Analysis of the Installation of a Series of Piles for Offshore Wind Turbine Foundations

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Master Thesis

presented in partial fulfillment
of the requirements for the double degree:
"Advanced Master in Naval Architecture" conferred by University of Liege
"Master of Sciences in Applied Mechanics, specialization in Hydrodynamics, Energetics and Propulsion" conferred by Ecole Centrale de Nantes

developed at University of Rostock
in the framework of the

"EMSHIP"
Erasmus Mundus Master Course
in "Integrated Advanced Ship Design"

Ref. 159652-1-2009-1-BE-ERA MUNDUS-EMMC

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Rostock, February 2014

NOTE TO THIS EDITION

The present master thesis is a reduced edition. Figures and data that are subject to a non-disclosure agreement are removed. The removal is always indicated in the caption of the concerning table or graph, or overwritten with the abbreviation NDA (non-disclosure agreement).

ABSTRACT

The offshore wind farm industry is evolving towards a developed stage, resulting in increasing competition between offshore contractors. The tendency of larger offshore wind farms in deeper waters challenges the cost effectiveness of offshore wind turbine support structures. Jackets and tripods are appropriate for deep waters. They are fixed to the seabed by foundation piles. Pre-piling is a technique that installs the foundation piles before the installation of the substructures, which realizes a cost reduction.

The present research focuses on the offshore operations of pre-piling. Controlling the cycle time is essential to finish a project successfully. An analysis of reported times of the offshore activities is carried out by means of SPC charts. The data for five pre-piling projects are collected and analysed. The production time is divided into seven activity groups: (1) jack-up platform positioning, (2) piling template handling, (3) offshore pile transfer, (4) upending and stabbing of piles, (5) pile driving, (6) top of pile dredging and (7) survey of piles. The primary objective regarding this approach is to define behaviours, trends and bottlenecks, of which further investigation leads to a better understanding, control and possible improvement.

Offshore operations are sensitive to weather conditions. Those have a major impact on the completion date of the project, which has on its turn a big influence on the overall cost of the project. A suitable weather window is defined by the weather limits and duration of the planned activity. The waiting on weather between activities is simulated by means of a monte carlo simulation to calculate the effects on the completion date. The monte carlo simulation is based on the cumulative frequency distributions of the weather window and downtime persistence.

The ultimate goal is to increase production by making use of shorter weather windows. The combination of the analysis of the cycle time and the simulation of the waiting on weather provides a tool to quantify the benefits and costs of different methodologies in a benchmark analysis on production efficiency. Concrete examples are presented and discussed.

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ABBREVIATIONS

c.t.c.	centre-to-centre
CFD	Cumulative Frequency Density
DP2	Dynamic Positioning with redundancy of all equipment to prevent failure.
Hs	significant wave height
ILT	Internal Lifting Tool
JUP	Jack-Up Platform
NDA	Non-Disclosure Agreement
nm	nautical miles (= 1.852 km)
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine
PSV	Platform Supply Vessel
ROV	Remote Operateble Vehicle
WOW	Waiting On Weather
WW	Weather Window

DECLARATION OF AUTHORSHIP

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Where I have consulted the published work of others, this is always clearly attributed.

Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

I have acknowledged all main sources of help.

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1 INTRODUCTION

The offshore wind farm industry is evolving towards a developed stage, resulting in increasing competition between offshore contractors. The installation techniques and methodologies are an important quality to strengthen its position in the market. In order to maintain this position an analysis of the current installation techniques is essential to tender for future projects and to manage ongoing projects. One of the current techniques is pre-piling, which involves the installation of a series of piles. The present study focuses on tools to analyse a project under construction.

The resources on project level are limited. Therefore it is important to focus on the areas where improvements can easily be achieved. Lean six sigma introduces methods to find this so-called "low-hanging fruit". Nevertheless eliminating bottlenecks may require an investment. Quantifying the costs and benefits of these investments are not straightforward since a lot of factors influence the installation process. Three parameters have a substantial impact on the cycle time: technology, weather conditions and soil profile. These have an unpredictable character. A learning curve is present with new technology (project specific tools). Soil profiles are obtained by cone penetration tests and site surveys, but these provide discrete data or uncertain coordinates of singularities, such as boulders that may affect the installation. Weather forecasts can fail. Moreover, the design of the piles varies for each offshore wind turbine location.

The objective of the study is to provide a tool that helps to decide whether an investment is profitable. The proposed tool is based on the analysis of reported time data and takes into account the weather downtime by means of a monte carlo simulation.

Further in this chapter the offshore wind farm industry and construction are discussed, providing the context of pre-piling projects. The following chapter describes the pre-piling technique and its advantages and disadvantages. Then, the analysis methods are explained, introducing the lean six sigma methodology. The next chapter presents five pre-piling projects of which the time data are collected. Thereafter the monte carlo simulation to make a prognosis of the completion date is explained. Finally, the results of the analysis are discussed and the use of the monte carlo simulation in combination with results from the analysis are demonstrated. The last chapter contains conclusions and recommendations for future research.

1.1 Offshore Wind Farm Industry

Offshore wind farms (OWFs) produce more energy per year than onshore wind farms for the same rotor diameter and tip height. The wind speeds offshore are higher than onshore, which results in higher wind turbine power outputs, according to the following formula (Burton, Jenkins, Sharpe, & Bossanyi, 2011):

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

where P is the wind turbine power output, ρ air density, Cp the power coefficient, A the rotor swept area, and U the wind speed. Indeed the power output increases with the wind speed to the third power. An offshore wind turbine has also more operating hours per year than onshore ones. Higher power and longer operating time make the energy output per year higher, which is clearly seen in the basic formula of energy:

$$E = P \cdot t'$$

with E the energy output per year [Wh/y], P the power output [W] and t' the operating hours per year [h/y]. This is one side of the picture.

The cost of OWF are higher than a wind farm on land due to the larger structures (support structures) and more complex installation. The benefits of the better wind conditions have to be higher than these extra costs to make the OWF profitable and hence interesting. Nevertheless, there are other reasons to build OWF. For example in the dense populated EU onshore wind farms experience a lot of resistance by NIMBY people, i.e. not in my back yard (Weaver, 2012).Visual pollution, noise of the rotor and shadow flicker of the rotating blades are the main reasons for people to block new plans to build onshore wind farms, resulting in an estimated constant trend for onshore and an increasing trend for offshore energy, see Figure 1.

Renewable energy, such as wind energy, is regarded as one of the solution to counter global warming. Governments around the world include concerns about climate change in their policy. The president of the USA, Barack Obama, launched a promotion video to announce his initiative about climate change, (Compton, 2013). China, amongst others, started drafting a climate change law (Harrabin, 2013). Other incentives, such as security of supply, play also a role. The European Union (EU) has already implemented environmental friendly measures, the well-known 20-20-20 targets. They pursuit by 2020 a 20 % decrease of greenhouse gasses w.r.t . the level of 1990, being 20 % more energy efficient against business as usual, and a 20 % share of the total energy consumption generated by renewable energy sources. Many EU member states focus on the electricity sector to accomplish the targets, see Figure 2. Wind energy forms one of the spearheads of their policy. The member states of the EU plan to install 44 GW of offshore wind farms. Therefore, the international energy agency (IEA) predicts that by 2035 wind energy will be one quarter of the global renewable energy, which will provide 31 % of the total generation. This will require investments, see Figure 3 for a prediction.

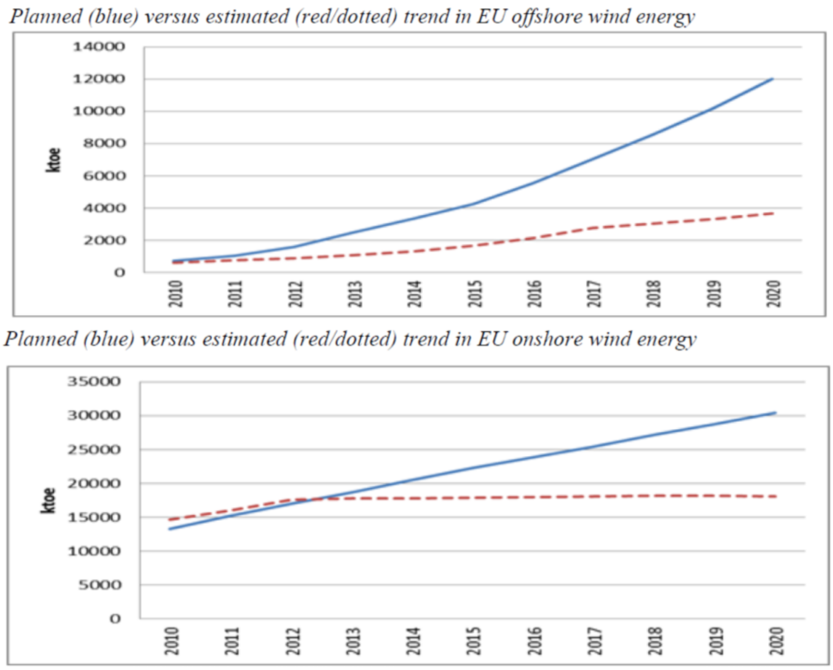

Figure 1: Top: offshore wind energy trend in the EU. Bottom: onshore wind energy trend in the EU (European Commission, 2013).

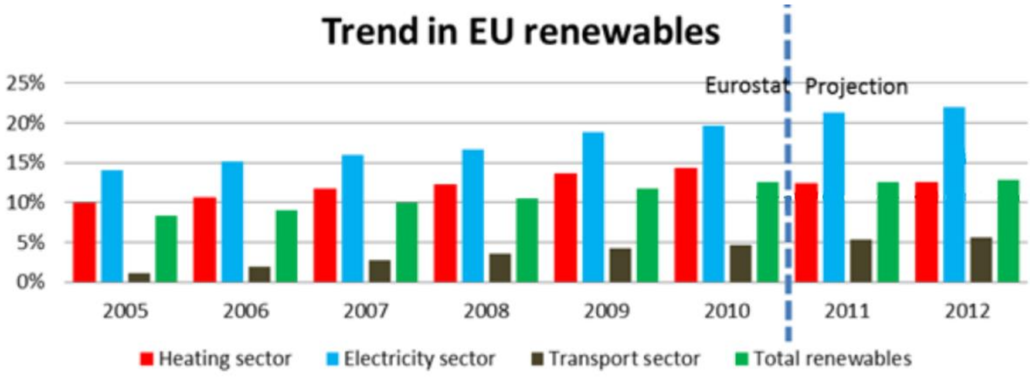

Figure 2: Sectorial and overall growth of renewable energy in the EU (European Commission, 2013).

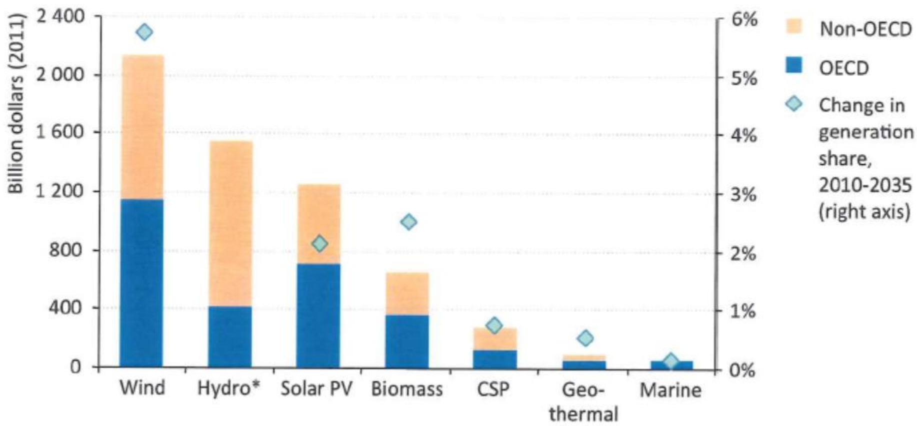

Figure 3: Cumulative investment in renewable-based electricity generation by region and type in the New Policies Scenario, 2012-2035 (Birol, 2012).

It is clear that the offshore wind energy market will continue to increase (Figure 4). This also means that more companies will switch their focus to OWF and enter the market, for example companies from the oil and gas sector, which already have experience offshore. Whilst the market is developing competition will eliminate companies and only the most cost effective companies will survive on the long term. It is therefore important for companies to invest in production and service optimization to bring the cost down. A methodology to obtain this is lean six sigma (Murman, 2008).

