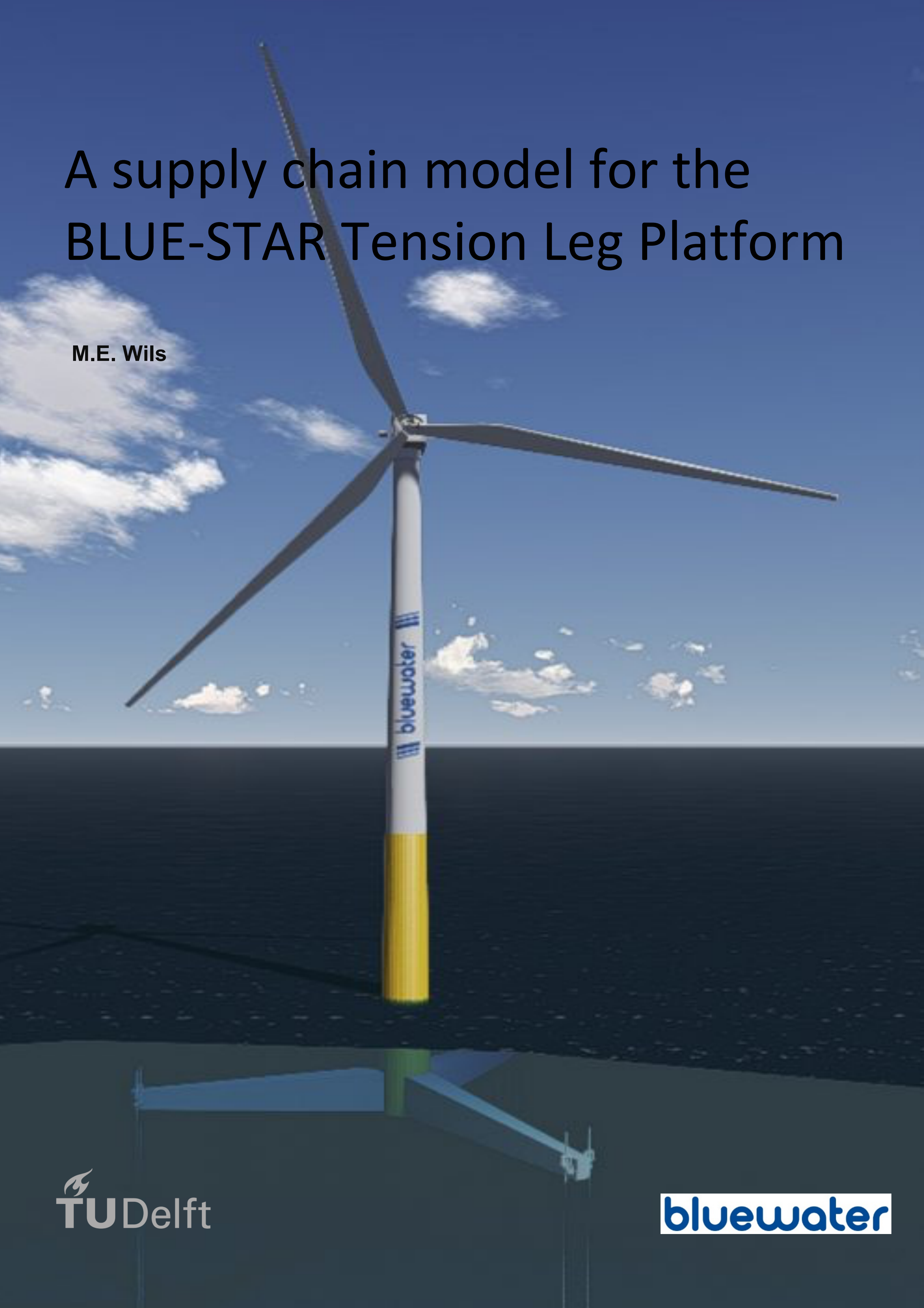
A supply chain model for the BLUE-STAR Tension Leg Platform

M.E. Wils



A supply chain model for the BLUE-STAR Tension Leg Platform

By

M. E. Wils

in partial fulfilment of the requirements for the degree of

Master of Science
in Construction Management & Engineering

at the Delft University of Technology,

Student number:	4127951
Project duration:	June, 2020 – June, 2021

Thesis committee:	Dr. ir. O.M. Napoles,	TU Delft (Chair)
	Dr. ir. M. Nogal Macho,	TU Delft (1st supervisor)
	Ir. J.S. Hoving,	TU Delft (2nd supervisor)
	Ir. C. van der Nat,	Bluewater

TU Delft

bluewater

This page is left blank intentionally

Abstract

The offshore wind market is developing fast due to climate change. To fulfil in the growing demand for offshore wind market, one has to look for floating offshore wind solutions as nearshore shallow waters are depleting. Several types of floating wind structures can be distinguished in the following categories; Spar, semi-submersible and Tension Leg Platform (TLP) structures. Bluewater developed a floating wind TLP, the BLUE-STAR, which is still under development and has not yet been applied in offshore wind projects. At the moment there are many factors unknown about the concept. This in comparison to semi-submersible structures of which more knowledge is available.

The aim of the thesis is to describe, if the TLP concept has an advantage over the semi-submersible structure and if the newly developed TLP concept is a viable solution, using a simulation model to simulate the logistics both structures. First, different types of offshore wind turbines are classified, including TLP and semi-submersible structures. The described classification is followed by challenges the logistics of offshore wind farms are currently confronted with. This point out that the most important challenges are due to substructures, environmental conditions and T&I.

the logistic processes of both the TLP and SSB structure are described. This is followed by a literature review divided into literature on weather conditions and literature on operations and logistics, in which the analytical approach and simulation-based methods are described. After the literature review it is found that Discrete Event Simulation is used for the simulation model. For the simulation, Matlab is used.

This is followed by an extensive description of the logistic process in general. The second part of the chapter elaborates on implementation of both structures into the described model. The fourth part of this thesis, elaborates on implementation of the simulation model by explaining the decisions and assumptions made for the simulation model. Furthermore, this part also discusses the inputs of the logistic process simulation.

The weather data provided by Bluewater for the use of the simulation model is presented and this part of the thesis gives an evaluation of the simulation model. Based on this evaluation, is it concluded the simulation model functions correctly.

In the final part of this thesis, the results of the logistic simulations of both structures are compared and a sensitivity analysis is performed. For the sensitivity analysis, 4 cases are studied, these are: varying wind speed and wave height, variation of transport duration, varying team performance. The aim of this sensitivity analysis is to study the influences of different input conditions.

Finally, results of the simulations and performed sensitivity analysis indicate that the newly developed TLP concept is not a realistic alternative compared to the SSB structure.

Preface

This thesis is the final step for completion of my master Construction Management & Engineering. I conclude my student life at the same university I also started it. After switching studies a few times at different universities, I returned to TU Delft for a master.

First of all, I want to thank my thesis committee members Jeroen Hoving and Oswaldo Morales-Napoles for their guidance and steering me in the right direction. Special thanks to my daily supervisor, Maria Nogal. I am really gratefull she teached me how to work with Matlab and for always being available to answer my questions and giving feedback. Also, I want to thank Clemens van der Nat from Bluewater for the opportunity to complete my thesis at Bluewater.

Finally, I would like to thank my family for always supporting me during my studies and my friends for our talks and coffees, especially during the Corona months

Martine Wils
Wassenaar, June 2021

Table of Contents

Table of Figures

Table of Tables

List of Abbreviations

The following list gives an overview of the used abbreviations in this thesis with their used/accompanying description.

DES	Discrete Event Simulation
FOWT	Floating Offshore Wind Turbine
MCS	Monte Carlo Simulation
MILP	Mixed Integer Linear Programming
NM	Nautical Mile (1 NM = 1,852 km)
O&M	Operation & Maintenance
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine
SSB	Semi-Submersible
SWH	Significant Wave Height
TLP	Tension Leg Platform
T&I	Transport and installation
WTG	Wind Turbine Generator

This page is left blank intentionally

1. Introduction

1.1 Background

With growing world population, a growing economy and urbanization, the energy demand increases (Wang et al., 2018). Nowadays, most energy is produced by the use of fossil fuels (Wang et al., 2018). Fossil fuels are limited and it is expected they will be depleted by 2040. Thereby, fossil fuels are a threat to the environment due to emission of CO_2 resulting in climate change (Wang et al., 2018). Increasing energy demand, depleting fossil fuels and climate change asks for renewable resources which need to be reached out to: “the renewable, energy-efficient and eco-friendly resources” (Joy et al., 2019, p. 841), which have both environmental and economic advantages (Wang et al., 2018). As stated by Kota et al., (2015), the environment can be improved and climate change can be potentially mitigated by an inexhaustible resource, offshore wind.

Out of all various renewing energy possibilities for generating energy (solar, geothermal, ocean, tidal and wind), wind energy is believed to be most promising (Joy et al., 2019; Wang et al., 2018). Wind is known to be a clean, inexhaustible source for generating energy. Hence the switch to wind energy will contribute to reduction of greenhouse gas emissions (Sun et al., 2012).

For several reasons, offshore wind energy is becoming more important than onshore wind energy (Joy et al., 2019). In the first place, onshore space is limited and onshore and near-shore wind farms can also cause visual and noise impact (J. J. Yang & He, 2020, p. 678). Moreover, available space in shallow waters is depleting, reason why one has to look for installation methods suitable for deeper waters. Deep waters are defined as waters deeper than 50 m (Madsen et al., 2020). In deep waters, wind speed is higher and more constant, which contributes to a higher power generation efficiency (Yang & He, 2020). Furthermore, wind can run smoother at sea without hindrance of mountains and hills present on land. Application of wind turbines in deep water requires a floating wind turbine design.

Over the past years, research into the development of floating substructures for offshore wind turbines pointed out that they are a promising solution for overcoming the difficulties faced with non-floating structures (Lerch et al., 2018), especially with deep water applications. So far, several options for floating structures have been developed. The most important are the Tension Leg Platforms (TLP) and semi-submersible systems (Sun et al., 2012).

In order to ensure reliability, survivability but also safety of offshore wind turbines (Sun et al., 2012), a new Tension Leg Platform (TLP) concept for a floating offshore wind turbine has recently been developed by Bluewater. The TLP concept can be deployed in deep waters greater than 60 m and equally important, it can be employed in the harshest weather conditions such as hurricane- and earthquake-prone regions.

1.2 Problem statement

Installation of the TLP concept of Bluewater differs from installation of a semi-submersible structure and earlier developed TLP designs. The TLP concept is installed offshore in different phases while semi-submersible structures are pre-assembled at the quay in port after which they are towed-out as a fully equipped system. Therefore, the logistic process of the TLP concept and semi-submersible structures are different. Since offshore wind farms move further offshore into deeper waters, an increase in operational durations is noticeable. This is accompanied with an increasing complexity for the installation process as also the sensitivity to weather conditions increases (Barlow et al., 2018). This makes that logistic challenges arise and risk factors increase (Lange et al., 2012).

Environmental conditions differ per installation site and as earlier research shows (Lerch et al., 2018), they have a significant influence on the installation window. In case of weather downtime, additional installation costs are required. The TLP concept has a phased installation approach resulting in wider installation weather windows compared to semi-submersible structures.
The number of installed floating wind turbines is very limited; hence, no sufficient data is available for a probabilistic approach. So far, only prototypes of floating wind systems have been installed (Maienza et al., 2020). For the installed prototypes, such as semi-submersible and spar systems, the uncertainties are partially known as they have already been constructed and tested in offshore wind farms.
Before the TLP concept can be properly applied in offshore wind farm projects, the risks involved, as well as the risks related to the weather downtime of the TLP concept of the logistical process, need to be quantified and compared to the ones of semi-submersible structures.

1.3 Research objective

The objective of this research is to evaluate whether the TLP concept can be a realistic alternative when compared to a float-out based semi-submersible structure. For this, a simulation model is used to prove the viability of the transport and installation process of the newly developed TLP concept. With the use of the simulation model, the logistic process of the TLP concept and semi-submersible structure are compared. Successful completion of the research will remove barriers for future floating offshore wind projects as the identified risks can be better managed.

The following research question is stated:
Has the logistic process of the TLP concept an advantage over the logistic process of a semi-submersible structure, based on a new developed simulation model?

In order to answer the main research question, the following sub-questions are formulated.

1. *How does the logistic process of the BLUE-STAR Tension Leg Platform relate to the logistic process of a float-out based semi-submersible structure?*
2. *Which part of the transport and installation stages of both the TLP and SSB cause most of the delay?*
3. *Can the developed simulation model assess optimal project installation time?*

1.4 Methodology

To conduct the research, the following methodology is proposed. Both quantitative and qualitative approaches will be used in order to answer the research questions.

1.4.1 Literature study

The literature study will focus on the logistical processes and the current problems involved for offshore wind turbine farms. Also, literature is studied on weather conditions and operations and logistics. For this, different databases will be used and available reports, articles and papers will be studied.

1.4.2 Data gathering and simulation

First, a description of the logistic processes of the TLP and semi-submersible structure will be given. Then, a simulation model is developed using a probabilistic approach to compare these logistic processes. With this model, risks of both the TLP concept and semi-submersible structures during transport and installation can be identified. For this simulation model, input data is required. So far, insufficient data is available for a probabilistic approach. The input data for this model, historical weather data for wind speed and wave height for a specific location, is provided by Bluewater and the available data will be reviewed. With the use of the constructed simulation model, a Monte Carlo Simulation will be performed to asses a probability distribution of the total project duration.

1.4.3 Verification and sensitivity analysis

The model will be verified and validated. The model will be verified by critically studying the results. Furthermore, for validation of the model, several cases will be tested for the model and results will be compared to existing literature. Also, a sensitivity analysis is performed as part of the validation.

1.4.4 Conclusion and recommendations

The final chapter(s) summarizes the research and gives the conclusion of the thesis. Finally, it will provide the reader with recommendations for future offshore floating wind farm projects.

1.5 Thesis outline

This section presents the outline of the report. Chapter 2 gives an introduction on the offshore wind market, different types of offshore wind turbines are clarified and it presents the logistic processes of the TLP concept and semi-submersible structures. Also, the challenges the logistic processes are currently facing are illustrated. The 3rd chapter gives a detailed description of the model which will be implemented later on. Subsequently, this chapter gives the functioning of the model for the TLP concept and semi-submersible structure. This is followed by chapter 4, which elaborates on implementation of the designed simulation model. In chapter 5, the weather records are introduced and the model is evaluated. This chapter is followed by chapter 6 in which the obtained results are presented and a sensitivity analysis is performed. Finally, based on the previous chapters, the discussion and conclusion of the study are presented in chapter 7. Figure 1-1 portrays the research approach.

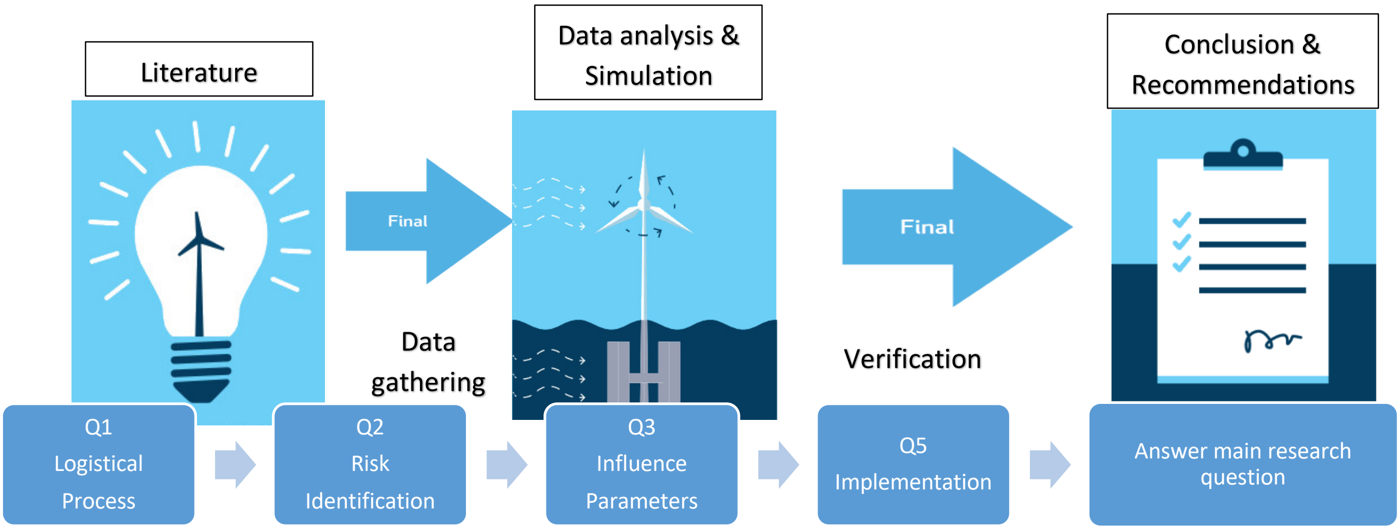


Figure 1-1 Proposed research approach (own illustration & (Lifes50+, n.d.))

2. Theoretical background

This chapter will offer a short introduction into the offshore wind market. Followed by an explanation of the logistical processes of the TLP concept and semi-submersible structures during transport and installation. Finally, this chapter will identify possible problems involved in the transport and installation of the TLP concept.

2.1 Current offshore wind market

The offshore wind industry developed tremendously over the past years as a solution for the growing energy demand and the changing climate for which renewable energy sources a necessary. The offshore wind market is expected to grow continuous.

Back in 1990, Sweden installed its first offshore wind turbine and since then the offshore wind industry has developed fast (Sun et al.,2012). Installation was solely by bottom fixed structures. In 1990, research into developments of offshore wind for deeper waters started (Athanasia & Genachtea, 2013). The first test TLP prototype floating wind turbine was installed in Italy by Blue H technologies in 2007. With installation of this floating wind prototype, Blue H demonstrated that floating wind structures are a feasible option. In 2009, the first floating wind turbine which was grid connected, Hywind, was installed in Norway by Statoil (Athanasia & Genachtea, 2013). The first successfully floating wind farm consisting of spar buoy floaters, was installed in the Hywind Scotland Pilot Park and is in operation since 2017 (Madsen et al., 2020).

Most of the offshore wind sector, 84%, is located in European waters (Lerch et al., 2018). In 2012, Europe installed a new capacity of 1.16 GW (Athanasia & Genachtea, 2013). In 2019, Europe again set a record for the net offshore wind power capacity by adding 3,623 MW. This capacity increased the total installed offshore wind capacity to 22,072 MW (Walsh, 2019). This is equal to 5,074 connected wind turbines spread across 12 European countries (Walsh, 2019). The European top suppliers are the UK, Germany, Denmark, Belgium and Portugal. These alone produced 1,764; 1,111; 374; 370 and 8 MW, respectively (Walsh, 2019). Figure 2-1 shows per country the installed capacity a year from 2009 up to 2019.

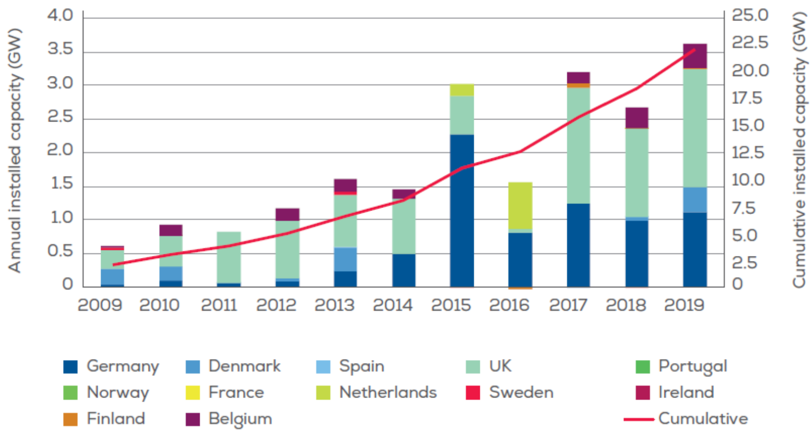


Figure 2-1 Installed annual capacity per European country (Walsh, 2019)

The UK, Germany, Denmark, Belgium and the Netherlands together have 99% of the installed capacity in Europe (Figure 2-2).

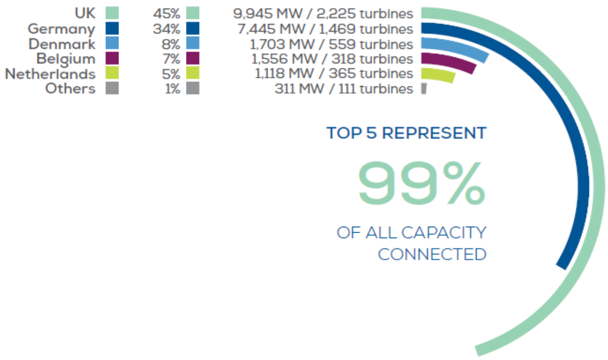


Figure 2-2 Cumulative installed capacity and number of installed turbines per country (Walsh, 2019)

Both offshore wind turbines and offshore wind farms are increasing in size as the demand for offshore wind energy keeps growing. Since 2014, the average wind turbine size has increased with 16% yearly with an average capacity of installed turbines of 7.8 MW in 2019. Wind farms have doubled in size, since 2010 they grew from 313 MW to 621 MW in 2019 (Walsh, 2019).

Figure 2-3 shows the number of the installed foundation types by the end of 2019. Nearly all installed structures are bottom fixed with 70% monopiles. By the end of 2019, only two semi-submersible substructures were installed in Europe (Walsh, 2019).

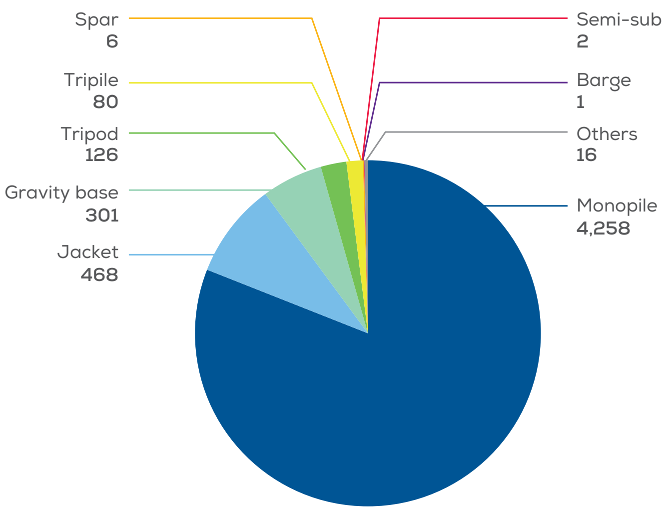


Figure 2-3 Number of foundations grid-connected by substructure type (Walsh, 2019)

Research demonstrates (Maienza et al., 2020), that in fact only prototypes of floating structures exist and only spar and semi-submersible systems have been used in projects. Tension Leg Platforms (TLP) are a new technology, still under development and have not yet been applied in projects. A prototype of a single TLP, Gicon, will be installed in the Baltic Sea (Maienza et al., 2020).
Even tough floating wind turbines are a fairly new application compared to the total offshore wind turbine capacity worldwide, Europe has already installed 45 MW of floating wind in 2019. This is 70% of the worldwide offshore floating wind fleet and this being the case, Europe is thereby world leading (Walsh, 2019). Nowadays, offshore wind energy becomes more economically attractive but more research is needed for it to be more profitable.

2.2 Classification of offshore wind turbine substructures

A wind turbine consists of a substructure and a top structure. A general explanation of top structure components is given in Appendix A. The substructure is designed to support the top structure under all weather conditions and can be classified in bottom fixed and floating structures. This is illustrated in Figure 2-4.

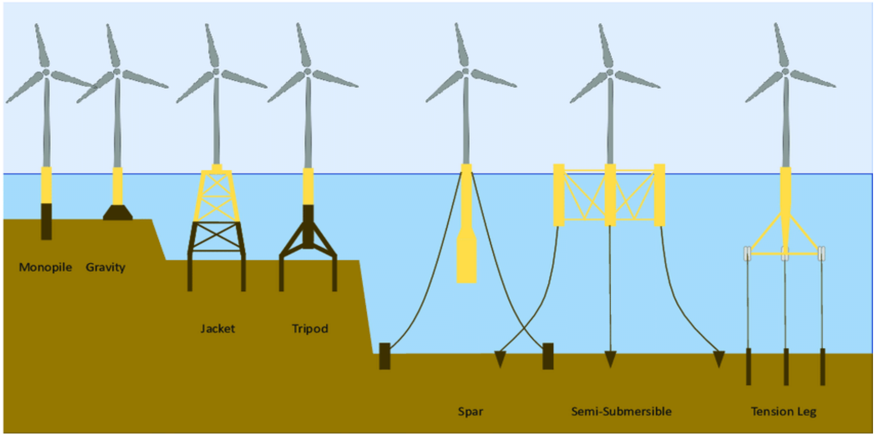


Figure 2-4 General overview of offshore wind turbine support structures including water depth (Dornhelm et al., 2019)

Offshore Wind Towers (OWT's) can be classified on several criteria which are all related to each other (Joy et al., 2019):

- The supporting method; bottom fixed or floating;
- The water depth;
- How static stability of a floating platform is obtained;
- Method by which the substructure is moored.

A bottom fixed substructure is constructed onto the sea bottom while floating substructures are mounted to the seabed by mooring lines. The installation of floating substructures is fairly new and is still under development. On the other hand, bottom fixed and semi-submersible substructures are nowadays widely used and therefore these installation procedures are well known and more often discussed in literature.

The supporting method (bottom fixed or floating) determines the water depth in which the wind turbines can be installed. The water depth also prescribes the method by which the substructure is moored. In contrast to bottom fixed structures, the loads acting on a floating structure are defined by environmental forces (i.e. wind speed and wave height) and by the dynamics of the system (Martini et al., 2018). However, floating structures have important advantages compared to fixed structures. They are applicable in a wider range of weather conditions (Liu et al., 2016). The construction and installation procedures of floating structures are more flexible. Also, floating structures are easier to decommission and remove. Finally, the construction costs for floating structures in deeper water are lower than the construction costs of fixed structures.

Floating substructures can be classified in three different types; Spar, semi-submersible and Tension Leg Platforms (Liu et al., 2016). A comparison for these floating structures is illustrated in Table 1.

Table 1 Generic comparisons of the three mainstream floating structures (Liu et al., 2016)

+ Relative advantage 0 Neutral -Relative disadvantage	TLP	Spar	Semi-submersible
Pitch stability	Mooring	Ballast	Buoyancy
Natural periods	+	0	–
Coupled motion	+	0	–
Wave sensitivity	0	+	–
Turbine weight	0	–	+
Moorings	+	–	–
Anchors	–	+	+
Construction and installation	–	–	+
Maintenance	+	0	–

Floating structures must have enough buoyancy to carry the load of the wind turbine. A spar and semi-submersible system must have enough rotational stability to prevent from capsizing. A spar system is a cylindrical floating structure and can be seen as a buoy. This type of structure will not be further discussed in this thesis. To withstand the forces of the ocean waves, floating structures need a proper motion response (Joy et al., 2019). In the design of a floating wind turbine, the natural periods of the platform and system structures should be taken into account in such a way, they do not interfere with the range of typical wave periods, as well as the typical turbine related harmonic forces. The remainder of this paragraph will in short discuss TLP, semi-submersible and bottom fixed substructures.

2.2.1 Tension Leg Platform

The TLP floater has six modular sections: three pontoons, a turbine column, the parts for connection of pontoons to column and the access platform. The turbine column is a slender central, vertical mono-column to which the three floaters are connected. Each pontoon has a length of about 50 meters. The length of a floater depends on the location where it will be deployed and the size of the turbine. To allow vessels to operate above the pontoons, the pontoons of the TLP lie fairly deep under the sea surface. Figure 2-5 shows a typical layout of a TLP platform.

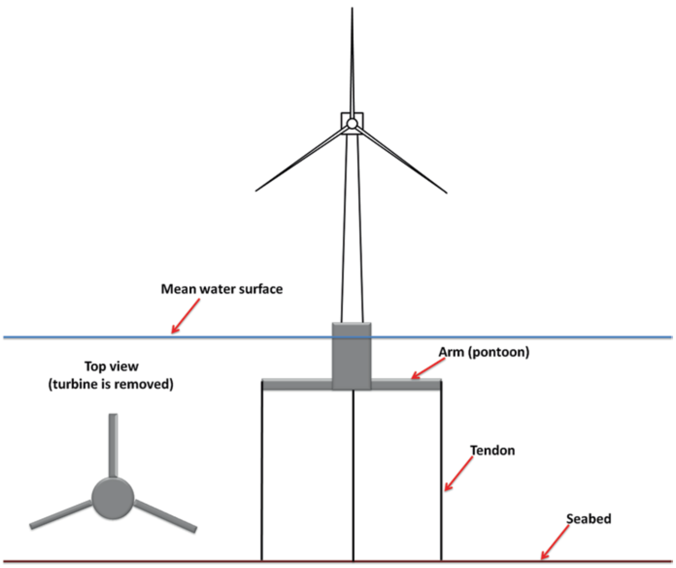


Figure 2-5 Layout of a TLP structure (Karimirad, 2014).

The forces due to the buoyancy and total self-weight of the structure counteract. For stabilization, the tension legs at the bottom of the column compensate these resulting forces (Karimirad, 2014). The pontoons are connected to anchor points located at the seabed by means of taut mooring lines. The anchor points are hammered or vibrated into the seabed. This type mooring system consists of taut, light-weight lines that slightly radiate outward (Journee & Massie, 2001) and they have a minimum footprint of approximately 100m x 100m. Due to the stretch of the mooring lines, the system obtains its restoring horizontal displacement forces (Journee & Massie, 2001). Furthermore, this type of mooring system prevents mooring lines from lying on the seabed since the lines run almost vertically. As the mooring lines are flexible, this allows pre-rigging of the lines to the TLP pontoons. This is a benefit in severe offshore environments when the mooring lines are connected to the anchor points that are fastened to the seabed. This allows for a wider installation window as the mooring system can be installed with "Remote Operate Vehicles" (ROV) which are able to operate close to the seabed in harsh sea conditions.

2.2.2 Semi-submersible structure

Semi-submersible structures (SSB) were originally developed for the oil and gas industry. Figure 2-6 shows a typical layout of a SSB structure (Liu et al., 2016).

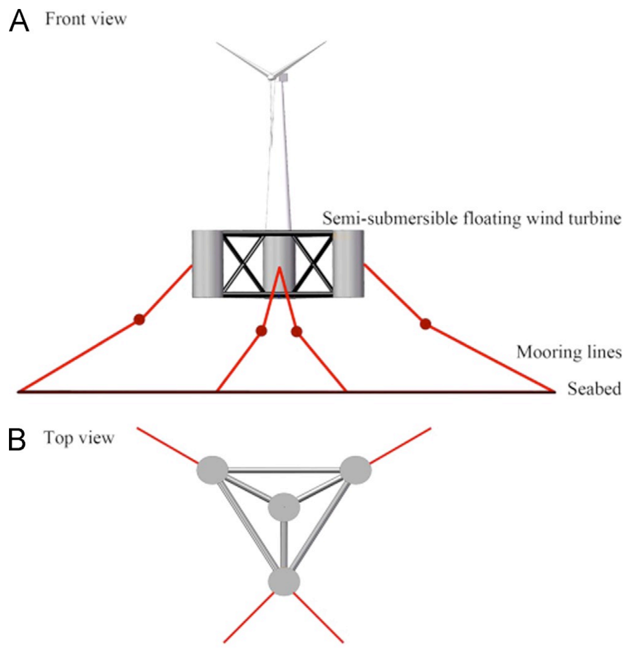


Figure 2-6 Layout semi-submersible structure (Liu et al., 2016)

These structures have a so called "wave cancellation effect", this can improve the "wave-induced dynamic responses of the offshore structure" (Liu et al., 2016, p. 436). SSB structures also have a convenient installation procedure. This includes commissioning of the structure near shore (installation of the wind turbine on the substructure) after which the structure is floated to the installation location (Karimirad, 2014). This reduces activities needed for the installation process on site. Also, a heavy offshore lift is not necessary thereby creating a more convenient process.

SSB structures exist of 3 or 4 columns that are kept in place by a catenary mooring system (catenary mooring lines) that is attached to anchor points at the seabed. A catenary mooring system is the most common and oldest type of mooring system currently in use. The mooring lines are stretched out over the sea bottom with a large footprint. On the other hand, for slowly varying motions, the mooring lines also create some freedom (Karimirad, 2014). The way in which the columns are connected with each other varies, depending on the used concept, but are mostly connected via braces. The arrangement and surface area of the columns creates the stability of the structure (Karimirad, 2014). Figure 2-7 shows the tow of a fully equipped SSB wind turbine.

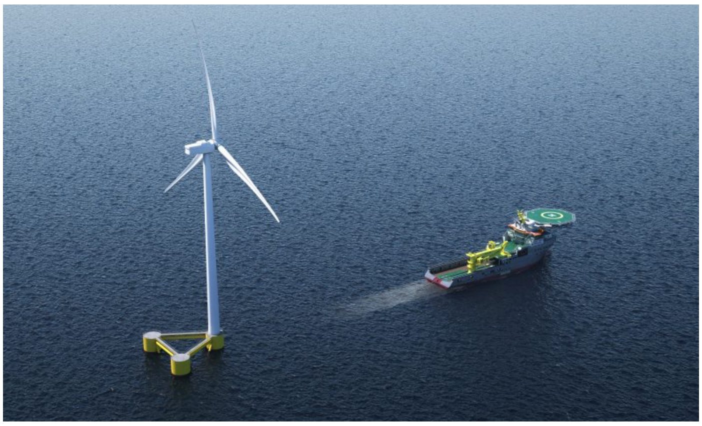


Figure 2-7 Tow of a semi-submersible structure (Energyfacts.eu, 2020)

2.2.3 Bottom fixed structures

Currently, bottom fixed structures are the most used structures to support offshore wind turbines. Although not the focus of this thesis, this section will in short discuss this kind of structure.
Installation of a bottom fixed structure requires a different installation process than installation of a floating structure. The kind of installation vessel used, depends on what kind of fixed substructure will be installed. For example, installation of a single fixed monopile structure requires a jack-up vessel (Figure 2-8) or a floating crane vessel. The for this thesis relevant transport and installation vessels are in short discussed in Appendix B.

First, a jack-up vessel will be loaded with foundation piles at the quayside in port. A jack-up installation vessel consists of four legs that are lowered to the seabed and thereby lift the vessel above sea level. As soon as the jack-up vessel is lifted, the foundation is installed. A jack-up vessel can be employed in water depths up to approx. 60 meters due to length limitations of the legs.

