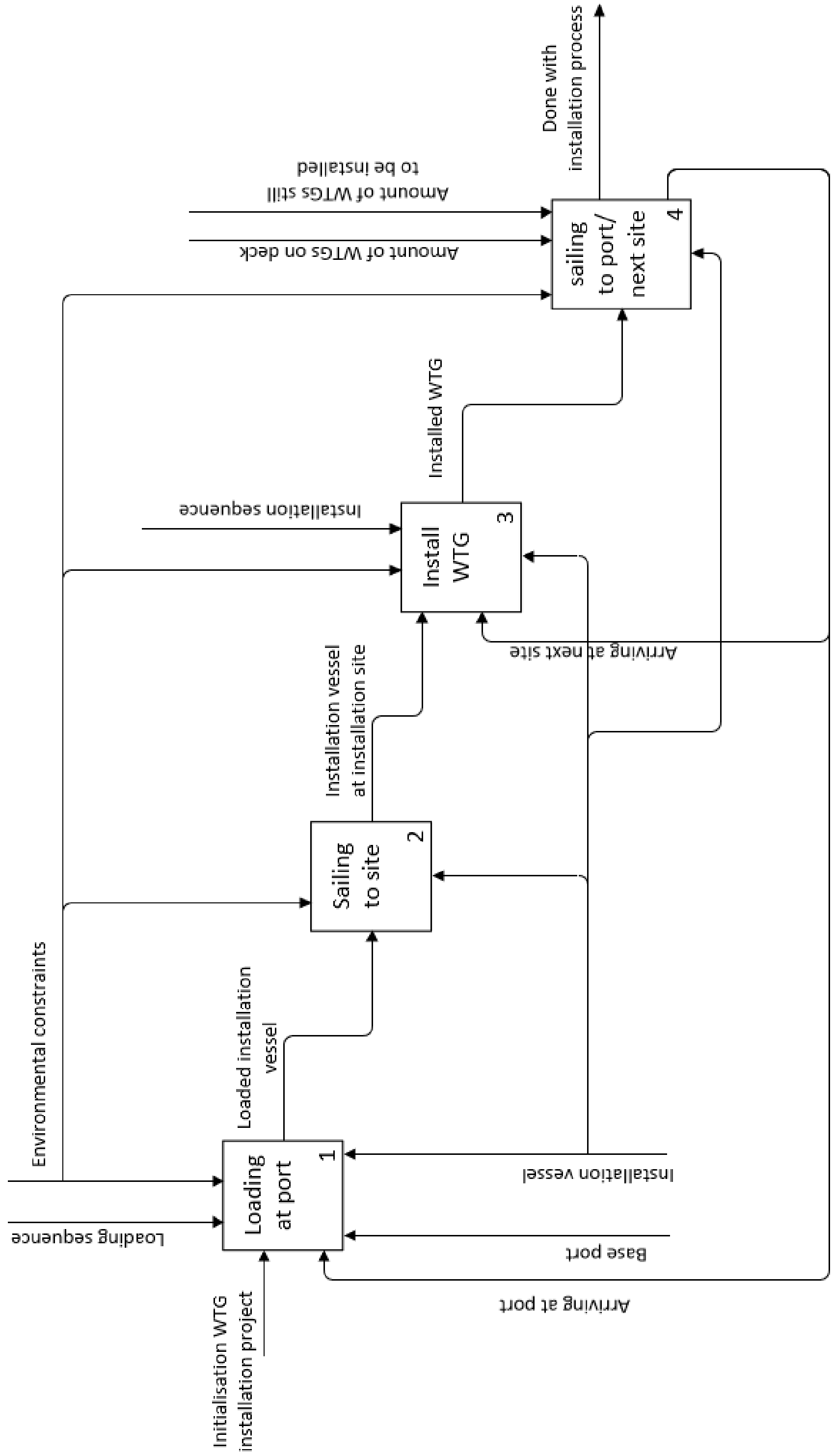


Figure E.1: Conventional method IDEF0 diagram

E.2 Feeder method IDEF0

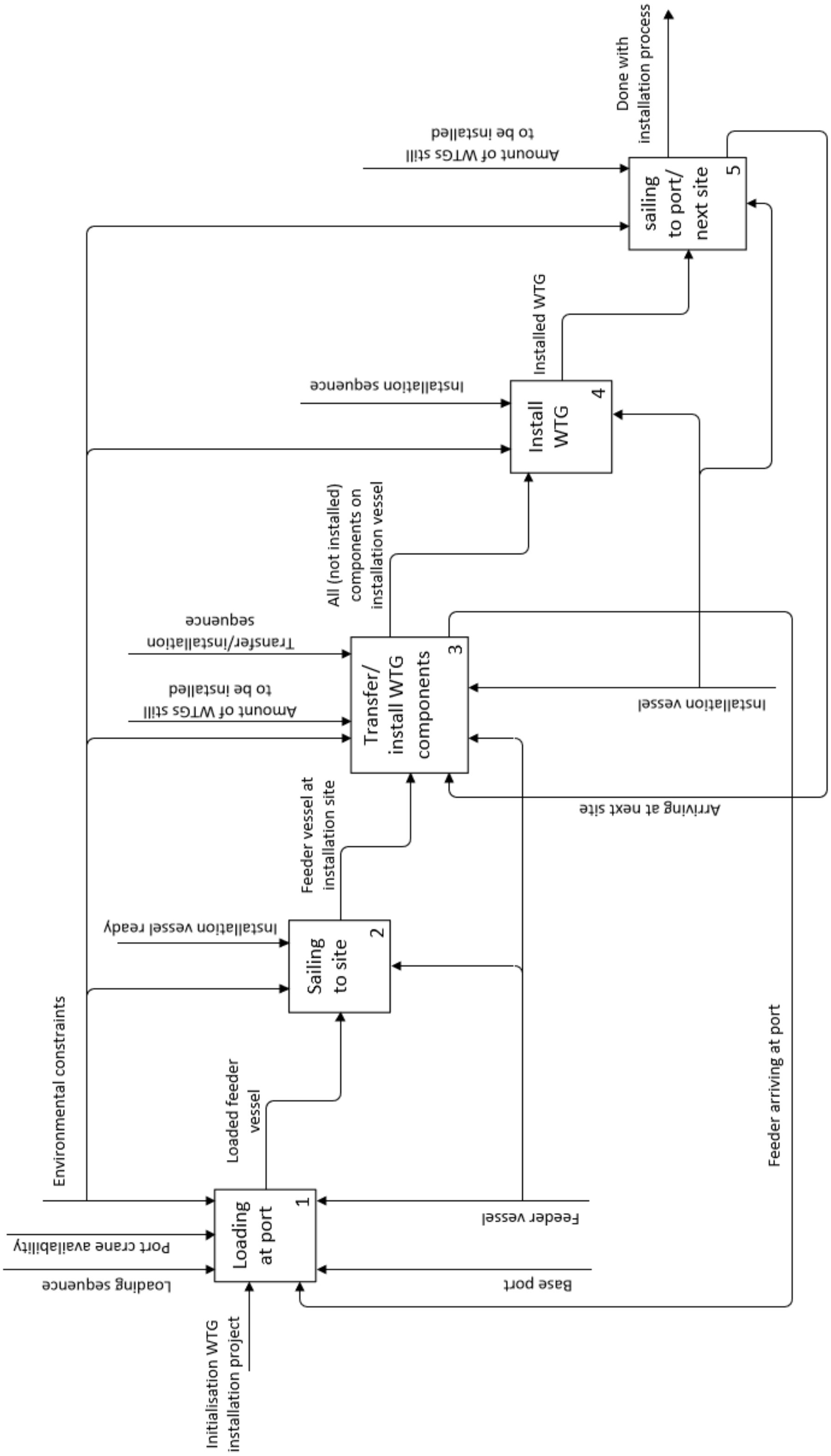


Figure E.2: Feeder method IDEF0 diagram

Appendix F: Simulation input parameters

This Appendix contains confidential information and is therefore excluded from the public thesis version.

Appendix G: Q-Q plots

The Q-Q plots show whether the results follow a normal distribution. It is safe to say that the results are close to a normal distribution while having 15 simulations, especially for larger distances. More simulation would provide a closer fit to the normal point in the plots. However, the simulations would also take much more time.