In the cost breakdown of a wind farm it is remarkable that the support structures has a bigger share in OWF. The onshore support structures take up 6.5 % of the capital cost, whilst offshore support structures consume 34 % on average (Horgan, 2013). One reason is the higher installation cost. Support structures at the first OWF at commercial scale took up around 21 % of the capital cost (Lemming, Morthorst, & Clausen, 2008). The increase from 21 to 34 % may be explained by the trend of new OWFs being built further away from the shore and in deeper waters. Another trend is the larger number of wind turbines in new OWFs, making it definitely worth to look at the installation of the support structure as a process and optimize it.

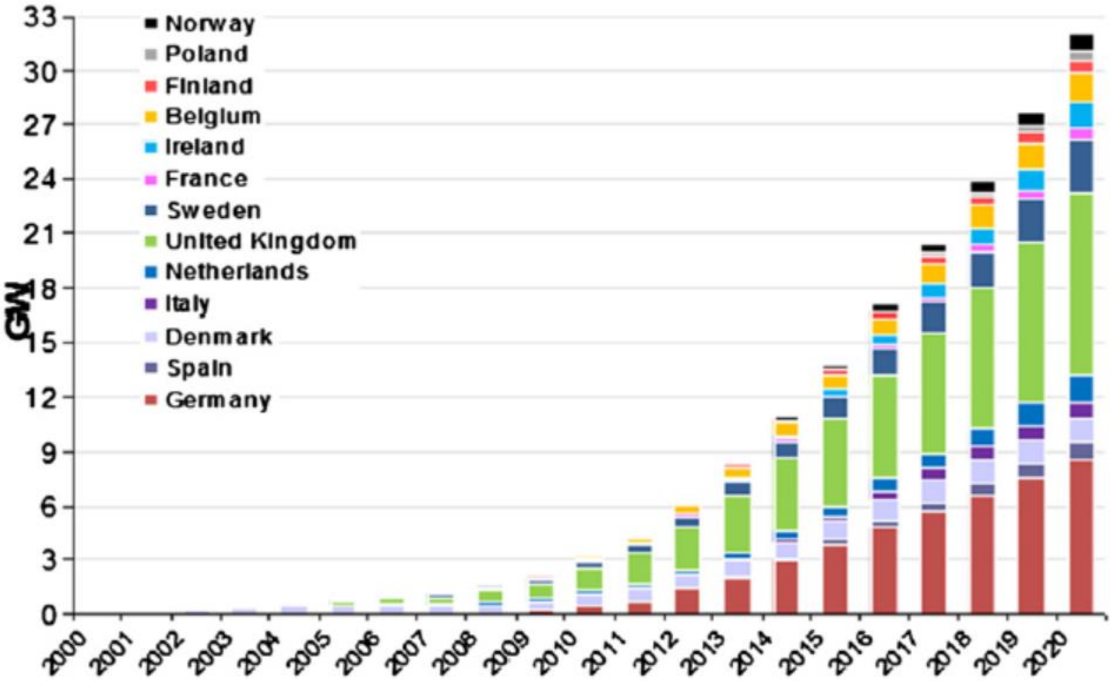

Figure 4: Installed capacity of offshore wind farms for different countries, forecasting from 2012 (T. Weaver, 2012).

1.2 Offshore Wind Farm Construction

An offshore wind farm (OWF) consists of a number of wind turbines and an electrical transmission system. The latter includes inner-array cables, an export cable, and possibly a substation. A wind turbine has basically three components: the rotor converting wind energy to mechanical energy, the nacelle housing the generator which converts the mechanical energy to electrical energy, and the tower, see Figure 5 (Thomsen, 2012). In particular an offshore wind turbine (OWT) has a support structure with a foundation in the seabed, a substructure to bridge the water depth, and a platform on which the turbine tower is placed. Although previous terminology is quite clear, different terminologies are used in literature

(Zaaijer, 2003). So (Thomsen, 2012) uses the term foundation for the entire structure below sea level. Others, such as (Zaaijer, 2003), include the turbine tower in the support structure. The choice of terminology in this paper is based on the terminology in literature dedicated to the installation of OWF. The turbine tower is installed together with the nacelle and the rotor, while the support structure (foundation and substructure) are installed in a previous phase (Kaiser & Snyder, 2013). The right panel of Figure 10 presents the terminology used in this report.

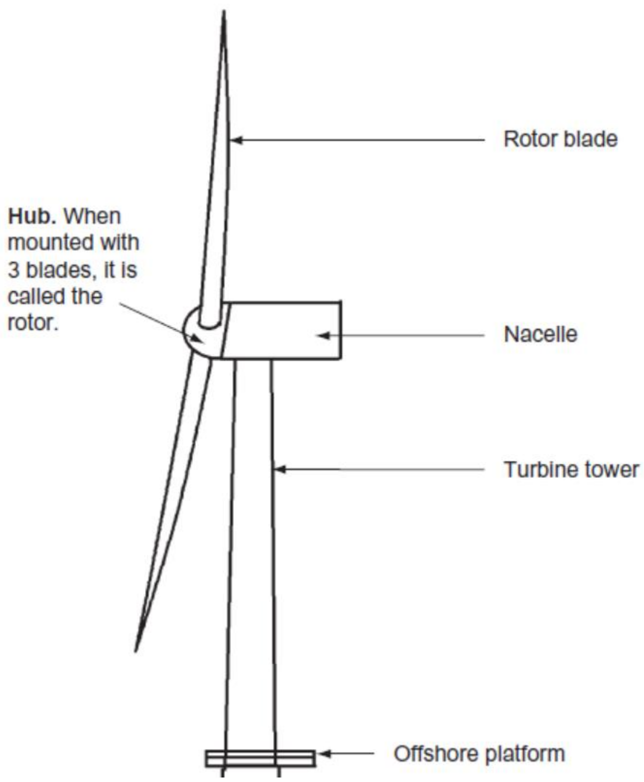

Figure 5: Components of an offshore wind turbine above water level (Thomsen, 2012).

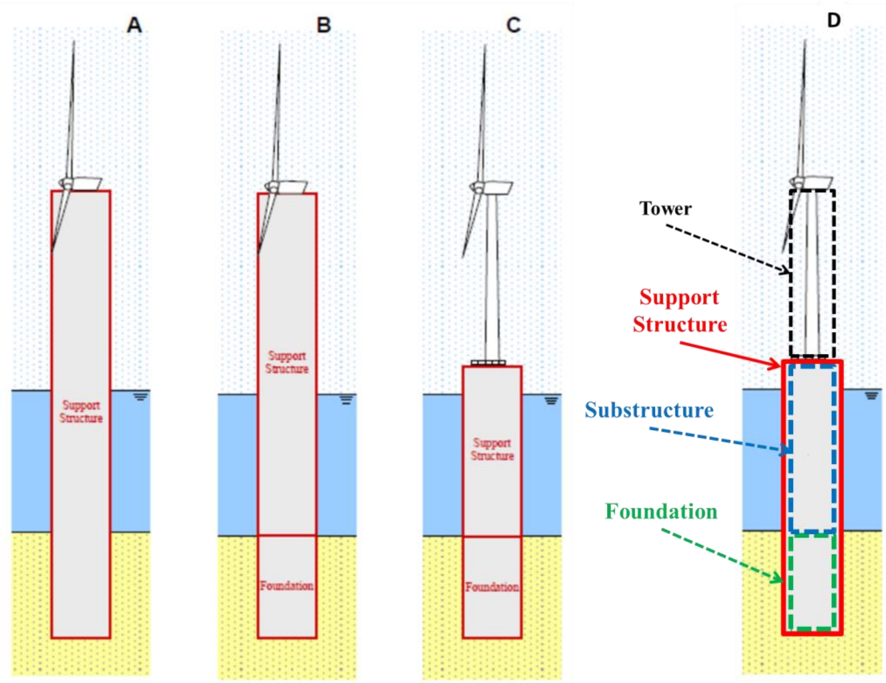

Figure 6: Different definitions for support structure. Right hand side the terminology used in this report. Pictures based on figure 1 in (deVries, et al., 2007).

1.2.1 Types of Support Structures

Different combinations of foundations and substructures are described in the literature, an overview is given in Table 1. The foundation secures the attachment to the sea bed in order to resist uplift of the support structure generated by overturning moments due to sea and wind loads, (Burton, Jenkins, Sharpe, & Bossanyi, 2011). There are three types: gravity foundations, piles and suction caissons. Gravity foundations are heavy and wide structures placed in a shallow pit in the sea bed. The self-weight creates an eccentric reaction to the overturning moment. Piles are steel cylindrical tubes driven into the seabed. In the case of a single pile (monopile) the restoring moment is provided by mobilizing lateral soil loads. In the case of multiple piles, the overturning moment tends to lift a pile up, but this is resisted by friction on the surface of the piles. Suction caissons are common in the oil industry, and since 1995 proposed as foundation for offshore wind turbines (Singh & Mistri, 2010). In spite of this they aren’t wide spread in current offshore wind farms. Suction caissons look like a upside down bucket placed on the seabed. Inside the caisson a lower pressure is created, sucking itself into the soil. This sucking provides the attachment to the sea bed, which resists uplift of one side or the whole caisson when sea or / and wind apply an overturning moment.

Table 1: Overview combinations substructures and foundations.

substructure	Foundation		
	Gravity	piles	suction caissons
monopod	aka “**gravity-based**”	aka “**monopile**”	aka “**suction bucket**”
jacket	n/a	common practice	under investigation*
tripod	if legs are enough spaced*	common practice**	under investigation**
tripile	n/a	implied by substructure	n/a
floating concepts	gravity anchor***	suction pile anchor***	

* (Burton, Jenkins, Sharpe, & Bossanyi, 2011), ** (Breton & Moe, 2009), *** (Castro-Santos, González, & Diaz-Casas, 2013)

The design of support structures is primarily based on the water depth, soils and morphology, turbine and wave loads, manufacturing and installation (EWEA, Offshore support structures, 2009). In the literature the terms in bold in Table 1 are mostly used to name the total support structure. Figure 7 presents the maturity of these support structures in relation with the water depth. The first built offshore wind farms were small and close to the shore in shallow waters in order to lower the cost and risk. Simple concepts as the gravity-based and monopile support structures fitted in this way of thinking. In this regard these support structures were the only one installed, see Figure 8. Price difference in steel and concrete had an influence. In deeper water the support structure is obviously taller, which implies bigger lever arms and hence increased moments due to wave and turbine loads. Length and diameter needs to be increased in order to bridge the water depth and reinforce the support structure respectively, resulting in higher weight. This makes gravity-based support structures impractical, since they are already heavy. The monopile is for this reason the most popular. For even deeper water the monopile encounter the same issues: a higher weight is directly related to the manufacturing cost by the amount of needed raw materials and to the installation cost by the need for more advanced equipment that can handle these heavier weights. Jacket structures are estimated lighter than monopiles. The trend of offshore wind farms is tending to bigger OWF and in deeper waters, and so the jacket structures are coming on, see right hand side Figure 8. Bigger OWFs motivate to investigate alternative support structures that may be cheaper, for example tripod with suction caissons (Singh & Mistri, 2010). Figure 9 lists the existing support structures and some alternatives.