Figure 2-8 Jack-up installation vessel

When a floating vessel is used for installation of the foundation, it is kept in place by mooring lines or thrusters of its dynamic positioning system throughout the installation. Once the substructure has been installed, the Wind Turbine Generator (WTG) is installed on the foundation also using a jack-up vessel or a crane installation vessel. For a complete wind farm, more WTG's will be installed and the described installation sequence is repeated. A WTG can only be installed after the monopile, including transition piece, has been installed. In other words; the installation of a WTG will start once the installation of a foundation is completed.

Installation of bottom fixed structures is therefore a complex process restricted to water depths. An advantage of floating structures is that they can be installed up to 300 m water depth (Liu et al., 2016). Because the TLP floater has more technical advantages than semi-submersible structures, the TLP seems to be the most promising solution.

2.3 Current logistic process challenges

Transport and installation of an offshore wind farm is a complex process (Vis & Ursavas, 2016). It involves many uncertainties due to environmental conditions, the increasing size of the wind turbines and longer offshore travel distances. The planning involved for installation of an offshore wind farm is complex due to weather restrictions and weather windows that are required for certain offshore operations. For project efficiency, it is essential the right logistic approach is combined with the conditions specific at the project location (Vis & Ursavas, 2016). Barlow et al., (2015) state that by innovation the area of logistics and installation can achieve substantial cost reductions. These innovations aim at larger turbines, new foundations and array layout optimization. This section summarizes the most important challenges offshore wind farm logistics are currently facing.

2.3.1 Challenge 1: substructures

As already stated, OWF's need to move further away from shore into deeper waters. Consequently, longer travel times are needed and thereby increasing costs. The substructure in combination with water depth and offshore distance, mainly define the installation period of the wind turbine and therefore the logistics involved. Also, the port of origin is a deciding factor for the travel duration. Logistic challenges arise as new methods have to be developed which are suitable for installation in deeper waters.

2.3.2 Challenge 2: Weather

The installation phase of an offshore wind turbine is considered the main bottleneck of the logistic process, because this phase is most dependent on weather conditions. A disturbance may interfere with the transport phase and consequently disturb the other phases (Vis & Ursavas, 2016). Because installation of wind farms further offshore is accompanied with increasing transportation times, greater changes in weather conditions may be expected. Consequently, both transport and installation of offshore wind turbines face challenges.

One reason to install wind turbines further offshore is that wind energy can be more utilized. As a consequence, project sites are chosen with higher wind speeds. A high wind speed is a positive contribution to energy generation, but also brings challenges to deal with as ocean waves increase. Higher wind speeds especially limit offshore lifting operations as a high wind speed may exceed the prescribed limits for crane lifting operations since a lifting operation cannot be paused in the middle of the operation. As wind turbine dimensions are increasing, even more challenges arise. Due to the growing dimensions, larger equipment is necessary which limits the available weather windows for offshore lifting operations.

Weather is uncertain and therefore hard to predict. It therefore creates many uncertainties. The environmental conditions can also influence the route for transport and thereby the duration of transport. The installation time and finally the overall project duration all depend on the unpredictable weather. To deal with uncertainties related to weather, operational windows should be identified per activity based on the local weather. Besides, weather forecasts should be obtained prior to transport and installation of a WTG.

2.3.3 Challenge 3: Transport and installation

If a logistic process is well coordinated, the process through various phases (production, storage and transport) can be tracked. An efficient flow of the logistic process can be achieved by being aware where each of the assets is located at what time in the process (Bass, n.d.). In Figure 2-9 the sequence of the supply chain and possible disturbances for the installation of OWF's are illustrated.

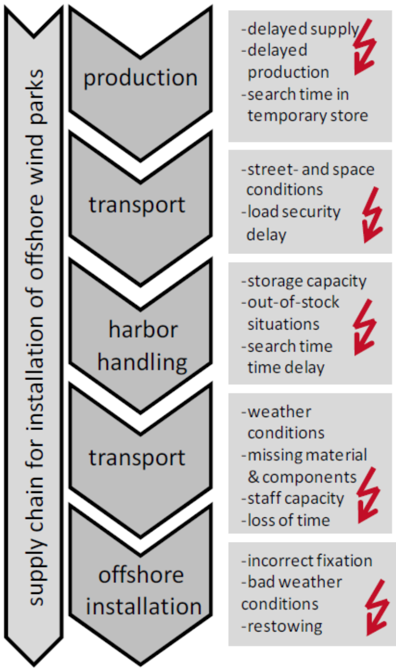


Figure 2-9 Supply chain and disturbances for installation of OWFs (Scholz-Reiter et al., 2010)

If components cannot be transported, challenges for transport and installation arise and possibly lead to capacity problems in port. Eventually, this will cause delays in the logistic process (Scholz-Reiter et al., 2010). In order to react fast to a disturbance, the logistic process for offshore components of OWF's should be flexible (Scholz-Reiter et al., 2010). In case of a disturbance during transport, it is possible that the installation vessel has to return to port, which subsequently causes increasing project times and higher transportation or manufacturing costs (Scholz-Reiter et al., 2010).

SSB structures are transported fully equipped to the offshore site. These structures seem to be more sensitive to weather conditions which affect transport logistics. In the future, installation sites will be located further offshore. Consequently, the time required to transport a system to the offshore site will increase. For the TLP floater concept developed by Bluewater, the wind turbine is not pre-installed on the floater which allows for transport and installation of the wind turbine in a wider weather window. Keeping in mind that harsher environmental conditions apply further offshore.

2.3.4 Conclusion

To overcome the challenges of the logistic process, it is important to understand the impact of the decisions made for transport and installation. This may result in more efficient transport and installation processes for future offshore wind farm projects and may minimize the duration of the project and project cost. Weather is uncertain so you have to cope with these uncertainties and adjust, mainly by improvements in wind turbine design, such as the TLP concept, and optimization of the use of a weather window. Once the challenges are mapped, it is more certain what risks can be mitigated for future offshore wind projects.

2.4 Logistic process TLP floater concept and semi-submersible structure

A general logistic process for installation of an OWF is shown in Figure 2-10. The duration of all activities together, result in the total project duration. As SSB structures have been installed more often, the logistical process involved is better known, compared to TLP floaters that have not been installed that often. To get a better understanding of the logistic process, the activities required for transport and installation of the TLP floater and SSB structure will be described. First, the logistic process of a TLP floater concept is illustrated.

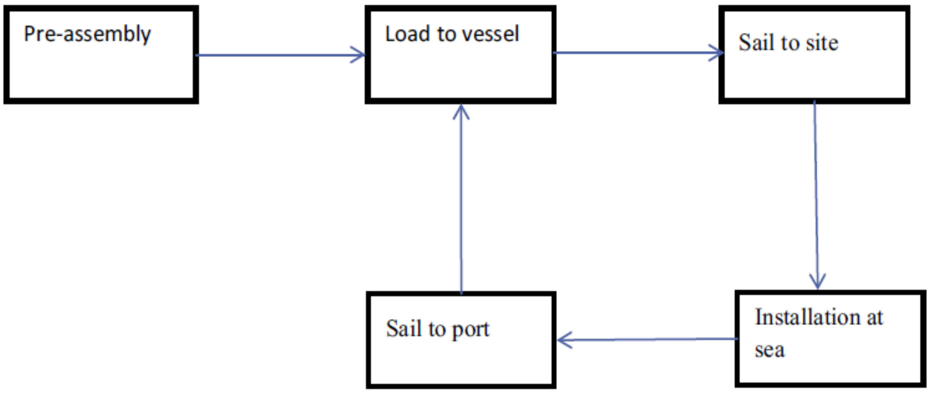


Figure 2-10 General installation process of OWFs (Vis & Ursavas, 2016)

2.4.1 Logistics TLP floater concept

Preparation construction- and offshore sites

The installation process of an offshore wind turbine starts in port with preparation of the construction site. Most of the substructure and components of the wind turbine will be pre-assembled in port. It is necessary that the construction site has enough space available to store the large, fragile and heavy wind turbine components (Vis & Ursavas, 2016). One of the reasons to store the wind turbine components in port is related to the fact that the right equipment, like heavy lifting equipment, is readily available. If the components are available in port when needed, the risk of delay is minimized (Vis & Ursavas, 2016).
Meanwhile, the offshore site is prepared for a smooth installation process. First, the offshore installation site is marked with buoys (Thomsen, 2014a). For a proper installation the seabed is surveyed. Once surveyed, the anchor points are hammered or vibrated into the seabed and the mooring system is pre-installed. When both construction- and offshore sites are prepared and ready for use, the next phase may start.

Pre-assembly TLP and WTG components

Once the onshore and offshore construction sites are prepared, the components can be stored at the quays of the fabrication yards and the offshore installation process may start. To reduce offshore working hours, the components of the TLP floater are assembled at the assembly yard. The modular sections are assembled at the quayside by the use of land-based lifting. The access platform will be transported from the TLP construction yard to the assembly yard and is integrated to the WTG tower. The access platform contains the female part of the slip joint connection and the TLP floater column holds the male part of the slip joint connection. The slip joint technique will be explained later on.

The components of the WTG (rotors, tower, and nacelle) are fabricated each at their own manufacturing yard. When the parts are pre-assembled, they need a large space due to their dimensions (Thomsen, 2014b). The assembled components of the WTG are transported from their production yard to the offshore installation site by means of a transportation vessel. Transportation vessels are able to transport multiple towers, nacelles or blades at once but this depends on the project.

Transport TLP floater

This thesis only describes the transport between assembly yard and offshore installation site. The total transportation costs depends on vessel specific parameters such as day rate, fuel consumption, rental time and usage of the vessel as well as mobilization and demobilization cost (Lerch et al., 2018). Transportation costs are not included in this thesis. For the tow of the floater to the offshore site, 2 or 3 tug boats, depending on project characteristics, are required. Tug boats can transport only one floater at the time which results in several trips per vessel.

After pre-assembly at the yard, and if the expected weather conditions do not exceed the limits for unloading and transportation (Vis & Ursavas, 2016), the tug boat(s) will sail to the installation site with the TLP floater on a barge. The floater is light weight and stable due to its relatively large water plane area and is therefore able to float at the sea surface (Han et al., 2017). This allows a tow out of the floater to the offshore location without the necessity of any buoyancy elements. Figure 2-11 illustrates the float-out of a TLP floater on a barge.

Figure 2-11 Float-out TLP floater (van der Nat, 2020)

Transport WTG components

The blades, nacelles and towers are each assembled at the quayside of their own production yard and loaded onto a Heavy Transportation Vessel (HTV) and shipped to the offshore site. That is, the components are transported as separate parts. The number of components which can be transported at once depends on the storage capacity of the HTV. This transportation concept is defined by Ait-Alla et al., (2017, p. 608) as the "offshore feeder-ship concept" and is displayed in Figure 2-12.

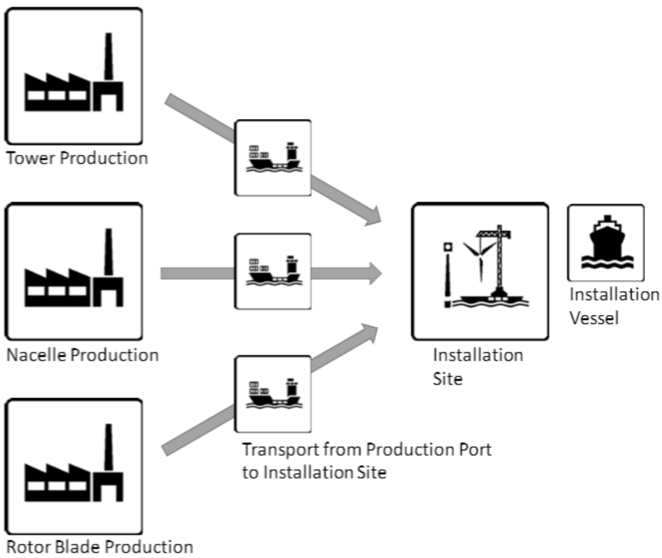


Figure 2-12 Transportation concept (Ait-Alla et al., 2017)

This method ensures an efficient use of the expensive installation vessel offshore while the less expensive HTV's are only used to supply the installation vessel. It is expected this will save costs for services and besides, limits crane use in base port and saves storage spaces (Ait-Alla et al., 2017). Also, by separation of the supply chains for fabrication, the supply chain of the floater is not dependent on the limited capacities of the assembly port.

Installation TLP floater

After arrival, the TLP is load-out from the barge as illustrated in Figure 2-13. The heavy WTG is not yet installed on the TLP floater creating a more stable structure. Therefore, it can be installed in harsher weather conditions. This also applies for the available operational weather window for the TLP. When an installation vessel is available, the TLP is ballasted by pumping water into the pontoons. Once ballasted and at its installation draught, the mooring lines are connected to the TLP. The mooring lines are hooked to the anchor points at the sea bottom by a quick connector system. The anchor points and mooring lines are pre-installed with the use of a torque tool. The helical anchor piles (including anchor points) are screwed into the seabed with the torque tool. After connection to the mooring lines, the TLP is set and de-ballasted, meanwhile tensioning the mooring lines. Now, the WTG can be installed on the TLP floater. This method creates a two phased installation approach. One phase for the TLP floater and one phase for the WTG. The supply chains are separated creating two independent supply chains and thereby reduces risks for the project schedule.

Figure 2-13 Load-out of TLP from barge (van der Nat, 2020)

Installation WTG

A floating vessel, other than the HTV, will be used for assembly and installation of a WTG. For example, a semi-submersible Heavy Lift Vessel (HLV) will be used for installation of a WTG on a pre-installed TLP. This is done because an installation vessel is more expensive and should therefore only be used for less expensive operations. For example, assembly of the components and offshore installation of the WTG. From the moment an HTV, containing either blades, nacelles or towers, arrived offshore, the components can be unloaded to the installation vessel as soon as it is available. Once the components have been loaded to the HLV, a WTG will be assembled on the ship. If a HTV is emptied, it will return to port to reload. After assembly of a WTG, the WTG is positioned on the pre-installed TLP floater. A WTG is installed via a single lift using the slip joint technique as explained later on. For the lift, the wind speed should be below the operational limits, which are discussed later on, and a HLV with limited motions is required. Furthermore, the installation vessel can stay offshore to install turbines while the transportation ships sail back and forth to the offshore site to deliver WTG components. Moreover, the activities can be carried out parallel to each other which is more efficient and cost reducing.

For installation of the WTG, an innovative slip joint technique is used resulting in a fast, offshore installation. This installation approach extremely reduces the number of required offshore lifts as now only one single lift for installation of the WTG is needed. Hence, the installation time of a single wind turbine is much shorter and the installation can be performed within a shorter weather window required for the offshore heavy lift.

Furthermore, the slip joint technique ensures a fast and safe installation method between the WTG and the floater column. The wind turbine column will be installed from a floating vessel on the already moored TLP floater which is equipped with a slip joint transition piece. The TLP column is equipped with the "male" part of the slip joint while the turbine contains the "female" part of the slip joint. Via a single lift, the WTG will be lowered on its counterpart, the TLP floater. In Figure 2-14, a visualization of the slip joint technique is shown.

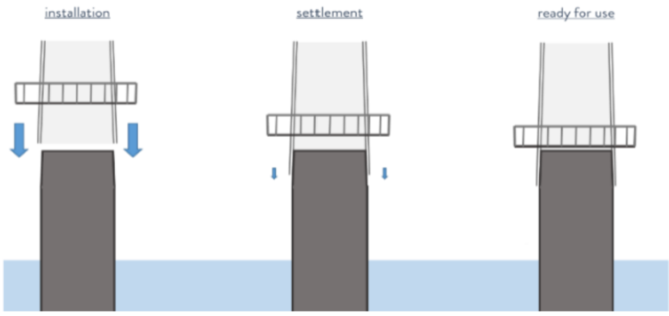


Figure 2-14 Example slip joint technique (van der Nat, 2020)

The weather conditions in which the WTG can be installed on top of the TLP floater, can be linked to the type of installation vessel that will perform the lift. The installation in two steps ensures that the supply chains of the system are decoupled. This will mitigate the risks involved within the project schedule. Figure 2-15 illustrates offshore installation of a WTG on a TLP floater by the use of the slip joint technique.

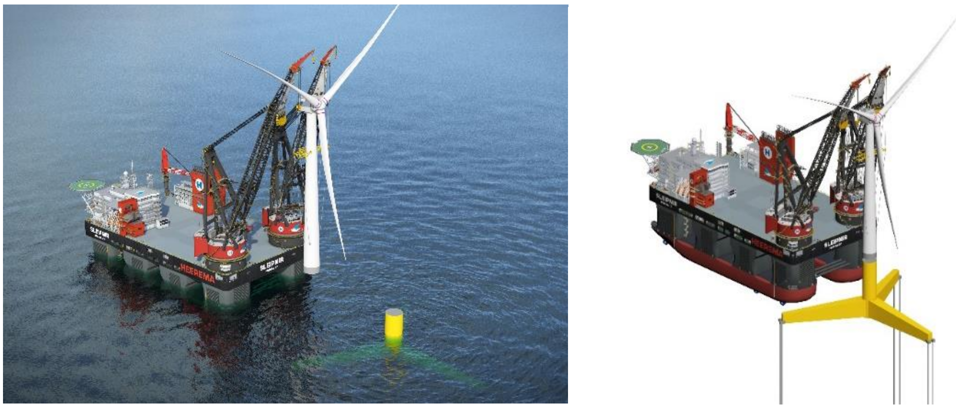


Figure 2-15 Offshore installation WTG on TLP floater (van der Nat, 2020)

As demonstrated, the TLP concept is installed in two phases creating two independent supply chains, a supply chain for the floater and a supply chain for the WTG. The TLP structure and WTG are merged at the offshore installation site which creates the opportunity these two independent supply chains can be executed separately. This is expected to be an advantage in comparison to installation of semi-submersible structures. Figure 2-16 shows an installed TLP including all components.

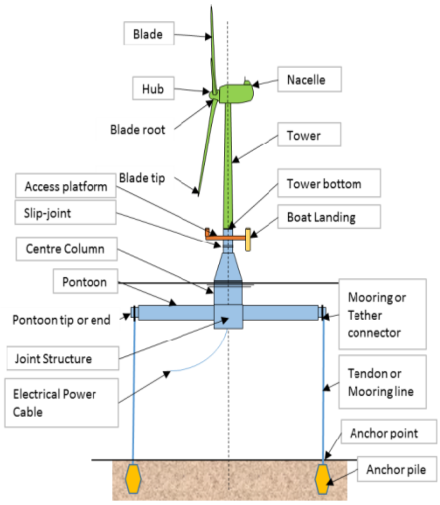


Figure 2-16 Main components of the TLP concept (van der Nat,2020)

2.4.2 Logistics semi-submersible structure

This section explains the logistic process for transport and installation of a float-out based SSB structure. The transport and installation process of a SSB structure has a different approach compared to the one of a TLP floater. Hence, something both logistic processes have in common is their dependency on weather conditions.

At first, all components (tower, nacelle, blades and substructure) are manufactured each at its own fabrication yard. Hereafter the components are transported from their production yard to a marshalling yard which is used as storage space and construction yard. All components are pre-assembled at the quayside of the marshalling yard. At first, a semi-submersible substructure is assembled nearshore by means of floating barges, in a dry dock or at quayside. Thereafter, the substructure is positioned along the quayside. Once all components have been assembled, the WTG will be constructed and mounted on the SSB structure. Hereafter, the fully assembled system is towed to the offshore installation site by means of tug boats. The heavy WTG is placed on top of the substructure at the quayside. In this way, a heavy installation vessel is not necessary offshore as the fully assembled system will be towed to the offshore installation location by tug boats. This is a main difference between the TLP floater and SSB structure. As floating wind turbines mostly targets deeper offshore waters, the float out tends to be further offshore acquiring longer towing times, this may result in significant towing times. In addition, further away from shore one has to deal with severe weather conditions. This results in more time needed to reach the offshore site and besides, a longer weather window is required. Arrived at the installation site, the SSB structure will be positioned, connected to the pre-installed catenary mooring lines, de-submerged and is ready for use.
Another main difference of this installation process compared to the one of a TLP floater is that this installation process is performed by tug boats only, no other vessels than tug boats are required in comparison with the transport and installation of a TLP structure which also requires a transport and installation vessel. SSB structures have lower transportation and installation costs as they are already assembled at the port and if necessary, the floating structure can be towed back to shore by tug boats for maintenance and repair (Lerch et al., 2018).

However, a possible disadvantage to tow a pre-assembled system to the offshore installation site presents a logistical challenge as the fully assembled floating system is vulnerable to motions and accelerations at nacelle level. Therefore, it is expected the system is highly sensitive to weather conditions and hence creates many uncertainties. This is due to the limits of acceleration on the blades and bearing in the nacelle. On the other hand, pre-installation of the WTG on the SSB structure already at the marshalling yard, prevents a heavy offshore lift and a smaller weather window satisfies. An example of T&I of the WindFloat SSB is illustrated in Figure 2-17.

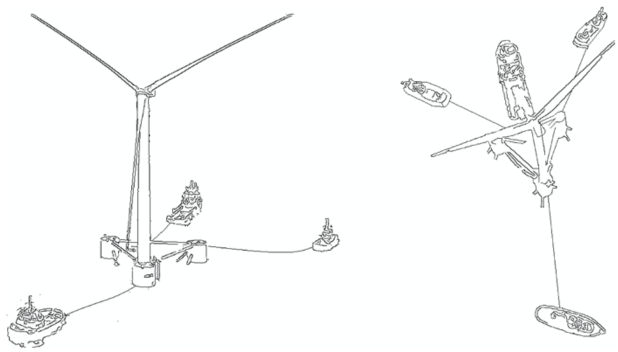


Figure 2-17 Transport and installation WindFloat SSB structure (Jiang, 2021)

2.5 State of the art on Offshore Wind Turbine processes

2.5.1 Literature on weather conditions

This section elaborates on previous research for different ways to determine how weather conditions for offshore operations related to offshore wind turbines can be modelled. Several studies have been dedicated to methods to determine the weather window for offshore wind turbines based on offshore weather conditions. These studies mainly cover the O&M phase of offshore wind turbines. Also, the mentioned studies are often related to bottom fixed structures as the floating offshore wind market is fairly new.

Weather windows

The total duration of an offshore operation mainly depends on the offshore weather conditions. For a smooth installation process without possible delay, appropriate weather conditions should apply. Also, the possible downtime due to bad weather conditions should be taken into account (Thomsen, Chapter Five - Project Preparation, 2014). The time frame in which the weather limits for an offshore operation are not exceeded is the so-called weather window and it is crucial to determine such a weather window. When a weather window is determined, the duration of the related activity should be known as the calculated weather window should be longer than the duration of the activity to take uncertainty into account. If not a sufficient weather window is determined, or weather conditions change unexpected, it may be necessary to abort the offshore operation, increasing the project costs and duration (Walker et al., 2013). Literature on weather window estimation is limited, although, several studies focused on different approaches for weather window estimation while the majority of studies focuses on estimation of weather windows for bottom fixed wind turbines. An example of a study which focused on weather window determination is performed by Walker et al., (2013). While the authors perform a case study on a wave energy device, they use both recorded and modelled weather data of wave height to assess the variability of available weather windows. The by the paper applied method, can be used for any marine operation as concluded by the authors (Walker et al., 2013).

Time series

It is difficult to predict when a suitable weather window occurs as it depends on the continuously changing offshore weather conditions (Gintautas & Sørensen, 2017). Weather time series can be used for simulation to determine the appropriate weather window of for weather forecasting. A time series is a sequence of sets of data observed consecutive in time and exist of many sets of these data (Box et al., 2015). For weather time series these are most of the time related to environmental conditions such as, wind speed, significant wave height, air temperature, etc. The data sets are measurements of monitoring the variables over time. Generally, weather windows are mainly determined by simple metocean parameters, such as significant wave height and wind speed. Significant wave height and wind speed are normally used as input variables since they are often provided by weather forecasts. Historical weather data can be used to obtain the distinct pattern of each variable over a certain time period.

Alpha-factor method

Some ways exist to capture the stochasticity of weather. Standard method for weather window estimation uses simple metocean parameters, such as significant wave height and wind speed (Gintautas & Sørensen, 2017). Often, the standard methodology for weather window estimation does not take into account the related uncertainty for weather forecasting. Weather window predictions are influenced by uncertainties related to weather forecasts as it is not possible to predict the development of the weather with 100% certainty. Therefore, researchers have introduced the alpha-factor method which is a measure to take into account the uncertainties related to weather window forecasting. This methodology uses a certain alpha-factor whereby the weather restrictions of the operation are scaled down. In this way, the weather restrictions, the limits, related to the operation are made more conservative.

The alpha factor depends on the significant wave height, wind speed and operational duration. Generally, it can be defined as the ratio between the "maximum metocean condition with a probability of exceedance of 10^{-4} during a certain period" and the "maximum metocean condition with a probability of exceedance of 10^{-4} during a certain period, taking into account the bias and variance of the weather forecast" (Gintautas & Sørensen, 2016). To define the operational weather restrictions, an equation is used in which the alpha-factor is utilized through multiplication of the alpha-factor with the operational environmental limiting criteria. This is the limit criteria of, for example, the wave height or wind speed. While the alpha-factor is < 1, the metocean operation condition limits are scaled down. Most of the time the alpha factor is tabulated but can also be determined for the specific working sites. This method has been used in previous literature (Gintautas et al., 2016; Gintautas & Sørensen, 2017). In the research, the authors (Gintautas & Sørensen, 2017) successfully use the alpha-factor to conduct a benchmark of the state of the art alpha-factor method. The goal of the paper is to present a method in which weather windows for weather sensitive offshore operations can be determined. The proposed methodology uses a novel methodology as basis in which by statistical analysis extreme equipment response distributions are obtained through numerical simulation results. By evaluating the exceedance of the maximum allowable magnitudes of the probability of relevant equipment responses, the expected probabilities of operation failure were established with the use of the vessel and equipment responses. The obtained probabilities were combined to represent total probability of operation failure. Finally, to establish suitable weather windows, the total probability and maximum allowable probability of mission failure can be compared.

While the same authors (Gintautas et al., 2016) also use the alpha factor method. The study compares the alpha-factor method to a new, in the paper, proposed approach. The authors use the method for the same purpose, to include uncertainty related to weather window prediction.

Copulas

Yet, another method to include the stochasticity of weather conditions is based on Copula modelling. The word 'Copula' was introduced for the first time by Sklar back in 1959 and is a Latin noun which stands for "a link, tie, bond" (Nelsen, 2006, p. 2). It was used in a mathematical or statistical sense to describe one-dimensional distribution functions that join to form multivariate distribution functions (Nelsen, 2006).

Copulas itself are functions with which the coupling of multivariate distribution functions to their one-dimensional marginal distribution functions is described. As an alternative, copulas are multivariate distribution functions whose one-dimensional margins are uniform on the interval of (0,1) (Nelsen, 2006, p. 1). Can be used to study the dependence between multiple random variables. This is achieved by "decoupling the marginal properties of the random variables and the dependence structures" (de Nie et al., 2019, p. 601). Copulas take into account the autocorrelation and dependence of the limiting environmental characteristics by which the corresponding time series can be acquired. To obtain this information, it is necessary to have large number of environmental time series available. These can be used to substantiate the uncertainties related to metocean parameters that limit the operations. Data sets should be obtained in order to calculate the probability distributions. Evidence in the use of Copulas to construct realistic time series can be found in papers by Leontaris et al., (2016) and Leontaris et al., (2017). The authors use Copulas to obtain realistic time series for both significant wave height and wind speed. While first performing three statistical tests to figure which Copula model can be used best for the data sets (Leontaris et al., 2017). A study by Yang & Zhang (2013) is another example of a study in which Copula method is used to determine, by comparison of various copula functions, the joint probability distributions for significant wave height and wind speed.

2.5.2 Literature on operations and logistics

Different ways exist to study systems, processes and their behavior. One way to study systems and processes is by creating a model. A computer program solves the equations for the parameters of interest. The variables can be changed to see how the model reacts. As the complexity of the process increases, also the complexity of the model increases. With the use of simulation, these complex models can be studied. Simulation is a widely used methodological approach in operational research problems (Barlow et al., 2015) and creates the opportunity to simulate a model and besides, the performance of the model can be evaluated. The intention of this thesis is to compare and evaluate the logistic process of two transport and installation methods for OWF's. This section provides a concise overview of aforementioned methods for simulation of (floating) offshore wind farms operations, for example, an analytical approach or simulation-based can be distinguished. This section is dedicated to various tools to model operations and logistics.

Analytical approach

A mathematical model is based on physical phenomena described by a set of equations. Most of these models are very detailed and complex mathematical descriptions-based OWT models. Up to now, the available models are primarily cost, planning and optimisation based (Asgarpour, 2016). Next to this, much research has been done in the field of logistics for Operation and Maintenance (O&M) for OWT's. Research focused on the options for the logistics of transportation and installation of floating offshore wind turbines has not been given very much attention to date. To realistically simulate the environmental conditions and installation process, thereby including uncertainty, it is necessary to use an appropriate tool. Several analytical methods for simulation of installation processes have been found in literature. An example of the analytical approach are Markov chains.

A Markov chain uses a transition matrix to define how transitions take place. The transition matrix describes the transition probabilities between states. The transitions are defined by a probability for transition of any state to any other state of a system. The future states probabilities can be obtained by multiplication of the transition matrices. An example of a study which uses Markov Chain method is conducted by Nfaoui et al., (2004). The authors examine the limiting behavior of the Markov Chains. To underpin the limiting behavior the authors, compare to a histogram of observed wind speed. It was demonstrated that a 12 x 12 transition probability matrix was needed to be able to construct legitimate synthetic time series.

Simulation-based methods

Next to an analytical approach to model operations, another approach which can be implemented is a simulation-based method. Several kinds of simulation can be distinguished; static vs. dynamic, continuous vs. discrete and deterministic vs. stochastic. With simulation one gains insight in the behavior of a system.

Computer simulation tools create the opportunity to build models. The model represents the involved resources for carrying out the work and the working environment of the project.
Vis and Ursavas (2016) note that simulation is useful if in the project, which will be modelled, the operations are sequential and repetitive. This especially refers to operations which are dependent on external factors, such as weather conditions. The complexity of the problem can be simplified by using a simulation tool. Additionally, the problem described in this thesis involves unique and complex aspects enhanced by stochastic environmental conditions. To clarify this, a simulation approach is used in this thesis. By simulation, the system's transparency is increased as a livelier representation of the system can be created (Vis & Ursavas, 2016). Moreover, the simulation tool thereby creates a visualization of a real-world problem. As the researched logistic process is a sequence of activities which are dependent on multiple external factors, mainly weather conditions, it is chosen to simulate the real-world problem for transport and installation of a TLP floater to obtain a more realistic view of the problem and thereby answer the main research question of this thesis.

A simulation-based method that is widely used is Monte Carlo Simulation (MCS). Monte Carlo Simulation is frequently used to find an adequate configuration of the system. It is the most used approach for solving deterministic or stochastic mathematical problems (Marks, 2014). Running many scenarios containing random variables, will calculate a realistic future output of the simulation. Completion of the simulation gives a sample of the multiple results. Within Monte Carlo, long series of environmental data are used for simulation by taking into account critical conditions within an appropriate time interval (Tyapin, Hovland, & Jorde, 2011). After running a sufficient quantity of simulations, a probability distribution of the entire project duration is determined. Tyapin et al., (2011) use MCS in their research for installation of bottom fixed offshore wind turbines. They compare the MCS with the previous discussed Markov Chain method to determine the weather downtime and duration of offshore operations. Both methods estimate the duration of marine operations and weather downtime.

In comparison to MCS, in which the probability distribution for the duration of offshore operations is obtained through simulation, the Markov chain method uses an analytical approach to establish the probability distribution. An advantage of the Markov chain compared to Monte Carlo simulation is that the factors that influence the execution duration of an activity the most, are better understandable through Markov chain (Anastasiou & Tsekos, 1996). Another difference compared to the Monte Carlo simulation is that this methodology is not applied in the time domain (the probability distribution of the duration for Markov Chain is not obtained through simulation but determined analytically) and since Monte Carlo simulations are applied in the time domain, these take a longer computational time. As mentioned earlier, the behavior of a Markov chain is described by a transition matrix defined by its transition probabilities. This is a possible disadvantage given the difficulties to estimate such probabilities.

Discrete Event Simulation (DES) is yet another way to model offshore operations. With DES, a complex dynamic systems behavior is simulated by only considering discrete points in time (Muhabie et al., 2015). At discrete points in time, individual units move through a series of activities and queues. With the occurrence of an event, a change in the system state is indicated. For sequential events, the simulation goes from one event to the following event in time as it assumed no changes in the system can occur. While continuous simulation can only be analyzed analytically.

Several authors used DES in their research either with or without combining it with other simulation approaches. An example of research in which DES is included is conducted by Muhabie et al., (2015). The authors perform an analysis in which both historical weather data and the probabilistic approach are used through DES. The developed tool aims to give insight, before construction starts, in the planning of the logistics activities. Yet, the research concludes that future OWF projects can benefit of simulation using the probabilistic approach in improving the planning of the project besides, the logistics chains can be better controlled (Muhabie et al., 2015). Another research by the same author (Muhabie et al., 2018), also use DES to evaluate which installation strategy is most favorable using deterministic and probabilistic metocean weather data.

Finally, another method which is simulation-based is multi-agent modelling. Multi-agent is described as follows; in the system, each part ('agent') can be individually modeled through this approach. Next, the interactions with the other agents and external environment (for example, weather) are used for decision making. Another modelling approach which can be considered the same as a multi-agent system, is agent-based modelling. Hence, agent-based modelling also has the capacity to make decisions based on the interaction with other agents and the external conditions. The paper by Sahnoun et al., (2019), explains that Multi-Agent System (MAS) modelling is widely used for many application domains. The paper itself uses multi-agent modelling in which different maintenance strategies for OWF's are analyzed and selected.

As shown by Ait-Alla et al., (2017), multi-agent and DES can be combined to investigate the impact of two different installation concepts on the logistic costs. The simulation is performed by taking into account 16 different scenarios. Furthermore, the model considers both the impact of weather restrictions and the wind farm size. Although, for some of the simulated scenarios the authors did not include weather restrictions. The weather forecast is considered by historical data of 1-hour time series for wind speed and wave height for 50 years. Although the aim of the research was to investigate the impact on the logistic costs, the findings also pointed out the impact on the installation duration. Finally, the authors conclude that the conventional installation concept (uses both an installation vessel and a base port) turns out to be the best concept strategy.