G.1 One PSV - indirect

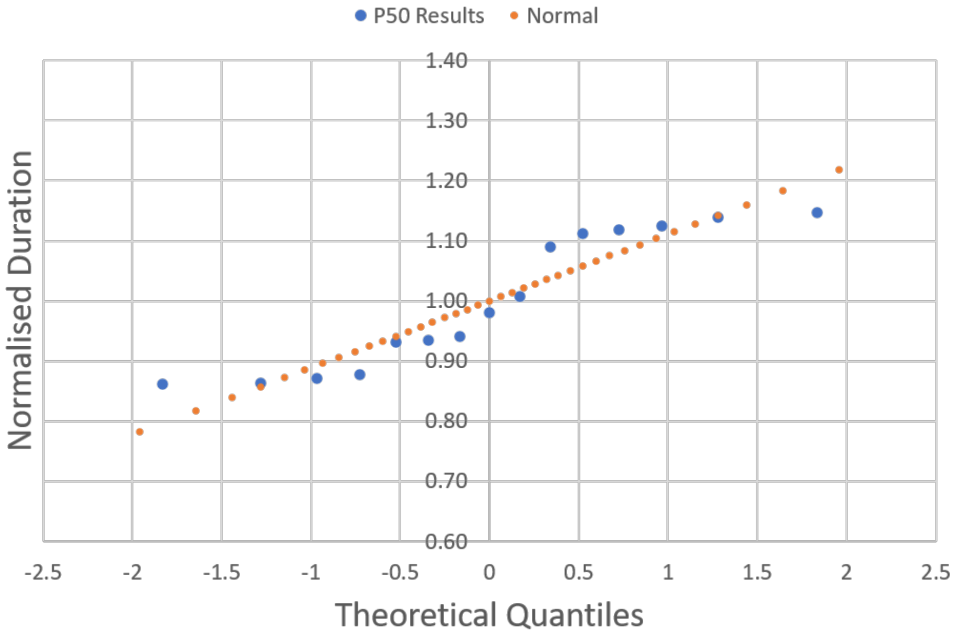


Figure G.1: Q-Q plot, 1 PSV indirect feedering - 20 nm

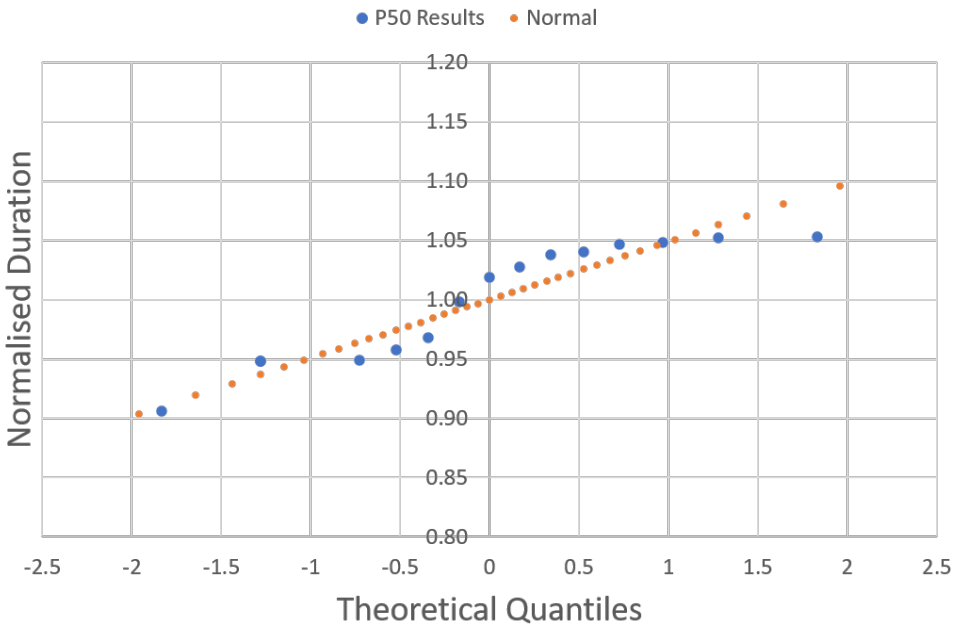


Figure G.2: Q-Q plot, 1 PSV indirect feedering - 188 nm

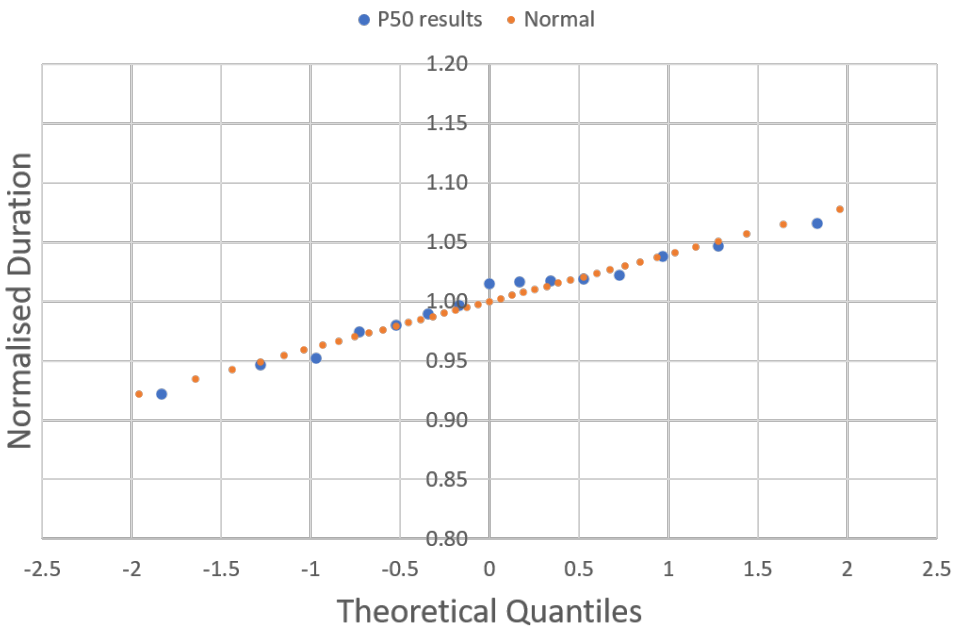


Figure G.3: Q-Q plot, 1 PSV indirect feedering - 300 nm

G.2 Two PSVs - direct