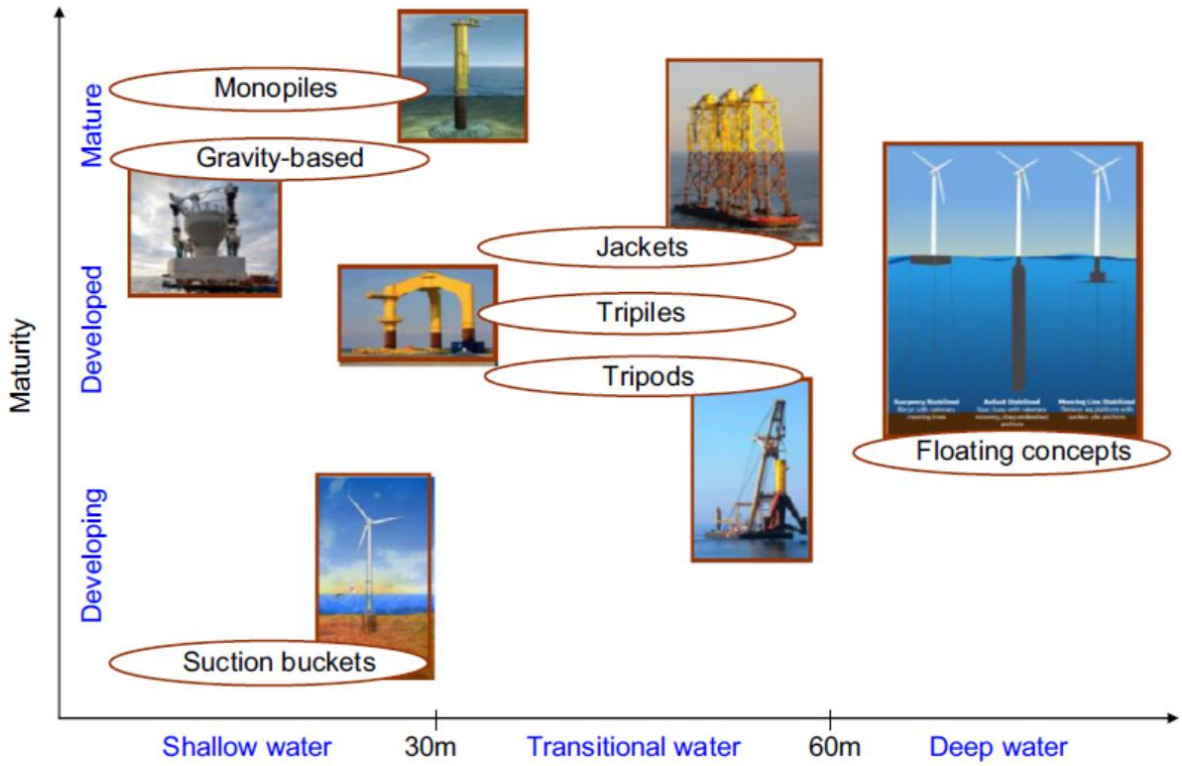

Figure 7: Main support structure technology in relation to water depth (Kaldellis & Kapsali, 2012).

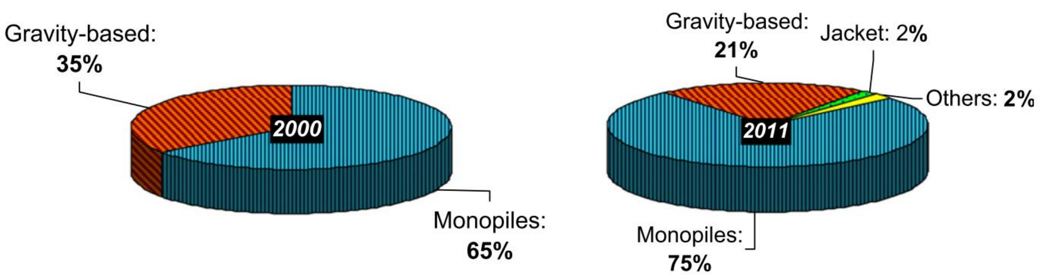

Figure 8: Share of support structures types for the in operation wind farms in 2011 (Kaldellis & Kapsali, 2012).

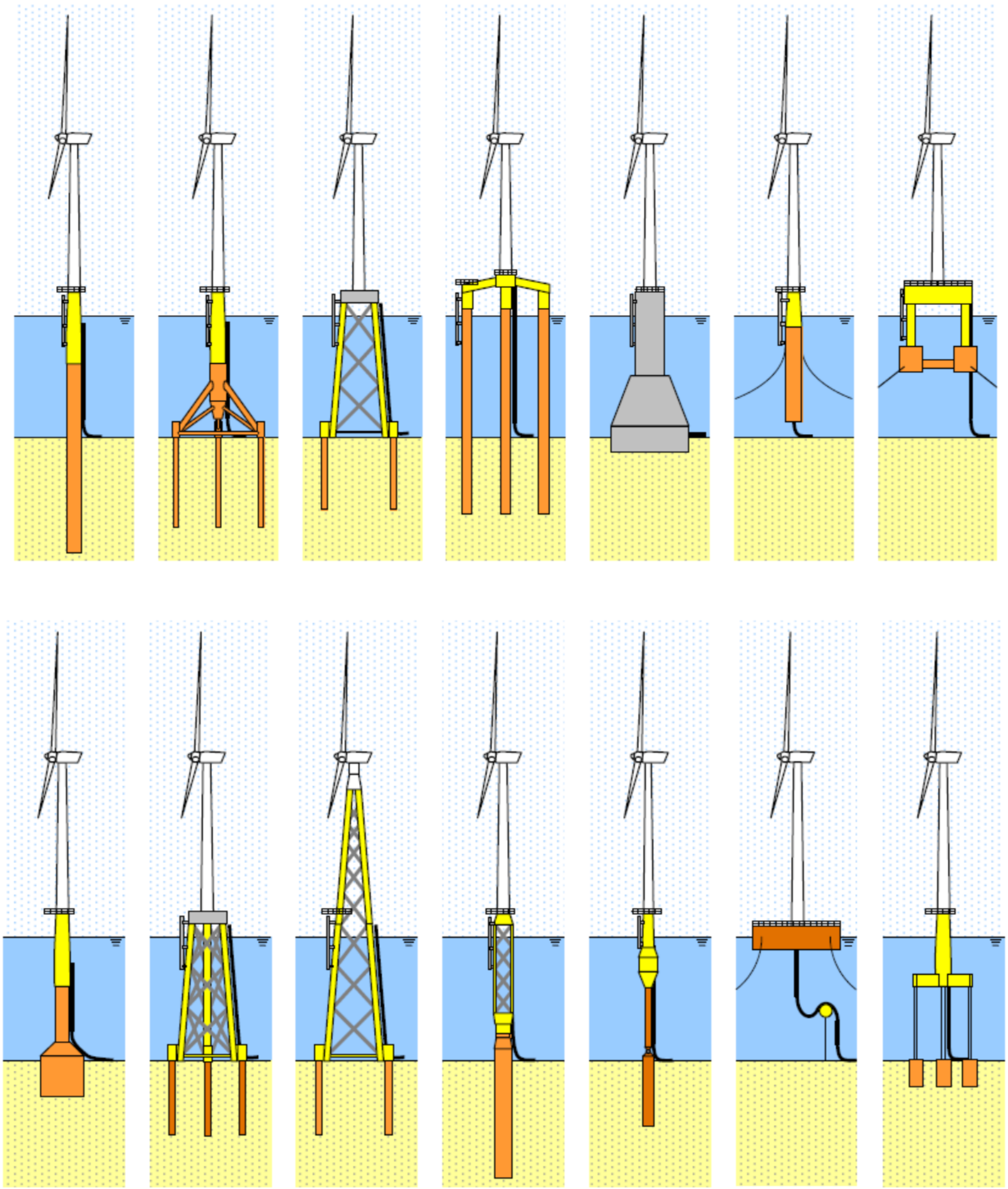

Figure 9: Existing and alternative support structures (not to scale) from left to right: monopile, tripod, jacket, tripile, gravity base structure, spar floater, semisubmersible floater, suction bucket, three legged jacket, full truss tower, compliant structure, articulated buoyant tower, barge floater, tension leg platform , (de Vries, et al., 2011).

1.2.2 Installation of Jacket Support Structures

The pre-piling technique can be applied to jacket substructures and tripod substructures. As an example the installation of a jacket support structure is discussed. Figure 10 shows the components of a jacket support structure. The main components are the transition piece which facilitates connection between substructure and turbine tower, the four leg lattice structure and the piles.

Assembly of the complete offshore wind turbine is done as much as possible onshore in order to reduce expensive installation time offshore (Snyder & Kaiser, 2009), but this is limited by crane capacity. The substructure including lattice structure, transition piece and secondary steel (ladders, J-tube for electricity cable, work platforms etc.) can be transported as a whole. The tower and turbine are installed separately in a next phase and isn't discussed in this section.

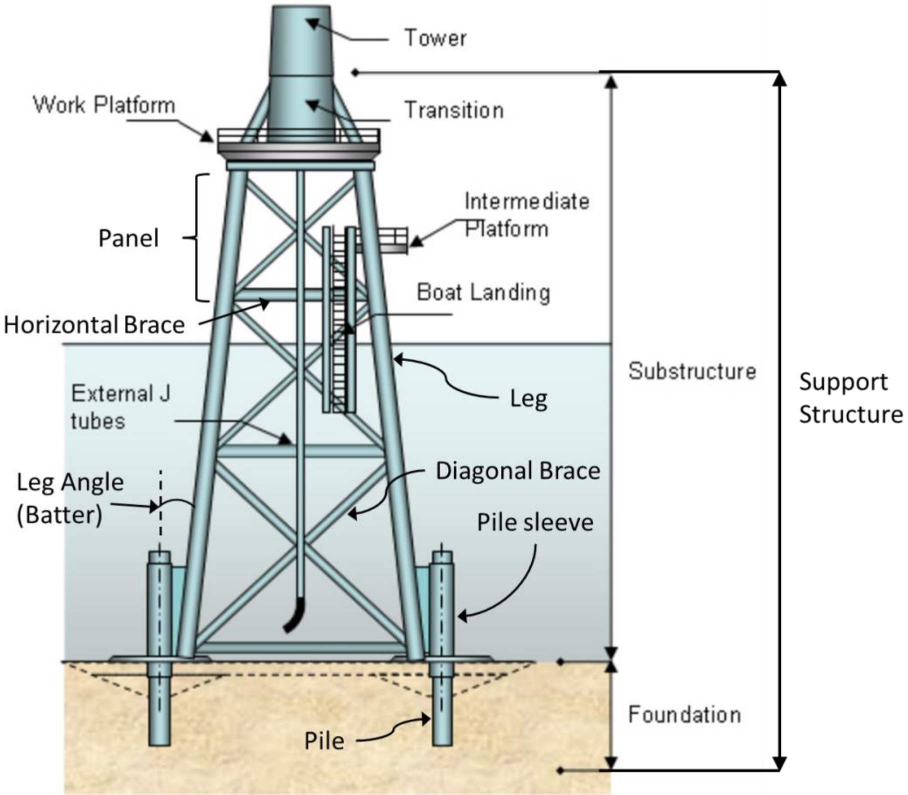

Figure 10: Jacket structure in the case of post-piling (EWEA, Offshore support structures, 2009).

The main installation phases of the jacket support structure are as follows:

- Load-out
- Transport
- Installation

Almost all installation of offshore structures have these breakdown. The load-out consists of moving the jacket structure from the storage place in the harbour to the vessel or barge that will transport it. Enough space in the port eases the manoeuvres of the huge jackets. A crane with an appropriate grab, fasteners, and a plan that indicates the position on the vessel or barge are needed. Figure 11 shows a horizontal and vertical configurations of the jackets on a barge. The vertical position is more difficult to obtain, but has some clear advantages: deck space is more efficiently used and turning the jacket in upright position has not to be done on site, reducing the installation time offshore.

Transport can be done with a barge and tug boats or with a crane vessel. Barges are cheaper than a crane vessel, but a crane vessel is anyway needed to install the jackets. Another consideration is that the crane vessel can prepare and position itself whilst the barge transports the jackets. Transport takes several hours. For example a transport in the Baltic Sea of 180 km is scheduled 15 hours in (Thomsen, 2012).

The installation involves lifting of the substructure, positioning on the seabed, piling and coupling piles to jacket legs. Piling can be done before or after placing the substructure, known as pre-piling or post-piling respectively. Pre-piling and post-piling are discussed in next chapters. There are two methods to install the piles into the seabed. One method is driving the piles with the help of a hammer. The other is inserting the pile in a drilled whole and fix it with grout. Different types of hammer are available. The most appropriate is the hydraulic hammer, since it can operate underwater (Rajapakse, 2008). There are two common methods to couple the piles and jacket legs, grouting and swaging. The former fills the annulus between the pile and jacket leg with cement grout (FoundOcean, 2011). Weld beads are put on the foundation pile to ensure a good connection with the grout. Figure 12 depicts the coupling by swaging. The pile steel is pressed into slots of the pile sleeve By means of hydraulic pressure.

All the installation phases are strongly influenced by the weather conditions. Therefore the weather forecasting determines if the installation can occur. A time period of suitable weather is called the operational weather window. Reduced installation time decreases not only the cost, but also increases the chance on a long enough operational weather window.