Barlow et al., (2018) introduce a model which combines optimization and DES to improve the planning for installation of OWF's. The research presents a robust optimization model which generates a robust schedule. The by model proposed project duration is greater than or equal to the real project duration, including a percentage of deviating tasks. This considered an advantage of such a robust schedule (Barlow et al., 2018). While, optimization is out of the scope of this thesis, this paper is discussed as it shows the use of a model in which both optimization and DES are combined.

To conclude, simulation-based models can also be used for optimization. For example, Mixed Integer Linear Programming (MILP). These models calculate the most optimal installation planning based on vessels loading sets and various weather conditions for OWF's. The weather data is implemented in the model as deterministic input and thereby aims to calculate the minimal installation duration and costs (Barlow, et al., 2018) based on up-to-date and seasonal weather forecasts (Scholz-Reiter et al., 2011). The model will gather statistically significant results. MILP is applied in a study by Scholz-Reiter et al., (2010). They calculated the most optimal installation schedule by using MILP with the introduction of a mathematical model for OWF's. While another study which uses MILP is conducted by Ait-Alla et al., (2013). The authors develop a mathematical model to optimize the installation planning problem for OWF. However, as optimization is also an important aspect for OWF installation, it is decided to mention to what extend simulation-based models have been used for this purpose, even though, optimization is out of the scope of this research.

The discussed literature in which different approaches for weather conditions and simulation of OWT's have been identified, are summarized in Table 2.

Table 2 Literature summary

Weather conditions/ Operations	Author(s)	Goal	Approach	Deterministic/ Stochastic	Static/ Dynamic	Continuous/ Discrete
Weather	(Walker et al., 2013)	Present a method with which the weather window availability for marine operations can be identified.	Present a method based on a Weibull model in which the cumulative distributions of the mean duration of persistence of exceedance are used.	Stochastic	Dynamic	Discrete
Weather	(Gintautas & Sørensen, 2017)	Present a method with which weather windows for weather sensitive offshore operations can be determined.	Comparison of presented method with one of the state of the art methods, the alpha-factor method.	Stochastic	Dynamic	Discrete
Weather	(Gintautas et al., 2016)	Propose an approach in which the effect of uncertainties for weather forecasting on weather windows predictions are assessed.	Use of physical limits for various offshore operations as basis for determination of weather windows	Stochastic	Dynamic	Discrete
Weather	(Leontaris et al., 2016)	Obtain realistic time series for both significant wave height and wind speed	Method using Copula modeling	Stochastic	Dynamic	Discrete
Weather	(Leontaris et al., 2017)	Study the impact on the installation duration caused by possible disturbances in the supply of components and, specified to cable installation	Development of stochastic simulation model	Stochastic	Dynamic	Discrete
Weather	(X. C. Yang & Zhang, 2013)	Determine the joint probability distributions for significant wave height and wind speed	Comparison of various copula functions and use of most optimal Copula method	Stochastic	Dynamic	Discrete
Operations	(Muhabie et al., 2015)	Give insight, before construction starts, in the planning of the logistics activities	Historical weather data and the probabilistic approach are used through DES	Stochastic	Dynamic	Discrete
Operations	(Muhabie et al., 2018)	Identify the most favorable installation strategies by taking into account the effect of different weather scenarios on the logistical process	DES to evaluate which installation strategy is most favorable using deterministic and probabilistic metocean weather data	Stochastic	Dynamic	Discrete
Operations	(Scholz-Reiter et al., 2010)	Develop a concept of a planning system for the installation scheduling of offshore wind farms	Mixed Integer Linear Programming (MILP) with the introduction of a mathematical/analytical model for OWF's	Deterministic	Dynamic	Continuous
Operations	(Ait-Alla et al., 2013)	Develop a mathematical model to optimize the installation planning problem for OWF	Develop a mathematical model, Mixed Integer Linear Programming (MILP)	Deterministic	Dynamic	Discrete
Operations	(Ait-Alla et al., 2017)	Investigate the impact on the logistic costs and installation duration	Use of multi-agent and DES model	Stochastic	Dynamic	Discrete
Operations	(Barlow et al., 2018)	Integrate the modelling approaches to yield a mixed-method framework and decision	A combination of optimization and DES to develop a mixed-method framework	Deterministic	Dynamic	Discrete

		support tool that improves logistical decision-making at the planning stage of an OWF installation				
Operations	(Nfaoui et al., 2004)	Generate synthetic time series	Use of Markov Chain model	Stochastic	Dynamic	Discrete
Operations	(Sahnoun et al., 2019)	Analyse and select different maintenance strategies for OWF's.	Use of multi-agent modelling	Stochastic	Dynamic	Discrete
Operations	(Tyapin et al., 2011)	Determine the weather downtime and duration of offshore operations for bottom fixed wind turbines	Comparison of MCS and Markov Chain method.	Stochastic	Dynamic	Discrete

2.5.3 Conclusion

The aim of the presented literature is to give insight into different ways how weather conditions for offshore operations of offshore wind turbines, can be modelled. Moreover, this literature study also aims to give insight in the various existing tools to model operations and logistics for offshore wind farms.
The studied methods are all based on determination of weather conditions and methods for operations and logistics. The chosen methodology depends on the desired result of the research and besides, on the focus of the research. With respect to the goal of this research, a simulation-based approach is used for the research. The selection for the most accurate approach is based on the advantages and disadvantages for both the analytical and simulation-based method as found in literature.
With the use of this method, the complexity of the problem can be simplified and besides, the sequential and repetitive operations that are present and depend on external factors, can be modelled in such a way a visualization of the real-world problem is created.
Both Markov Chain and Monte Carlo Simulation methods are discussed. The first method establishes the probability distribution analytically while MCS establishes the same, only with the use of simulation. Taking into account the advantages and disadvantages of both discussed methods, Monte Carlo Simulation is used in this thesis. Although the time required for simulation will be longer when using MCS, it is thought to have more benefits over Markov Chain as it is harder to obtain the required transition probabilities for the transition matrix and is therefore more difficult to implement.
Furthermore, as a result of the aforementioned literature review, Discrete Event Simulation (DES) approach is used for simulation of the logistic processes. DES is more intuitive than analytical approaches from the implementation point of view and besides, complex processes can be realistically presented through DES. Due to discretization of time, it will help to better understand the logistics as bottlenecks can be easier identified. Since only exact points in time are considered, this approach is able to jump from one event to the next event in time as no changes of the system occur in between the discrete points. This contrasts with continuous simulation which can only be analyzed analytically.

After considering the aforementioned methods found in literature, the simulation-based approach is implemented in this thesis to simulate the key activities to understand the logistics of both the TLP concept and SSB structure. Additionally, the main differences between the logistics when including weather windows, can be mapped. For this purpose, the simulation code will be self-developed as it will be easier to control the dynamics of the simulation. For example, it is self-decided what assumptions and decisions are made for the model. To perform the simulation, Matlab is used as this is a widely used, and accessible tool for simulation.

3. Model description

To verify which installation strategy is most optimal, considering weather uncertainty, a model is described to simulate the transport and installation process for two installation strategies. This chapter gives the model description of the logistical process in general. The process from leaving the assembly port(s), transportation to the offshore site and the installation of the OWT is included in the model description. The supporting main elements for clarification of the described model, can be found in Appendix C.

3.1 General model description

This section describes the outline of the activities required for installation of a wind turbine unit. The definitions as described in Appendix C are used to support the general simulation model description. The objective of the model is to simulate the logistic process as described in chapter 2. The logistic process simulation for transport and installation, is developed to evaluate the project duration for installation of an entire OWF including the probabilistic nature of the local weather during transport and installation activities. In the project description, several values are preset such as the location of the project, fabrication sites and marshalling yards, the inputs will be discussed in chapter 4. A project description illustrates a transport and installation method including the required equipment. It will be possible to use the developed model for simulation of various project descriptions.

The simulation model describes the logistic process for transport and installation of a wind turbine unit. The project begins on a certain date, this is the starting point of the project. In the model, the passed project time, is displayed on a project time line, which will be further explained in section 3.3.1. A project timeline is divided in time steps (see section 3.3.3). At the beginning of a time step activities may start or continue making progress, provided that the described pre-conditions (see section 3.3.4) are met. In a time step, the active activity chains (see section 3.3.2) may make progress and at the end of a time step the progress of an activity becomes known. The progress of an activity is related to a status an activity will take. The status an activity may take can be 'active', 'on hold', 'aborted', or 'completed' (see section 3.3.2). For an activity to obtain the status 'completed', the progress of the activity should be 100% and besides, (if any) possible post-condition should be fulfilled. This is further explained in sections 3.1.3 and 3.1.4, respectively. In the model, a wind turbine unit has its own activity chain, existing of several sequential activities that are needed to transport and install one wind turbine unit. The activities and the activity chain of a wind turbine unit will be further explained in paragraph 3.3.2. In the model equipment (see section 3.3.5) is required to execute the activities in an activity chain. Equipment has slot spaces that indicate the use of the equipment in the activity (see section 3.3.5). The slot spaces of equipment can take various statuses, 'available', 'occupied' or 'empty', which is further explained in section 3.3.5. For an activity (several) pre-condition(s) can be defined that must be fulfilled to start the activity to or to make progress. For some activities the weather conditions are required as pre-condition while for other activities it is necessary to calculate the needed weather window (see section 3.3.6). Sometimes an activity requires a post-condition to enable an activity to become completed.

The simulation model will repeat all activities till all activity chains become 'completed'. When the last activity in the last activity chain is completed, the project is finished, this indicates that all floating wind turbine units have been installed in the offshore field.
Unless specified differently, the model description is the same for both a TLP structure and for a SSB structure. Figure 3-1 illustrates the components of the in this chapter described model.

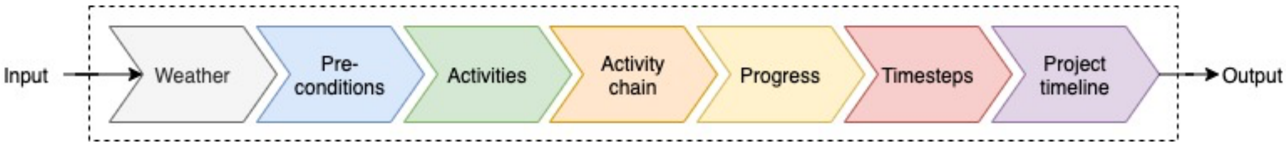


Figure 3-1 Components of the model

3.1.1 Project timeline

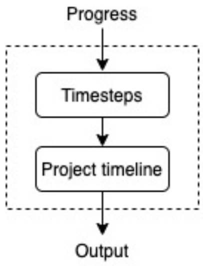


Figure 3-2 Project timeline components

Figure 3-2 shows the model components discussed in this section. The project starts on a chosen calendar date, this date-time is t = 0. This start, initiates the project timeline as soon as the first activity of the first activity chain starts. A project timeline is based on a sequence of time steps and the start of the project timeline means that for the simulation model the first time step will start and the time for the project starts counting. Time steps are further explained in section 3.3.3.

3.1.2 Activities and activity chain

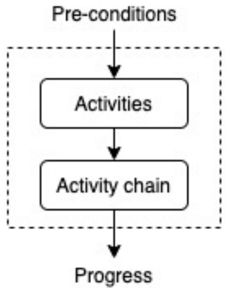


Figure 3-3 Activity and activity chain components

Figure 3-3 illustrates the in this section discussed model components. For one complete wind turbine unit to be installed, several activities in a sequential order, an activity chain, are required to happen. Although this may differ for the installation method used, in general, an activity chain includes the following sequential activities: storage of components, loading components on equipment, installation of the mooring system, transport and installation of the substructure and transport and installation of WTG components to complete one wind turbine unit. The sequence of the activities is determined by pre-conditions as all activities will have a pre-condition to start the activity that includes the completion of an (earlier executed) activity.

As each wind turbine unit has its own activity chain, each wind turbine unit has, for instance, its own activity for installation of the foundations. Multiple activity chains may be executed simultaneously. This creates the opportunity to already install the first TLP floater while the mooring system for the last unit is not installed yet. For instance, installation of a mooring system of a wind turbine unit can be executed at the same time as the installation of a substructure of another unit. Without the mooring lines installed, the substructures cannot be installed as they cannot be tensioned to the mooring points at the sea bottom. All activities can have different statuses depending on the progress they made in a time step. When an activity chain is ‘active’, this means the activity chain can make progress. The status of an activity can also be ‘on hold’, ‘aborted’ or it can have the status ‘completed’. For an activity to become ‘active’, it should start or continue making progress in a time step. On the other hand, if no progress can be made in a time step due to pre- and/or post-conditions, the activity is ‘on hold’. An activity becomes ‘aborted’ if it cannot be completed. Not being able to complete an activity can have different causes but is mainly weather related. The result of an ‘aborted’ activity is that the progress becomes nil (0%) and the activity needs to restart. In case an activity is ‘aborted’, the model initiates a new activity that results from aborting. For example, if a transportation activity becomes ‘aborted’ during its journey to the offshore site due to a too bad weather forecast, the transport vessel must navigate to the nearest port to shelter against the coming bad weather. The activity ‘sail to nearest port for shelter’ is activated when the status of the original transport has become ‘aborted’. The progress of the original transportation activity is now put on 0%, and a new activity of transport is initiated. The original transport activity will be restarted when its pre-conditions are met, which includes the condition that the activity ‘sail to nearest port for shelter’ is completed and the forecasted weather window allows the activity to start. Finally, if all activities of an activity chain have the status ‘completed’ and the post-condition (if any) of the activity chain is met, then the activity chain becomes ‘completed’.

3.1.3 Time steps and progress

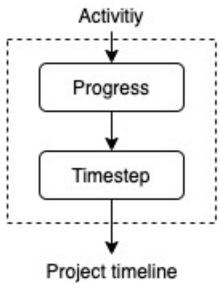


Figure 3-4 Timestep and progress components

Figure 3-4 shows the timestep and progress components as discussed in this section. In a time step, activities of multiple activity chains may be executed and it should be possible to make progress for an activity in a time step. For this thesis, each time step represents 3 hours as weather conditions are typically recorded in statistics with a duration of 3 hours as found in literature (Gintautas et al., 2016). At the beginning of a time step an activity may start making progress while at the end of the time step the status of the executed activities will become known by the model. After one or more time steps, progress of an activity will become 100% and the status of this activity is set 'completed', if also the post-condition is fulfilled (if any).

As long as an activity continues, progress is made for that activity in the time step. It is possible that multiple activity chains make the same progress. For instance, transport and installation vessels have a certain capacity available to store multiple components. It should be noted that for a transportation activity for, say unit 1, progress will be made during the time step of the sailing activity. All other sailing activities of the other units loaded on the same transportation vessel will make the same progress. This also applies the other way around, for instance for transportation of a TLP floater unit. In general, only one TLP floater unit (this number may vary depending on the size of the barge), is transported at the same time. In that case only that unit makes progress in the time step. If for example, multiple tug boats are used to transport TLP floaters units, multiple TLP units may make progress in the time step, unless they leave the port in different time steps.

It is possible an activity will need several time steps to finish. The activity makes a certain amount of progress in each of the needed time steps. At the beginning of a time step an activity starts and makes, for example, 30% progress in the time step and its status is 'active'. In the next time step the same activity is still ongoing as it is not yet completed and the activity makes another 40% progress. So far, at the end of time step 2, the activity made 70% progress and its status is still 'active'. In the third and last time step needed, the activity continues until it made 100% progress. If also the post-condition is fulfilled (if any), the status of this activity is set 'completed'. It should be noted that in a time step, activities can make 100% progress, while not the complete time step was necessary to achieve this. In the previous example, it can be seen that in time step 3, not the entire time step was necessary to reach 100% progress. Since an activity can only start at the beginning of a time step, some slack time can result in a project. For example, an activity may book 100% progress in time step 9 and can therefore be completed between time step 9 and 10, for example at 9.50 or 9.75 time step. On the other hand, for this thesis it is assumed activities cannot start between two time steps. An activity can only start at the beginning of, for example, time step 9 or at time step 10. While it cannot start at, for example, 9.75.

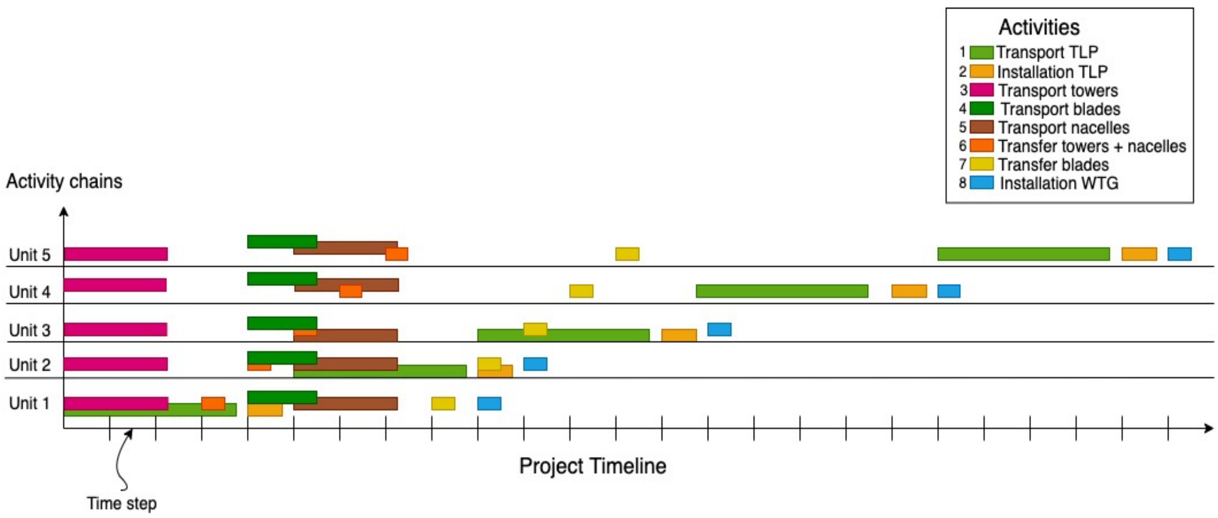


Figure 3-5 Example project timeline

Figure 3-5 illustrates an example of the activities for unit 1 to unit 5 on the project timeline. It should be mentioned that in this figure not all units that will be simulated, are included. This is due to the size of the figure. Also, the durations of the activities are randomly chosen. The figure shows that not the complete time step is needed to finish an activity while it can only start at the beginning of a time step. From the figure it should also be clear that multiple activities for different units can be executed at the same time.

3.1.4 Pre- and post-conditions

Activities are part of an activity chain and to determine if an activity may start, the pre-conditions of all non-active and non-completed activity chains will be checked at each time step. If the required pre-conditions are met, the non-active and non-completed activity chains may start. Completion of an activity is in general a pre-condition for a following activity in the activity chain to start this activity and to make progress. At the end of the time step the model checks for a possible post-condition to for example, complete an activity. If the progress of an activity is 100% and it has no post-condition or if there are and these are met, then the status of this activity will become 'completed'. For instance, for an installation activity to be completed, progress should be 100% and also the described post-condition (if any) should be met whereafter the activity is completed and the following activity in the activity chain may start. For the pre- and post-conditions, the current weather as well as the weather forecast may be used. This is discussed in section 3.37. As it is possible that activities are executed simultaneously, a possible pre-condition for an activity to start may also be a calendar date on which the activity is allowed to start. A calendar date may be included as pre-condition since this indicates the earliest date on which an activity can start and this will ensure an activity will start for example, one season later than other activities. It should be noted that it is possible the activity will start later than the indicated calendar date. The in this section discussed components are illustrated in Figure 3-6.

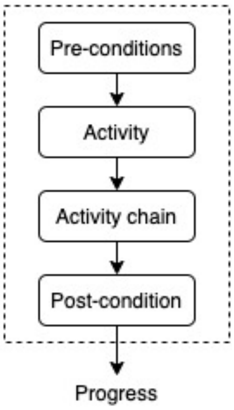


Figure 3-6 Pre- and post-conditions components

3.1.5 Equipment and components

Figure 3-7 illustrates the components that will be discussed in this section. Components are all parts that are needed for installation of one wind turbine unit. Components can be in a storage location, either on a quay site in a port and/or on all equipment (transport and installation vessels). For example, on the equipment 'transportation vessel', it should be possible to store tower components or nacelle components or blade components. Each storage location has a certain number of slots available. For this thesis it is assumed all components are always available at the fabrication yards. During an activity, slot spaces on a vessel will become 'occupied' or become 'available' and thus the status of a slot can change during an activity. For example, during an activity a slot status changes from 'available' to 'occupied'. The status of a slot can be used in the pre- and post-conditions of activities definitions. For instance, to start a lifting activity, a prescribed pre-condition is that the status of the crane slot must be 'available' to ensure the crane can be used to lift the component. In another instance, a transport vessel has 20 slots available to store components during transport and the activity 'loading component' has as pre-condition the check for an available slot on the transport vessel. When after one or more time steps a loading activity for a wind turbine unit becomes completed, the slot for this unit out of the mentioned 20 slots becomes 'occupied' and is not available for components of other units. This is repeated in the following time steps until the maximum capacity of the transport vessel is reached and all slots (in this case 20 slots) are occupied, before the vessel may start the activity 'sailing' and will leave the production port. It is assumed the slots of all equipment are 'empty' at the start of the project. Besides, it is assumed that all transportation vessels are ready for loading at the quay site of their fabrication yard.

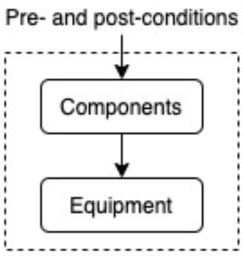


Figure 3-7 Equipment components

For unloading, assembly and installation of a WTG, a Heavy Lift Vessel (HLV) will be used. This vessel has two cranes available for lifting, and thus has two crane slots. Since the same HLV will be used for assembly and installation of a WTG, one crane will be used for installation of the WTG while the other crane will be used for unloading the components of the transport vessel onto the storage space on the HLV. The crane used for unloading the components of the transport vessel will also be used for assembly of a WTG. This makes it possible to install the WTG by the other crane. To make sure there is no confusion about which crane is used for which activity, from now on the crane used for lifting and assembly of the components is denoted as **crane 1** while the crane used for installation of the WTG is denoted as **crane 2**. Both cranes have only one slot space available which can have the status 'available' or 'occupied'. These statuses can be used in a pre- and post-condition as described above.

Upon arrival of the transport vessel at its destination, the activity 'sailing' will become completed and the unloading activity can start. A slot on a transport vessel becomes 'empty' after unloading, while it becomes 'available' when the vessel sailed back to the production port and is ready to load a new number of components. The availability of a slot space can be a post-condition to complete an activity. For example, after components have been lifted-off a transport vessel offshore, the slots on the vessel become 'empty'. Once 'empty, the vessel returns to the production port where the slot spaces become 'available' again and the post-condition of the unloading activity is met. Now the unloading activity becomes 'completed'.

3.1.6 Weather windows and weather limits

For some activities it is necessary to calculate the weather window needed for the activity. Two kinds of weather windows are distinguished, a forecasted and a required weather window. For some activities the forecasted weather is important to know as it shows how future weather will develop and indicates if the weather will be good enough to continue and complete the activity for an upcoming period and act correspondingly. For example, a weather forecast can be for the coming 10 days, depending on the activity. The required weather window will be determined by means of the time needed to complete an activity and the required weather limits. In Figure 3-8, the components as discussed in this section are illustrated.

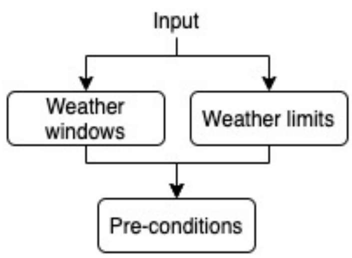


Figure 3-8 Weather components

At the start of the upcoming time step, the required weather window is used to check if the activity is expected to be finished within the remaining time of the forecasted weather window and thus progress can be made in the time step for the activity. If the weather window does not suffice, the activity cannot be completed within the forecasted time needed for the activity. In that case, the activity may be put 'on hold' or must be 'aborted'. An activity is put 'on hold' if it cannot make progress in a time step. If an activity cannot be completed at all, it will be 'aborted'. If the weather conditions are too bad and the activity is 'aborted', the vessel needs to go to the nearest port instead of returning to the port of origin. The nearest port is chosen as the travel time needed to reach this port is the shortest.
Calculating both weather windows is important for activities that require to be finished in one go as these activities cannot be aborted. This is especially important for installation activities, where the forecast that the weather window should be sufficient long to start and complete the follow-up activity as this activity cannot be put 'on hold' or 'aborted' when the activity has started. For example, it is not possible to abort an installation activity due to weather conditions. The required weather window for the installation should include more time than actual required for the activity. In general, the weather window should therefore really cover the time needed for installation of a wind turbine unit.
To include some uncertainty, the forecasted weather window should be larger, for example a time step longer, than the required weather window which is actually needed for the activity. For instance, to start an installation activity, a pre-condition that may be included is that the forecasted weather window should be larger than the required weather window. This is checked to ensure the weather windows are sufficient large

to enable the activity to be completed within the weather window and thus without the need to put the activity ‘on hold’ or ‘abort’ the activity.

Both the forecasted weather window as well as the actual weather need to be determined as input for evaluation of the activities in the upcoming time step. The actual and forecasted weather conditions at the relevant location of the activity are based on a probabilistic approach using historical weather data and is determined at the beginning of each time step. During the project, the actual weather in a later time step can deviate from the forecasted weather in the current time step. Also, the actual weather should be determined to check if the activity indeed can start while the limits for the activity will not be exceeded. The actual weather should also be known at the moment the activity will start making progress as this indicates if the activity indeed may start without exceeding the weather limit.

The weather limits for the transport and installation process of offshore wind turbines can vary per project location and these variables may depend on the combination of the activity and equipment used in the project. This is outlined in the project description. Weather limits are defined using limits for significant wave height and wind speed. The values of the limits are illustrated later on. Significant wave height and wind speed should be obtained from historical time series as these parameters are known to influence the transport and installation processes for offshore projects the most. Per activity the criteria are described in pre-conditions.

For the specific location of the wind farm, historical weather data for a certain period of time will be acquired. Weather is stochastic due to its uncertain and random nature. Datasets for significant wave height and wind speed will be obtained. If the measures of the datasets are not equal, they should be equalized so they will be coherent. Hereafter, the datasets should be analyzed and time series can be generated out of the datasets to represent the weather conditions as realistically as possible at the specified location. Time series are generated on a 3-hour time interval. At the start of each time step, the model determines the actual weather and the required weather window, using historical weather data.

As mentioned above, in the upcoming time step the actual weather as well as the weather window should be known as input for evaluation of the activities. Besides, also the progress an activity made in the time step is necessary as input. The progress made, may depend on both the actual weather conditions in the time step at the location of the activity as well as the forecasted weather conditions. For instance, the speed of a transport vessel depends on the actual weather, while the forecasted weather determines the routing and potential speed along the route, hence, the distance and time to reach the destination.

3.1.7 Transportation

In Figure 3-9, the components that will be discussed in this section are illustrated. This paragraph in general describes the transport of wind turbine unit components, including accompanying pre- and post-conditions. Transport includes several activities and has pre- and post-condition(s) which should be fulfilled before an activity may start, continue or may be completed. In general, transportation includes the following sequence of activities: loading, sailing, unloading and sailing-back. Before a transport may start, the components are first loaded on the accompanying transportation vessel. Loading the components onto the transportation vessel has as described pre-condition that a crane slot on the quay and a storage slot space on the vessel should be available. Once the component is loaded onto the vessel, next is the activity of transport. To may start the transportation activity, the pre-conditions will be checked. For the activity of transport, a pre-condition is to check whether all slot spaces on the vessel are occupied before the vessel can leave port. This pre-condition will not be required when the last unit is on the vessel, in that case the vessel can sail half full. Another pre-condition required for this activity is that the weather limits during transportation are not exceeded. Depending on the structure which is transported, also a sufficient weather

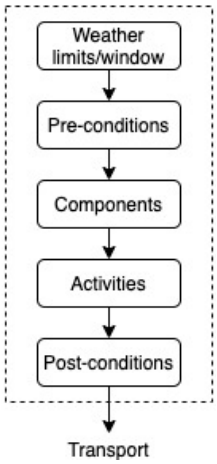


Figure 3-9 Transportation model components

window during the activity of transport is of great importance. For example, for a semi-submersible structure, which is highly sensitive to weather conditions, a sufficient weather window is of great importance. The forecasted weather window should therefore be considerably long to cover the time required for transport (the required weather window). So, for this installation activity a larger weather window for transport is required than the expected actual duration of the activity of transport.
Once the pre-conditions are met, the loaded vessel may leave port to sail to the offshore installation site. After arrival, the transportation activity is set 'completed' as it has no post-condition that need to be fulfilled. In case of the TLP installation strategy, a described pre-condition for un-loading a vessel is that the equipment 'crane' should have a slot available, while in case of un-loading onto a HLV, another described pre-condition is that there is a storage slot available for component on the vessel. Also, the unloading activity has no post-condition so once a component is unloaded, the loading activity is set 'completed'.
After successful unloading of the components, the HTV's will sail back empty to the production port(s). A described pre-condition to start the return voyage is that all slots on the transport vessel have the status 'empty'. Upon arrival at the port (progress is 100%) the status of the slots of the HTV changes and becomes 'available' (again). A described post-condition for the return voyage activity is that the status of the slots on the HTV changes from 'empty' to 'available' (again).

The described model, assumes that only one transport vessel, per kind of component, will transport components at the same time. For example, one vessel to transport the towers, one vessel to transport the nacelles and one vessel to transport the blades. If in the model, multiple transportation vessels are used per component (for example two vessels for transportation of the towers instead of one vessel), it is possible the next transportation vessel(s) just arrive or are already waiting for an installation vessel to become available for unloading. This depends on the journey time and weather conditions. It will also be possible to use combined transportation vessel in the model. A combined vessel is able to transport different kinds of components at the same time.

3.1.8 Installation

For installation, various activities are needed including fulfilling the described pre- and post-condition(s) before the activity may start, continue or be completed. In general, the following sequential activities are included for installation: assembly, installation and hook-up.
For some components, installation includes the activity of offshore assembly of the components. This activity has multiple pre-conditions including that the needed components are available for assembly. Another pre-condition is that crane 2 on the installation vessel, has the status 'available'. A final important prescribed pre-condition is that there should be a sufficient weather window that is larger than the required weather window for the duration of the installation activity.

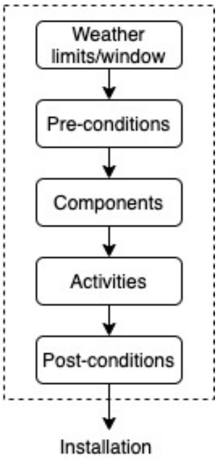


Figure 3-10 Installation model components

At the start of the installation activity the crane will be assigned to the unit number of the components that will be assembled, thereby changing the slot status of the equipment 'crane' on the installation vessel which changes from 'available' to 'occupied'. During installation, the activity 'assembly components' makes progress until progress becomes 100% in the time step and its status is set 'completed'. When the pre-conditions for the installation activity are fulfilled, the activity may start and when progress becomes 100% this activity is set 'completed' as there is no post-condition included. The installation activity is identical for all components that need to be installed. In Figure 3-10, the discussed components are illustrated.

3.1.9 Scenario's

The described simulation model can be implemented for different weather realizations. The weather realizations (data sets) are related to the weather model that is used as this mainly determines how the weather is calculated. When implementing different weather realizations into the simulation model, different scenarios are simulated and different results will be obtained. In the described model a scenario is simulated for a project using a certain realization for the weather conditions that occurs during the timeline of the project. When the simulation is repeated multiple times for different realizations of the weather conditions, the probability density of the project duration will become visible. It is noted that the model includes only the weather as stochastic input to simulate the project duration. In reality, activity progress itself may also be stochastic and not only due to weather conditions, but this will not be considered in this thesis.

3.2 Simulation model description TLP floater concept

This section will implement the model as described in the previous section to simulate a project which includes transport and installation of a TLP wind turbine farm. In the project, a TLP floater and WTG will be transported and installed.

To be able to install a TLP, first an anchorage needs to be installed. The anchorage, further referred to as mooring system, consists of the following components: mooring piles and mooring lines. Furthermore, the TLP floater consists of six components: three pontoons, a column, the parts for connection of pontoons to column and the access platform. These components are installed at an assembly yard. Finally, a WTG consists of a tower, nacelle and three blades. Each component should be loaded onto the corresponding equipment in the port where fabrication of the component (tower or nacelle or blade) takes place.
The equipment is needed for transport and installation activities for all components of a TLP wind turbine unit. For transport and installation of the mooring system, the same vessel will be used. This vessel will be further referred to as transport vessel. At first, the TLP components will be transported from their production yard to the assembly yard by a Heavy Transport Vessel (HTV) while for transport and installation of a TLP floater, a barge and tug boat(s) will be used. WTG components will be transported by HTV while installation of a WTG will be done by a Heavy Lift Vessel (HLV).

The first activity in the activity chain for installation of a TLP unit is transport of the mooring system from the production port to the offshore site. The transport vessel has a certain number of slot spaces available to store the components during transport and installation. Once the pre-conditions, as described in the previous section for transportation, for this activity are met, the activity may start. The next activity in the activity chain of unit 1 is transport of the mooring system to the offshore site. After arrival of the mooring system of unit 1 at the offshore site, along with the other components loaded on the vessel, the following activity in an activity chain is installation of the mooring system. This installation activity contains installation of the piles and mooring lines. First the piles will be installed, followed by installation of the mooring lines. For installation of the mooring lines, the transport vessel is equipped with two cranes that can only operate in pre-defined weather conditions, normally in sea states with significant wave heights of less than 2,5 meters. More details about sea states will be discussed later on in chapter 4. The activity of installation of the mooring systems is repeated for the mooring systems present on the transportation vessel.
Once installation of the mooring system is completed, the following activity in the activity chain is sailing back to the production port to reload (if not yet completed) with mooring systems if also the pre-condition(s) are met (see section 3.1.7). The return voyage activity starts for all activity chains of which the mooring system has been installed.