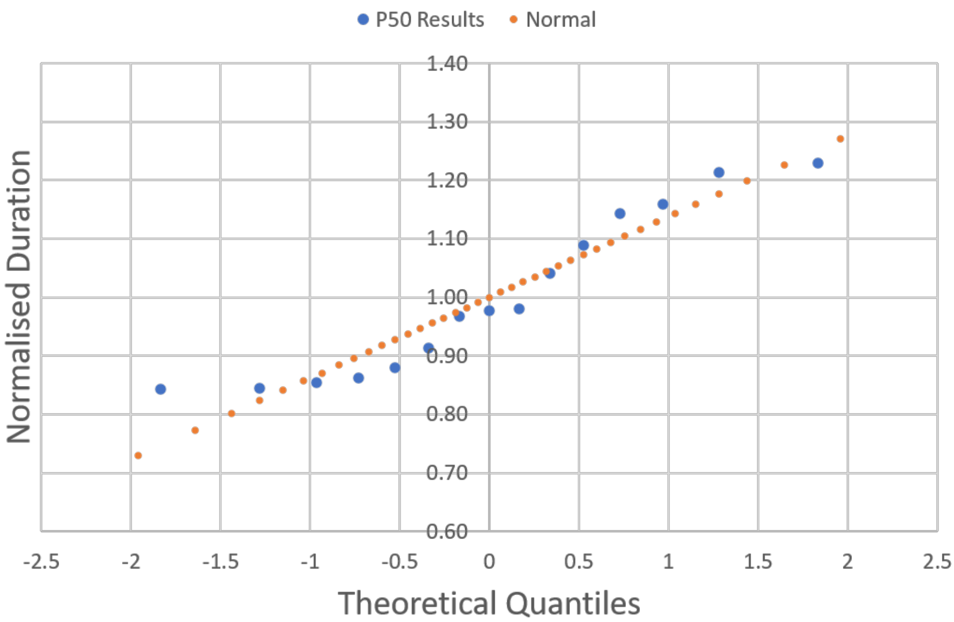


Figure G.4: Q-Q plot, 2 PSVs direct feedering - 20 nm

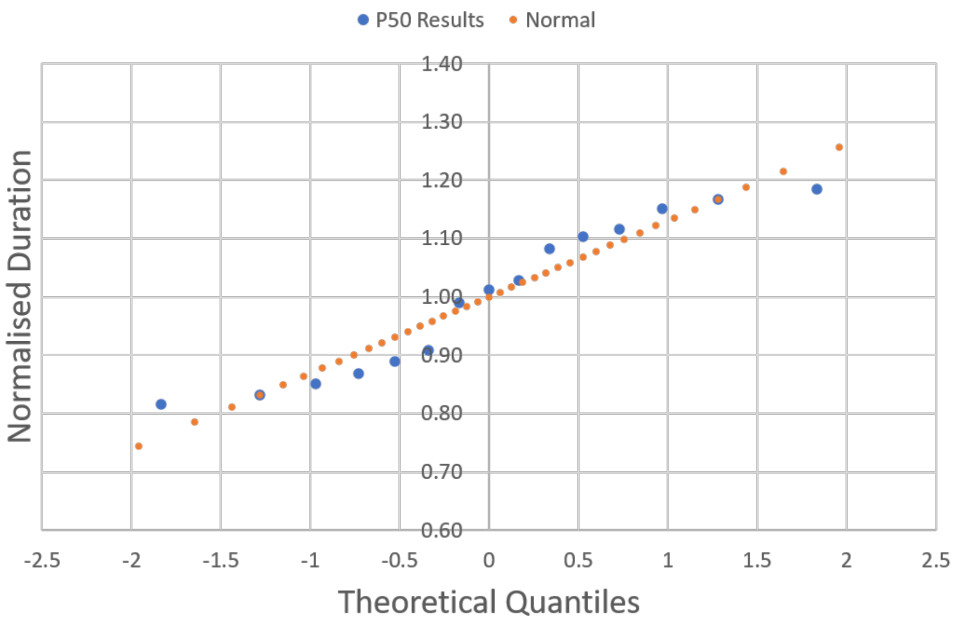


Figure G.5: Q-Q plot, 2 PSVs direct feedering - 188 nm

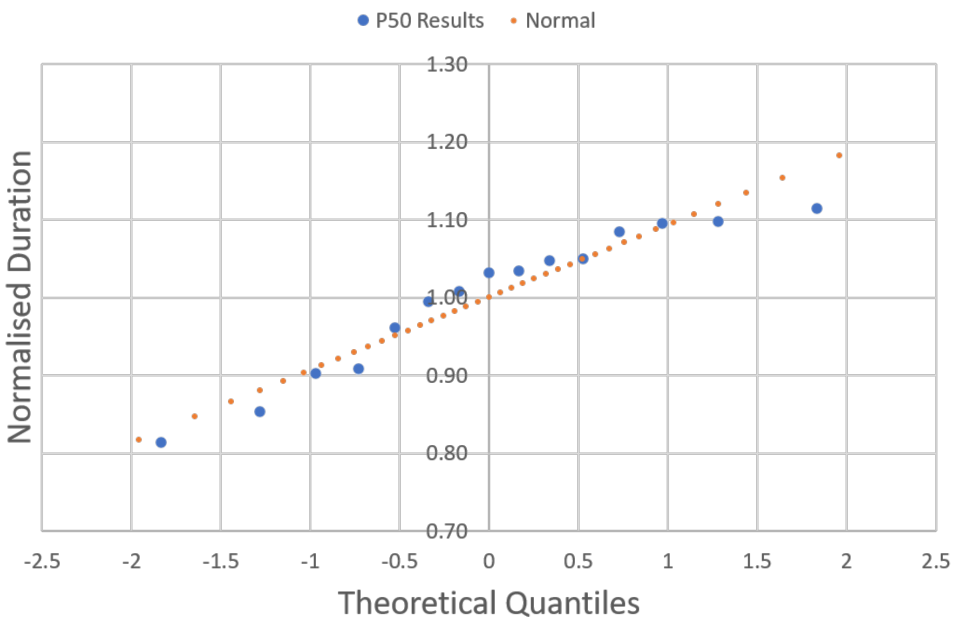


Figure G.6: Q-Q plot, 2 PSVs direct feedering - 300 nm

Appendix H: P0 results

This Appendix contains confidential information and is therefore excluded from the public thesis version.

Appendix I: Initial P50 results

This Appendix contains confidential information and is therefore excluded from the public thesis version.

Appendix J: P50 scenario results

This Appendix contains confidential information and is therefore excluded from the public thesis version.