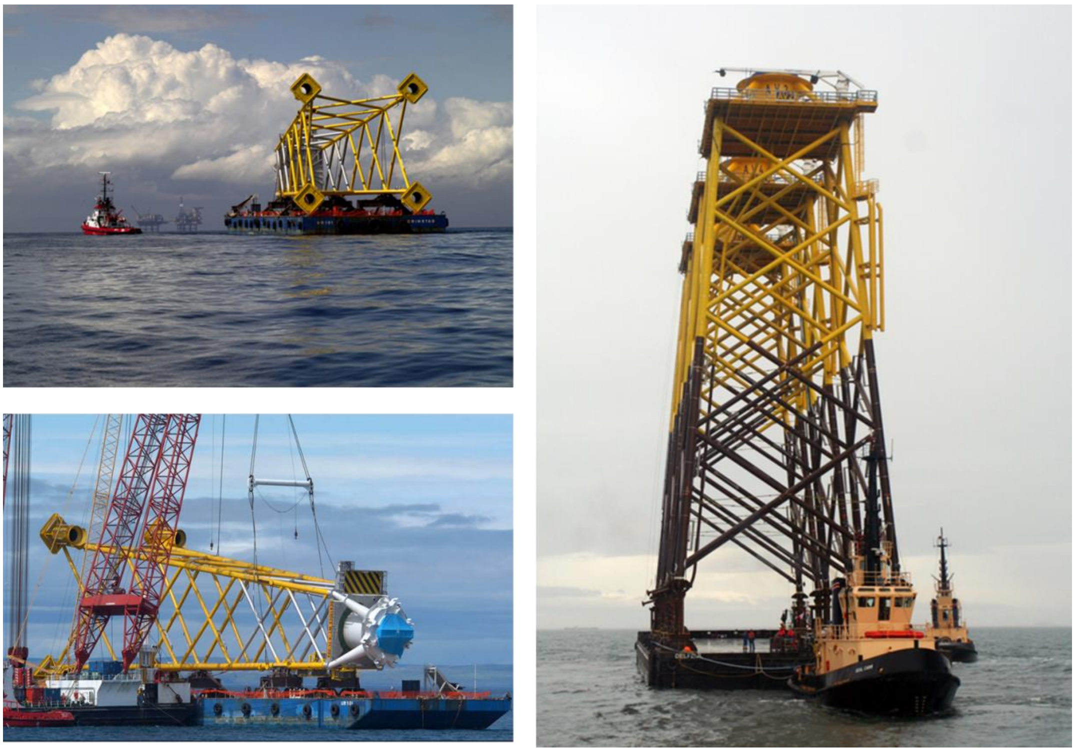

Figure 11: Transport of jackets. Left: horizontal. Right: vertical. Pictures avalaible on http://www.bifab.co.uk/view/experience.aspx and http://www.beatricewind.co.uk/press/images.asp.

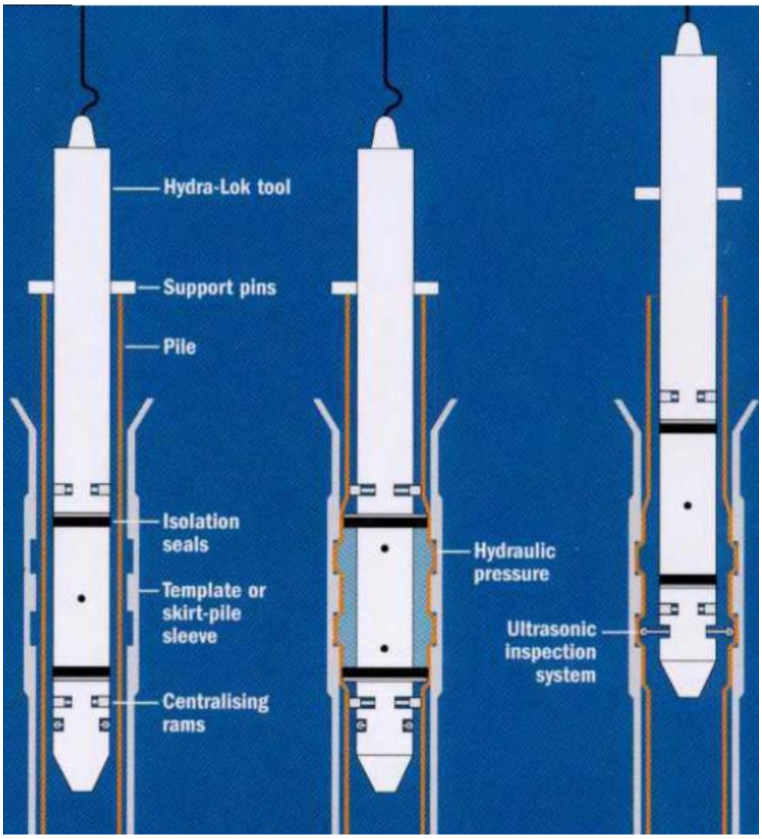

Figure 12: Coupling of pile and pile sleeve by swaging (ten Haaf C. , 2010).

Figure 13: Jacket with jacket stab-ins. The right aft stab-in is longer and will be placed first in a pre-driven pile as a pivot. Picture available on http://www.lorc.dk/offshore-wind/foundations/jackets .

2 PRE-PILING

2.1 Pre-piling Concept

Figure 14 depicts the sequence of installing a jacket support structure when pre-piling is applied. The same principle is valid in case of a tripod. Firstly, a template is placed on the seabed, through which the piles are driven by a hydraulic hammer. The template secures that the piles have the same centre-to-centre distance as the legs of the jacket substructure and verticality. The piles are driven with the same batter as the jacket legs to avoid later bending of the piles (ten Haaf C. , 2011). When all piles are installed, the template is removed. Secondly, the jacket substructure is placed on the piles by means of jacket stab-ins. Each jacket leg has a stab-in. On Figure 13 it can be seen that one of the stab-ins is longer than the others. This stab-in will be placed first into one of the pre-driven piles and will be used as a pivot to orient the complete jacket substructure on the other pre-driven piles. At OWF Thorntonbank two diametrical stab-ins were longer. First the longest was inserted in the piles, thereafter the second longest, which fixed the orientation of the complete substructure (Strubbe, 2012). Finally, the stab-ins and piles are coupled by swaging or grouting. The substructure rests initially on the foundation piles by means of a pile stopper. After grouting the pile stopper is removed, so that the substructure is borne by the grout junction. Since the stab-in usually inserts the pile till below the mud line, the piles have to be preliminary dredged to enable a smooth entering of the stab-in. In addition, the pile should be cleaned to remove possible marine growth and dirt, ensuring a successful grout connection. A pre-check before installing the jacket is recommended (de Vries, et al., 2011).

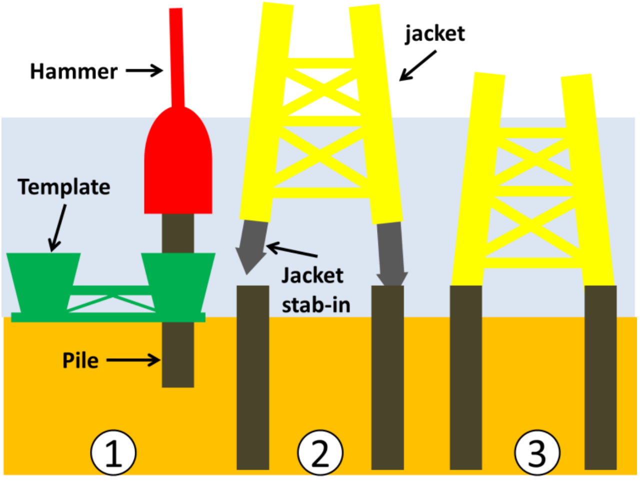

Figure 14: Pre-piling principle.

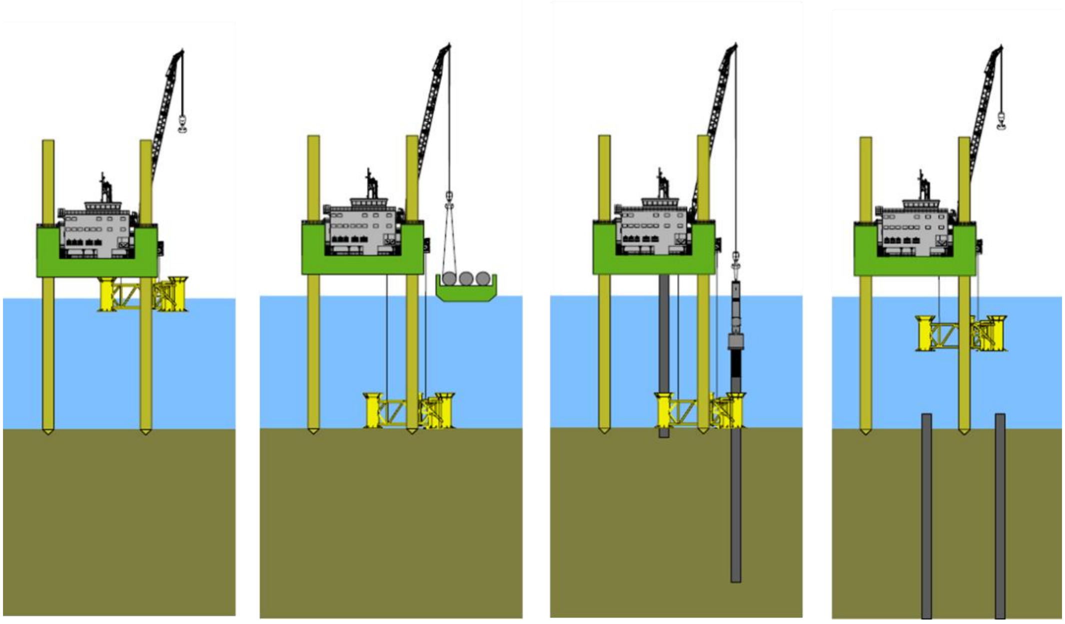

Figure 15. Pre-piling methodology with jack-up platform.

Figure 14 outlines the process of pre-piling in more detail. A jack-up platform positions with its DP2 system or anchors to the right position where the OWT will be built. Then, the template is lowered. Next, the foundation piles are transferred to the JUP from a platform supply vessel (PSV). Thereafter, the crane on the JUP upends the pile and places it into the template one by one. Further a hydraulic hammer drives the piles into the seabed. Finally, after a survey of the piles, the template is recovered and the JUP is ready to jack down and sail to the next OWT location.

2.2 Post-piling versus pre-piling

Post-piling implies the reverse of Figure 14. The jacket substructure is positioned on the right position on the seabed. Thereafter the foundation piles are stabbed into the seabed through sleeves welded at each jacket leg, see Figure 10. Then the piles are driven with a hammer till the pile just sticks up above the jacket leg sleeve, see Figure 18. Finally the pile is coupled to the jacket leg sleeve by swaging or grouting.

Pre-piling allows to split the installation process of a jacket support structure in two parts, namely step 1 and steps 2 & 3 in Figure 14, allowing to operate in shorter weather windows. Furthermore, the positioning of the jacket substructure goes easier with the pre-driven piles, reducing the weather window even more. Pre-piling can be executed with a smaller crane vessel than needed for the installation of the jacket substructure, which reduces the total cost. Also pile sleeves and mud mats at the substructure are not needed any more, which can result in a reduction of 10 % in weight and hence material cost. The pile sleeves in the Beatrice Demonstrator OWF weighted 163 tons w.r.t. 1296 tons of the complete support structure (Burton, Jenkins, Sharpe, & Bossanyi, 2011). The piling template is an additional cost, but can be covered by the benefits of the previous advantages, which is increasing with the number of support structures. As the pre-piling is prior to the substructure installation, the operations should be planned carefully.

2.3 Equipment and Vessels

Equipment is an important parameter in the installation process. They have their limits and requirements. Figure 17 shows the capability of lifting of a jack-up vessel equipped with a crane. The bigger the outreach the lesser weight the crane can lift. The depth where the vessel can operate is limited by the soil conditions (leg penetration) and by the weather conditions (minimum air gap). A procedure of pre-loading alternately two diametrical spuds of the JUP lowers the risk on a punch through.

Efficient use of different kind of vessels leads to a cost-effective installation process. Figure 16 demonstrates this by showing a big semi-submersible floating platform to install the jacket substructures on the right side and a smaller jack-up barge to accomplish the pre-piling.

Figure 16: Left: Piling template at jack-up barge. Right: Installation of jacket with stab-ins. Pictures available on http://www.twd.nl/projects/offshore-wind-projects/project-details/piling-template-ormonde-windfarm.html and http://www.lorc.dk/offshore-wind/foundations/jackets.