Meanwhile, the first activity for transport and installation of a TLP floater for the activity chain of unit 1 will start, unless as pre-condition a specific calendar date is defined on which the activity at the earliest can start (see section 3.1.4). At first, the TLP components are transported from their production port to the assembly yard from where the following activity starts. The following activity is loading a TLP floater unit nr 1 on a barge. The barge only has one single slot available for a TLP floater. After completion of the loading activity, the following activity in the activity chain of a TLP floater unit, sailing to the offshore site, may start once the pre-condition(s) as described in section 3.1.7 are fulfilled.

After arrival of the first TLP floater unit at the offshore site, the activity of transport for unit nr 1 is completed, as there is no described post-condition, this means the following activity may start. The next activity in the activity chain is installation of the TLP floater. For the installation activity of TLP floater unit nr 1, first the TLP will be positioned by tugs. When the TLP is positioned, it should be lowered by pumping ballast water in the TLP structure. Hereafter the mooring lines are mounted and tensioned to the TLP by using winches. After tensioning the mooring lines, the activity of installation is completed as also this activity has no described post-condition.

While the previous described activities of the first activity chains are being executed, the wind turbine components (towers, nacelles and blades) of the first units may be loaded on the transportation vessel(s). The vessel used to transport the wind turbine components is a Heavy Transportation Vessel (HTV). The blades, nacelle and rotors are each loaded on a HTV in different fabrication yards and transported from their own fabrication yard to the offshore location. The loading activity is repeated until the maximum capacity of the HTV is reached. The components are loaded and transported from different fabrication yards however, the loading activities of the components do have the same pre-condition(s) as described in section 3.1.7. Once the loading activity is completed, the following activity of the activity chain may start. The next activity is sailing the WTG components to the offshore site and this activity may start as soon as the pre-conditions as described in section 3.1.7 are fulfilled. This activity is completed when the WTG components arrived offshore as this activity has no prescribed post-condition and the following activity of unloading the components, may start. The components are loaded from the HTV onto the HLV using the equipment 'crane' as described in section 3.1.5. During the unloading activity, the tower of the first wind turbine unit, is lifted from the HTV onto the HLV by crane 1 once the pre-condition(s) are met (see section 3.1.5). The towers will be unloaded one at the time and this activity will be repeated for all towers present on the HTV as a HLV has multiple slots available to store WTG components. The preliminary described activities are needed for loading and transport of a tower and it should be noted that the same activities for loading and transport are needed for the blades and nacelle
After completion of the on-board lifting activity, the activity of assembly of the WTG may start once the pre-conditions, as described in section 3.1.8, are met. It should be noted that in the activity chain the activity of lifting the components on the HLV is executed prior to the assembly activity. If a slot space on the HLV becomes available, the activity of lifting will be executed unless no slots on the HLV are available or no HLV is present in the offshore field to be unloaded. If this is the case, then the assembly activity will start as the slot of crane 1 is available for the assembly activity.

If an WTG is assembled and the pre-conditions as described in section 3.1.8 are met, the activity of installation of the WTG may start in the following time step. After successful completion of installation of a wind turbine unit, the HLV sails to the installation location of the next TLP floater unit. At the beginning of the next time step, and only if the storage slots on the HLV are available, the components for a next unit are lifted one by one onto the HLV. The same activities with accompanying pre- and post-conditions are performed once again. In the following time steps, this process is repeated until all available components are installed. If all slots of a HTV become 'available', the vessel is 'empty', the following activity in the activity chains of the unloaded units starts. This is the return voyage activity of the HTV('s). The vessel(s) sail back to their production port where the HTV('s) will be provided by another load of components (if there are still components left in port) to start the same process of activity chains for the subsequent units over again. The return voyage of a HTV is a separate activity with pre- and post-conditions. The project is finished when all wind turbine units have been installed.

Appendix D includes an overview of all activities that are part of an activity chain for transport and installation of a TLP floater. For each activity the related pre- and post-conditions are described.

3.3 Simulation model semi-submersible wind turbine

This paragraph will use the description of the model as shown in section 3.1 for simulation which includes the transport and installation of a semi-submersible wind turbine farm. In the project, a fully assembled semi-submersible structure including a WTG will be transported and installed. For this type of floating wind turbine, the same simulation model applies as for a TLP floater. Main difference compared to the logistic process of a TLP is its transport and installation methodology.

In the project, a WTG including a SSB substructure is transported and installed. To be able to install a SSB substructure, first the anchorage is installed. This is further referred to as the mooring system and consists of the following components: mooring piles and mooring lines. The substructure is assumed to be one component while the WTG consists of three components (tower, nacelle and blades). As discussed in chapter 2, the components are produced at the fabrication yard from where they will be shipped to the marshalling yard. At the marshalling yard the WTG components will be assembled and installed on the substructure. Finally, a fully assembled system is towed to the offshore site for installation.

Equipment is needed for transport and installation activities of a SSB wind turbine unit. For transport and installation of the mooring system, only one and the same vessel will be used. This vessel will be further referred to as transport vessel. The logistic process for SSB structures, starts at the fabrication yards of the components. Each part of the SSB structure is fabricated at a different yard. After fabrication, the component is transported to the marshalling yard by a Heavy Transport Vessel (HTV). For assembly of the SSB substructure, a crane at the quay will be used. For transport and installation of a SSB structure, including a WTG, tug boats will be used.

First activity in the activity chain is transport and installation of the mooring system for a SSB structure. A mooring system will be transported from the production yard to the offshore site. To transport and install a mooring system, the transport vessel has a certain number of slot spaces available to store the mooring system. First, the mooring system of unit 1 is loaded on the transport vessel. When the mooring system of unit 1 is loaded onto the vessel, along with all other mooring systems units and the pre-conditions as described in section 3.1.7 are met, the transport activity may start. When the mooring system of unit 1 arrived at the offshore site, along with the other components loaded on the vessel, the following activity in an activity chain is installation of the mooring system. The activity of installation of the mooring system includes installation of the piles and mooring lines. Firstly, the piles are installed, followed by installation of the mooring lines. For installation of the mooring lines, the transport vessel is equipped with two cranes that can only operate in pre-defined weather conditions, normally in sea states with significant wave heights of less than 2,5 meters. The sea states will be discussed in chapter 5. The activity of installation of the mooring systems is repeated for the available mooring systems on the transport vessel.
When the installation activity of the mooring system is completed, the next activity of the activity chain is may start, sailing back of the transport vessel to the production port to reload (if not yet completed) with mooring systems. When the pre-conditions, as prescribed in section 3.1.7 are met, the activity may start. The return voyage activity starts for all activity chains for which the mooring system has been installed.

While the mooring system(s) are being installed, the first activity for transport and installation of the SSB structure of unit 1 will start. From this point on, the installation method is different compared to the installation method of a TLP floater.
First, a SSB substructure is positioned along quayside. Hereafter, a WTG is assembled by a crane and installed on the SSB substructure. This activity may start when the pre-conditions as described in section 3.1.8 are fulfilled. When this activity is completed, a fully assembled structure is ready for next activity in the activity chain of the first unit. The next activity of the activity chain is towing the fully assembled SSB structure, including WTG, to the offshore installation site. At the start of a time step, and if the pre-conditions are met, the fully assembled system of unit 1 will be transported by tug boats to the offshore site. The tug boats, that

will perform the tow, have a slot available to transport a SSB structure once the pre-conditions are fulfilled. The pre-conditions apply as described in section 3.1.7.
After arrival of the first SSB unit at the offshore site, the activity of transport for unit nr 1 is completed as there is no described post-condition meaning, the following activity may start. The next activity, installation activity of the SSB structure, can start as soon as the pre-conditions are fulfilled. First, the SSB structure will be positioned by tug boats. This is followed by the hook-up of the structure to the pre-installed mooring system. Finally, the structure is de-submerged and hereafter, the installation activity is completed as there is no prescribed post-condition.
The final activity in the activity chain of first SSB unit, is the return voyage activity of the tug boats. The vessel(s) sail back to the marshalling yard where they will reload with another semi-submersible structure (if there are still any structures left at the yard) to start the same process of activity chains for the subsequent units, over again. The return voyage of a tug boat is a separate activity with prescribed pre- and post-conditions. The pre- and post-conditions are described in section 3.1.9. The project is finished when all SSB wind turbine units have been installed at the offshore site.

As for this installation method only tug boats are needed for transport and installation, this will most likely reduce costs. While on the other hand, the float out of a fully assembled system will bring greater risks as it is more sensitive to weather conditions. Appendix E gives an overview of the activity chain including the needed activities, a description of the activity and the pre- and post-conditions.

4. Simulation model implementation

4.1 Introduction

The objective of the simulation is to develop a tool by which the logistic process for transport and installation of an OWF for various installation methodologies can be illustrated. A simplification of the model, as described in chapter 3 will be implemented in Matlab. This chapter elaborates on the simplification by explaining the decisions made for the simulation model. The model boundaries are indicated and the assumptions made are explained. Finally, the architecture of the simulation model is illustrated.

4.2 Decisions for the simulation model

As stated, the simulation model is a simplification of the model as described in chapter 3. In order for simplification, several modelling decisions have been made. This section describes these decisions for the simulation model.

As mentioned in chapter 3.2.3, the model uses a timestep of 3 hours. This time step duration is chosen as it is commonly recorded in statistics as found in literature (Anastasiou & Tsekos, 1996; Gintautas et al., 2016). Moreover, a 3-hour timestep is chosen as the shortest activity has a duration of 3 hours. Kerkhove and Vanhoucke (2017) use a 4-hour time interval to evaluate, through simulation, the impact of weather conditions on the economy. They state that their decision for a 4-hour interval is based on an economic point of view, as a very short timestep in that case is not relevant. Moreover, autocorrelation can be better estimated using a longer timestep (Kerkhove & Vanhoucke, 2017). In case a very short time step is used, it is based on a 1-hour time interval.

Besides the decisions made on the aspects included in both models, there are also aspects which are not included in the model, but will affect the outcome when they are included.
In both simulation models, not all activities as described in chapter 3 (and Appendix D and E), are included. It is decided to not include all activities since an important aspect of this research is to study the impact of environmental conditions on the logistic process. This approach aims at using the key activities that are affected the most by weather conditions. Also, these activities cover the entire process. Moreover, operations and logistics are mostly influenced by these key activities. For the TLP floater, eight key activities per unit are implemented in the simulation model. Simulation of SSB structures requires less activities than the TLP concept. This simulation model also solely includes the most important activities as these reflect the performance of operations and logistics the best. The simulation model for SSB structures includes three key activities per unit. As stated earlier, a unit is a complete wind turbine consisting of substructure and top structure. Table 3 shows a summary of the used key activities for a TLP unit and a SSB unit. These activities are the most important ones and thereby capture the aspects of a logistic process for transport and installation of the TLP concept and SSB structures the best.
When all prescribed activities are included in the model, this will definitely have an impact on the outcome. This will result in a longer project duration. Even though, these are the activities that are not, or a little affected by weather conditions. Adding activities that are not affected by the weather, will result in a longer project duration. That is, the time needed to finish all activities requires more time. On the other hand, including the activities that are a little affected by the weather may cause more delay. This will also result in a longer project time.

Table 3 Summary key activities TLP floater and semi-submersible structure

# Activity	TLP floater unit	Semi-submersible unit
1	TLP transport	Assembly semi-submersible structure
2	TLP installation	Transport semi-submersible structure
3	Transport towers	Installation semi-submersible structure
4	Transport blades	-
5	Transport nacelles	-
6	Transfer towers + nacelles	-
7	Transfer blades	-
8	Installation WTG	-

Not all activities, as described in appendix D and E, are included in the simulation models. Some of the left-out activities require a post-condition to complete that activity. As the post-conditions are linked to some of the excluded activities, these are automatically not included in the model. That is, the activities which require a post-condition, do not belong to the in this model used key activities. Therefore, no post-conditions are required in the model for the used key activities. The post-conditions can be found in appendix D and E for the TLP and SSB structure, respectively.
When the activities to which a post-condition is prescribed are included in the models, this may change the outcome of both simulations. For example, when including post-conditions, a longer project time can be expected. If a post-condition is included, more time is required to finish the activity as this activity can only be completed when the prescribed post-condition is fulfilled. In any case, to finish the activity it needs to be checked if the extra condition is fulfilled.

4.3 Boundaries of the simulation model

The set model boundaries are explained in this section. To really capture the processes that are most of all affected by weather, boundaries are set. In chapter 3, the model is described for both the TLP concept and SSB structure. A model description is given from fabrication yard to cable connection. Also, loading of the vessels and installation of the mooring system is included in the description.
For this thesis, simulation will start at transport of the TLP floater and finish with installation of the WTG on the pre-installed TLP floater. All other activities are not included in the model boundaries. For example, loading of the vessels and installation of the mooring systems are not included. In addition, this all will be simulated by implementation of the provided environmental conditions. This applies to both TLP and SSB structures. That is, for this thesis the simulation models only analyse the transport and installation stages. Also, the impact of weather conditions on these stages are studied. Additionally, the problems related to the supply chain, are not part of the scope of this thesis.

4.4 Simulation model assumptions

The model, as described in chapter 3, is used to simulate transport and installation of a TLP and SSB structure. As it is not possible to perfectly simulate reality, it is necessary to make some assumptions for the simulation model. A comprehensive list of most significant assumptions is stated below:

- It is assumed the transportation and installation vessels are never broken, so no hiccup in transport and installation due to a broken ship, no probability of failure for the vessels is included.
- It is assumed WTG components, TLP floater components and SSB substructure are always available at quayside of its fabrication yard. The stock level of the fabrication site is not included in the scope of this thesis.
- For the TLP strategy: an installation vessel will never leave the offshore site, only the transportation ships will go back and forth, leave site empty and come back loaded.
- The substructure, blades, nacelles and towers all leave from their own production port to the offshore site therefore, different travel times per component are considered.

- An installation vessel is completely empty (so no WTG components) before a new batch can be transferred.
- An activity only starts at the beginning of a time step, not in between time steps.
- The barge, for transportation of a TLP floater, can only transport one structure at the time. The same accounts for transportation of the SSB structure. Also, a HTV will transport components for 8 units at the time. Table 4 summarizes the number of components that are transported at the time.

Table 4 Summary of the number of components that are transported at the time

TLP floater	WTG components	SSB substructure
1	8	1

4.5 Inputs logistic process simulation

As input for the model, major aspects that influence the logistical process of the TLP and SSB structures should be provided by the user. Some variables will be fixed during simulation such as the number of OWT's in the farm as well as the number of activities and the duration of each activity. To run the simulation model, the required input needs to be defined to introduce the information. User inputs is data that can vary depending on the kind of strategy used is extensive and for this research includes:

- Duration activity: time required for an activity to be completed;
- Size windfarm: the number of wind turbine units that will be installed.
- Start date: the date on which the activities of the project commence.
- Activity sequence: order the activities take place for installation of one wind turbine unit described in conditions per activity;
- Operational limits: wind and wave limits per activity;
- Number of simulations: the number of simulations required to get the most reliable results.

4.6 Outline logistic process simulation

As mentioned earlier, the simulation is performed using Matlab. The complete simulation code can be found in Appendix F for the TLP concept and in Appendix G for the SSB structure. This section elaborates on how both simulation models are build up. As mentioned in section 4.2, the simulation model comprises various key activities. These key activities should be executed in a prescribed sequential order according to the specified conditions, as illustrated.
The received data set is imported in Matlab to be able to specify the weather limits of the activities and to determine the weather windows needed for the activities. Each activity has a weather limit. If the weather limit is exceeded, the activity may not start or continue. For the model to determine whether the activity may start, continue or should be put 'on hold', conditions are prescribed to the model. These conditions state that the wind speed or wave height should be smaller than the given weather limit for that activity. If the limit is exceeded, the condition is not true and the activity is not started, continued or put 'on hold'. The durations of the activities are prescribed to the model. The weather windows are determined by looking forward in the data set for the execution time of the activity. Finally, a large number of simulations (Monte Carlo) is performed to acquire a good representation of the time that is needed for the installation of the number of units and to become stochastic relevant. The simulation model for the TLP concept as described in this chapter, is illustrated in Figure 4-1 to support the described model.
For the SSB model it is important to know how many vessels are available to transport a SSB substructure to the installation site. In this case it is assumed that 5 vessels are available for transport. This means that once a structure is assembled, it can be transported. This is visible in the outline of the simulation model. Once a structure is assembled, it can be transported. If unit 2 is assembled, it can be transported and for unit 3 assembly can start. In Figure 4-2 the outline of the SSB simulation model is illustrated to support the model as described in this chapter.

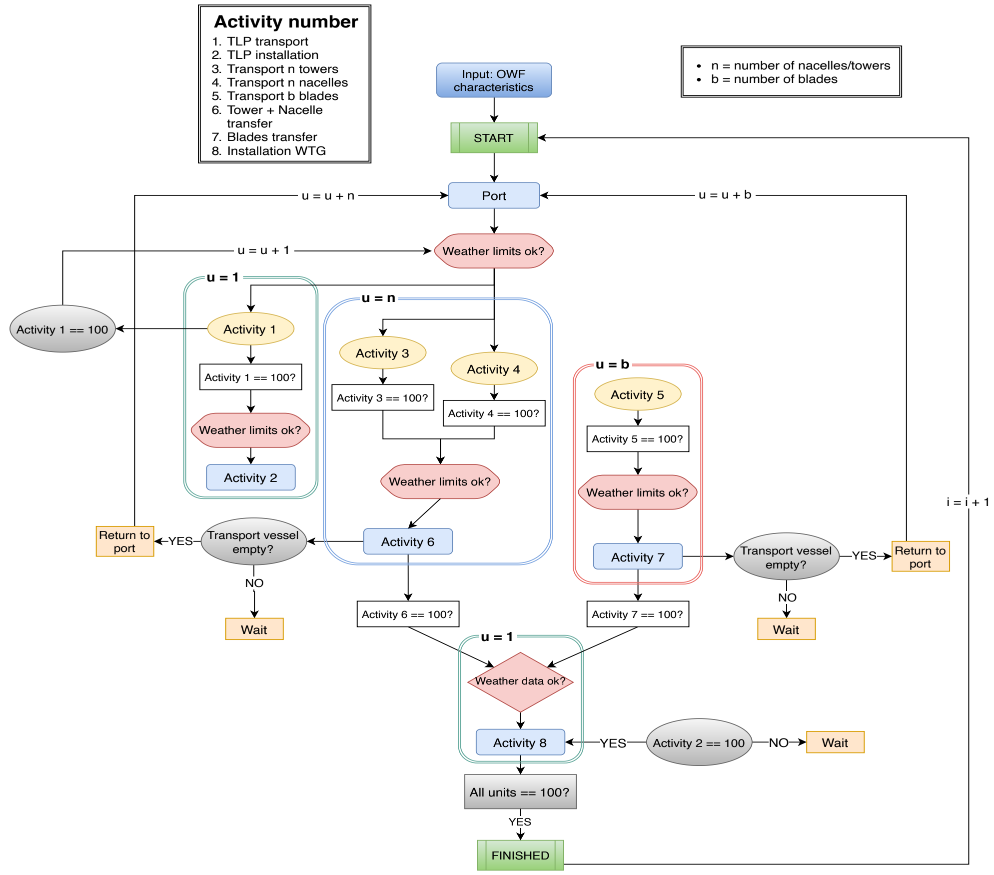


Figure 4-1 Outline TLP simulation model

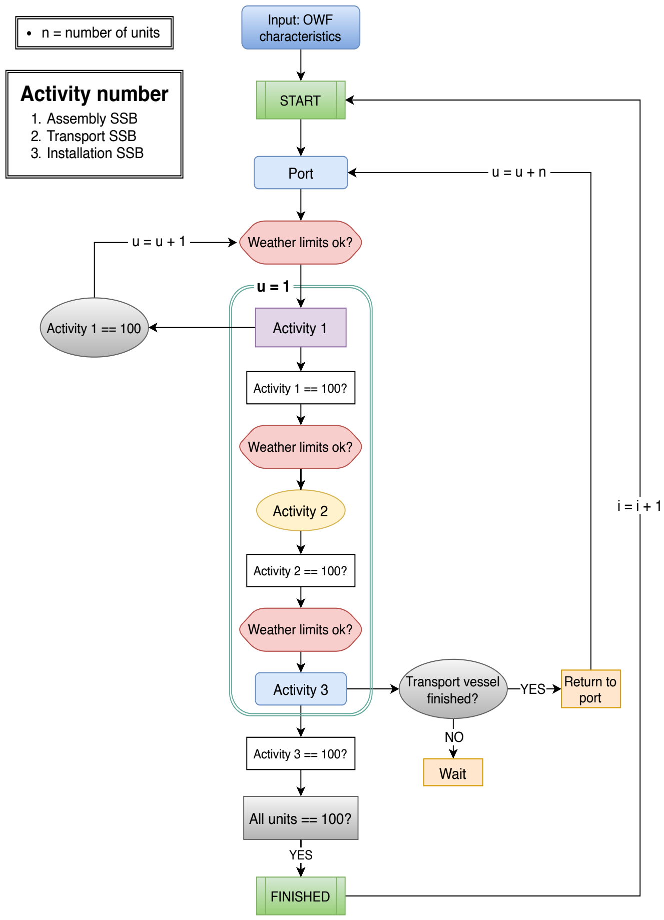


Figure 4-2 Outline SSB simulation model

5. Evaluation simulation model

This chapter presents the evaluation of the simulation model. First, the location of the OWF for which the simulation model is evaluated, is introduced. This is followed by an explanation of the operational limits. Finally, the simulation model is verified and validated.

5.1 Introduction weather data

In order to simulate the logistic processes of the TLP concept and semi-submersible structure, historical time series are required. For the evaluation of the simulation model, data was provided by Bluewater for the Ross and Blake oil and gas field in the North Sea, shown in Figure 5-1 (Talisman Energy, 2008). It is located 64 miles from Aberdeen in the Outer Moray Firth in the UK North Sea. Ross field is located around 110 km North-East of Aberdeen, operating since 1999. The Blake field has been operating since 2001 and lies around 12 km North-East of the Ross field. The fields were merged and are now operating together.

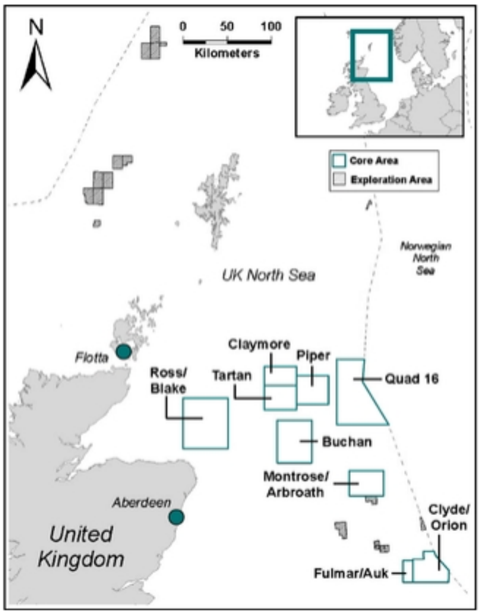


Figure 5-1 Location OWF

The provided data set contains maximum wind speed (m/s) and maximum wave height (m) data for the years 1996 to 2001 with a 3-hour time interval. That is, for both wind speed and wave height, the maximum measured value over three hours. The elevation at which the wind speed is measured in unknown. This data set is used as input for the simulation models in this thesis.

The tow-out of the TLP concept and SSB structure have the same conditions. Their travel duration dependents on the sailing speed of the tow, which is typically 4-6 knots. For the tow-out of both structures, an average of 5 knots is taken into account as sailing speed. Considering the mentioned distance of 64 miles from Aberdeen, this results in a travel time of 11,1 hours. That is, 4 timesteps of 3 hours should be considered as travel time for both TLP concept and SSB structure.

Figure 5-3 illustrates the weather measurements of all years of the data set (1996 to 2001). As can be seen from the plot, no data is available for the first months of 1996 (January – April). Also, for the last months of 2001 no data is available (May - December).

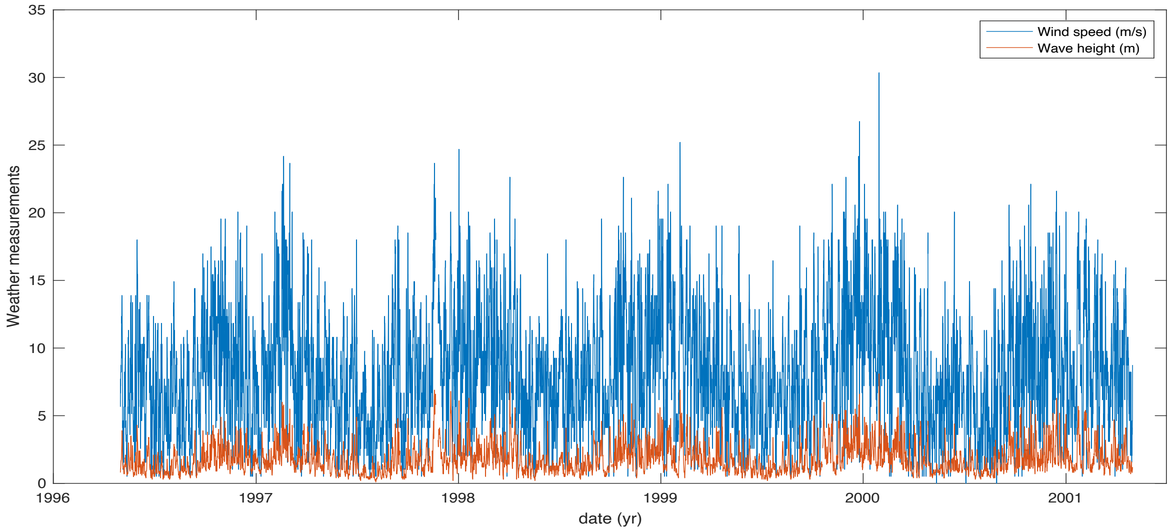


Figure 5-3 Measurements maximum wave heigt and maximum wind speed 1996 - 2001

Since no measurements are present for the first months of 1996 and for the last months of 2001, data from 1st of January 1997 till 31st of December 1999 is used. That is, three years of maximum wind speed and maximum wave height data for the given location, is used. The reason why these three years of data are selected is to make optimal use of the data as for the other years, too many datapoints are missing. Wind speed and wave height measurements for these years are illustrated in Figure 5-2.

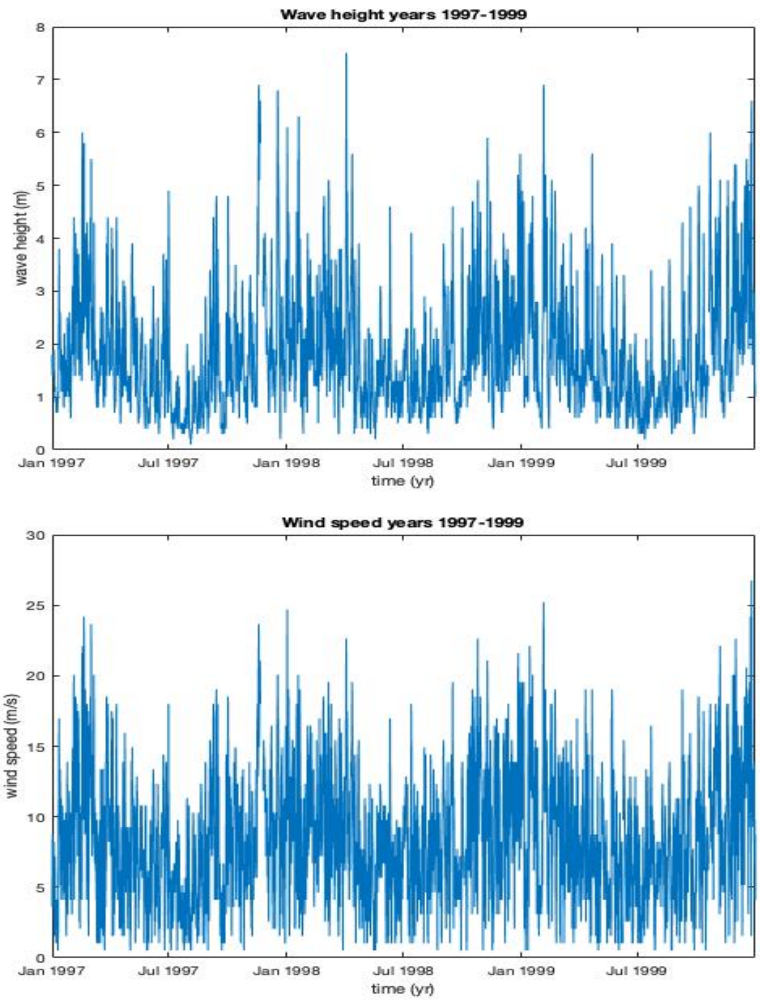


Figure 5-2 Top: Wave height (m) for 1997-1999. Bottom: Wind speed (m/s) for 1997-1999

5.2 Operational limits and inputs of base case model

Each activity has its own operational limits for the maximum wave height and maximum wind speed. Next to this, also other inputs used for the base case of the simulation model should are defined. This section describes the operational limits and other important inputs as used for the base case.

5.2.1 Operational limits

If the operational limit of an activity of either wind speed or wave height (or both) is exceeded, the activity cannot start or proceed. When the variable is below the set operational limit, the activity may start or continue. The operational limits used in this thesis were decided based on the literatures (Ait-Alla et al., 2013, 2017; Golbert et al., 2015; Rippel et al., 2019) and agreed with Bluewater. The operational limits as used for simulation of the TLP concept are summarized in Table 5.

Table 5 Operational limits TLP concept

Operation/Activity	Wave height [m]	Wind speed [m/s]
1. TLP transport	2	13
2. TLP installation	1	13
3. Transport towers	2	14
4. Transport nacelles	2	12
5. Transport blades	2	12
6. Transfer towers + nacelles	1.5	13
7. Transfer blades	1.5	13
8. Installation WTG	1.5	10

Due to the different activities involved in transport and installation of a SSB structure and to the fact this is a different type of structure, different operational limits apply in comparison with the TLP concept. The operational limits as used for the simulation model of SSB structure are summarized in Table 6.

Table 6 Operational limits semi-submersible structure

Operation/Activity	Wave height [m]	Wind speed [m/s]
Assembly semi-submersible structure	1.5	13
Transport semi-submersible structure	2	13
Installation semi-submersible structure	2	13

5.2.2 Inputs base case simulation model

As mentioned in section 5.1, a weather data set including maximum wind speed and maximum wave height, is provided by Bluewater for the Ross and Blake oil and gas field. All cases for simulation, consider T&I of 8 units. The number of activities per unit, depends on whether it concerns the TLP concept or SSB structure, as mentioned in section 4.3. Moreover, to acquire a reliable output of both models, often a large number of simulations needs to be performed. For this study, 1000 Monte Carlo simulations are performed for all cases of both models. Each activity has its own duration, dependent on weather conditions or not. Table 7 specifies, for both the TLP and SSB, the duration of each activity, indicated in timesteps.

Table 7 Duration activities TLP and duration activities SSB

TLP floater unit	Duration [timestep]	Semi-submersible unit	Duration [timestep]
1. TLP transport	4	1. Assembly SSB structure	3
2. TLP installation	3	2. Transport SSB structure	4
3. Transport towers	4	3. Installation SSB structure	1
4. Transport blades	2	-	-
5. Transport nacelles	6	-	-
6. Transfer towers + nacelles	5	-	-
7. Transfer blades	3	-	-
8. Installation WTG	1	-	-
Total duration [timestep]	28	**Total duration [timestep]**	8

5.3 Verification

This section elaborates on the verification of the simulation model. It is evaluated whether the simulation model meets the desired specifications. With this aim, the results of the model for different cases are analysed and compared using existing literature. More precisely, the model results used in this verification are:

- "No weather" case;
- Verification of the project duration;
- Assignment of work and wait hours (workability);
- Right execution of listed activities.

5.3.1 Verification "no weather" case

For this case, weather data is excluded of the simulation models. Weather data is excluded through multiplication of the wind speed and wave height record by 0. By excluding weather data of the simulation models, it can be seen if both models correctly determine the activity durations. That is, what happens to the model if there is no weather impact. For this, both unedited output matrices are displayed in Figure 5-4 (TLP) and Figure 5-5 (SSB). The results as shown in the figures, are solely based on the execution order, conditions and duration of the activities. The first column of both matrices, indicate the number of the activity. Each of the following columns, corresponds to a timestep (1 timestep equals 3 hours).

For the TLP model, this results in the output matrix as shown in Figure 5-4 and for the SSB model, the result is illustrated in Figure 5-5. As can be observed of both figures, no values assigned of 2 are shown in the output matrix. Since no weather data is included, no delay (values assigned of 2) is possible to occur. As only 0, 1 and 100 are presented, this only reflects the duration and execution order of the activities. To check if the number of 1's shown are correctly in the output matrix, that is, the model is working correctly, the number of 1's should be equal to the number of timesteps as shown in Table 7. Figure 5-4 shows 224 times values assigned of 1 in the TLP output matrix. This corresponds to the total timesteps (8 units * 28 timesteps) required for the TLP.

1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100
3	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	0	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	0	0	1	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
6	0	0	0	0	1	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
7	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100

Figure 5-4 Output matrix TLP simulation model excluding weather data, where 0 means; activity did not yet start, 1 means; activity has started/is active, and 100 means; the activity is completed

For the SSB structure, the same check is performed as for the TLP. Figure 5-5 shows 64 times values assigned of 1 in the SSB output matrix. This corresponds to the total timesteps (8 units * 8 timesteps) required for the SSB. Based on both figures, the correctness of the TLP and SSB model is verified without the impact of weather data. As can be expected, the output matrices as shown in Figure 5-4 and Figure 5-5, show a significant difference in size. This difference is due to the different number of activities involved for the TLP concept and SSB structure.

1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100	100	100	100
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100	100	100	100
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100	100	100	100
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	100	100	100	100	100	100	100	100	100
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	100	100	100	100	100
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100	100	100	100

Figure 5-5 Output matrix SSB simulation model excluding weather data, where 0 means; activity did not yet start, 1 means; activity has started/is active, and 100 means; the activity is completed

5.3.2 Verification project duration

For this case, it is verified whether the model correctly determines the project duration. This is checked for both the TLP and SSB simulation model. Figure 5-6 shows the CDF curves for both structures of the average project duration, in days. The distribution is based on 1000 simulations. The starting days of the simulations are randomly selected. Based on the figure, the correctness of the TLP and SSB model to determine the project duration, is verified. Figure 5-6 shows a difference between both CDF distributions, as can be expected. The difference can be explained due to the fact that each structure has its own specific set of operational limits. Moreover, the number of activities involved differ per structure. Also, the durations of the activities are unequal, causing the notable differences in average project duration. Since a larger number of activities is required for T&I of the TLP concept compared to the SSB structure, more and longer weather windows are required, resulting in a longer average project duration for the TLP concept.
Finally, the results as illustrated in Figure 5-6, is what can be expected based on literature (Barlow et al., 2018). In the paper, 10 turbines are installed in a total time of approximately 20 days, using 2 vessels.