The capacity of the PSV should be chosen in order to avoid waiting times of the JUP on the delivery of the foundation piles. The PSV has to be equipped with a DP2 system to assure a safe approach to the JUP and offshore pile transfer.

A tug boat is deployed to tow the JUP for longer distances or for relocation if the JUP is not self-propelled. The bollard pull of the tug boat guarantees sufficient power to tow the JUP which can have outboard structures increasing the resistance in water. Furthermore, the tug boat is deployed to support the JUP logistically (food containers etc.). A tug boat has sufficient deck space to enable crew transfers by means of a suspended carrier for personnel, which is the most common way of crew transfers when the JUP is jacked up. An additional crew vessel may be required if the number of needed crew changes exceeds the capacity of the tug boat.

Equipment to carry out the pre-piling is project specific. In general a pre-piling spread comprises a piling template, a system to upend the piles and a hammer assembly. More details are described in chapter 4.

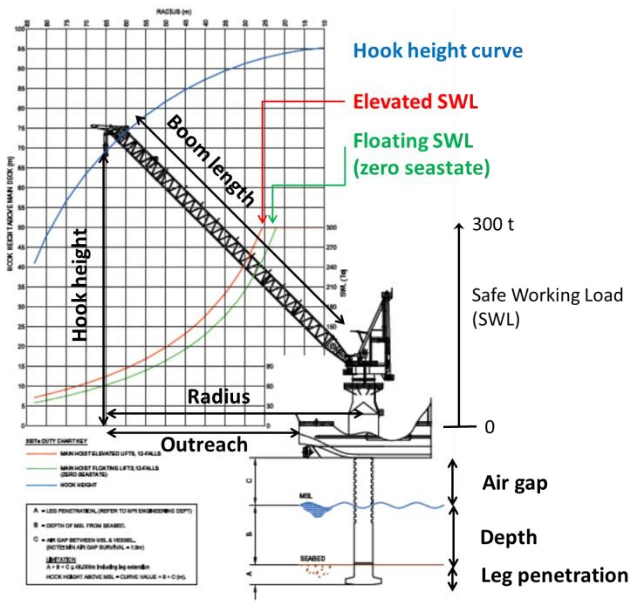

Figure 17: Jack-up vessel with crane (MPI-offshore, 2010).

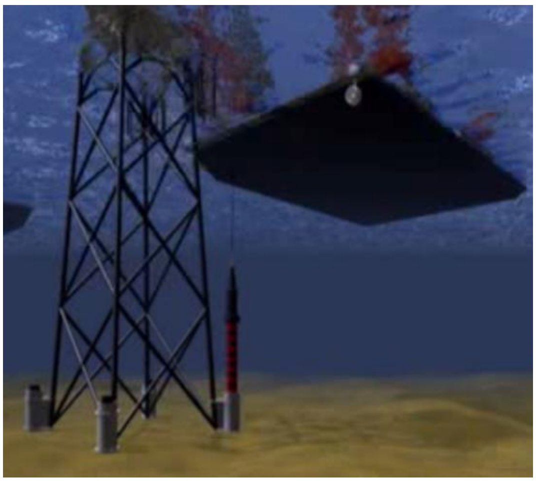

Figure 18: Installation of the piles in the Beatrice Wind Farm Demonstrator Project (Talisman Energy, 2007).

3 ANALYSIS

3.1 Lean Six Sigma

Lean six sigma is a combination of two methodologies to increase productivity and hence decreasing the cost of processes, see Table 2. The ‘lean’ methodology aims to eliminate waste, which isn’t only the materials but also all non-added value activities. Lean minimizes the difference between the perfect way of executing the process and the actual situation. Six Sigma refers to the symbol sigma in statistics, which denotes the standard deviation. Six Sigma tries to minimize variation.

Table 2: Comparison of Lean and Six Sigma (Murman, 2008).

	Six Sigma	**Lean**
Objective	Deliver value to customer	Deliver value to customer
Theory	Reduce variation	Remove waste
Focus	Problem focused	Flow focused
Assumption	• A problem exists. • Figures and numbers are valued. • System output improves if variation in all processes inputs is reduced.	• Waste removal will improve business performance. • Many small improvements are better than system analysis.

In order to evaluate improvements metrics are needed. Choosing the right metrics is important and can be obtained by having a look at the objective of the company and at those who can effect and are affected by the achievement of these objectives, aka the stakeholders. Possible metrics for pre-piling can be:

- the needed time per completed location in order to deliver on-time and satisfy the wish of the customer,
- the noise level during piling in order to protect sea life and satisfy the environmental policy of the government, and
- tolerance of the position of the piles in order to ease the installation of the substructure and satisfy the team responsible for this.

This study will focus on the time per completed location. The client delivers the piles to the offshore contractor who deploys a JUP to install them. Completion in time is important so that the next phase of the erection of the OWF can start. Optimization will result in a learning curve, which can be detected by the metric ‘time’. Also amongst OWFs there is a learning process, although each OWF is unique to a certain extent. Their commonalities allow to estimate cost and time of a new project (Koch & Sondergaard, 2010), although awareness of the differences is a must. According to (Lemming, Morthorst, & Clausen, 2008) the learning rates of OWFs are higher than onshore, since OWFs are a relatively young area. They predict a learning rate of 10 % for OWF until 2030.

One of the lean six sigma tools is establishing a process map. The process map presents the flow of all the activities. The emphasis is on the asset, which is in this case the JUP. Each activity of the JUP is qualified as value added or non-value added. The non-value added activities are classified as pure waste or necessary waste. The border between value added and non-value added activities is not always clear. For example, necessary waste can be the noise reducing techniques, applied to follow the law. Or it can also be considered as a friendly environmental measure, which has marketing value, and then it becomes an added value activity.

The process map belongs to the DMAIC. This acronym stands for Define, Measure, Analyze, Improve and Control. Visualization is one of the important methods to control. It provides fast information and helps to keep the overview, examples are SPC charts and projections of the completion date.

3.2 Reports

Reporting is the measurement system of the metrics. Therefore it is important to report in a consistent way to avoid reporting noise. The following discussion involves only time data and not pile survey data, for which a separate reporting system is available.

To establish a reporting system, it is useful to define the goals of the report. Apart from production optimization there are other goals that the report should serve. Ideally the report should fulfil all following goals:

1. reporting to client, involving operational, waiting on weather and idle time,

2. determining the weather window duration,
3. production optimization.

The superintendent or project engineer on board of the JUP records the times of all activities and enters the records in the reporting system by means of dropdown lists with defined activities. Each activity is linked to a top layer of five time divisions: weather downtime, technical breakdown, operational standby, auxiliary and operational time. The last two form the production time. The production time at one location is the net cycle time. Net cycle times are compared to each other to detect trends in performance. To avoid that interruptions by downtime or standby prolong the net cycle time, one should report as outlined in Figure 19. A downtime or standby ends when the production cycle can continue where it was interrupted.

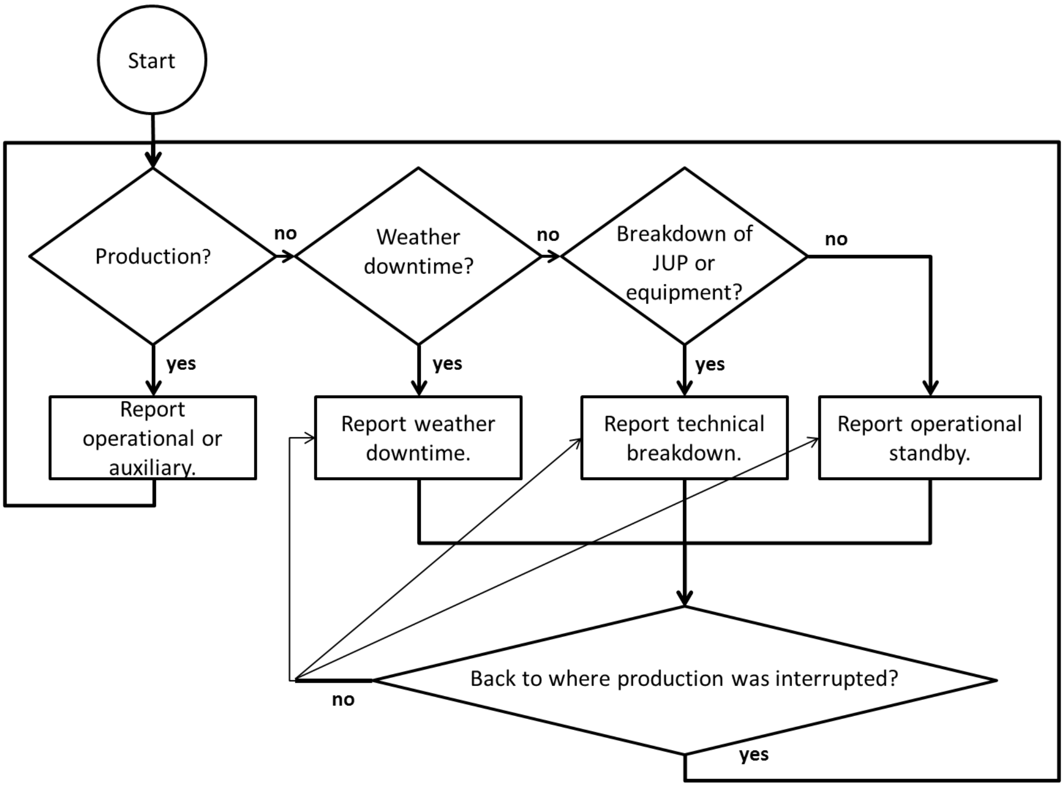

Figure 19. Reporting flowchart.

The activities are hierarchically divided in main activities and subactivities. The superintendent can navigate easily to the actual activity by first selecting a main activity and then a more specific subactivity. The main activities represents the weather windows. The subactivities allow to record specific actions within the main activity which looks interesting to optimize. The aim is to report the critical path of the pre-piling production process. The critical path will identify the bottlenecks in the production cycle.

A cost benefit analysis using time data from this reporting to check whether an investment is profitable, has to be carried out carefully, as eliminating an activity from the critical path can reveal another activity in the critical path, meaning that time saving by eliminating one activity can be reduced by the activity popping up in the critical path. For instance consider Figure 20, the maximum gain of reducing the time of activity 2 will be *t2 - t2'*.

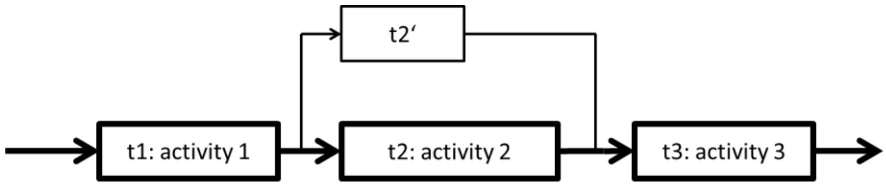

Figure 20. Representation of critical path.

As explained in previous section about lean six sigma, there are value added activities and non-value added activities. The latter can be split in necessary and pure waste non-value added activities. This division can be represented in reporting by assigning each subactivity to one of the five time divisions. The necessary non-value added activities are seen as auxiliary activities and the pure waste non-value added activities are operational standby, weather standby and technical breakdown. One may see a grey zone between the parts of this subdivision. Especially the difference between operational standby and auxiliary activity are subject to interpretation.

Auxiliary activities should be defined as activities that are necessary to continue the operation, but that are not always appear in the critical path of the cycle. Operational standby activities block the production process whilst everything is ready to continue. For example, the transfer of piles can be blocked due to a late arrival of the PSV. This should be reported as operational standby. During the transfer of piles the PSV has to reposition to allow a safe transfer. This should be reported as an auxiliary activity. The difference is that the late arrival of the PSV could be prevented by an earlier call, whilst the repositioning is necessary to continue the operation, because, for instance, the crane radius is not sufficient to reach the other side of the PSV, unless the PSV turns 180 degrees.

3.3 Processing Time Data

3.3.1 Pareto

A Pareto chart is a column graph that arranges the duration of each activity in descending order. The function is to visualize the most time consuming activities in order to focus the effort of optimization on the activities were most time saving could be gained. The underlying idea is the famous 20-80 rule: historically 80 % of the problems are due to 20 % of the factors (Montgomery, 2005). This could be translated in “20 % of the activities consumes 80 % of the time” in the present context.

3.3.2 Statistical Process Control (SPC)

A SPC chart visualizes data measured during a process with a centre line and two control limits, which helps to interpret the values. Process data is in its nature random. This can be due to random effects during the process or due to the noise of the measuring system. In the present study the measured data are times to complete pre-piling activities. The measuring system is a time report by the staff on board. There is variation on the duration of a pre-piling activity due to different conditions (e.g. soil, water depth), different piles or simply because connecting a sling to a crane hook does not take always exactly the same time. The reports contain noise as the report is filled out by different people and times are not clocked on exactly the same point of an activity. To avoid reporting noise the concerning activities are defined with a start and end action.

The control limits of a SPC are determined by the mean of the data and the mean of the moving range (MR). The moving range is the absolute value of the difference between a value and its predecessor. Table 3 presents an example of the moving range. A lower control limit (LCL) and upper control limit (UCL) can be calculated as follows:

$$\mathrm{LCL} = \bar{t} - 3 \cdot \frac{\overline{MR}}{x}$$

$$\mathrm{UCL} = \bar{t} + 3 \cdot \frac{\overline{MR}}{x}$$

with $\bar{t}$ and $\overline{MR}$ the average of the time data and moving range respectively, and x a factor that is chosen to approximate three standard deviations. The latter can be found in literature. The SPC chart of this example is displayed in Figure 21. The centre line is the mean value. An estimate (or target) can be added to the chart to visualize performance. Each time an activity is passed the control limits and centre line are adjusted.

Table 3. Example of the calculation of moving range.

Time [h]	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA
Moving range		NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA	NDA

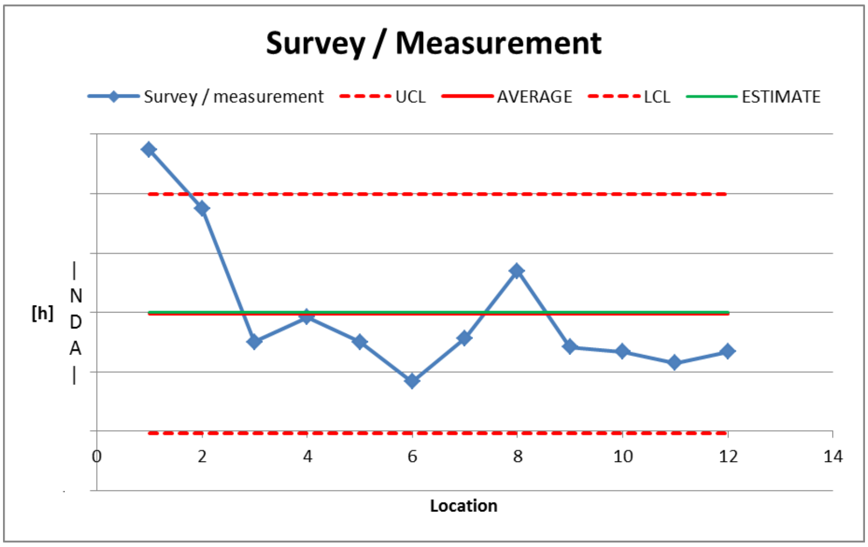

Figure 21. Example of a SPC chart (OWF Baltic 2).

An SPC chart helps to interpret the evolution of an activity. There are rules described in the literature to identify out-of-control points and conditions (Kubiak & Benbow, 2009). For example, he first point in Figure 21 is out of control, because it exceeds the upper control line. This very first point can be addressed to a learning curve along which the crew familiarizes with the equipment and methodology. Another example of an out-of-control rule is seven successive points under (or above) the centre line (Hutchins, 1991), others recommend nine successive points (Kubiak & Benbow, 2009). These trends may be addressed to changes in the process.

3.4 Key figures

In order to compare different projects the following activity groups are determined:

1. JUP positioning and transit,
2. piling template handling,
3. pile transfer,
4. pile upending and stabbing,
5. pile hammering,
6. pile top dredging,
7. pile survey.

The times of the activity groups will be presented per locations, since this is the unit in which progress of the project is expressed. Only the activities contributing to production (auxiliary and operational) are considered, operational standby and technical breakdown not. Any noise mitigation is carried out in parallel with these activities or reported as operational standby. Preliminary work such as dredging of the seabed (OWF Thorntonbank) or boulder relocation (OWF Baltic 2) is not conducted by the JUP deployed for pre-piling, and thus not considered.

The activity group ‘JUP positioning and transit’ contains all activities related to leaving and going onto location such that the activities on board can be executed without interruption of JUP operations. This means that repositioning or re-levelling of the JUP also belongs to this group. The seafastening is also part of this group, since this is necessary to sail safely. Figure 22 shows a possible sequence of JUP transit and positioning. Between the other activities repositioning might be necessary, as in OWF Alpha Ventus, this would imply the same sequence without transit. Re-levelling of the JUP would imply only jacking down or jacking up. This might be necessary to adjust the weather sensitivity of the JUP. If the result is sheltering, then the re-levelling should be considered as weather downtime. If the releveling results in continuing operation, this should be considered as part of the production cycle, as an auxiliary activity.

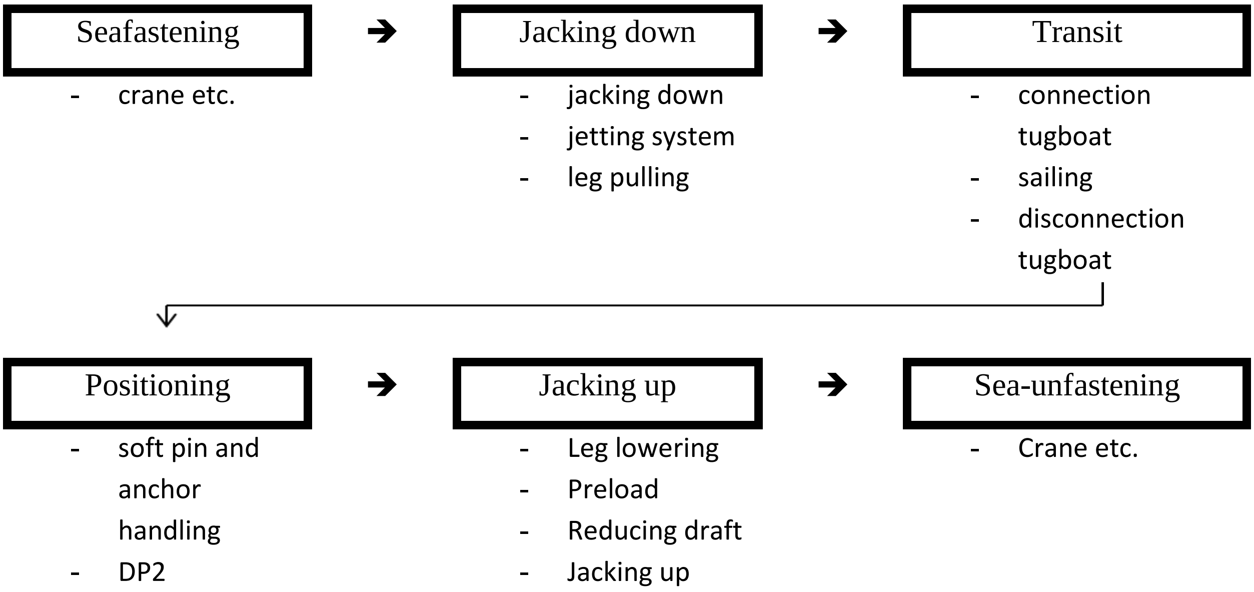

Figure 22. Possible sequence of JUP positioning and transit.

The activity group ‘piling template handling’ considers all activities related to the deployment of the piling template. Since the piling template endure violent conditions, such as water loads during sailing, or vibrations during hammering, maintenance is frequently executed. The activity maintenance belongs to operational standby and is not admitted in this activity group.

The activity group ‘pile transfer’ considers all activities related to the offshore transfer of the foundation piles from the PSV to the JUP. This includes preparing the lifting arrangement (spreader beam etc.), lifting and manoeuvring the pile to its storage place on board of the JUP and putting all equipment back to its place. The slings are kept around the piles from the onshore load-out, to reduce the time offshore. The slings remain around the piles to move them to the upending frame in a later stage. Approaching of the vessel and returning old slings (of the previous batch of piles) are considered as operational standby and thus not included in this activity group.

The activity group ‘upending and stabbing’ considers all activities needed to fulfil the upending of the pile and stab it in the seabed through the template sleeve. This includes a possible move from the storage frame to the upending frame, horizontally move in the upending frame, the lift itself from upend till position in piling template and retrieving the lifting tool. The moving in the upending frame is to install first the lifting tool, then the upending hooks and finally to connect the lifting tool to the crane tackle.

The activity group ‘pile hammering’ includes all activities that are related to hammering of the pile. Sea-unfastening of the hammer, assembling of the hammer on the follower (not for OWF Alpha Ventus), lifting the hammer on the pile, pile driving and retrieving of the hammer on board belong to this group.

The activity group ‘pile top dredging’ are all activities related to dredging of the pile. This includes lifting of the dredging equipment, discharging in case of grabber, and the dredging itself. This is an auxiliary activity to deal with flooding of the soil plug in the pile (OWF Baltic 2).

The activity group ‘pile survey’ covers all activities related to the measurements of pile top elevation and inclination. The piling template ensures that the pile is installed within the tolerances, but a more accurate pile top elevation and inclination are needed to prepare the shimming of the substructure.

4 CASE STUDIES

This chapter describes the five pre-piling projects so far conducted. Figure 23 presents their locations.

Figure 23. Locations of pre-piling projects.

4.1 Alpha Ventus

Removed due to non-disclosure agreement.

4.2 Ormonde

Removed due to non-disclosure agreement.

4.3 Thornton Bank

Removed due to non-disclosure agreement.

4.4 Baltic 2

Removed due to non-disclosure agreement.

5 PROGNOSIS OF THE COMPLETION DATE

The completion date of a project has a big impact on its overall cost. A delay of one day means an additional cost of the day rate of the total installation spread, which in the end of the project can amount to a significant impact in cost. Moreover, the delay of the current project can cause a delay of the next phase of the construction of the OWF or / and a delay of another project where the main vessel was scheduled, increasing the lost profit for the offshore contractor. Therefore the completion date should be monitored continuously as one of the most influential milestones during the project's development.

One of the major influences on the completion date are the environmental conditions of the site. As can be seen from the pareto graph in Figure 24, weather downtime is the "activity" that consumes most time. Not surprisingly weather downtime is the main factor causing delays.

Removed due to non-disclosure agreement.

Figure 24. Pareto chart of sub-activities during the pre-piling phase of OWF Thorntonbank.

The present chapter deals with the variability involved with the prognosis of the completion date, with particular focus on weather downtime. A method is proposed to assess the completion date based on a monte carlo simulation taking into account the probability of waiting on weather (WOW). Firstly, weather statistics are discussed, which forms the base of the probability density functions. Secondly, the wind and wave characteristics of the OWF Baltic 2 are presented. Thirdly, the proposed method is explained. The issue is finally approached in a way it can support the project's planning and management decision making.

5.1 From historical data to probabilities

Weather data is collected in the past, comprising wind, wave and current (including tides). Prior to the construction of a OWF, a site assessment is carried out, including the collection of wind data. This was necessary to design the foundations, but more elementary to corroborate the economic feasibility of the OWF. Wave and current data are available from the wave buoys that are deployed in the European seas[1]. All the data appear as time series of average quantities over a certain period.

The wind data may need to be adjusted for the height and the averaging period, for which formulas available in the literature or wind profiles (boundary layer) estimated from the measurements during the site assessment are appropriate. For example, if the wind speeds v_1 and v_2 are measured at heights h_1 and h_2 respectively, the wind speed v_3 at height h_3 can be estimated by the following formula (Oner, Ozcira, Bekiroglu, & Senol, 2013):

$$v_3 = v_2 \left(\frac{h_3}{h_2}\right)^{\frac{\ln\left(\frac{v_2}{v_1}\right)}{\ln\left(\frac{h_2}{h_1}\right)}}$$

An example of a wind profile adjusting the averaging period as well is given by (DNV, Environmental Conditions and Environmental Loads, 2007):

$$v(T,h) = v_{10}(1 + 0.137 \ln\left(\frac{h}{H}\right) - 0.047 \ln\left(\frac{T}{T_{10}}\right)$$

With v the wind speed, T the averaging period, h the measuring height, H is 10 m and T_{10} is 10 minutes.