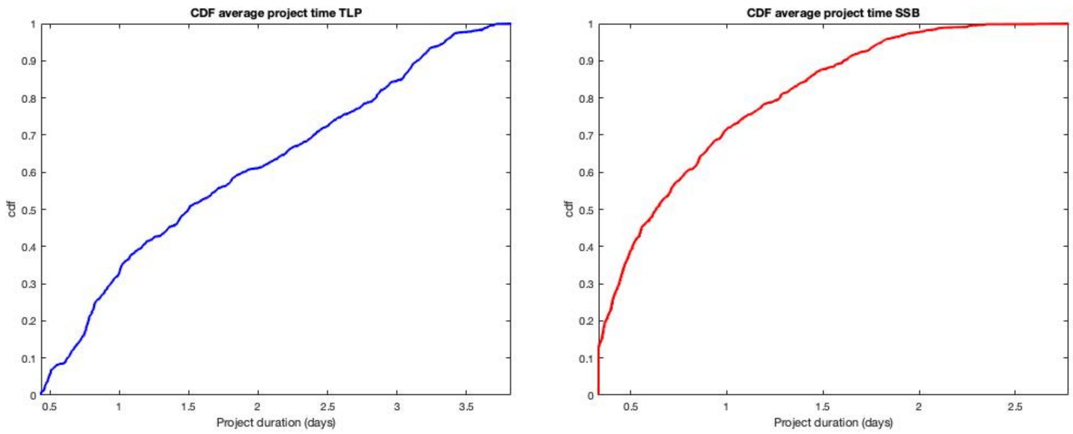


Figure 5-6 Cumulative distribution of the average project duration based on 1000 simulations considering randomly selected starting days over the time period studied

5.3.3 Verification assignment waiting and working time

This check verifies whether the model determines the work and wait times correctly. Figure 5-7 presents the average work and wait times of the simulation for the TLP concept and SSB structure. For both structures, the work and wait times are obtained considering 1000 randomly selected starting days, over the time period studied. To obtain the distribution for average waiting days, the wait times are sorted according to start date. In this way the distributions according to start date are illustrated. The work times are obtained the same way. Compared to wait times, work times are fixed durations and are therefore shown as a constant value, the green bars.

Mostly during winter times more severe environmental conditions are present while during summer months, gentler environmental conditions apply. Harsher weather conditions imply that the operational limits will be exceeded more often, creating more uncertainty. This trend of increasing and decreasing waiting times due to environmental conditions is illustrated in Figure 5-7.

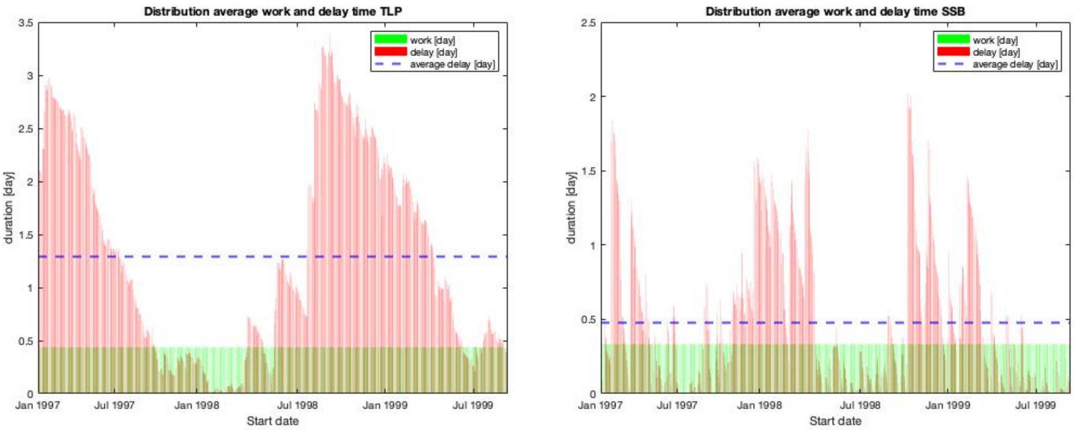


Figure 5-7 Distribution of the average work and wait times [days] based on 1000 simulations considering randomly selected starting days over the time period studied based on starting date

As mentioned, work days are constant as the duration of the activities are fixed and do not depend on the weather conditions. Wait times vary depending on environmental conditions. When comparing the results of the TLP concept and SSB structure, shown in Figure 5-7, it is clear a difference in average waiting times between both structures can be observed. As mentioned earlier, it is expected the TLP concept is less vulnerable to environmental conditions. Therefore, it can be expected that the results of the TLP model shows less waiting time in comparison to the SSB model. This is not visible in Figure 5-7, which shows that on average more waiting time is acquired for the TLP model. This can be explained to the fact that the TLP concept requires more activity that are affected by weather conditions. Eventually, this will result in more delay. Finally, the above mentioned results indicate that the simulation model correctly determines work and wait days for both structures.

5.3.4 Verification execution order activities

For this check it is verified if the obtained results are acquired by the execution of the right sequence of the activities as wanted. That is, if the activities are executed in the correct chronological order. For this, the operational limits and other inputs as specified in section 5.2 are included in the simulation. It is tested whether the model associates the correct duration and start and stopping conditions per activity as specified in the model. A modified output matrix of a single simulation is shown as an example to illustrate how the verification of the execution times has been conducted, although the output matrices of many other simulations have been verified. Figure 5-8 presents an example of a single output matrix for the SSB structure, including 8 units with three activities each. These activities are as described in section 4.2 with corresponding operational limits a shown in Table 6. In the figure, each unit has its own color range.

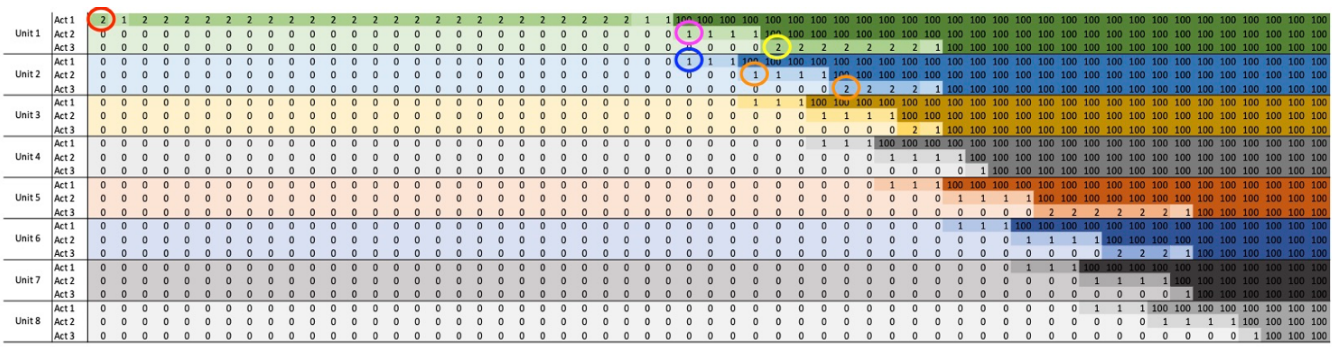


Figure 5-8 Modified output matrix SSB, where 0 means; activity did not yet start, 1 means; activity has started/is active, 2 means; activity is on hold, and 100 means; the activity is completed

For simulation of a SSB structure the following conditions, only activity related, are implemented per unit:

- Activity 1 starts (assigned a value of 2 due to the weather conditions at that timestep) at t = 0 (indicated as red circle in Figure 5-8);
- Activity 2 starts (assigned a value of 1) at the same time the row of activity 1 shows its first 100 (indicated as pink circle in Figure 5-8);
- Activity 3 starts (assigned a value of 2 due to the weather conditions at that timestep) at the same time the row of activity 2 shows its first 100 (indicated as yellow circle Figure 5-8);
- The first activity of the following unit (unit 2) starts at the same time the row of activity 1 of the previous unit shows its first 100 (indicated as blue circle in Figure 5-8);
- Activities 2 (assigned a value of 1) and 3 (assigned a value of 2 due to the weather conditions at that timestep) of unit 2, should be executed according to the previous stated conditions of these activities for unit 1 (indicated as orange circles in Figure 5-8).

The subsequent activities of the following units, are executed under the same conditions as described above. Figure 5-8 illustrates the correct assignment of the activity duration and starting and stopping of the activity. This figure is a good example of a simulation output as it also shows "on holds" (assigned a value of 2). It correctly shows the duration of the activity and when the next activity is supposed to start. The duration of an activity is as described in Table 7. These values should be equal to the number of 1's in the row of that activity. For example, activity 1 of the SSB, has a duration of 3 timesteps. This is visible as three 1's in all rows corresponding to activity 1 in the output matrix of Figure 5-8. The same holds for the other activity durations. If a value of '2' is assigned to the row of an activity in the output matrix, this implies the activity is 'on hold'. In that case it takes longer for it to be completed (delay). So, more time is required for a value of '100' to be assigned to the row of that activity.
As discussed, simulation of the TLP structure includes more key activities. This simulation also results in the same output matrix as shown in Figure 5-8. Only difference compared to the SSB structure is that more activities are required per unit, resulting in a much bigger output matrix. Concluding, the output matrix correctly shows the duration of each activity.

Conclusion
Based on the results presented, it can be concluded that the model performs as intended, reflecting an adequate relationship between the T&I and environmental conditions.

5.4 Validation

A model validation is a process in which model outputs are compared to independent real-world observations to judge the quantitative and qualitative correspondence with reality. However, as mentioned, there is no real data to validate the model. Alternatively, it is a common practice to perform sensitivity analyses of the model to the different input parameters. The results of the sensitivity analysis are then discussed under two perspectives, the trend and the amount of change of the model responds when varying the input parameters. The observed trends when performing such an analysis should reflect the real behavior. For instance, an increment of the wind speed should result in larger values of the project duration. On the other hand, the increment should be realistic, and ben contained in a reasonable range.

The sensitivity analysis is presented in section 6.2, where 4 cases are analysed. This is, the influences of different input conditions are studied. The 4 cases analysed are, the effect of:

- Varying wind speed and wave height;
- Seasonality;
- Varying travel durations;
- Variation of team performance.

5.4.1 Comparison of simulation results to existing literature

In order to determine if the simulation model performs as intended, the obtained values are compared to existing literature. When comparing to existing literature, papers including the installation of a TLP structure are not found. Only papers including transport and installation of a SSB structure. The majority of papers focused on transport and installation of bottom fixed structures. As papers including transport and installation of TLP's structures cannot be compared to, it is chosen to use literature including processes for other floating structures as these types of structures make more sense to compare to. Also, bottom fixed structures are considered.

As result of the comparison, it is found that the simulation model performs accurately. By comparison, the correctness of the influence of environmental conditions on the project time is evaluated. The following show the accurate working of the simulation model:

- Weather limits significant influence the transport and installation times of bottom fixed structures (Beinke et al., 2017). Even though, different parameters are used.
- Scenarios in which weather restrictions are included show for all activities an increase in project time using discrete event simulation (Ait-Alla et al., 2017).
- A paper by Barlow et al., (2018), presents a Gantt chart for installation of 10 WTG's. The Gantt chart includes mostly the same activities for transport and installation as the ones considered in this project. On average 27 days are needed. Also, it is stated that on average the time needed when starting in March, is the lowest. This is also visible in Figure 5-7. Moreover, this also depends on the environmental conditions present at the installation site and the distance to the offshore wind farm from shore. While starting in summer months, installation times may increase with 50%, showing a noticeable variability in task durations. This is in line with the results obtained from the simulation model. As shown in Figure 5-7, during winter months, the project duration shows an increase, around 30-50%, in average waiting times.

6. Results logistics simulation model

This chapter presents the results of simulation of the logistic process of the TLP concept and this is compared to the results of the simulation of the logistic process of the SSB structure. Finally, a sensitivity analysis is performed.

6.1 Results TLP concept vs. SSB structure

This section presents the results of 1000 simulations for both the TLP concept and SSB structure. The results obtained for the TLP concept consider a 3-hour timestep and 8 units with 8 activities each are included. The obtained results of the SSB structure also consider a 3-hour timestep and 8 units with 3 activities per unit. The same weather data as presented in chapter 4 is implemented using randomly selected starting days. In Figure 6-1 the curves of average project duration according to start date for the TLP (left) and SSB (right) in days, are presented.

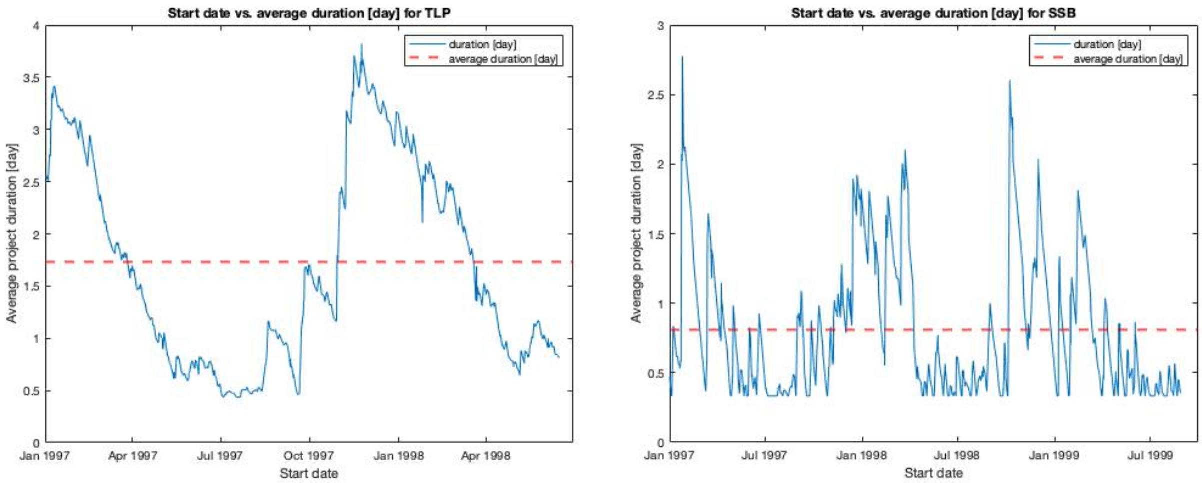


Figure 6-1 Distribution of the average project duration for the TLP (left) and SSB structure (right) in days

Comparing both curves, it can be seen that the results of the SSB model use a longer time span (January 1997 to August 1999). Whereas, the curve of the TLP model show for a shorter time span (January 1997 to May/June 1998). This difference is related to the number of activities, and thus, the total time required to complete these activities. For the TLP structure more activities are included in the model which require more time steps to be completed. That is, based on the 3 years of data used in the model, this is the latest start date, as calculated by the model, the project may start. Otherwise, the project cannot be completed within the time span of the data set. On the other hand, for the SSB structure less activities are included, resulting in less time steps required to finish the project. Since less activities are required for the SSB model, the maximum start date for this structure is further located in the future compared to the TLP model. This explains the differences visible for the considered time period of the figures. The gap on the right side of the figure indicates the project can be completed within the time span of the data set. That is, if not enough data is left to be able to finish the simulation, the project will not start and the model will select another start date instead.

Both figures also show the response of starting in different seasons. The average duration over all simulations is 1.7 days for the TLP and 0.8 days for the SSB. Starting during winter times, results in higher average project durations while starting more towards spring or summer months, the average project duration for both structures decreases. As can be seen from both curves, the SSB structure shows sharp increases and strong declines in project duration. This in contrast to the TLP concept which shows slight increases and decreases. The TLP shows over a longer time period, higher durations and for example, slowly decreases towards summer months. The SSB shows sudden changes within a shorter time period, shows more fluctuating results. This difference can be explained by the fact that the SSB structure requires less activities. Resulting in a shorter time period in which the project is completed. Also, the SSB structure requires les weather windows, as less activities are required. This decreases the weather uncertainty. Concluding, sudden changes in weather are therefore really notable for the SSB structure.

For both structures, the minimum, maximum and average project duration are plotted in Figure 6-2. As can be seen from the plots, the distribution of the maximum project duration follows more or less the same trend as the plots of Figure 6-1. During winter months, it is highly unlikely that a project can start at the selected start date, as harsher weather conditions can be expected during this time of the year. This is why the highest durations are observed during winter times. On the contrary, during summer months, when less severe weather conditions are present, it is more likely a project can start at the selected start date. In that case, less or not delay can be expected, resulting in lower maxima during summer months compared to the maximum durations during winter months.

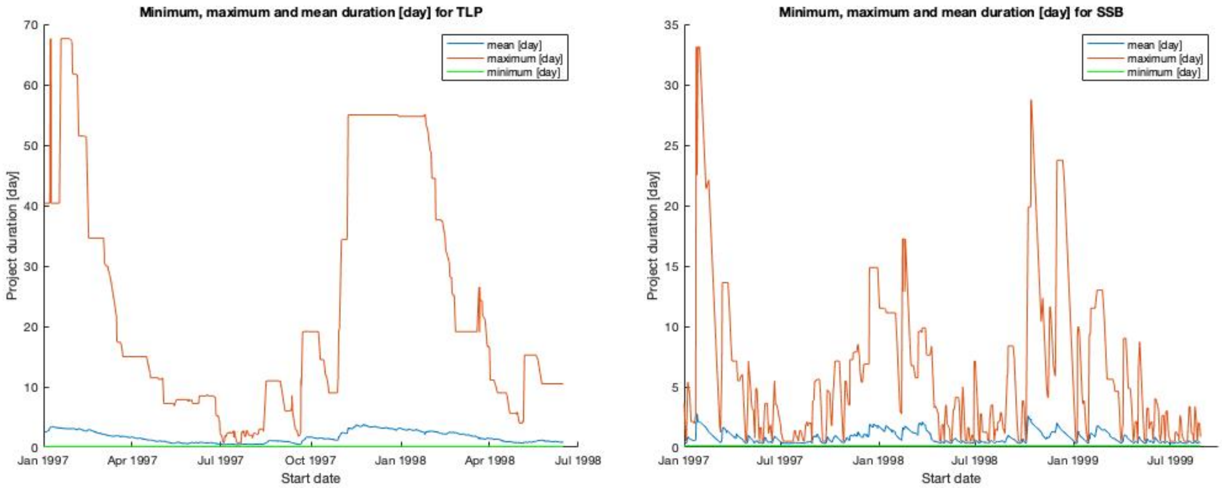


Figure 6-2 Distribution of minimum, maximum and average project duration according to starting date

Over the considered time span of both structures, the maximum duration for the TLP concept is almost twice as high compared to the maximum of the SSB structure. The fact that the curve of the SSB structure shows more fluctuations, can be explained by the fact that for the SSB structure a longer time period is considered due to the fewer activities involved compared to the TLP concept. As explained earlier, the SSB simulation model can use a longer time period of the used data set as it requires less time to finish, so a start date closer to the end of the data set can be selected. For the TLP concept, this is not the case as it takes relatively long to install the TLP more time should be in between the latest start date and the end of the data set to be able to finish the simulation. The values over which the maximum, minimum and average values reach, are summarized in Table 8.

Table 8 Ranges of the maximum, minimum and average curves

	TLP concept	SSB structure
Maximum values	0.75 – 67.6 days	0.5 – 33.1 days
Average values	0.4 – 3.8 days	0.3 – 2.7 days
Minimum values	3 hours	3 hours

The fact that the minimum value is constant throughout all simulations, can be explained by the fact that the minimum value is calculated as the sum of the work and wait times. If, at a start day no delay is present, and the duration of the shortest activity is 3 hours, this value is the minimum value present. Throughout all start dates, the duration of the shortest activity, without delay, is the minimum value (3 hours). This explains why the curve of the minimum duration results in a constant value of 3 hours. Additionally, it is chosen to describe the minimum value in hours instead of days to illustrate how the minimum duration relates to the shortest duration of an activity. For both structures, the duration of the shortest activity is 3 hours.

Figure 6-3 presents the results of the calculation of the average work and delay time per activity for the TLP and SSB model. From the plots, it can be seen that for the TLP concept, activity 2 causes most of the delay, on average 51.6 days. Activity 2 covers installation of the TLP floater, as described in Table 5. For the SSB structure, it can be observed that activity 1 on average causes most of the delay, on average 8.7 days. Activity 1 of the SSB structure covers assembly of the SSB substructure, as described in Table 6. Both activities are executed in early stages of the project. When taking the operational limits of the activities that cause most of the delay into consideration, it can be seen that these activities, for both structures, have the lowest operational limits. For the TLP concept that is, 1 m wave height and 13 m/s wind speed. For the SSB structure that is, 1.5 m wave height and 13 m/s wind speed. For both structures account that the activities with the lowest wave height operational limit cause most of the delay. Compared to the results of the performed sensitivity analysis for increasing wind speed and wave height records, it can be seen that an increase in wave height causes the most sensitive changes for both structures. This can explain the fact that the activities for which the lowest operational limit for wave height accounts, show the most of the delay of all activities involved for both structures.

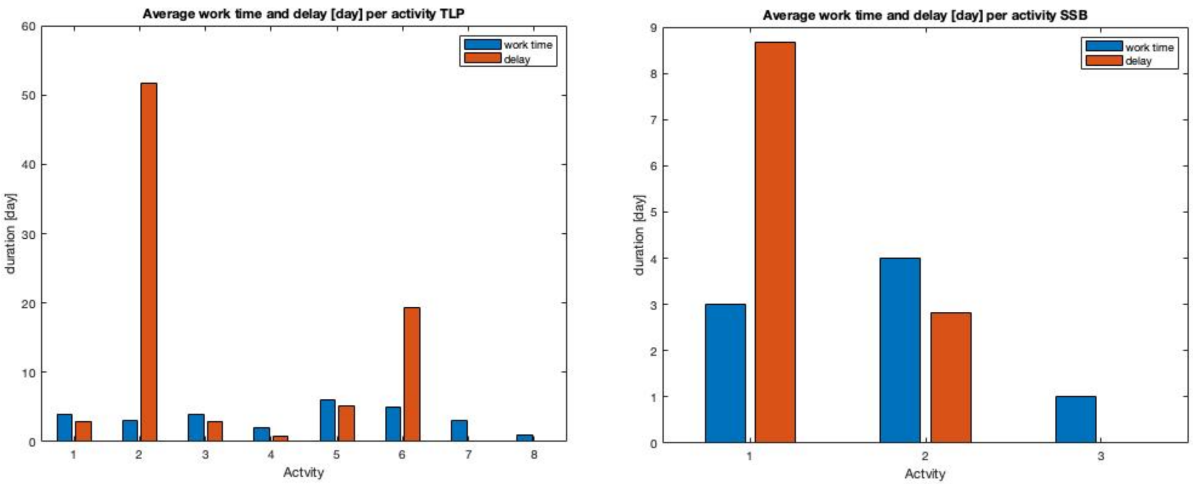


Figure 6-3 Average work time and delay plot per activity

The activity that causes most of the delay for both structures, indicates that this activity is most sensitive to weather conditions and is therefore the activity that affects the logistic process the most. Even though, it does not seem to affect the other activities as well.
There is no link between the duration of the activity and the delay it is causing. For example, activity 5 of the TLP has the longest duration while it does not cause most of the delay. Compared to the SSB structure, this also accounts. Activity 2 has the longest duration but does not cause most of the delay. This points out that delay mostly depends on the weather conditions and the operational limit for that activity. On the other hand, activities with the shortest duration (activity 8 for the TLP concept and activity 3 for the SSB structure) show no delay at all. As can be observed from the plots, delay due to transport of the TLP floater (activity 2), does not cause any additional delay to other activities. This can be related to the two phased installation approach creating two independent supply chains.

Comparing the discussed results to the result of the "no weather" case in section 5.3.1, it can be well observed how environmental conditions affect the T&I stages of both structures. The "no weather'' case, solely presents the duration of the activities. Compared to the results discussed in this section, for which weather data is included, it can be seen that environmental conditions have a significant influence on the project duration (Figure 6-1). Finally, it turns out that primarily the TLP concept is affected by the weather as most of the delay is shown for the TLP concept.

6.2 Sensitivity analysis

As mentioned in section 5.4, this section will elaborate on the performed sensitivity analysis as part of the validation since no real data to compare with, is available. The following 4 cases are studied: varying wind speed and wave height, seasonality, varying travel time and finally, varying the team performance.

6.2.1 Sensitivity analysis 1: varying wind speed and wave height

This section will discuss the sensitivity analysis for variation of wind speed and wave height. First, the variation of wind speed is studied.

Variation of wind speed

In this case, the effect on the project duration when increasing the wind speed record is analysed. To do so, the records of wind speed used in this project are multiplied by a coefficient. In this way, harder wind conditions are simulated. The wind speed data is multiplied by 1.01, 1.05, 1.10, 1.15, 1.20 and 1.25, respectively. Table 9 and Table 10 show the results for the TLP and SSB structure, when the wind speed record has been increased. Due to the increased wind speed, the workability will decrease as the probability increases that the operational limits are exceeded. This results in increasing waiting times. Consequently, the overall project duration will increase. This discussed trend can be seen in Table 9 for the TLP concept and in Table 10 for the SSB structure. Each coefficient has a randomly selected start date. This explains why for an increasing coefficients no ascending start dates are visible. Instead, random start dates over the considered time span of the study are shown.

Table 9 Results of variation of wind speed records for the TLP structure

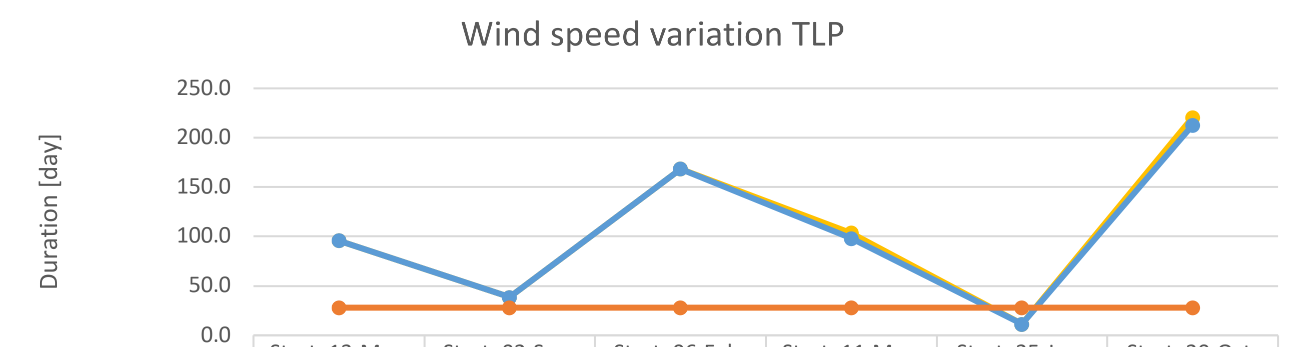
TLP variation wind speed												
Coefficient	1.01		1.05		1.10		1.15		1.20		1.25	
Start date	13-Mar-1998		02-Sep-1997		06-Feb-1997		11-Mar-1998		25-Jun-1997		20-Oct-1997	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	28	95,9	28	38,6	28	168,4	28	103,7	28	11,5	28	220,7
No coefficient	-		-		-		-		-		-	
Start date	13-Mar-1998		02-Sep-1997		06-Feb-1997		11-Mar-1998		25-Jun-1997		20-Oct-1997	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	28	95,9	28	38,6	28	168,4	28	98,1	28	11,5	28	212,8

Table 10 Results of variation of wind speed records for the SSB structure

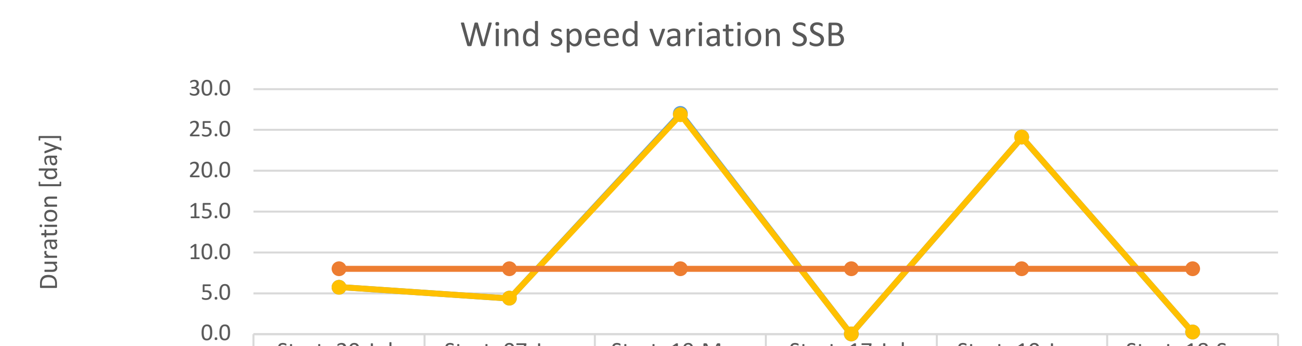
SSB variation wind speed												
Coefficient	1.01		1.05		1.10		1.15		1.20		1.25	
Start date	20-Jul-1999		07-Jun-1998		19-Mar-1997		17-Jun-1999		10-Jan-1998		18-Oct-1998	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	8	5,7	8	4,4	8	27	8	0	8	24,1	8	0,25
No coefficient	-		-		-		-		-		-	
Start date	20-Jul-1999		07-Jun-1998		19-Mar-1997		17-Jun-1999		10-Jan-1998		18-Oct-1998	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	8	5,7	8	4,4	8	26,9	8	0	8	24,1	8	0,25

Due to the increased wind speed record with a coefficient, an increment in waiting hours is notable for the TLP model when increasing the records of wind speed with 15% and 25%. That is, an increment of 5.7% and 3.7% of waiting hours, respectively. It should be noticed that, when increasing the wind speed record with 20% for the TLP model, no increment is visible. This can be related to the fact that for this coefficient a start date during summer is selected (25th of June 1997), during which softer environmental conditions are be present. On the other hand, for the SSB model, only one coefficient (1.10) shows a minimal increase in waiting times (0.5%). The fact no differences are visible, can be explained by the fact that the increment of the wind speed record after multiplication is so small, that this increase does not affect the operational limits, especially

during spring and/or summer months. Moreover, when starting T&I during winter months, more delay may be expected. This trend is summarized in Figure 6-4.
The delay for the SSB structure seems to be realistic. For these starting days, the maximum waiting time is 27 days. For the TLP the highest wait times are observed after increasing the wind speed record with 25%, approximately 221 days. Also, on the same start date without coefficient, a significant number of waiting days can be seen, approximately 213 days. For both, with and without coefficient, this seems to be fairly high. This can be explained by the fact that during that time period, a storm is present as winter months are approaching. This storm may cause extra high wind speed records by which the operational limits are easily exceeded. On the other hand, it is remarkable to see that for example, when increasing the wind speed for the SSB structure with a factor 1.10, this results in an increment of 3 hours waiting time while the subsequent factors (1.15, 1.2 and 1.25), show no increase in waiting time at all. Compared to the TLP, only for increasing with a factor 1.15 and 1.25, an increment can be seen. This can indicate that the TLP concept is more vulnerable to increasing wind speed records than the SSB structure.
Also, Figure 6-4 points out that the month in which the project is started causes increasing or decreasing waiting times. For example, when starting in December, a higher number of waiting times can be expected in comparison to start dates in July. The discussed results, and as illustrated in Table 9 and Table 10, are summarized in Figure 6-4.



	Start: 13-Mar-1998, coeff 1.01	Start: 02-Sep-1997, coeff 1.05	Start: 06-Feb-1997, coeff 1.10	Start: 11-Mar-1998, coeff 1.15	Start: 25-Jun-1997, coeff 1.20	Start: 20-Oct-1997, coeff 1.25
coeff delay	95.9	38.6	168.4	103.8	11.5	220.8
no coeff delay	95.9	38.6	168.4	98.1	11.5	212.9
work time	28	28	28	28	28	28



	Start: 20-Jul-1999, coeff 1.01	Start: 07-Jun-1998, coeff 1.05	Start: 19-Mar-1997, coeff 1.10	Start: 17-Jul-1999, coeff 1.15	Start: 10-Jan-1998, coeff 1.20	Start: 18-Sep-1998, coeff 1.25
coeff delay	5.8	4.4	27.0	0.0	24.1	0.3
no coeff delay	5.8	4.4	26.9	0.0	24.1	0.3
work	8	8	8	8	8	8

Figure 6-4 Summary wind speed variation TLP and SSB structure

Variation of wave height

For this case, the wave height is varied. The wave height is varied by multiplication with the same coefficients as in the previous case (1.01, 1.05, 1.1, 1.15, 1.20 and 1.25). If the wave height record is increased, this may result in an increasing possibility that the operational limits of the activities are exceeded. Consequently, this results in a decreasing workability. That is, increasing project duration as delay (waiting times) are increasing. As accompanying result, the total project duration will increase. It is expected that the work time remain the same This regardless the increase in wave height as the durations of the operations are fixed and are not affected by the wave height. Solely delay depends on environmental conditions as this is caused by exceeding the pre-scribed operational limits. This expected trend is illustrated in Table 11 and Table 12 for the TLP and SSB, respectively. Both tables illustrate the effect on the delay when including or excluding a coefficient to the wave height record. For the TLP model it is shown that for all coefficients an increment in waiting times is visible. That is, increments of 11%, 1%, 18%, 8%, 35% and 31% can be observed. Increments of 0%, 0%, 1%, 100%, 123% and 50% are observed for the SSB structure.