The time series can contain gaps due to malfunction of the measurement systems. Hindcast models are developed to fill these gaps and make the data set complete (Walker, van Nieuwkoop-McCall, Johanning, & Parkinson, 2013).

The time series are processed by means of counting the time during which certain weather limits are met. The ratio of this time to the total time yields the probability of occurrence of a weather window (WW). The same can be done to obtain also the probability of occurrence of waiting on weather (WOW). The length of neither WW nor WOW is known. Preferably, the

[1] Example of a European network is the French CANDHIS (http://candhis.cetmef.developpement-durable.gouv.fr/).

weather limits are a combination of all the limits applied on an activity, for instance the activity JUP positioning and transit is limited by a maximum wave height and a wave period range. In the literature weather limits are usually treated individually (Stallard, Dhedin, Saviot, & Noguera, 2010). In that case individual probabilities are obtained. A relation between the probabilities is not straightforward, implicating the assessment of the WOW probability, which will become clear in the following. Consider another common weather limitation compounding a maximum wave height and a maximum wind speed. It is well known that wind generates waves and in that sense the probability of the wind limit excess goes together with the probability of the wave height limit excess. Nevertheless, there is a lag between the rising of the wind and the generated waves (Met Office, 2013), meaning wind excess can occur without wave excess. Furthermore, besides waves due to local wind, there are also swell waves, meaning wave height excess can occur without wind speed excess. Taking only into account one limit instead of the compound, even if the most severe is chosen, will underestimate the WOW.

In order to execute an activity subject to weather limits safely, the weather conditions should be below the limits for a persistent period, which is the weather window length. There are two methods to obtain the probabilities of a weather window for a given limit and length. One is based on statistical methods using the probability of occurrence, the other is reprocessing the time series and count only the time for which weather conditions persist for a minimum WW length (Stallard, Dhedin, Saviot, & Noguera, 2010). Figure 25 shows an example of the first method. Figure 26 shows an example of the second method.

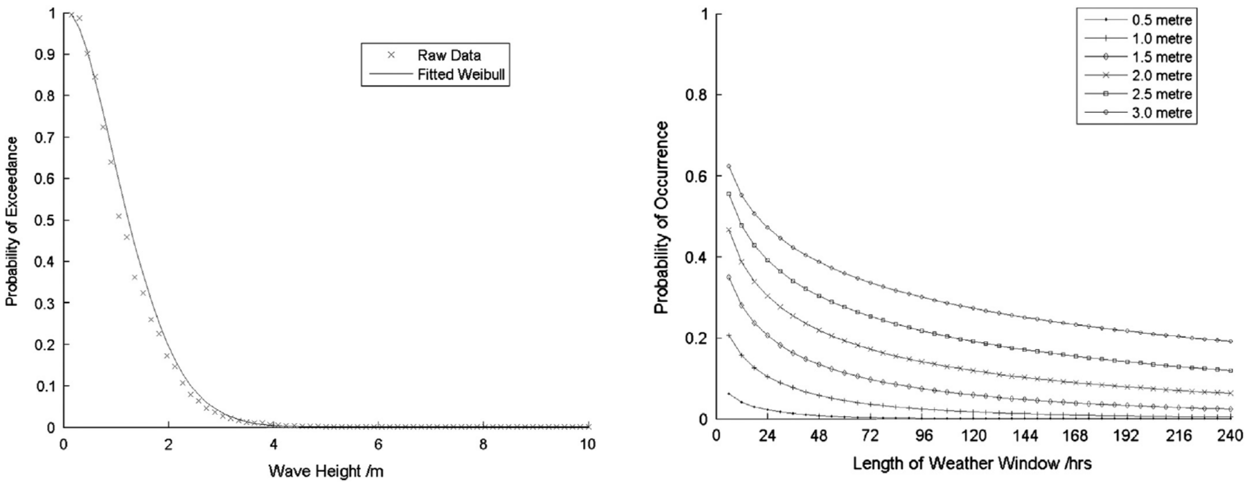

Figure 25. Statistical methods such as the Weibull persistence method deduce the probability of a weather window length (right) from the probability of occurrence of a minimum wave height (left), (Walker, van Nieuwkoop-McCall, Johanning, & Parkinson, 2013).

Significant Wave Height (m)	M1 Mean Annual Windows																
2.5	45	43	41	39	38	37	36	32	31	28	26	25	23	22	21	18	17
2.4	42	39	38	36	34	33	32	29	27	26	24	22	21	20	18	17	16
2.3	38	36	34	33	31	30	28	26	25	23	22	20	19	18	17	15	14
2.2	35	32	31	29	29	26	24	23	20	20	19	18	17	15	15	13	13
2.1	31	29	27	26	25	23	22	20	18	17	16	15	14	13	12	11	11
2	28	26	24	23	21	20	18	17	15	14	14	12	11	10	9	8	7
1.9	24	23	21	20	18	17	16	14	13	12	11	9	8	7	7	6	5
1.8	21	20	19	17	16	15	13	12	11	10	9	8	6	6	6	4	4
1.7	18	17	16	14	14	12	11	10	9	8	7	6	5	5	4	3	3
1.6	16	14	13	12	11	10	9	8	7	6	5	4	4	4	3	3	3
1.5	13	12	10	10	9	8	7	6	5	5	4	3	3	3	2	1	1
1.4	11	9	8	8	7	6	5	4	3	3	3	1	1	1	1	0	0
1.3	8	7	6	5	4	4	3	3	2	2	1	1	1	1	0	0	0
1.2	6	5	4	4	3	3	2	2	2	1	1	1	0	0	0	0	0
1.1	4	3	3	2	2	1	1	1	0	0	0	0	0	0	0	0	0
1	2	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Minimum Length of windows (Hrs)	1	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96

% Occurence

Figure 26. Processing of weather time series for different window lengths, (O'Connor, Lewis, & Dalton, 2013)

5.2 Statistical data of OWF Baltic 2

Table 4 lists the weather limits for the different activities at OWF Baltic 2. All activities are subjected to a maximum significant wave height (Hs). All activities involving lifts are limited by a maximum wind speed. Only sailing of the JUP is limited by a range of wave period.

The statistical data available for OWF Baltic 2 is obtained by time series analysis as explained in previous section. Figure 27 shows a histogram as an result of such an analysis. From Figure 27 the cumulative distribution can be derived, as displayed in Figure 28. Figure 28 presents the zero probability duration added by extrapolation of known values. This was necessary for the simulation of the WOW, which will be explained in the next session. Figure 28 includes a curve for a less critical limit. The probability of downtime is lower. Figure 29 shows a cumulative distribution of weather windows. The probability decreases for longer durations and more restrictive limits.

Table 4. Weather window limits and lengths for OWF Baltic 2 (average of 12 first locations).

	sequence	duration [h]	Time contingency factor*	required WW length [h]	max Hs [m]	max wind speed	Min wave period	max wave period
JUP transit & positioning	1	NDA	1,5	NDA	NDA	NDA	NDA	NDA
template lowering	2	NDA	1,5	NDA	NDA	NDA	NDA	NDA
pile transfer	3	NDA	1,5	NDA	NDA	NDA	NDA	NDA
upending & stabbing	4	NDA	1,5	NDA	NDA	NDA	NDA	NDA
piling to preliminary depth	5	NDA	1,5	NDA	NDA	NDA	NDA	NDA
dredging	6	NDA	1,5	NDA	NDA	NDA	NDA	NDA
piling to final depth	7	NDA	1,5	NDA	NDA	NDA	NDA	NDA
survey/measurement	8	NDA	1,5	NDA	NDA	NDA	NDA	NDA
template recovery	9	NDA	1,5	NDA	NDA	NDA	NDA	NDA

* From p. 29 in (DNV, Marine Operations, General, 2011).

The available statistical data does not compound weather limits and the data is not available for further analysis. Therefore the present study will only uses the wave data in spite of the underestimation of WOW as explained in the previous section. The wave data was chosen because all activities are affected by WOW due to waves. Moreover, the wave data was analysed for the applicable limits, which was not the case for wind. All statistical wave data can be found in appendix A.

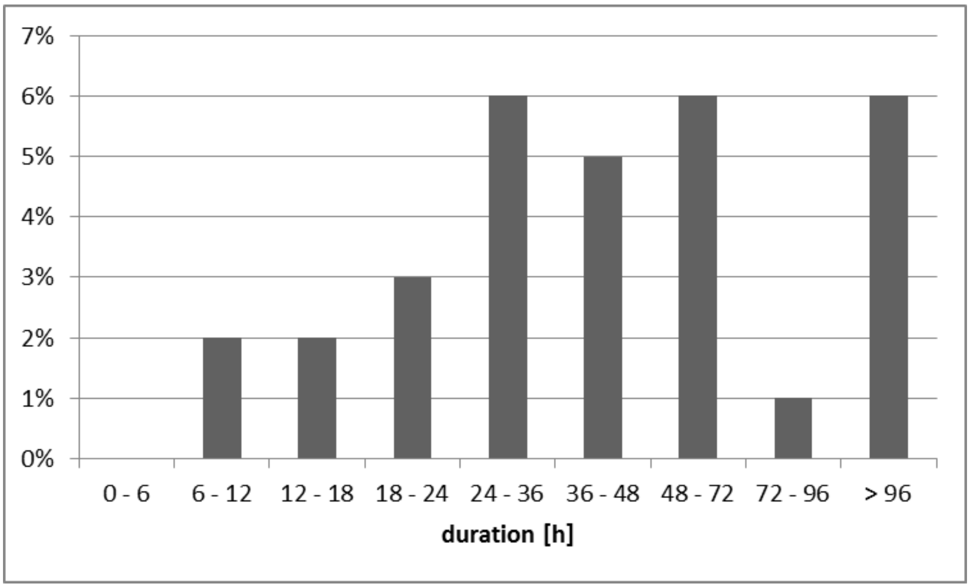

Figure 27. Histogram of Hs exceedance for different durations.

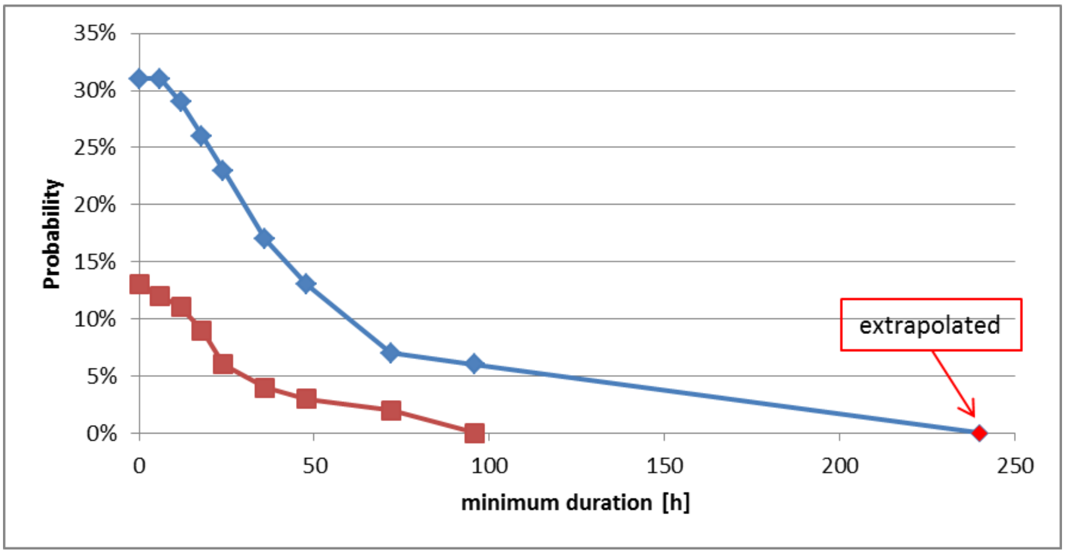

Figure 28. Cumulative distribution of downtime for Hs.