Table 11 Results of variation of wave height records for the TLP structure

TLP variation wave height												
Coefficient	1.01		1.05		1.10		1.15		1.20		1.25	
Start date	13-Mar-1998		02-Sep-1997		06-Feb-1997		11-Mar-1998		25-Jun-1997		20-Oct-1997	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	28	106,6	28	39,1	28	200	28	106,7	28	15,6	28	280,1
No coefficient	-		-		-		-		-		-	
Start date	13-Mar-1998		02-Sep-1997		06-Feb-1997		11-Mar-1998		25-Jun-1997		20-Oct-1997	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	28	95,9	28	38,6	28	168,4	28	98,1	28	11,5	28	212,9

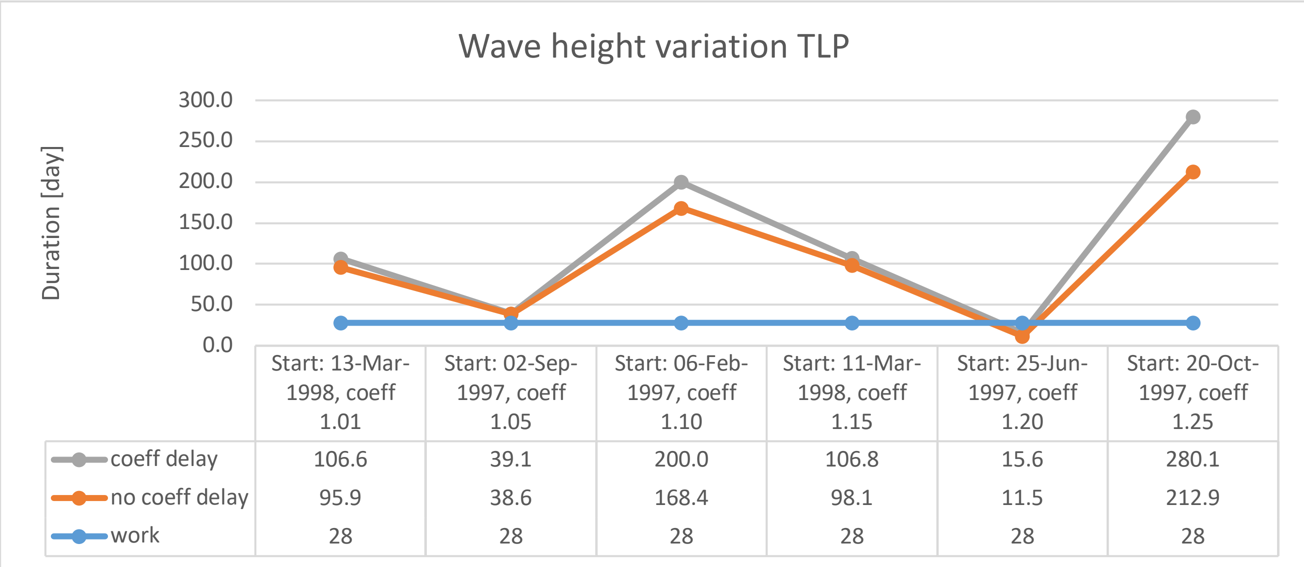
Table 12 Results of variation of wave height record for the SSB structure

SSB variation wave height												
Coefficient	1.01		1.05		1.10		1.15		1.20		1.25	
Start date	20-Jul-1999		07-Jun-1998		19-Mar-1997		17-Jun-1999		10-Jan-1998		18-Oct-1998	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	8	5,1	8	6	8	26,4	8	1,7	8	35,7	8	0,4
No coefficient	-		-		-		-		-		-	
Start date	20-Jul-1999		07-Jun-1998		19-Mar-1997		17-Jun-1999		10-Jan-1998		18-Oct-1998	
Work/wait [day]	work	wait	work	wait	work	wait	work	wait	work	wait	work	wait
# days	8	5,1	8	6	8	26	8	0	8	16	8	0,25

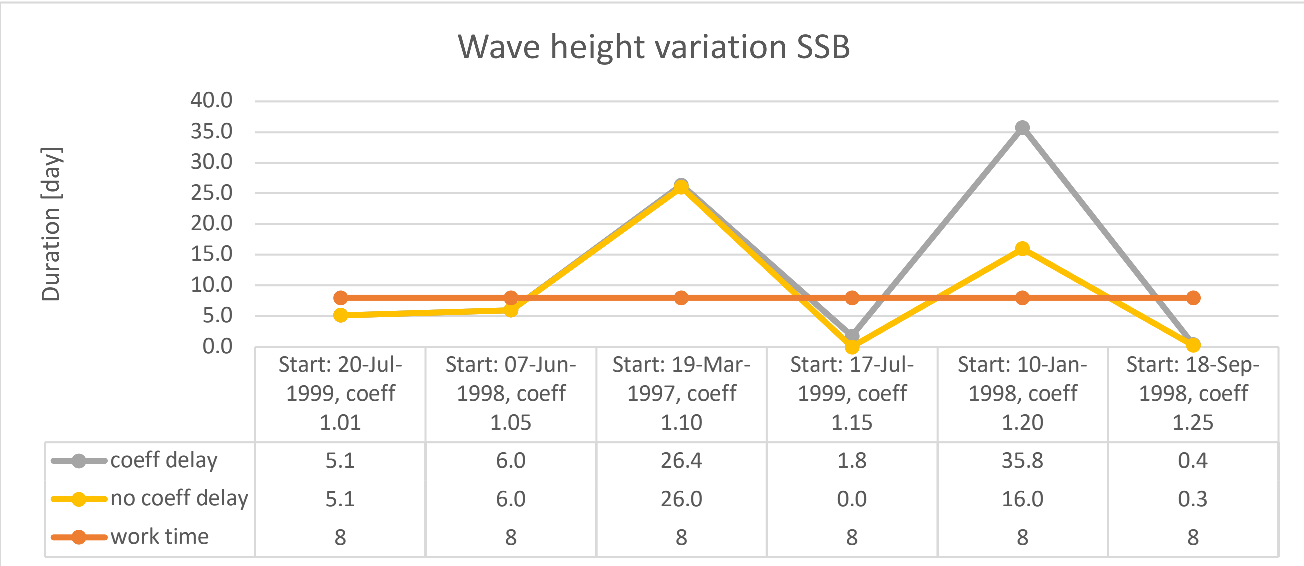
Comparing the increments of both structures, the anticipated trend of that an increase in wave height will result in an increase in wait times. The SSB seems to be the most affected by increasing wave height with a coefficient of 1.15, 1.20 and 1.25. This is in line with what can be expected when increasing the wave height with a coefficient. While the TLP is mostly affected by increasing with a coefficient of 1.20 and 1.25. In general, is seems that the TLP is more sensitive when increasing wave heights compared to the SSB. For the TLP more sensitive changes can be seen.

In general, an increase in wave height results in increasing number of waiting days. While the wait times seem to be less realistic. For the TLP, the highest wait time is 280 days. Even though that this seems to be unrealistic, Barlow et al., (2018), present 535 days for a project that is mostly executed during winter months. It should be mentioned that this article considers installation of bottom fixed structures.

The discussed trends are summarized in Figure 6-5. The plots show that, if an increment is observed, this increment is higher during winter months compared to summer months, where no increase or a small increase in waiting times can be observed.



	Start: 13-Mar-1998, coeff 1.01	Start: 02-Sep-1997, coeff 1.05	Start: 06-Feb-1997, coeff 1.10	Start: 11-Mar-1998, coeff 1.15	Start: 25-Jun-1997, coeff 1.20	Start: 20-Oct-1997, coeff 1.25
coeff delay	106.6	39.1	200.0	106.8	15.6	280.1
no coeff delay	95.9	38.6	168.4	98.1	11.5	212.9
work	28	28	28	28	28	28



	Start: 20-Jul-1999, coeff 1.01	Start: 07-Jun-1998, coeff 1.05	Start: 19-Mar-1997, coeff 1.10	Start: 17-Jul-1999, coeff 1.15	Start: 10-Jan-1998, coeff 1.20	Start: 18-Sep-1998, coeff 1.25
coeff delay	5.1	6.0	26.4	1.8	35.8	0.4
no coeff delay	5.1	6.0	26.0	0.0	16.0	0.3
work time	8	8	8	8	8	8

Figure 6-5 Summary wave height variation TLP and SSB structure

Conclusion

The sensitivity of both structures when increasing wind speed and wave height is analyzed. This test is performed by introducing variation in the wind speed and wave height input. Both inputs are separately varied based on multiplication with a coefficient ranging from 1.01 to 1.25. For both models, simulation was run varying the input in order to obtain the influence these parameters have on the overall project duration. The results point out that, that when a coefficient is applied to the wave height record, a bigger increment in waiting hours is notable compared to increasing the record of the wind speed. From this is can be concluded that wave height is more limiting than increasing wind speed record. Both structures are most sensitive to increasing the wave height record. Moreover, the TLP structure shows the most sensitive changes when increasing the wave height compared to the SSB structure.

6.2.2 Sensitivity analysis 2: seasonality

The goal of this sensitivity analysis is to determine the influence of starting T&I during winter or summer months. The results of sensitivity of variation in starting day, is illustrated in Figure 6-6. The figure illustrates the results of variation in starting day according to season for the TLP concept and SSB structure, respectively. To obtain the results, simulation was started during winter or summer months. For winter season, starting dates range from November to March. For summer season, start dates range from June to September. According to the acquired results in Figure 6-6, it can be validated if the acquired results make sense. The horizontal line presents the average duration over all considered start dates (1000 simulations).

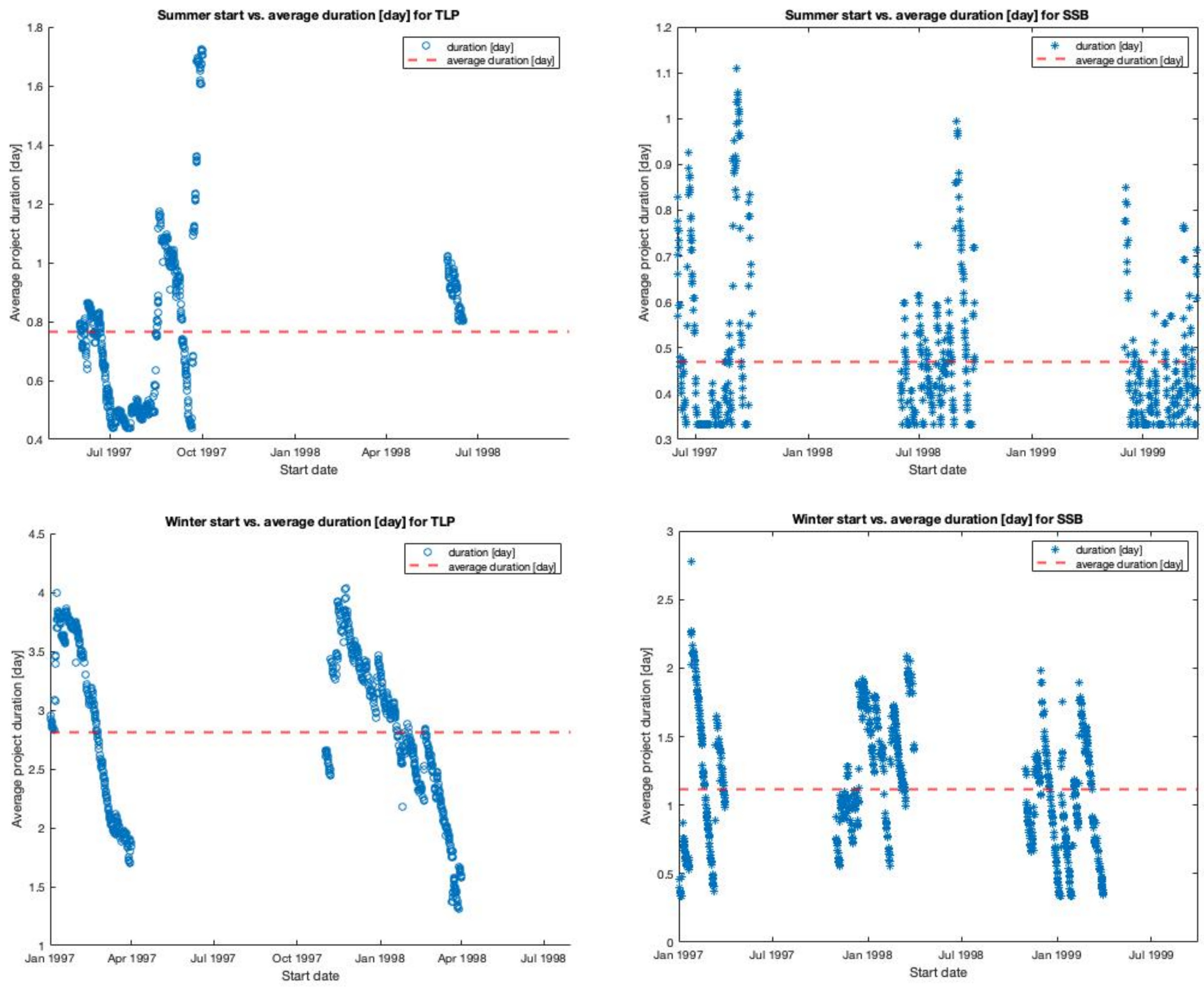


Figure 6-6 Distribution of average project duration for randomly selected starting days during summer and winter months

The figure indicates that variation in starting day has a significant effect on the average project duration. It can be seen that when a starting day during winter season is selected, the average duration significantly increases. When starting during summer, the average project duration is much lower. It is visible that once spring is approaching, the project duration decreases. During winter and summer times, remarkable peaks are noticeable. This can be explained due to extreme weather conditions. In general, winter season is known for more severe weather conditions. The earlier a random start day during winter months is selected, the longer the average project times. This trend is also visible in Figure 6-6, when starting "earlier" in winter season will result in longer project times than when starting later in winter season. Then the required times are linearly decreasing. For summer season applies that when summer months are approaching, June/July/August, the average times decreases. As soon as summer season is ending, the project times rises again.

Most of the time during winter months harsher weather conditions apply and thus, an increase in total project duration can be expected. This is also visible in Figure 6-6. However, some peaks during summer time can be observed. While during summer times, normally, weather conditions are less severe, this results in less time needed to complete the project as a small number of delay may be expected.
Comparing the results of both structures for start dates during summer months, it can be observed that the results of average project times are more or less the same. During winter season, the figure for the TLP concept shows a bit higher average compared to the average project duration of the SSB structure during winter months. This makes sense as this can be assigned to the fact that the TLP model includes more activities, and thus, a longer project time. Moreover, this trend can be assigned to the combination of the TLP concept requiring more activities and the fact that during summer months there is a lower possibility that the operational limits are exceeded. That is, the distributions of starting during summer months in this case primarily show the working times. Since not that much waiting times can be expected. While the TLP concept requires higher work times compared to the SSB structure, this explains why this anticipated trend for the TLP concept indeed shows a higher average time.

The scatter diagrams of both structures follow the same trend (see Figure 6-6). It is indicated that when starting during winter time, more sensitive changes are produced regarding the average project duration of both structures. Starting from June to September has the lowest sensitivity changes on the average project time. Furthermore, starting from November to March, has the highest sensitivity changes. This anticipated trend is visible for both structures. It can be seen that for both TLP concept and SSB structure, the model well establishes the relation between starting the project in different season seasons and harsher weather conditions. The obtained values of the average project duration vary per season, as anticipated. The scatter diagrams point out that for the TLP concept more fluctuating changes are observed compared to the mean value. This indicates that the TLP concept is more affect by starting in different seasons, especially winter months.

6.2.3 Sensitivity analysis 3: varying travel duration

In this section, the third case is described. The duration of activities which involves travelling, are varied. The influence of variation of the distance to the work site location is studied. For the base case, 11.1 hours of transport for both TLP concept and SSB structure is required. Activities including traveling are multiplied by a factor 1, 1.5, 2 and 2.5. The base case (coefficient of 1) is included as reference. Figure 6-7 shows the average project duration for variation of the travel durations for the TLP and SSB model.

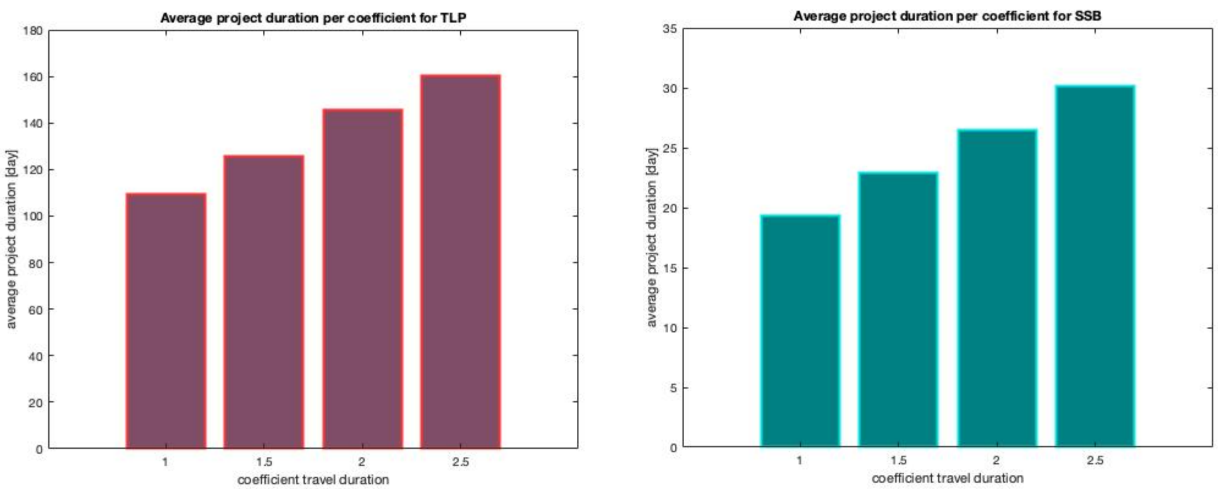


Figure 6-7 Evolution variation of travel duration for the TLP and SSB structure

It can be seen that with increasing travel times, also the total project duration increases. This is in line with what can be expected. If more time is needed to complete a travel activity, the overall project duration is affected and will therefore increase. The longer the time that is required for transportation activities, the higher the total project duration will be. These rises resemble with what can be expected and this trend is visible in Figure 6-7. As for coefficient 2.5 the highest increment (compared to the base case) can be observed (approximately 46% for the TLP and 57% for the SSB), the distribution of this coefficient is plotted in Figure 6-8 for both TLP concept and SSB structure. When the coefficients of the TLP are mutually compared, it is observed the lowest sensitivity changes exist between coefficient 2 and 2.5 (10%) while for the other coefficients (1, 1.5 and 2) a higher increment is observed (15%). Moreover, for the SSB the following increments between the coefficients are observed: approximately 20%, 14% and 13%, for increasing coefficients, respectively. As illustrated, both the TLP concept and SSB structure follow the same trend while the increment of the SSB structure is higher. Therefore, the SSB structure is more sensitive to variation of the travel duration.

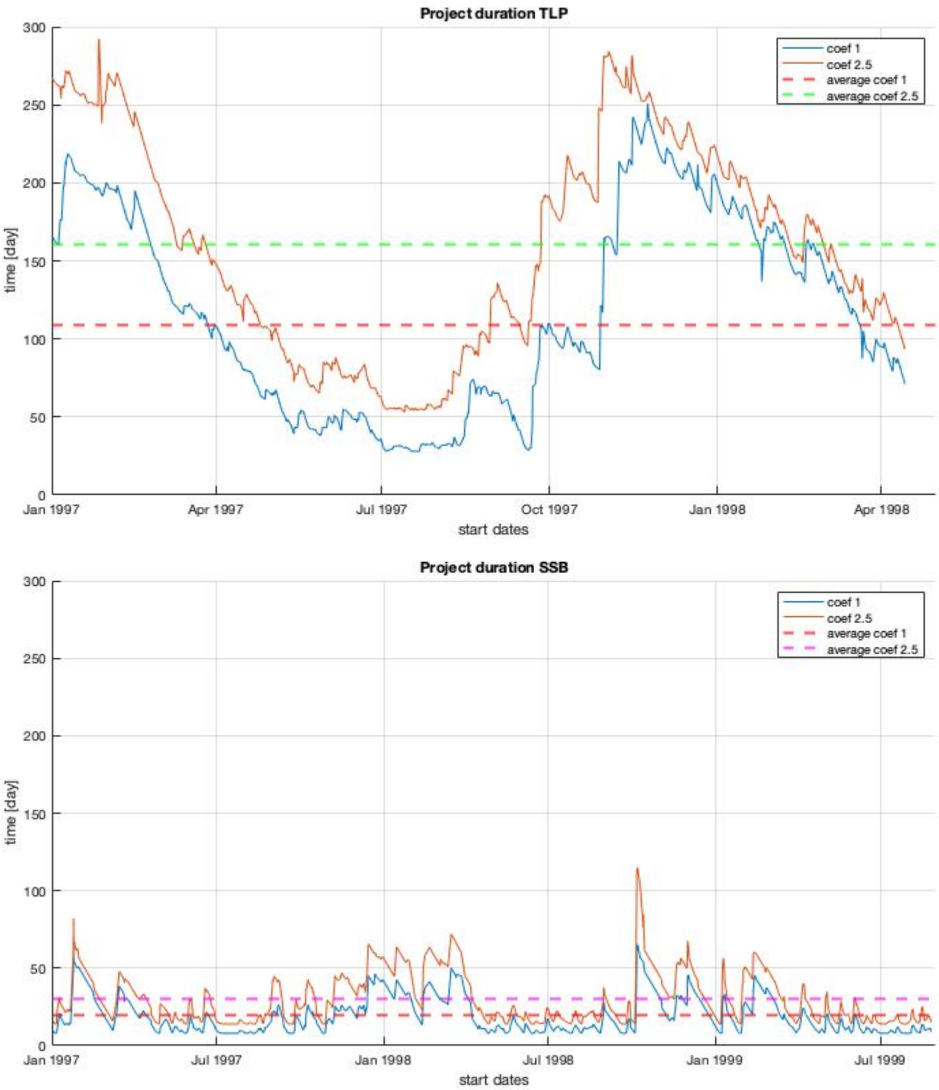


Figure 6-8 Distribution of variation of the travel duration for the base case (coefficient 1) and for coefficient 2.5 for the TLP (top) and SSB (bottom) structures

Figure 6-8 illustrates the distribution of the project duration for both the base case and for coefficient 2.5. As illustrated, the curves of both coefficients follow more or less the same trend. This is in line with what can be expected when travel durations increase. On average (coefficient of 1) for the TLP concept, the project duration is approximately 109 days. After increasing (coefficient of 2.5), the average project duration also increases, 160 days. This is an increase of 47%. For the SSB structure, on average (coefficient of 1) the project duration is approximately 19 days while after increasing with a coefficient of 2.5 the average project duration increases to 30 days. This is an increase of 58%. Compared to the TLP concept, the SSB structure shows the highest increase between the base case and increasing with a coefficient of 2.5. Additionally, from this figure it is indicated that the SSB structure shows more sensitive changes when increasing the travel duration compared to the TLP concept.

6.2.4 Sensitivity analysis 4: team performance

Figure 6-9 presents the results for variation in team performance. Team performance is introduced in this model as the time required by the team to finish the activities. For this, the time is varied by multiplying all activities with a coefficient, except the activities involving transport. Travel activities are excluded as the travel distances cannot be influenced by performance. These are fixed values and therefore remain the same.

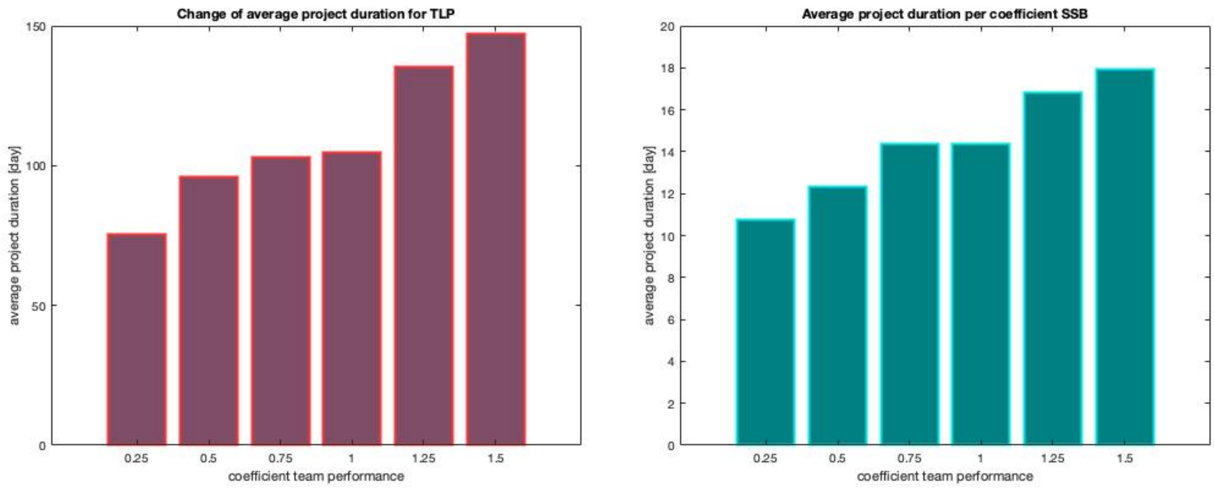


Figure 6-9 Evolution variation of team performance for the TLP concept and SSB structure

The time to finish the activities are multiplied by 0.25, 0.5, 0.75, 1, 1.25 and 1.5. Also for this case coefficient of 1 is the base case and is added as reference. Multiplication with a coefficient smaller than 1, evaluates what happens if the team performs well that is, works faster. Multiplication by 1.25 and 1.5 indicates the team does not perform well and less work is done is the same time period. The trend of the average project duration for both the TLP and SSB model is in line with what can be expected. If a project team works faster, the project duration will decrease in comparison to the base case. Moreover, if the team does not perform well, the project duration will increase, compared to the base case. This trend is visible in Figure 6-9. For the SSB structure, multiplication with 0.75 result in the same duration compared to the duration of the base case. This can be explained by the fact that activities can end but not start in between time steps. Therefore, the value of 0.75 is rounded up resulting in the same duration as the base case.

The results of Figure 6-9 indicate that decreasing productivity with a factor 0.75, produces the lowest sensitivity to the time required for the project (< 1%). Moreover, increasing team performance with 50% (coefficient of 1.5) indicates the biggest sensitivity change for the average project duration. This is an 22% increment for the SSB structure and a 40% increment for the TLP structure.

The TLP concept involves more activities than the SSB structure and the travel distance and travel speed remain the same for both structures. Both structures follow the same expected trend when increasing or decreasing team performance but the highest increment is observed for the TLP structure. Concluding, this structure is more sensitive to changes in team performance compared to the SSB structure.

7. Conclusions

To conclude this thesis, this chapter cites the conclusions of the research and gives recommendations for future research. Answers to the main question and sub questions, as given in chapter 1, will be provided.

7.1 Conclusions

The objective of this thesis is to compare the logistic process of the TLP concept to the logistic process of a float-out based semi-submersible structure in order to evaluate whether the newly developed TLP concept can be a realistic alternative. This is established by development of a simulation tool for both structures. An important aspect of the research was to study to what extend environmental conditions affect the logistic processes. By answering the sub-questions, the main research question is given answer to.

1. How does the logistic process of the BLUE-STAR Tension Leg Platform relate to the logistic process of a float-out based semi-submersible structure?

To investigate how the logistic process of the TLP concept relates to the logistic process of a SSB structure, both logistic processes are assessed. It is observed the logistic process of the TLP concept and SSB structure have significant differences.

The logistic process of the TLP has a two phased approach, creating two independent supply chains. A supply chain for the floater and a supply chain for the WTG. Either phase of the logistic process includes the TLP floater. The floater is transported on a barge, towed by tugboats. At the offshore installation site, the TLP floater is hooked to the pre-installed mooring lines and ready to receive a wind turbine. The other phase includes the WTG components. The components are transported by the so called, "offshore feeder-ship concept". That is, they are transported to the offshore installation site each from their own production yard. At the offshore installation site, the WTG components are assembled followed by installation of the wind turbine on the pre-installed TLP floater. This concept ensures that the more expensive installation vessel can be optimally used offshore while the less expensive transportation vessels travel back and forth delivering the WTG components. In comparison to T&I of SSB structures this two phased approach is seen as an advantage as the SSB structure is considered to be more sensitive to weather conditions.

The logistic process of SSB structures has a different approach. The logistic process of a SSB structure consists of one phase. That is, one supply chain. The components are transported from their production yards to the marshalling yard after which they are assembled. In the meantime, a SSB substructure is positioned along the quay and prepared to receive the top structure, the wind turbine. After installation of the top structure, the fully equipped system is towed, by tugboats, to the offshore installation site. Arrived at the installation site, the structure is hooked to the pre-installed mooring lines, de-submerged and hereafter, ready for use. As a SSB structure is transported as a fully equipped system, less activities are involved for the logistic process compared to the logistic process of the TLP concept.

An important aspect after comparison of both logistic processes is the fact that the logistic process of the TLP concept seems to be less complex and seems to be less vulnerable to environmental conditions as the supply chains are separated. On the other hand, more activities are required for the logistic process in a way that you can expect it to be more complex. Also, this results in the structure being more vulnerable to weather conditions.

2. Which part of the transport and installation stages, of both the TLP concept and SSB structure, cause most of the delay?
To answer this question, it is investigated which activities cause most of the delay and in what part of the project they affect. For this, the wait times per activity for both structures are calculated. The average over 1000 simulations is considered to obtain the most reliable result.

It is observed that for the TLP concept, most of the delay (on average 51.6 days) is caused by activity 2, installation of the TLP floater. For the SSB structure, most of the delay (on average 8.7 days) is caused by activity 1, assembly of the SSB substructure. Both activities are executed in early stages of the project. The operational limits of these activities are the lowest of all operational limits of the activities included in this research. For the TLP that is, 1 m wave height and 13 m/s wind speed. For the SSB structure that is, 1.5 m wave height and 13 m/s wind speed. It is observed that the activities with the lowest operational limit for wave height, cause most of the delay.
Regarding the results of the performed sensitivity analysis for variation of wind speed and wave height records, it was shown that variation of wave heights creates the most sensitive changes to both structures. It follows from this that the activities which have the lowest operational limits for wave height, cause most of the delay. Compared to activity 1 of the SSB structure, activity 2 of the TLP causes more delay. For both, the delay is triggered in early stages of the project. Concluding, activity 2 of the TLP concept and activity 1 of the SSB structure cause most of the delay. Considering the height of the delay, in particularly the TLP concept is most sensitive to environmental conditions, especially for wave height.

3. Can the developed simulation model assess optimal project installation time for the TLP concept and SSB structure?
In order to determine whether the model can assess optimal project installation time, first two simulation models were developed. For this, two simulation models are designed, one for the TLP concept and one for the SSB structure. As the logistic processes, which are simulated with the use of the designed models, are mainly affected by environmental conditions, the weather conditions as provided by Bluewater for the Ross and Blake oil and gas field in the North Sea, are implemented in the model. The provided weather data set exists of the maximum wind speed and maximum wave height data for the years 1997 – 2001, with a 3-hour time interval. After reviewing the complete data set and based on the curves of the maximum wind speed and wave height (see Figure 5-3), it was decided to use the data of the years 1997, 1998 and 1999.
The durations of the activities including their limiting conditions are pre-scribed to the model. The conditions specify whether an activity can start, continue or finish based on the set operational limit for the activity. Other input parameters pre-scribed to the model are: the number of units that will be installed, the order in which the activities are executed by the model and finally, the number of simulations. With these model inputs, the simulation model can assess the project installation time.

The project installation time obtained for both structures by the simulation model, is visualized in different ways. In Figure 6-1, the distribution of the average project duration according to start date, is illustrated. For the TLP concept, peaks are shown ranging from 3 to 4 days during winter months and declines ranging from 0.5 to 1 day during summer months. The average duration over all simulations is 1.7 days for the TLP concept. For the SSB, peaks fluctuate more throughout the considered data while these are higher during winter months, with the highest being approximately 2.7 days. Also, fluctuating declines can be seen. The average duration over all simulations is 0.8 days for the SSB structure.

Another way by which the optimal project duration is assessed, is with the use of a calculated curve containing the minimum, maximum and average days according to start date (Figure 6-2). Table 13 presents a summary including the ranges of the maximum, minimum and average curves. The minimum solely consists of one value, 3 hours. That is, it presents the minimum duration of the sum of the work and wait times. If no delay is included, it will display the shortest duration of an activity, which is 3 hours for both structures.

Table 13 Summary of the maximum, minimum and average durations

	TLP concept	SSB structure
Maximum values	0,75 – 67,6 days	0,5 – 33,1 days
Mean values	0.4 – 3.8 days	0.3 – 2.7 days
Minimum values	3 hours	3 hours (min duration of an act)

As illustrated by the discussed figures in section 6.1, all curves follow the same trend. During winter months, higher project durations can be observed while during summer months, a decrease of days can be observed.

Concluding, the model can determine the project installation time. Finally, it can also be concluded that the model also correctly assesses the work and wait times of every activity separately. With this knowledge of the time required for wait and wait hours, depending on weather conditions present, it is also shown which activities may cause the most potential delay, even though, these results are site specific.

Main question: Has the logistic process of the TLP concept an advantage over the logistic process of a semi-submersible based on a newly developed model?
The objective of this research is to evaluate whether the TLP concept can be a realistic alternative when compared to a float-out based semi-submersible structure. The simulation results of both logistic processes aim to give a better insight in the given problem.

An advantage of the TLP concept compared to the SSB structure, and not related to the operational limits, is its two phased installation approach. This approach ensures a more efficient installation process as this approach creates two independent supply chains. Another advantage of the TLP concept, while the TLP concept requires more operations for complete installation, the structure creates the opportunity to be installed in deeper waters and is more stable compared to a SSB structure. Besides, the advantage of transport and installation in a two phased approach complies with a more efficient installation process.
An advantage of both structures, for transportation of the substructures, no vessels other than tugboats are needed.

The developed simulation model, representing a simplification of the described system, displays the logistic process of the TLP concept and the logistic process of a semi-submersible structure. To obtain an answer to the main research question, several inputs are required for the simulation models. Table 3, summarizes the key activities as implemented in the simulation model. Moreover, Table 5 and Table 6 present the operational limits used for the TLP and SSB, respectively.
As illustrated, the tow-out of both the TLP concept and SSB structures can be performed using similar operational conditions. While for installation of both structures different operational limits apply. The TLP floater can be installed with 1m wave height and 13 m/s wind speed, while SSB structures can only be installed in more severe weather conditions, 2m wave height and 13 m/s wind speed. Some operational limits are provided by Bluewater, while the other missing operational limits are based on existing literature.
The TLP structure is fairly new and it has not yet been installed. So far, not many studies have been conducted into this type of structure and specifically, the operational limits. Therefore, it should be mentioned that it is uncertain whether the operational limits, for as far as they are known and mentioned in literature, are reliable. That is, not all operational limits for the TLP concept and SSB structure are known for sure. Therefore, it is more difficult to draw a solid conclusion.

The average project duration of the TLP concept, compared to the average project duration for the SSB structure, is higher. Moreover, as more operations are required for T&I of the TLP concept, it can be observed that on average, also more waiting time is required for this structure compared to the SSB structure. The SSB structure seems to be less vulnerable to severe weather conditions, as on average less delay is observed from the results of the simulations.

Moreover, except for case 3 of the sensitivity analysis, all other cases of the performed sensitivity analysis point out that the TLP concept shows the most sensitive changes compared to the SSB structure. This indicates that the TLP concept is more vulnerable to modifications on various fields. This is a major disadvantage for the TLP concept.

Additionally, as more operations are included in the simulation of the TLP concept, also more weather windows are required. In comparison to the activities of the SSB structure, also the average time of an activity is longer, resulting in longer weather windows. This results in more weather data that needs to be considered when the operational limits are verified. This creates the opportunity that the operational limits are exceeded more frequently. Thus, more weather uncertainty is included for the TLP concept than for the SSB structure. Based on this, the TLP concept is more vulnerable to weather conditions than the SSB structure.

To conclude, the main result of this research provides two models with which the logistic process of both structures can be studied. In this way it can be determined whether the TLP concept can be a realistic alternative compared to a SSB structure. Overall, the logistic process of the newly developed TLP concept does not have an advantage compared to the logistic process of a SSB structure. Even though, the developed simulation models do not include all operations required for the TLP concept, the results of the simulation obtained with the described key activities show that the TLP concept will have major disadvantages by installing it offshore compared to the simulation results of a SSB structure. In addition, this area requires further investigation to be more certain about possible advantages for the newly developed TLP concept.

7.2 Recommendations

This section elaborates on several recommendations for future research.
For a more complete analysis, it would be useful that first all operational limits of a TLP should be known. As presented in this study, not all operational limits were known. With insufficient data, it is harder to give a complete conclusion on which substructure has an advantage compared to the each other. For now, some operational limits were certain, others are based on literature. For as far it was possible to find literature related to TLP structures as they have not yet been installed. Moreover, when all operational limits are known, a more accurate simulation results can be obtained.

Moreover, for future study it is recommended to include more weather uncertainties. Now, only maximum wind speed and maximum wave height are taken into account. Other important environmental conditions that have a significant influence on the T&I should also be included. For example, wind direction, current, wave period, wave direction, etc. By including more environmental conditions, a more accurate and reliable model is obtained.

Furthermore, for this study no real data was available for a proper validation. It is recommended that once real data is available, a proper validation of the model should be performed. This ensures a more reliable simulation model that can evaluate the project installation time more certain and less uncertainty is then included.

Finally, it should be noted that the performed simulation did only include key activities that are affected the most by weather conditions. For a more reliable result, it is suggested to include more activities, or all real-life operations, in the simulation model than the key activities used in this thesis. When more activities are included, a more complete analysis of the project time for both structures can be obtained.

Bibliography

Ait-Alla, A., Oelker, S., Lewandowski, M., Freitag, M., & Thoben, K. D. (2017). A study of new installation concepts of offshore wind farms by means of simulation model. *Proceedings of the International Offshore and Polar Engineering Conference*, *2017*, 607–612.

Ait-Alla, A., Quandt, M., & Lütjen, M. (2013). Simulation-based aggregate Installation Planning of Offshore Wind Farms. *International Journal Of Energy*, *7*(2), 23–30. http://www.naun.org/main/NAUN/energy/b012001-201.pdf

Anastasiou, K., & Tsekos, C. (1996). Operability analysis of marine projects based on Markov theory. In *Applied Ocean Research* (Vol. 18).

Asgarpour, M. (2016). Assembly, transportation, installation and commissioning of offshore wind farms. In *Offshore Wind Farms: Technologies, Design and Operation*. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100779-2.00017-9

Athanasia, A., & Genachtea, A. B. (2013). Deep offshore and new foundation concepts. *Energy Procedia*, *35*, 198–209. https://doi.org/10.1016/j.egypro.2013.07.173

Barlow, E., Tezcaner Öztürk, D., Revie, M., Akartunalı, K., Day, A. H., & Boulougouris, E. (2018). A mixed-method optimisation and simulation framework for supporting logistical decisions during offshore wind farm installations. *European Journal of Operational Research*, *264*(3), 894–906. https://doi.org/10.1016/j.ejor.2017.05.043

Barlow, E., Tezcaner Öztürk, D., Revie, M., Boulougouris, E., Day, A. H., & Akartunali, K. (2015). Exploring the impact of innovative developments to the installation process for an offshore wind farm. *Ocean Engineering*, *109*, 623–634. https://doi.org/10.1016/j.oceaneng.2015.09.047

Bass, B. (n.d.). *What Are Logistical Processes?* Small Business. Retrieved July 16, 2020, from https://smallbusiness.chron.com/logistical-processes-13120.html#:~:text=within the organization.-,Logistical Processes,factors associated with these locations.

Beinke, T., Ait Alla, A., & Freitag, M. (2017). Resource Sharing in the Logistics of the Offshore Wind Farm Installation Process based on a Simulation Study. *International Journal of E-Navigation and Maritime Economy*, *7*, 42–54. https://doi.org/10.1016/j.enavi.2017.06.005

Box, G. E. P., Jenkins, G. M., Reinsel, G. C., Ljung, G. M., & Ljung, G. M. (2015). *Time Series Analysis: Forecasting and Control*.

de Nie, R., Leontaris, G., Hoogendoorn, D., & Wolfert, A. R. M. (Rogier. (2019). Offshore infrastructure planning using a vine copula approach for environmental conditions: an application for replacement maintenance of tidal energy infrastructure. *Structure and Infrastructure Engineering*, *15*(5), 600–617. https://doi.org/10.1080/15732479.2018.1558268

Dornhelm, E., Seyr, H., & Muskulus, M. (2019). Vindby - A serious offshorewind farm design game. *Energies*, *12*(8). https://doi.org/10.3390/en12081499

Energyfacts.eu. (2020). *Boskalis bags two exceptional transport and installation projects*. https://www.energyfacts.eu/boskalis-bags-two-exceptional-transport-and-installation-projects/

Gintautas, T., & Sørensen, J. D. (2016). Evaluating a novel approach to reliability decision support for offshore wind turbine installation. *Progress in Renewable Energies Offshore - Proceedings of 2nd International Conference on Renewable Energies Offshore, RENEW 2016*, *October*, 733–740. https://doi.org/10.1201/9781315229256-86

Gintautas, T., & Sørensen, J. D. (2017). Improved methodology of weather window prediction for offshore operations based on probabilities of operation failure. *Journal of Marine Science and Engineering*, *5*(2). https://doi.org/10.3390/jmse5020020

Gintautas, T., Sørensen, J. D., & Vatne, S. R. (2016). Towards a Risk-based Decision Support for Offshore Wind Turbine Installation and Operation & Maintenance. *Energy Procedia*, *94*(January), 207–217. https://doi.org/10.1016/j.egypro.2016.09.225

Golbert, D. R., Blanco, P. J., Clausse, A., & Feijóo, R. A. (2015). Floating Offshore Wind: Market and Technology Review. In *Journal of Computational Physics* (Vol. 311, Issue June).

https://doi.org/10.1016/j.jcp.2016.01.012
Han, Y., Le, C., Ding, H., Cheng, Z., & Zhang, P. (2017). Stability and dynamic response analysis of a submerged tension leg platform for offshore wind turbines. *Ocean Engineering*, *129*, 68–82. https://doi.org/10.1016/j.oceaneng.2016.10.048
Jiang, Z. (2021). Installation of offshore wind turbines: A technical review. *Renewable and Sustainable Energy Reviews*, *139*(November 2020), 110576. https://doi.org/10.1016/j.rser.2020.110576
Journee, J. M. J., & Massie, W. W. (2001). *Offshore Hydromechanics (Electronic Book)*. *January*. http://www.shipmotions.nl/DUT/LectureNotes/OffshoreHydromechanics.pdf
Joy, C. M., Joseph, A., & Mangal, L. (2019). An Overview of Offshore Wind Energy Tower Designs. *Journal of The Institution of Engineers (India): Series C*, *100*(5), 841–850. https://doi.org/10.1007/s40032-019-00511-3
Karan, C. (2020, September 15). *What are Tug Boats?* Types of Ships. https://www.marineinsight.com/types-of-ships/what-are-tug-boats/
Karimirad, M. (2014). Offshore Energy Structures. *Offshore Energy Structures*. https://doi.org/10.1007/978-3-319-12175-8
Kerkhove, L. P., & Vanhoucke, M. (2017). Optimised scheduling for weather sensitive offshore construction projects. *Omega (United Kingdom)*, *66*, 58–78. https://doi.org/10.1016/j.omega.2016.01.011
Kota, S., Bayne, S. B., & Nimmagadda, S. (2015). Offshore wind energy: A comparative analysis of UK, USA and India. *Renewable and Sustainable Energy Reviews*, *41*(5), 685–694. https://doi.org/10.1016/j.rser.2014.08.080
Lange, K., Rinne, A., & Haasis, H. D. (2012). Planning maritime logistics concepts for offshore wind farms: A newly developed decision support system. In *Computational Logistics* (Vol. 7555, pp. 142–158). https://doi.org/10.1007/978-3-642-33587-7_11
Leontaris, G., Morales-Nápoles, O., & Wolfert, A. R. M. (2017). Planning cable installation activities for offshore wind farms including risk of supply delays. *Risk, Reliability and Safety: Innovating Theory and Practice - Proceedings of the 26th European Safety and Reliability Conference, ESREL 2016*, *January*, 104. https://doi.org/10.1201/9781315374987-99
Leontaris, G., Morales-Nápoles, O., & Wolfert, A. R. M. (Rogier. (2016). Probabilistic scheduling of offshore operations using copula based environmental time series – An application for cable installation management for offshore wind farms. *Ocean Engineering*, *125*, 328–341. https://doi.org/10.1016/j.oceaneng.2016.08.029
Lerch, M., De-Prada-Gil, M., Molins, C., & Benveniste, G. (2018). Sensitivity analysis on the levelized cost of energy for floating offshore wind farms. *Sustainable Energy Technologies and Assessments*, *30*(September), 77–90. https://doi.org/10.1016/j.seta.2018.09.005
Liu, Y., Li, S., Yi, Q., & Chen, D. (2016). Developments in semi-submersible floating foundations supporting wind turbines: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *60*, 433–449. https://doi.org/10.1016/j.rser.2016.01.109
Madsen, F. J., Nielsen, T. R. L., Kim, T., Bredmose, H., Pegalajar-Jurado, A., Mikkelsen, R. F., Lomholt, A. K., Borg, M., Mirzaei, M., & Shin, P. (2020). Experimental analysis of the scaled DTU10MW TLP floating wind turbine with different control strategies. *Renewable Energy*, *155*, 330–346. https://doi.org/10.1016/j.renene.2020.03.145
Maienza, C., Avossa, A. M., Ricciardelli, F., Coiro, D., Troise, G., & Georgakis, C. T. (2020). A life cycle cost model for floating offshore wind farms. *Applied Energy*, *266*(March), 114716. https://doi.org/10.1016/j.apenergy.2020.114716
Marin. (n.d.). *Tug performance: Bollard Pull and Escort Trials*. www.marin.nl
Martini, M., Guanche, R., Losada-Campa, I., & Losada, I. J. (2018). The impact of downtime over the long-term energy yield of a floating wind farm. *Renewable Energy*, *117*, 1–11. https://doi.org/10.1016/j.renene.2017.10.032
Menon, A. (2020). *Understanding Heavy Lift Vessels (HLVs): Design, Operation and Types*. https://www.marineinsight.com/types-of-ships/heavy-lift-vessels-design-operation-and-types/
Muhabie, Y., Caprace, J.-D., Petcu, C., & Rigo, P. (2015). Improving the installation of offshore wind farms by

the use of discrete event simulation. *World Maritime Technology Conference (WMTC)*, 1–10.
Muhabie, Y., Rigo, P., Cepeda, M., de Almeida D'Agosto, M., & Caprace, J. D. (2018). A discrete-event simulation approach to evaluate the effect of stochastic parameters on offshore wind farms assembly strategies. *Ocean Engineering*, *149*, 279–290. https://doi.org/10.1016/j.oceaneng.2017.12.018
Nelsen, R. B. (2006). *An introduction to copulas* (2nd ed.). Springer, New York, NY.
Nfaoui, H., Essiarab, H., & Sayigh, A. A. M. (2004). A stochastic Markov chain model for simulating wind speed time series at Tangiers, Morocco. *Renewable Energy*, *29*(8), 1407–1418. https://doi.org/10.1016/S0960-1481(03)00143-5
Rippel, D., Jathe, N., Becker, M., Lütjen, M., Szczerbicka, H., & Freitag, M. (2019). A review on the planning problem for the installation of offshore wind farms. *IFAC-PapersOnLine*, *52*(13), 1337–1342. https://doi.org/10.1016/j.ifacol.2019.11.384
Sahnoun, M., Baudry, D., Mustafee, N., Louis, A., Smart, P. A., Godsiff, P., & Mazari, B. (2019). Modelling and simulation of operation and maintenance strategy for offshore wind farms based on multi-agent system. *Journal of Intelligent Manufacturing*, *30*(8), 2981–2997. https://doi.org/10.1007/s10845-015-1171-0
Scholz-Reiter, B., Heger, J., & Lütjen, M. (2011). A MILP for Installation Scheduling of Offshore Wind Farms. In *Article in International Journal of Mathematical Models and Methods in Applied Sciences*. https://www.researchgate.net/publication/259889797
Scholz-Reiter, B., Lütjen, M., Heger, J., & Schweizer, A. (2010). Planning and control of logistics for offshore wind farms. *International Conference on Mathematical and Computational Methods in Science and Engineering - Proceedings*, *January*, 242–247.
Sun, X., Huang, D., & Wu, G. (2012). The current state of offshore wind energy technology development. *Energy*, *41*(1), 298–312. https://doi.org/10.1016/j.energy.2012.02.054
Talisman Energy. (2008). *No Title*. https://www.sec.gov/Archives/edgar/data/201283/000104746909002372/a2190886zex-99_5.htm
Thomsen, K. E. (2014a). Chapter Six - Project Execution. In K. E. Thomsen (Ed.), *Offshore Wind (Second Edition)* (pp. 95–117). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-410422-8.00006-6
Thomsen, K. E. (2014b). Chapter Ten - Logistics Solutions. In K. E. Thomsen (Ed.), *Offshore Wind (Second Edition)* (pp. 171–175). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-410422-8.00010-8
Tyapin, I., Hovland, G., & Jorde, J. (2011). Comparison of Markov Theory and Monte Carlo Simulations for Analysis of Marine Operations Related to Installation of an Offshore Wind Turbine. *Proceedings of the 24th International Congress on Condition Monitoring (COMADEM), 30th May - 1st June*, 1071–1081.
Vis, I. F. A., & Ursavas, E. (2016). Assessment approaches to logistics for offshore wind energy installation. *Sustainable Energy Technologies and Assessments*, *14*, 80–91. https://doi.org/10.1016/j.seta.2016.02.001
Walker, R. T., Van Nieuwkoop-Mccall, J., Johanning, L., & Parkinson, R. J. (2013). Calculating weather windows: Application to transit, installation and the implications on deployment success. *Ocean Engineering*, *68*, 88–101. https://doi.org/10.1016/j.oceaneng.2013.04.015
Walsh, C. (2019). Offshore wind in Europe. In *Refocus* (Vol. 3, Issue 2). https://doi.org/10.1016/s1471-0846(02)80021-x
Wang, X., Zeng, X., Li, J., Yang, X., & Wang, H. (2018). A review on recent advancements of substructures for offshore wind turbines. In *Energy Conversion and Management* (Vol. 158, pp. 103–119). Elsevier Ltd. https://doi.org/10.1016/j.enconman.2017.12.061
Yang, J. J., & He, E. M. (2020). Coupled modeling and structural vibration control for floating offshore wind turbine. *Renewable Energy*, *157*, 678–694. https://doi.org/10.1016/j.renene.2020.05.075
Yang, X. C., & Zhang, Q. H. (2013). Joint probability distribution of winds and waves from wave simulation of 20 years (1989-2008) in Bohai Bay. *Water Science and Engineering*, *6*(3), 296–307. https://doi.org/10.3882/j.issn.1674-2370.2013.03.006

Appendix A

Wind turbine components

An OWT exists several main components and consist of a top- and sub-structure. The top structure of a wind turbine is the same for all types of supporting substructures and usually does not differ from the design of onshore wind turbines. It consists of the following main components and can be seen in: blades, hub, nacelle, tower and transition piece.

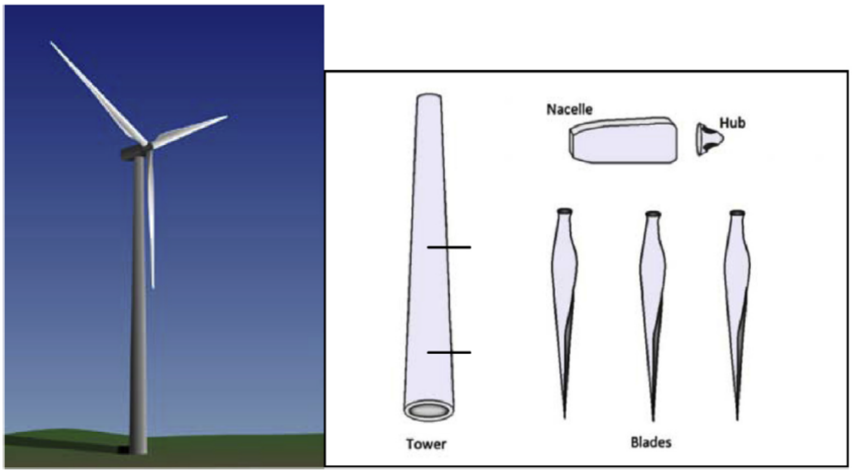


Figure 0-1 Offshore Wind Turbine main components (Vis & Ursavas, 2016)

Appendix B

Transport and installation of OWT's requires different types of vessels. For installation of offshore wind turbines, installation vessels are needed that can lift heavy components in various weather conditions. While for transport, tug boats are needed that have enough power to suffice in the towing performance which is required. The vessels which will be discussed are designed for different purposes and therefore have their own capabilities. Various types of vessels for transportation and installation are discussed.

B.1 Heavy Transportation Vessel

Wind turbine components need to be transported from the fabrication yard to the offshore location by means of a Heavy Transportation Vessel (HTV). These kinds of vessels are specialized in transportation of large and heavy cargoes. The vessels have a large deck area to store components of multiple WTG's.

B.2 Tug boats

Tug boats are highly maneuverable vessels used to tow or push non-self-propelled structures to an offshore location, positioning at open sea and assisting berthing operations by making the maneuvering operation easier. Tug boats are due to their relatively small size very powerful vessels (Karan, 2020).

Tug boats have a certain towing performance which is usually indicated in tons bollard pull (Marin, n.d.). Nowadays, tugs are equipped with a diesel engine of on average 680-3400 hp (500-2500 kW). Larger tugs used for deeper waters are equipped with engines of around 27200 hp (20,000 kW) (Karan, 2020). An example of a tub boat is illustrated in Figure 0-1.

Figure 0-1 Tug boat (Jiang, 2021)

When choosing the right tug boat for towing a TLP floater, several things should be kept in mind. Tug boats will be selected on their pull force. This depends especially on the currents for which a minimum pull is required for safe passage. The longer the vessel, Length Overall (LOA), the better it deals with swell and larger waves which are most certain to happen at locations further offshore (Thomsen, Chapter Twelve - Vessels and Transport to Offshore Installations, 2014). However, also the width, height and maximum draft of the vessel should be well considered. This is important for how the boat deals with high waves as it will be exposed to six free movement directions: pitch, roll, heave, sway, surge and yaw (Thomsen, Chapter Twelve - Vessels and Transport to Offshore Installations, 2014). Tug boats have a certain travel speed and the offshore installation site is located at a certain distance away from shore. The combination of the distance and the time needed to navigate to the offshore site brings challenges (Thomsen, Chapter Five - Project Preparation, 2014). If tugs are chosen with a lower travel speed, the required weather window will be longer since more time is needed to reach the offshore installation site (Thomsen, Chapter Five - Project Preparation, 2014). In case multiple tug boat spreads are used, the time needed for installation of the OWF will be shorter since less trips are needed.

B.3 Heavy Lift Vessels

A Heavy Lift Vessel (HLV) is used for the installation of a wind turbine on a substructure. Four classes of HLV's can be categorized (Menon, 2020):

- Semi-submersible vessels;
- Dock ships;
- Open deck cargo ships;
- Project cargo carriers.

This thesis will only consider semi-submersible HLV's. A HLV is a self-propelled vessel which has two cranes available for lifting. The deck has space available to store wind turbine components. While one crane will unload a transport vessel and assemble a WTG, the other crane will perform the lift for installation of a WTG. As HLV's are more expensive than HTV's, a HLV will stay at the offshore site to avoid higher costs due to travelling back and forth from port to the offshore site. An example of a semi-submersible HLV is shown in Figure 0-2.

Figure 0-2 Semi-submersible heavy lift vessel (Jiang, 2021)

Appendix C

Main elements model description

For clarification of the model description, this section first introduces some important main elements used in the model description. Hereafter, the structure of the simulation model is explained.

- **Activity**: An activity includes all actions needed to complete the described aim of the activity (transport of TLP sections, installation of WTG tower, etc.). For an activity to be completed and to start a next activity in the chain of activities, certain pre- and post-conditions may have to be met, see definitions of pre- and post-conditions.
- **Activity chain:** All activities needed for delivery of a wind turbine unit.
- **Activity property:** Activities have properties and these include pre- and post-conditions necessary to allow the activity to start or end. Also, the required weather window, duration, progress and status are activity properties. The status of an activity can be 'active' (progress can be made), 'on hold' (no progress can be made in time step due to a pre- or post-condition), 'aborted' (progress is nil and activity needs to re-start), 'completed' (activity is finished).
- **Actual weather**: Weather applicable during time step. Weather data includes data relevant for start, progress and termination of activities during the time step (data is defined by the applicable 3-hourly statistical data for wind and waves).
- **Component**: a part of a wind turbine or floater unit, this can be a TLP leg, column, tower, nacelle, blade, anchor points or a mooring line that is supplied to the project by fabricators. The split-up of the unit into components is defined in the project description.
- **Equipment**: All equipment that will be used in the logistic process. These include; tug boats, installation vessels, transportation vessels, etc. Equipment has slots that can become 'occupied' for pending activities or are 'available' for new activities.
- **Post-conditions:** particular conditions that need to be fulfilled before an activity can make progress in a time step or obtain the status 'completed' when progress is 100%. A post-condition can also be applicable for activity chains, when all activities in the chain have achieved the status 'completed'.
- **Pre-conditions**: particular conditions that need to be fulfilled before an activity or activity chain may start making progress in a time step or can continue making progress.
- **Progress:** Ratio between the duration from start of the activity to the current time step and the best estimated time to complete the activity. If progress is set to 0%, no progress is made. If progress is set to 100%, the activity may become 'completed' when the post-condition (if any) is fulfilled.
- **Project**: A description of all activities and activity chains from start to finish including all equipment used in the project. The activities include the definition of the components used in the description of the activities.
- **Project time line**: the duration of an entire project in days or hours. A project timeline displays all activity chains and their progress from start to finish.
- **Scenario**: One project that is executed and a certain weather realization used to determine per time step actual weather as well as forecasted weather.
- **Starting point project**: Calendar date on which the project starts. The start date is important as weather conditions vary per season. Therefore, it is vital to define at what time of the year simulation of the logistic process starts.
- **Storage space:** Space available to store components on either the marshalling site, on deck of the transport and installation vessels, etc. A storage space has slots that can be assigned to activities, similar to equipment. The status of a storage slot space can be 'available' (slot space is 'available' at the start of a new activity), 'occupied', 'empty'.
- **Time steps:** Segmentation of the time line in steps, typically with duration of the shortest activity. For example, time steps of 3 hours. The new status of all performed activities becomes known at the end of the time step.

- **Unit:** one complete TLP wind turbine floater. A unit includes mooring lines, anchor points, substructure, wind turbine and cable to power substation.
- **Weather forecast**: Predictions of upcoming weather, for example for the coming 10 days, based on historical weather and on actual weather conditions. A weather forecast update is required in each time step and needs to be predicted sufficient far in the future to also include the longest activity with a requirement for weather window.
- **Weather window**: Duration from current time step in which the weather limits for an activity are not exceeded. Allowing the activity to start or to make progress. This duration is based on the weather forecast. Not all activities need a weather window as not all activities are sensitive to weather changes.

Appendix D

Overview activities for the TLP floater

Group	Activity name	Description	Actions	Pre-condition(s)	Post-condition
Loading	Load(mooring_syst)	The start of an activity chain by loading a mooring system from a quay onto the transport vessel by a crane	**Start activity**: Status crane slot changes from 'available' to 'occupied' **Progress**: Storage slot status changes from 'available' to 'occupied' **End activity**: Crane slot becomes 'available' again	**Start activity:** Slot space available on vessel **Start activity:** Crane slot available	
Transport	Trans(mooring_syst)	A mooring system is transported to the offshore site by a transport vessel	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity**: All slot spaces on vessel are 'occupied', this pre-condition does not apply in case the last unit is on the vessel as the vessel can sail half full. **Start activity and progress**: Weather limits are not exceeded	
Installation	Inst(mooring_syst)	A mooring system is installed by a crane on the transport vessel	**Start activity:** Transport slot of transport vessel changes form 'occupied' to 'empty'	**Start activity:** Crane slot is 'available' **Start activity:** Mooring system available offshore **Start activity and progress:** Weather limits are not exceeded	
Transport	Sail(mooring_syst,vessel)	Transport vessel will return to base port	**End activity**: All slot spaces of transport vessel change from 'empty' to 'available'	**Start activity**: Mooring system vessel is 'empty'	**End activity**: Slot spaces mooring system vessel changes from 'empty' to 'available' again
Transport	Trans(TLP_column)	Transport of a TLP column from the production yard to assembly yard by HTV	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** All slot spaces on vessel are 'occupied', **Start activity and progress:** Weather limits are not exceeded	
Transport	Trans(TLP_cpiece)	Transport of a TLP connection piece from the production yard to assembly yard by HTV	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** All slot spaces on vessel are 'occupied' **Start activity and progress:** Weather limits are not exceeded	
Transport	Trans(TLP_pontoon)	Transport of a TLP pontoon from the production yard to assembly yard by HTV	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active'	**Start activity**: All slot spaces on vessel are 'occupied' **Start activity and progress:** Weather limits are not exceeded	

			End activity: Status is set 'completed' when progress is 100% as there is no post-condition included		
Transport	Trans(TLP_acc)	Transport of a TLP access platform from fabrication yard to assembly yard by HTV	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** All slot spaces on vessel are 'occupied' **Start activity and progress:** Weather limits are not exceeded	
Assembly	Ass(TLP)	A TLP floater is assembled at the assembly yard by a crane on the quayside	**Start activity:** Crane slot status changes from 'available' to 'occupied' **Progress:** Activity makes 100% progress when activity is 'active' **End activity:** Status is set 'completed' **End activity:** Crane slot status changes from 'occupied' to 'available' again	**Start activity:** Crane slot is 'available'	
Loading	Load(TLP)	A TLP floater is loaded onto on a barge by a crane on the quayside	**Start activity:** Crane slot status changes from 'available' to 'occupied' **Progress:** Storage slot status changes from 'available' to 'occupied' **End activity:** Crane slot status changes from 'occupied' to 'available' again	**Start activity:** A TLP is available for loading **Start activity:** Crane slot 'available' **Start activity:** Transport slot on barge 'available'	
Transport	Trans(TLP)	Barge with a TLP is pulled by tug boat(s) to offshore site	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** TLP slot on a barge is 'occupied' **Start activity and progress:** Weather limits are not exceeded	
Installation	Inst(TLP)	A TLP floater is installed, first it is positioned and thereafter mounted to a pre-installed mooring system	**End activity:** Storage slot status changes from 'occupied' to 'empty'	**Start activity:** Mooring system pre-installed **Start activity:** TLP available for installation **Start activity and progress:** Sufficient weather window	
Transport	Sail(barge_tugs)	Barge sails back to port	**End activity:** Storage slot status changes from 'empty' to 'available'	**Start activity:** Slot status of barge is 'empty'	**End activity**: Slot space of barge changes from 'empty' to 'available' again
Loading	Load(tower)	A tower is loaded from the quay at the fabrication yard onto available slot on HTV for transport	**Start activity:** Crane slot status changes from 'available' to 'occupied **Progress:** Storage slot status changes from 'available' to 'occupied' **End activity:** Crane slot status changes from 'occupied' to 'available' again	**Start activity:** Slot space available on HTV **Start activity:** Crane slot 'available' **Start activity:** Tower available for loading	

Loading	Load(nacelle)	A nacelle is loaded from the quay at the fabrication yard onto available slot on HTV for transport	**Start activity:** Crane slot status changes from 'available' to 'occupied **Progress:** Storage slot status changes from 'available' to 'occupied' **End activity:** Crane slot status changes from 'occupied' to 'available' again	**Start activity:** Slot space 'available' on HTV **Start activity:** Crane slot 'available' **Start activity:** Nacelle available for loading	
Loading	Load(blade)	A blade is loaded from the quay at the fabrication yard onto available slot on HTV for transport	**Start activity:** Crane slot status changes from 'available' to 'occupied **Progress:** Storage slot status changes from 'available' to 'occupied' **End activity:** Crane slot status changes from 'occupied' to 'available' again	**Start activity:** Slot space 'available' on HTV **Start activity:** Crane slot 'available' **Start activity:** Blade available for loading	
Transport	Trans(tower)	Transport of a tower from fabrication yard to offshore installation site by HTV	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** All slot spaces on a HTV are 'occupied', this pre-condition does not apply in case the last unit is on the vessel as the vessel can sail half full. **Start activity and progress:** Weather limits are not exceeded	
Transport	Trans(nacelle)	Transport of a nacelle from fabrication yard to offshore installation site by HTV	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** All slots spaces on a HTV are 'occupied', this pre-condition does not apply in case the last unit is on the vessel as the vessel can sail half full. **Start activity and progress:** Weather limits are not exceeded	
Transport	Trans(blade)	Transport of a blade from fabrication yard to offshore installation site by HTV	**Start activity:** Activity starts making progress as it becomes 'active' **Progress**: Activity makes 100% progress when activity is 'active' **End activity**: Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** All slots spaces on a HTV are 'occupied', this pre-condition does not apply in case the last unit is on the vessel as the vessel can sail half full. **Start activity and progress:** Weather limits not exceeded	
Loading	Unload(tower)	A tower is lifted from HTV on-board a slot space on the HLV by crane 1	**Start activity:** Status crane slot 1 of HLV changes from 'available' to 'occupied' **Start activity:** Storage slot status on HLV changes from 'available' to 'occupied' **End activity:** Status crane slot 1 of HLV changes from 'occupied' to 'available' again **End activity:** Storage slot status on HTV changes from 'occupied' to 'empty'	**Start activity:** Slot of crane 1 available **Start activity:** Tower storage space available on HLV	
Loading	Unload(nacelle)	A nacelle is lifted from HTV on-board a slot space on the HLV by crane 1	**Start activity:** Status crane slot 1 of HLV changes from 'available' to 'occupied' **Start activity:** Storage slot status on HLV changes from 'available' to 'occupied'	**Start activity:** Slot of crane 1 available **Start activity:** Nacelle storage space available on HLV	

			End activity: Status crane slot 1 of HLV changes from 'occupied' to 'available' again **End activity:** Storage slot status on HTV changes from 'occupied' to 'empty'		
Loading	Unload(blade)	A blade is lifted from HTV on-board a slot space on the HLV by crane 1	**Start activity:** Status crane slot 1 of HLV changes from 'available' to 'occupied' **Start activity:** Storage slot status on HLV changes from 'available' to 'occupied' **End activity:** Status crane slot 1 of HLV changes from 'occupied' to 'available' again **End activity:** Storage slot status on HTV changes from 'occupied' to 'empty'	**Start activity:** Slot of crane 1 is 'available' **Start activity:** Blade storage space available on HLV	
Assembly	Ass(WTG)	A WTG is assembled on the HLV with the components occupying a slot space on HLV by crane 1	**Start activity:** Crane slot 1 status of HLV changes from 'available' to 'occupied' **End activity:** Crane slot 1 status of HLV becomes 'available' again	**Start activity:** Components of a WTG are available on HLV **Start activity:** Slot of crane 1 is 'available' **Start activity and progress:** Sufficient weather window	
Installation	Inst(WTG)	An assembled WTG will be installed on a pre-installed TLP floater by crane 2 of the HLV	**Start activity:** Crane slot 2 status of HLV changes from 'available' to 'occupied' **End activity:** Crane slot 2 status of HLV becomes 'available' again **End activity:** A storage slot status of tower, blade and nacelle on HLV becomes 'available' again	**Start activity:** Slot of crane 2 is 'available' **Start activity:** Sufficient weather window **Start activity:** A wind turbine unit is assembled **Start activity:** TLP floater available and ready to receive WTG	
Transport	Sail(HTV)	HTV will sail back to base fabrication port for new load	**End activity:** Storage slot status changes from 'empty' to 'available'	**Start activity:** All slot statuses of HTV('s) are 'empty'	**End activity**: All slot spaces of HTV(s) change from 'empty' to 'available' again
Installation	Cable_con	Installation of connection cable from a wind turbine unit to the offshore power station	**Start activity:** Cable connection slot of WTG becomes 'occupied' **End activity:** Project status changes to 'completed'	**Start activity:** All wind turbine units are installed and ready to be connected	
Transport/ Installation	Sail_abort	When an activity cannot make progress and activity needs to restart	**Progress:** Progress is nil (0%) due to pre- or post-condition **End activity:** Status activity changes from 'active' to 'aborted'	**Progress:** Weather limits are exceeded	
Transport/ Installation	Sail_onhold	When an activity cannot make progress in a time step, the activity is put on 'on hold', will be finished later	**Progress:** No progress is made in time step **End activity:** Status activity changes from 'active' to 'on hold'	**Progress:** A pre- or post-condition(s) cannot be met	

Appendix E

Overview activities for the semi-submersible structure

Group	Activity name	Description	Actions	Pre-condition(s)	Post-condition
Loading	Load(mooring_syst)	The start of an activity chain by loading a mooring system from a quay onto the transport vessel by a crane	**Start activity:** Status crane slot changes from 'available' to 'occupied' **Progress:** Storage slot status changes from 'available' to 'occupied' **End activity:** Crane slot becomes 'available' again	**Start activity:** Slot space available on vessel **Start activity:** Crane slot available	
Transport	Trans(mooring_syst)	A mooring system is transported to the offshore site by transport vessel	**Start activity:** Activity starts making progress as it becomes 'active' **Progress:** Activity makes 100% progress when activity is 'active' **End activity:** Status is set 'completed' when progress is 100% as there is no post-condition included	**Start activity:** All slot spaces on vessel are 'occupied' **Start activity and progress:** Weather are limits not exceeded	
Installation	Inst(mooring_syst)	A mooring system is installed by a transport vessel	**Start activity:** Transport slot of transport vessel changes from 'occupied' to 'empty'	**Start activity:** Crane slot is 'available' **Start activity:** Mooring system available offshore **Start activity and progress:** Weather are limits not exceeded	
Transport	Sail(mooring_syst,vessel)	Transport vessel will return to base port	**End activity:** All slot spaces of transport vessel change from 'empty' to 'available'	**Start activity:** Mooring system vessel is 'empty'	**End activity:** Slot spaces changes from 'empty' to 'available' again
Assembly	Ass(semi)	A semi-submersible structure is positioned along the quay	**Start activity:** Storage slot along the quay changes from 'available' to 'occupied'	**Start activity:** A slot available along quayside	
Transport	Trans(tower)	Transport of a WTG tower from the fabrication yard to the assembly yard by HTV	**Start activity:** Activity start making progress as it becomes 'active' **Progress:** Activity makes 100% progress when activity is 'active' **End activity:** Status is set 'completed' when progress is 100% as there is not post-condition included	**Start activity:** All slot spaces on HTV are 'occupied' **Start activity and progress:** Weather limits are not exceeded	
Transport	Trans(nacelle)	Transport of a WTG nacelle from the fabrication yard to the assembly yard by HTV	**Start activity:** Activity start making progress as it becomes 'active' **Progress:** Activity makes 100% progress when activity is 'active'	**Start activity:** All slot spaces on HTV are 'occupied' **Start activity and progress:** Weather limits are not exceeded	

			End activity: Status is set 'completed' when progress is 100% as there is not post-condition included		
Transport	Trans(blade)	Transport of a WTG blade from the fabrication yard to the assembly yard by HTV	**Start activity:** Activity start making progress as it becomes 'active' **Progress:** Activity makes 100% progress when activity is 'active' **End activity:** Status is set 'completed' when progress is 100% as there is not post-condition included	**Start activity:** All slot spaces on HTV are 'occupied' **Start activity and progress:** Weather limits are not exceeded	
Loading	Unload(tower)	A tower is lifted of the HTV onto the quay by a crane	**Start activity:** Crane slot status changes from 'available' to 'occupied' **Progress:** Storage slot on quay changes from 'available' to 'occupied' **Progress:** Slot space HTV changes from 'occupied' to 'available' **End activity:** Crane slot changes from 'occupied' to 'available' again	**Start activity:** Crane slot is available **Start activity:** Tower storage space available on quay	
Loading	Unload(nacelle)	A nacelle is lifted of the HTV onto the quay by a crane	**Start activity:** Crane slot status changes from 'available' to 'occupied' **Progress:** Storage slot on quay changes from 'available' to 'occupied' **Progress:** Slot space HTV changes from 'occupied' to 'available' **End activity:** Crane slot changes from 'occupied' to 'available' again	**Start activity:** Crane slot is available **Start activity:** Nacelle storage space available on quay	
Loading	Unload(blade)	A blade is lifted of the HTV onto the quay by a crane	**Start activity:** Crane slot status changes from 'available' to 'occupied' **Progress:** Storage slot on quay changes from 'available' to 'occupied' **Progress:** Slot space HTV changes from 'occupied' to 'available' **End activity:** Crane slot changes from 'occupied' to 'available' again	**Start activity:** Crane slot is available **Start activity:** Tower storage space available on quay	
Assembly	Ass(WTG)	A WTG is assembled at the quay with the components stored at the marshalling yard by a crane	**Start activity:** Crane slot changes from 'available' to 'occupied' **Progress:** A storage slot of tower, blade and nacelle on the quay change from 'occupied' to 'available' **End activity:** Crane slot changes from 'occupied' to 'available' again	**Start activity:** Components of a WTG available on the quay **Start activity:** Crane slot is available at marshalling yard	
Installation	Inst(WTG)	An assembled WTG is installed on the semi-submersible substructure along the quayside by a crane	**Start activity:** Crane slot status changes from 'available' to 'occupied' **Progress:** Storage slot WTG changes from 'occupied' to 'available'	**Start activity:** A WTG unit is assembled **Start activity:** A semi-submersible structure available	

			End activity: Crane slot status change from 'occupied' to 'available' again	**Start activity:** Crane slot is available	
Transport	Tow(semi)	A fully assembled semi-submersible structure, including WTG, is towed to the offshore site by tug boats	**Start activity:** Slot status tug boats changes from 'available' to 'occupied'	**Start activity and progress:** Sufficient weather window **Start activity:** Slot of tug boats is 'occupied'	
Installation	Inst(semi)	Hook-up of a semi-submersible structure, including WTG, to pre-installed mooring system	**End activity:** Storage slot tug boats change from 'occupied' to 'empty'	**Start activity and progress:** Sufficient weather window **Start activity:** Mooring system available	
Transport	Sail(tugs)	Tug boats will sail back to the marshalling yard	**Start activity:** Storage slot status tug boats changes from 'occupied' to 'empty' **End activity:** Storage slot status tug boats changes from 'empty' to 'available'	**Start activity:** Slot status of tug boats is 'empty'	**End activity:** Slot space tug boats changes from 'empty' to 'available' again
Installation	Cable_con	Installation of connection cable from a wind turbine unit to the offshore power station	**Start activity:** Cable connection slot of WTG becomes 'occupied' **End activity:** Project status changes to 'completed'	**Start activity:** All wind turbine units are installed and ready to be connected	

Appendix F

Matlab code for the TLP concept

```
function rossfield_tlp_basecase_3
clear, clc, close all
tic
%% Base model, In this model a 3-hour time interval is implemented for TLP structures
%% Data:
unit = 8;
nact = 8;
totalact = unit*nact; %number of units times number of activities
step = 3; %timestep in hours, every day has 24/3 = 8 steps
timeanalysis = 4500; %length of analysis

%% Activities characteristics
act1 = 4; %Activity 1: tow-out TLP in time step. 64 miles distance with 5 knots sailing speed = 11,1
hrs travel time needed
act2 = 3; %Activity 2: installation TLP in time step. 3 hrs
act3 = 4; %Activity 3: traveltime tower in time step. 12 hrs
act4 = 2; %Activity 4: traveltime nacelle in time step. 15 hrs
act5 = 6; %Activity 5: traveltime blades in time step. 18 hrs
act6 = 5; %Activity 6: transfertime tower+nacelle in time step. 15 hrs
act7 = 3; %Activity 7: transfertime blades in time step. 9 hrs
act8 = 1; %Activity 8: installation turbine in time step. 6 hrs
totaltime = act1 + act2 + act3 + act4 + act5 + act6 + act7 + act8;

%% Load data:
T = readtimetable('ws_wv_rossfield.xls', 'PreserveVariableNames', true);
TR = timerange("1997-01-01","1999-12-31"); %use data from 01-01-1997 till 31-12-1999
date = T(TR,:);

%% Create summary of output data
nsimul= 1000; %number of simulations
summary = zeros(nsimul,2*unit*nact); %for each simulation the project time and waiting time of each
unit
Bsummary = zeros(nsimul,unit*nact);

rng(10) %to guarantee the same random collection of point
MaxStartDate=length(date.WS)-timeanalysis; %determine minimal required start date to be able to
finish simulation

%% Put loop:
for i = 1:nsimul %number of simulations

    %% Random data
    stdate=randi(MaxStartDate); %we select a random point

    wind_t = date.WS(stdate:end); %wind data start from random point to end
    waves_t = date.WV(stdate:end); %wave data start from random point to end

    %% Weather windows
    tsteps = ceil(timeanalysis/step)-1; %define number of columns, number of columns [step]
    record = zeros(totalact,tsteps); %allocating memory
    ind = zeros(nact*unit,1); %create an index for number of units + activities = rows, 1 column
    t_start=1; %initialise the start

    for u = 1:unit %loop through number of units, 1 to number of units
        D = nact * (u-1); %how much it should move in the loop every activity

        for t=1:tsteps   %loop through all columns, 1 to number of time steps
            %loop of first unit finished?
            if u>1
                %if so, check if not any value in record first loop are equal 100
                if ~any(record(7+(D-7),:)==100) %for act 1
                   break; %if so, stop and continue with code
                else %otherwise, find first value equal 100 in first row of u = 1 from t_start=1
                    t_start=find(record(D-6,:)==100,1,'first');  %%%%%%%%%%%
                end
            end

            %% Activity 1: TLP tranpsort
            output=0; %initialise the value
            %Have i finished the activity?
```

```
if (max(record(1+D,:))) == 100 || (sum(record(1+D,:) == 1) == act1)
    %if so, refilling rest of row with 100.
    output = 100;
else %otherwise, check if i can start?
    if any(waves_t(t+t_start:t+t_start+4) >= 2) && any(wind_t(t+t_start:t+t_start+4) >=
   13) ||  any(waves_t(t+t_start:t+t_start+4) >= 2) || any(wind_t(t+t_start:t+t_start+4)
   >= 13)
        output = 2; % have to wait
    else
        output = 1; % can go
    end
end
%save the results
record(1+D,t+t_start-1) = output;
record;

%% Activity 2: TLP installation
output=0; %initialise the value
%Have i finished with the activity?
if (max(record(2+D,:))) == 100 ||(sum(record(2+D,:) == 1) == act2)
    %if so, refill with 100's
    output = 100;
else %otherwise, check if i can start
    if any(record(1+D,:) == 100) %is it time to start? Previous act 100?
        %if so, check weather conditions
          if any(waves_t(t+t_start:t_start+t+3)>=1) &&
          any(wind_t(t+t_start:t_start+t+3)>=13) ||
          any(waves_t(t+t_start:t_start+t+3)>=1) ||
          any(wind_t(t+t_start:t_start+t+3)>=13)
           output = 2; %I have to wait
          else
           output = 1; %I can work
          end
    end
end
%save the results
record(2+D,t+t_start-1)= output;
record;

%% Activity 3: Transport towers
output=0; %initialise the value
%Have i finished the activity?
if (max(record(3+D,:))) == 100 || (sum(record(3+D,:) == 1) == act3)
    %if so, refill with 100
    output = 100;
else %otherwise, check if can start
    if any(waves_t(t+t_start:t+t_start+4)>=2) && any(wind_t(t+t_start:t+t_start+4)>=14)
   || any(wind_t(t+t_start:t+t_start+4)>=14) || any(waves_t(t+t_start:t+t_start+4)>=2)
        output = 2; %have to wait
    else
        output = 1; %i can work
    end
end
%save the results
record(3+D,t) = output;
record;

%% Activity 4: Transport nacelles
output=0; %initialise the value
%have i finished the activity?
if (max(record(4+D,:))) == 100 || (sum(record(4+D,:) == 1) == act4)
    %if so, refill with 100
    output = 100;
else %otherwise, check if can start
    if any(waves_t(t+t_start:t+t_start+2)>2) && any(wind_t(t+t_start:t+t_start+2)>12) ||
   any(waves_t(t+t_start:t+t_start+2)>2) || any(wind_t(t+t_start:t+t_start+2)>12)
        output = 2; %have to wait
    else
        output = 1; %I can work
    end
end
%save the results
record(4+D,t+1) = output;
record;

%% Activity 5: Transport blades
output=0; %initialise the value
%have i finished the activity?
if (max(record(5+D,:))) == 100 || (sum(record(5+D,:) == 1) == act5)
```

```
            %if so, refill with 100
            output = 100;
        else %otherwise, check if can start
            %if so, check the weather conditions
             if any(waves_t(t+t_start:t_start+t+5)>2) && any(wind_t(t+t_start:t_start+t+5)>12) ||
           any(waves_t(t+t_start:t_start+t+5)>2) || any(wind_t(t+t_start:t_start+t+5)>12)
                output = 2; %I have to wait
            else
                output = 1; %I can work
            end
        end
        %save the results
        record(5+D,t+2) = output;
        record;

        %% Activity 6: Transfer towers + nacelles
        output=0; %initialise the value
        % I have finished with this activity?
        if (max(record(6+D,:))) == 100 || (sum(record(6+D,:) == 1) == act6)
            %if so, Refilling with 100
            output=100;
        else %otherwise, I check if I can start
            if any(record(3+D,:) == 100) %is it time to start?
                % if so, I check the weather conditions
                if any(waves_t(t+t_start:t_start+t+5)>1.5) &&
           any(wind_t(t+t_start:t_start+t+5)>13) || any(waves_t(t+t_start:t_start+t+5)>1.5) ||
           any(wind_t(t+t_start:t_start+t+5)>13)
                    output = 2; %I have to wait
                else
                    output = 1; %I can work
                end
            end
        end
        %save the results
        record(6+D,t)= output;
        record;

        %% Activity 7: Transfer blades
        output=0; %initialise the value
        %Is the activity finished?
        if (max(record(7+D,:))) == 100 || (sum(record(7+D,:) == 1) == act7)
            %if so, refill with 100
            output = 100;
        else %otherwise, check if i can start
            if any(record(5+D,:) == 100) %is it time to start?
                %if so, I check the weather conditions
               if any(waves_t(t+t_start:t_start+3) > 1.5) && any(wind_t(t+t_start:t_start+3)>13)
    ||     any(waves_t(t+t_start:t_start+3)>1.5) || any(wind_t(t+t_start:t_start+3)>13)
                    output = 2; %i have to wait
                else
                    output = 1; %i can work
                end
            end
        end
        %save the results
        record(7+D,t+2)= output;
        record;

        %% Activity 8: Installation WTG
        output=0; %initialise the value
        %Have i finished the activity?
        if (max(record(8+D,:))) == 100 || (sum(record(8+D,:) == 1) == act8)
            %if so, refill with 100
            output=100;
        else %otherwise, check if i can start
            if any(record(2+D,:) == 100) && any(record(6+D,:) == 100) && any(record(7+D,:) ==
100) %is it time to start?
                %if so, check the weather conditions
                if any(waves_t(t+t_start:t_start+t+1)>1.5) &&
           any(wind_t(t+t_start:t_start+t+1)>10) || any(waves_t(t+t_start:t_start+t+1)>1.5) ||
           any(wind_t(t+t_start:t_start+t+1)>10)
                    output = 2; %i have to wait
                else
                    output = 1; %i can work
                end
            end
        end
        record(8+D,t+t_start)= output;
        record;
```

```
            filename = '2windwavedata.xlsx'; %save output matrix as excel file
            writematrix(record,'2windwavedata.xlsx','Sheet',1)

        end %tsteps

        ind(1+D:8+D) = (1:8); %create index
        Arecord = [ind,record] %create matrix of ind and record

    end %unit

    work_t = sum(record == 1,2); %length of working time == 1 in number of time steps.
    wait_t = sum(record == 2,2); %length of waiting time == 2 in number of time steps.
    work_h = work_t * 3; %total hours of working per activity
    wait_h = wait_t * 3; %total hours of waiting per activity
    B = [work_t,wait_t]; %matrix with wait time and work time columns per activity (rows)
    C = [work_h,wait_h];
    Q = sum(work_h + wait_h,2); %sum of waiting hours + working hours per activity.
    Woh = sum(work_h);
    Wah = sum(wait_h);
    proj_t=sum(Q',2); %total project time

    Dsummary(i,:) = [stdate]; %start date of simulation, in row number
    summary(i,:)=[work_h',wait_h']; %columns:nsimul, rows: working hours followed by waiting hours
    Bsummary(i,:)=[Q']; %summary duration per activity in hours. nsimul = rows, nact*units = columns
    Psummary(i,:)=[proj_t]; %total project duration in hours per simulation
    Qmean(i,:) =[mean(Q)]; %average duration PER ACTIVITY IN HOURS PER SIMULATION
    Qmin(i,:) = [min(Q)]; %minimum duration of all activities in hours per simulation
    Qmax(i,:) = [max(Q)]; %maximum duration of all activities in hours per simulation
    WoWaSum(i,:) = [Woh,Wah]; %matrix containing sum of work_h and wait_h per simulation

    sum1(i,:) = [sum(summary(i,1:8:57),2),sum(summary(i,65:8:end),2)]; %sum work & wait hours act 1.
    sum2(i,:) = [sum(summary(i,2:8:58),2),sum(summary(i,66:8:end),2)]; %sum work & wait hours act 2.
    sum3(i,:) = [sum(summary(i,3:8:59),2),sum(summary(i,67:8:end),2)]; %sum work & wait hours act 3.
    sum4(i,:) = [sum(summary(i,4:8:60),2),sum(summary(i,68:8:end),2)]; %sum work & wait hours act 4.
    sum5(i,:) = [sum(summary(i,5:8:61),2),sum(summary(i,69:8:end),2)]; %sum work & wait hours act 5.
    sum6(i,:) = [sum(summary(i,6:8:62),2),sum(summary(i,70:8:end),2)]; %sum work & wait hours act 6.
    sum7(i,:) = [sum(summary(i,7:8:63),2),sum(summary(i,71:8:end),2)]; %sum work & wait hours act 7.
    sum8(i,:) = [sum(summary(i,8:8:64),2),sum(summary(i,72:8:end),2)]; %sum work & wait hours act 8.

end %simulation

load('basecaseTLP.mat') %load saved data to run program faster

avP = sum(Psummary); %sum total project duration
summary; %matrix containing nsimul (rows) and work h per act and wait h FOR EACH ACTIVITY
Psummary; %duration per simulation in hours
Qmean; %mean project duration per simulation in hours
Qmin; %minimum project duration per simulation in hours
Qmax; %maximum project duration per simulation in hours

sum1mean = [(mean(sum1(:,1))/24),(mean(sum1(:,2))/24)]; %mean work & wait time activity 1 [days].
sum2mean = [(mean(sum2(:,1))/24),(mean(sum2(:,2))/24)]; %mean work & wait time activity 2 [days].
sum3mean = [(mean(sum3(:,1))/24),(mean(sum3(:,2))/24)]; %mean work & wait time activity 3 [days].
sum4mean = [(mean(sum4(:,1))/24),(mean(sum4(:,2))/24)]; %mean work & wait time activity 4 [days].
sum5mean = [(mean(sum5(:,1))/24),(mean(sum5(:,2))/24)]; %mean work & wait time activity 5 [days].
sum6mean = [(mean(sum6(:,1))/24),(mean(sum6(:,2))/24)]; %mean work & wait time activity 6 [days].
sum7mean = [(mean(sum7(:,1))/24),(mean(sum7(:,2))/24)]; %mean work & wait time activity 7 [days].
sum8mean = [(mean(sum8(:,1))/24),(mean(sum8(:,2))/24)]; %mean work & wait time activity 8 [days].

avPsum = (Psummary / (unit*nact)); %average duration PER simulation in HOURS per activity
meanavPsum = mean(avPsum); %average duration of ALL simulations in HOURS
meanPsummary = [mean(Psummary)]; %mean of ALL simulations.
Dsummary; %extract start dates, shown in row number
meanBsummary = mean(Bsummary); %mean

WoWaSum; %work_h = always the same, wait_h = different, check ok.
avWah = (WoWaSum(:,2)/ (unit*nact)); %average wait hours PER simulation in HOURS
avWoWa = WoWaSum / (unit*nact); %average of WORK & WAIT hours
meanWoWaSum = mean(WoWaSum(:,2));
Wah = sum(WoWaSum(:,2)); %total wait hours
meanWah = mean(Wah);

dates = date.DT(date.DT(Dsummary)); %convert row number of Dsummary to corresponding date.
[sorted_dates,ind]=sort(dates);
sorted_dates;
sorted_Psummary = Psummary(ind);
sorted_avWoWa = avWoWa(ind,:);
sorted_WoWa = WoWaSum(ind,:);
```

```
sorted_avPsum = avPsum(ind);
sorted_Qmean = Qmean(ind); %sorted Qmean
sorted_Qmin = Qmin(ind); %sorted Qmin
sorted_Qmax = Qmax(ind); %sorted Qmax

[sorted_duration,index] = sort(avPsum); %sorted duration
sorted_duration;
dates_sorted = dates(index);

%% Plotting
figure
barcz = bar(sorted_avWoWa/24) sorted average work and wait times in days
set(gca,'XTick',[1 164 339 553 740 927] );
set(gca,'xticklabel',{'Jan 1997','Jul 1997','Jan 1998', 'Jul 1998','Jan 1999','Jul 1999'})
barcz(2).FaceColor = [1 0 0];
barcz(1).FaceColor = [0 1 0];
title('Distribution average work and delay time TLP')
xlabel('Start date')
ylabel('duration [day]')
yline(mean(avWah/24), '--b', 'LineWidth', 2)
legend('work [day]','delay [day]', 'average delay [day]')

figure
plot(sorted_dates,(sorted_avPsum/24)) %sorted dates with sorted average duration in days
title('Start date vs. average duration [day] for TLP')
xlabel('Start date')
ylabel('Average project duration [day]')
hold on
yline((meanavPsum/24), '--r', 'LineWidth',2)
tstart = datetime(1997,01,1);
tend = datetime(1998,06,30);
xlim([tstart tend])
legend('duration [day]','average duration [day]')

figure
hold on
plot(sorted_dates,(sorted_Qmean/24)); %sorted Qmean according to dates in days
plot(sorted_dates,(sorted_Qmax/24)) %sorted Qmax according to dates in days
plot(sorted_dates,(sorted_Qmin/24),'g') %sorted Qmin according to dates in days
title('Minimum, maximum and mean duration [day] for TLP')
xlabel('Start date')
ylabel('Project duration [day]')
legend('mean [day]','maximum [day]', 'minimum [day]')

figure
X = categorical({'1','2','3','4','5','6','7','8'});
X = reordercats(X,{'1','2','3','4','5','6','7','8'});
Y =
[sum1mean(:,2),sum2mean(:,2),sum3mean(:,2),sum4mean(:,2),sum5mean(:,2),sum6mean(:,2),sum7mean(:,2),
sum8mean(:,2)]; %bar graph of average wait time per activity
bar(X,Y)
title('Average delay [day] per activity TLP')
xlabel('Actvity')
ylabel('duration [day]')
legend('delay')

figure
X = categorical({'1','2','3','4','5','6','7','8'});
X = reordercats(X,{'1','2','3','4','5','6','7','8'});
Y = [sum1mean',sum2mean',sum3mean',sum4mean',sum5mean',sum6mean',sum7mean',sum8mean'];
bar(X,Y) %bar graph of average work & wait time per activity
title('Average work time and delay [day] per activity TLP')
xlabel('Actvity')
ylabel('duration [day]')
legend('work time','delay')

figure
[cdf,x] = ecdf(avPsum/24); %average project duration in days
plot(x,cdf,'b','Linewidth',2)
title('CDF average project time TLP')
xlabel('Project duration (days)')
ylabel('cdf')
axis([min(x),max(x),0,1])
hold on
stairs(x,cdf,'b', 'LineWidth', 2)

toc
end
```

Appendix G

Matlab code for the semi-submersible structure

```
function rossfield_ssb_basecase
clear, clc, close all
tic
%% Base model, in this model a 3-hour time interval is implemented
%% Data:
unit = 8;
nact = 3;
totalact = unit*nact; %number of units times number of activities
step = 3; %timestep in hours, every day has 24/3 = 8 steps
timeanalysis = 1000; %length of analysis

%% Activities characteristics
act1 = 3; %Activity 1: assembly SSB structure. 9 hrs
act2 = 4; %Activity 2: tow-out SSB structure. 11 hrs
act3 = 1; %Activity 3: installation SSB structure. 3 hrs
totaltime = act1 + act2 + act3;

%% Load data:
T = readtimetable('ws_wv_rossfield.xls', 'PreserveVariableNames', true);
TR = timerange("1997-01-01","1999-12-31");
date = T(TR,:);

%% Create summary of output data
nsimul = 1000; %number of simulations
summary = zeros(nsimul,2*unit*nact); %for each simulation the project time and waiting time of each
unit
Bsummary = zeros(nsimul,unit*nact);

rng(35) %to guarantee the same random collection of point
MaxStartDate=length(date.WS)-timeanalysis; %determine minimal required start date to be able to
finish simulation

%% Put loop:
for i = 1:nsimul %number of simulations

    %% Random data
    stdate=randi(MaxStartDate); %select a random point

    wind_t = date.WS(stdate:end);
    waves_t = date.WV(stdate:end);

    %% Weather windows
    tsteps = ceil(timeanalysis/step)-1; %define number of columns, number of columns [step]
    record = zeros(totalact,tsteps); %allocating memory
    ind = zeros(nact*unit,1); %create an index for number of units + activities = rows, 1 column
    t_start=1; %initialise the start

    for u = 1:unit %loop through number of units, 1 to number of units
        D = nact * (u-1); %how much it should move in the loop every activity

        for t=1:tsteps   %loop through all columns, 1 to number of time steps
            %loop of first unit finished?
            if u>1
                %if so, check if not any value in record first loop are equal to 100
                if ~any(record(2+(D-2),:)==100) %for act 1
                    %if so, stop and continue with code
                    break;
                else %otherwise, find first value equal 100 in first row of u = 1 from t_start=1
                    t_start=find(record(D-2,:)==100,1,'first');
                end
            end

            %% Activity 1: Assembly SSB
            output=0; %initialise the value
            %Have i finished the activity?
            if (max(record(1+D,:))) == 100 || (sum(record(1+D,:) == 1) == act1)
                %if so, refilling rest of row with 100.
                output = 100;
            else %otherwise, check if i can start?
```

```
            if any(waves_t(t+t_start:t+t_start+3) >= 1.5) && any(wind_t(t+t_start:t+t_start+3) >=
           13) || any(waves_t(t+t_start:t+t_start+3) >= 1.5) || any(wind_t(t+t_start:t+t_start+3)
           >= 13)
                output = 2; % have to wait
            else
                output = 1; % can go
            end

        end
        %save the results
        record(1+D,t+t_start-1) = output;
        record;

        %% Activity 2: Transport SSB
        output=0; %initialise the value
        %Have i finished with the activity?
        if (max(record(2+D,:))) == 100 ||(sum(record(2+D,:) == 1) == act2)
            %if so, refill with 100's
            output = 100;
        else %otherwise, check if i can start
            if any(record(1+D,:) == 100) %is it time to start? Previous act 100?
                %if so, check weather conditions
                if any(waves_t(t+t_start:t_start+t+4)>=2) &&
           any(wind_t(t+t_start:t_start+t+4)>=13) || any(waves_t(t+t_start:t_start+t+4)>=2) ||
           any(wind_t(t+t_start:t_start+t+4)>=13)
                    output = 2; %I have to wait
                else
                    output = 1; %I can work
                end
            end
        end
        record(2+D,t+t_start-1)= output;
        record;

        %% Activity 3: Installation SSB
        output=0; %initialise the value
        %Have i finished the activity?
        if (max(record(3+D,:))) == 100 || (sum(record(3+D,:) == 1) == act3)
            %if so, refill with 100
            output = 100;
        else %otherwise, check if can start
            if any(record(2+D,:) == 100)
                %if so, check weather conditions
                if any(waves_t(t+t_start:t+t_start+1)>=2) &&
           any(wind_t(t+t_start:t+t_start+1)>=13) || any(wind_t(t+t_start:t+t_start+1)>=13) ||
           any(waves_t(t+t_start:t+t_start+1)>=2)
                    output = 2; %have to wait
                else
                    output = 1; %i can work
                end
            end
        end
        %save the results
        record(3+D,t+t_start-1) = output;
        record;

    end %tsteps

    ind(1+D:3+D) = (1:3); %create index
    Arecord = [ind,record] %create matrix of ind and record
    filename = 'final_ssbdata.xlsx'; %save output matrix in excel
    writematrix(Arecord,'final_ssbdata.xlsx','Sheet',1)

end %unit

work_t = sum(record == 1,2); %length of working time == 1 in number of time steps.
wait_t = sum(record == 2,2); %length of waiting time == 2 in number of time steps.
work_h = work_t * 3; %total hours of working per activity
wait_h = wait_t * 3; %total hours of waiting per activity
B = [work_t,wait_t]; %matrix with wait time and work time columns
Q = sum(work_h + wait_h,2); %sum of waiting hours + working hours per activity.
proj_t = sum(Q',2); %total project time
Woh = sum(work_h); %total work hours, 1 number for all activities together
Wah = sum(wait_h); %total wait hours, 1 number for all activities together

Dsummary(i,:) = [stdate]; %start date of simulation, in row number
summary(i,:)=[work_h',wait_h']; %columns: nsimul, rows: work hours followed by waiting hours
Bsummary(i,:)=[Q']; %sum of waiting + working hours per activity in hours.
Psummary(i,:)=[proj_t]; %total project duration in hours per simulation
```

```
    Qmean(i,:) =[mean(Q)]; %average duration PER ACTIVITY IN HOURS PER SIMULATION
    Qmin(i,:) = [min(Q)]; %minimum duration of all activities in hours per simulation
    Qmax(i,:) = [max(Q)]; %maximum duration of all activities in hours per simulation
    Esummary(i,:) = [work_h',wait_h',Q']; %work, waiting and total hours matrix
    WoWaSum(i,:) = [Woh,Wah]; %matrix containing sum of work_h and wait_h per simulation

    sum1(i,:) = [sum(summary(i,1:3:22),2),sum(summary(i,25:3:end),2)]; %work & wait hours act 1.
    sum2(i,:) = [sum(summary(i,2:3:23),2),sum(summary(i,26:3:end),2)]; %work & wait hours act 2.
    sum3(i,:) = [sum(summary(i,3:3:24),2),sum(summary(i,27:3:end),2)]; %work & wait hours act 3.
    totT = sum(sum2,2); %total sum travel time act 2 per coef


end %simulation

load('basecaseSSB.mat') %load saved data to run program faster

avP = sum(Psummary);
record;
summary;
Psummary; %total project duration in hours per simulation

Qmean; %mean project duration per simulation in hours
Qmin; %minimum project duration per simulation in hours
Qmax; %maximum project duration per simulation in hours

sum1mean = [(mean(sum1(:,1))/24),(mean(sum1(:,2))/24)]; %mean work & wait time activity 1 [days].
sum2mean = [(mean(sum2(:,1))/24),(mean(sum2(:,2))/24)]; %mean work & wait time activity 2 [days].
sum3mean = [(mean(sum3(:,1))/24),(mean(sum3(:,2))/24)]; %mean work & wait time activity 3 [days].

avPsum = (Psummary / (unit*nact)); %average duration PER simulation in HOURS
meanavPsum = mean(avPsum); %average duration of ALL simulations in HOURS
meanPsummary = mean(Psummary); %mean of ALL simulations.
Dsummary; %extract start dates, shown in row number

WoWaSum; %work_h = always the same, wait_h = different, check ok.
avWah = (WoWaSum(:,2)/ (unit*nact)); %average wait hours PER simulation in HOURS
avWoWa = WoWaSum / (unit*nact); %average work and wait hours

Wah = sum(WoWaSum(:,2)) %total wait hours
avW = (Wah / nsimul) %average wait hours PER simulation

dates = date.DT(date.DT(Dsummary)); %convert row number of Dsummary to corresponding date.
[sorted_dates,ind]=sort(dates); %sort dates
sorted_dates;
sorted_Psummary = Psummary(ind);
sorted_avWoWa = avWoWa(ind,:);
sorted_WoWa = WoWaSum(ind,:);
sorted_avPsum = avPsum(ind);

sorted_Qmean = Qmean(ind); %sort Qmean
sorted_Qmin = Qmin(ind); %sort Qmin
sorted_Qmax = Qmax(ind); %sort Qmax

[sorted_duration,index] = sort(avPsum); %sort something else iso dates, like duration or so
sorted_duration; %sorted average project duration in HOURS
dates_sorted = dates(index); %sort dates according to index

%% Plotting
figure
barcz = bar(sorted_avWoWa/24) %sorted average work and wait times in days
set(gca,'XTick',[1 164 339 553 740 927] );
set(gca,'xticklabel',{'Jan 1997','Jul 1997','Jan 1998', 'Jul 1998','Jan 1999','Jul 1999'})
barcz(2).FaceColor = [1 0 0];
barcz(1).FaceColor = [0 1 0];
title('Distribution average work and delay time SSB')
xlabel('Start date')
ylabel('duration [day]')
yline(mean(avWah/24), '--b', 'LineWidth', 2)
legend('work [day]','delay [day]', 'average delay [day]')


figure
plot(sorted_dates,(sorted_avPsum/24)) %sorted dates with sorted average duration in days
title('Start date vs. average duration [day] for SSB')
xlabel('Start date')
ylabel('Average project duration [day]')
hold on
yline((meanavPsum/24), '--r', 'LineWidth',2)
tstart = datetime(1997,01,1);
```

```
tend = datetime(1999,09,30);
xlim([tstart tend])
legend('duration [day]','average duration [day]')

figure
hold on
plot(sorted_dates,(sorted_Qmean/24)); %sorted Qmean according to dates in days
plot(sorted_dates,(sorted_Qmax/24)) %sorted Qmax according to dates in days
plot(sorted_dates,(sorted_Qmin/24),'g') %sorted Qmin according to dates in days
title('Minimum, maximum and mean duration [day] for SSB')
xlabel('Start date')
ylabel('Project duration [day]')
tstart = datetime(1997,01,1);
tend = datetime(1999,09,30);
xlim([tstart tend])
legend('mean [day]','maximum [day]', 'minimum [day]')

figure
X = categorical({'1','2','3'});
X = reordercats(X,{'1','2','3'});
Y = [sum1mean(:,2),sum2mean(:,2),sum3mean(:,2)]; %bar graph of average wait time per activity
bar(X,Y)
title('Average delay [day] per activity SSB')
xlabel('Actvity')
ylabel('duration [day]')
legend('delay')

figure
X = categorical({'1','2','3'});
X = reordercats(X,{'1','2','3'});
Y = [sum1mean',sum2mean',sum3mean']; %bar graph of average work & wait time per activity
bar(X,Y)
title('Average work time and delay [day] per activity SSB')
xlabel('Actvity')
ylabel('duration [day]')
legend('work time','delay')

figure
[cdf,x] = ecdf(avPsum/24); %average project duration in days
plot(x,cdf,'r','Linewidth',2)
title('CDF average project time SSB')
xlabel('Project duration (days)')
ylabel('cdf')
axis([min(x),max(x),0,1])
hold on
stairs(x,cdf,'r', 'LineWidth', 2)

toc
end
```