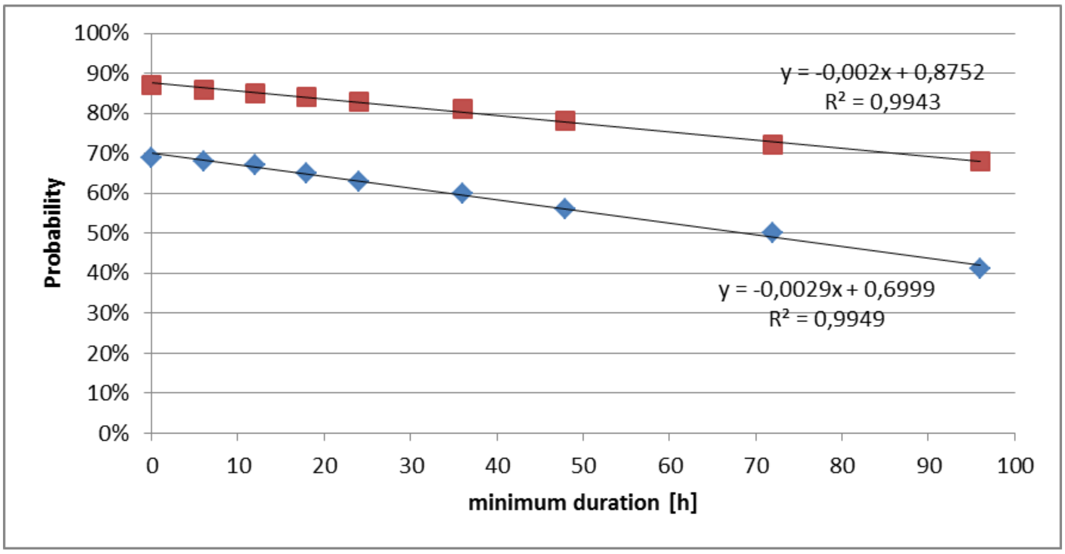

Figure 29. Cumulative distribution of weather window for Hs.

5.3 Waiting on weather simulation

The aim of the waiting on weather simulation is to determine the completion date taking into account the weather downtime. A production cycle consists of different activities, for which a minimum weather window is required. Between each activity there is a probability that the production cycle is interrupted by a WOW period or even does not begin. This WOW can be zero, but can also last for several days. In order to have a perspective of how this affects the cycle time, a monte carlo simulation was executed. Figure 30 depicts a diagram that describes its basic idea. A production cycle is subdivided in different stages (S_0 to S_n). Between each stage an activity is executed preceded by a WOW time. Different WOW durations are possible for each stage, resulting in a probability distribution of the complete cycle time. Table 4 represents the activities of one production cycle specific for OWF Baltic 2.

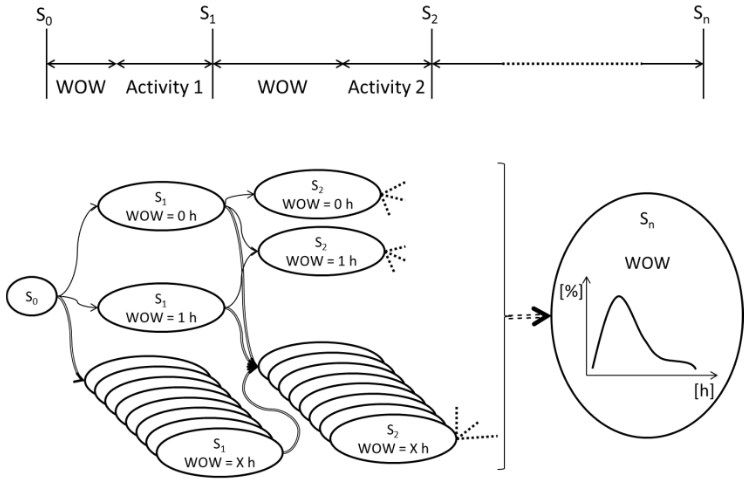

Figure 30. Diagram of a cycle with n Stages. Waiting on weather (WOW) between the stages varies, resulting in a distribution of cycle time.

There are three probabilities considered to determine the WOW duration. The first probability is the probability that a weather window is immediately available, and thus the WOW duration is zero. This probability is obtained by linear interpolation of the cumulative distribution of weather windows (Figure 29) for the required weather window length (P(<Hs;≥τ)). The required weather window length is longer than the actually duration of the activity, because a contingency time has to be foreseen. The contingency time is chosen according the DNV rules for repetitive operations (DNV, Marine Operations, General, 2011). The required weather window lengths are listed in Table 4. The probabilities are enclosed in appendix A. The second probability is that the weather limit is satisfied, but the duration is too short. This probability is the intersection of the cumulative distribution of weather windows with the vertical axis minus the first probability (P(<Hs;t=0) - P(<Hs;≥τ)). The third probability is the probability that the weather limit is not satisfied, and thus the weather downtime distribution such as Figure 28 can be used (1 - P(<Hs;t=0)). So far three states in which the main vessel can be have been determined: activity, interval between or before downtime and downtime as can be seen on the left in Figure 31. After a state of downtime a period of weather window has to occur. An interval implies downtime afterwards. A new activity imposes new weather requirements and that is why all three states are possible after an activity. No time is involved yet. In fact the downtime state consists of many states with all a different downtime duration, the same for the interval state, as is illustrated on the right in Figure 31. How the probability to these states of different durations is established is developed further ahead.

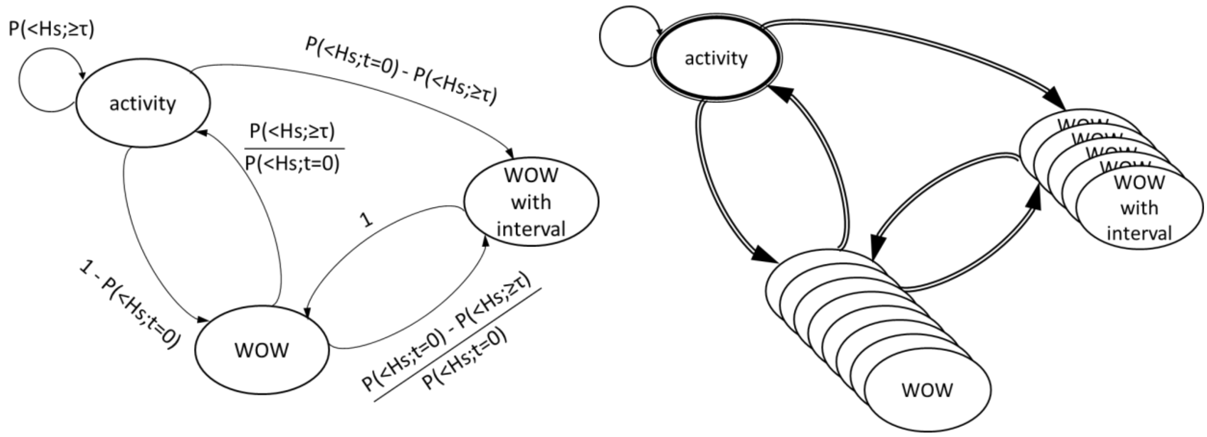

Figure 31. State diagrams.

A monte carlo simulation generates a random number in a certain range. This random number selects a part of the range which represents a probability. Many iterations of this procedure results in occurrence of these parts according to their probability. Figure 32 presents a flow chart of how this concept is applied on the WOW simulation. A random number is generated and this determines the state of the main vessel, as discussed in the previous paragraph. For the states 'WOW' and 'WOW with interval' another random number is generated between other bounds to eliminate states. After 'WOW' only 'WOW with interval' and 'activity' are possible, not 'WOW' again. After 'WOW with interval' only 'WOW' is possible. This is in conformity with Figure 31.

In order to select different durations for the weather window intervals and weather downtimes the respective cumulative density functions (CDF) such as perceived in Figure 29 and Figure 28 are used. Figure 33 shows how these CDFs are employed. The random number selects a point on the vertical axis, which corresponds to a duration. The duration is noted and the algorithm runs to the next state.

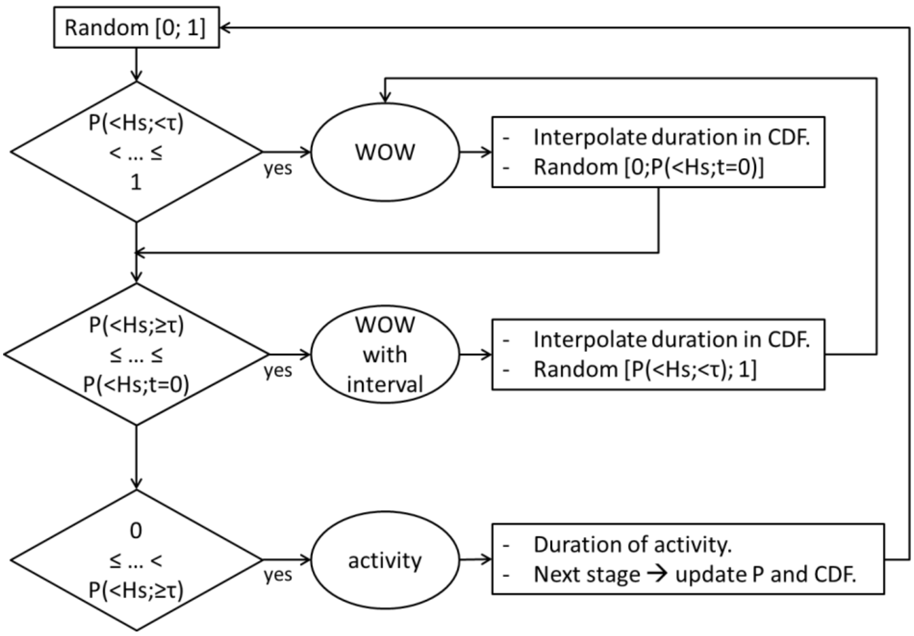

Figure 32. Flow chart describing the monte carlo simulation.

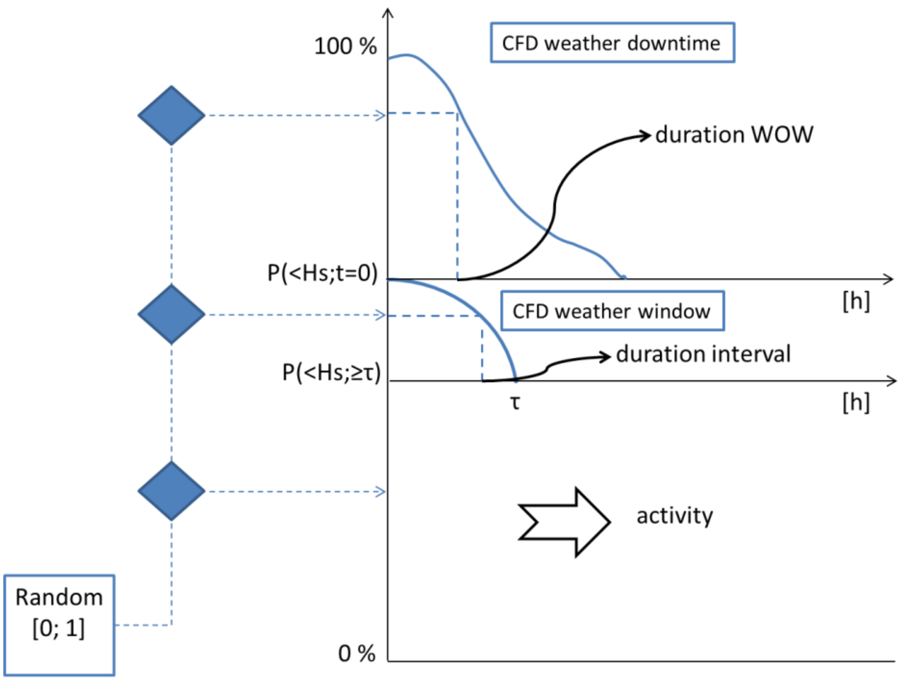

Figure 33. Principle of interpolation of CFD.

The monte carlo simulation runs for each month. All durations are summed and noted as elapsed time (eTime). The duration of the activities are also noted separately (aTime). The net activity times are considered, without the contingency time. The latter is only to determine the probabilities. When the elapsed time reaches the number of hours in the considered month the total activity duration is divided by the time to execute one cycle without WOW, resulting in the number of locations that could be finished in that month. The last state is possibly shorten to meet the exact number of hours in the considered month. The iterations were run for minimum 18 000 months for each different month. The state and stage with which a month starts is arbitrary, which is also the closest to reality. Figure 34 and Figure 35 display the histogram and CFD for each month respectively for the benchmark conditions in Table 4. The CFD represents the probability that minimum X locations are completed in the considered month.

Table 5 displays a comparison of the average, median and standard deviation for different runs. The full extent of the table is enclosed in appendix B. The differences are negligible small, concluding that averages of different scenarios can be compared to each other. The differences were calculated relatively, $\frac{\text{run x}-\text{run 5}}{\text{run 5}}$, with x varying from 1 to 4.

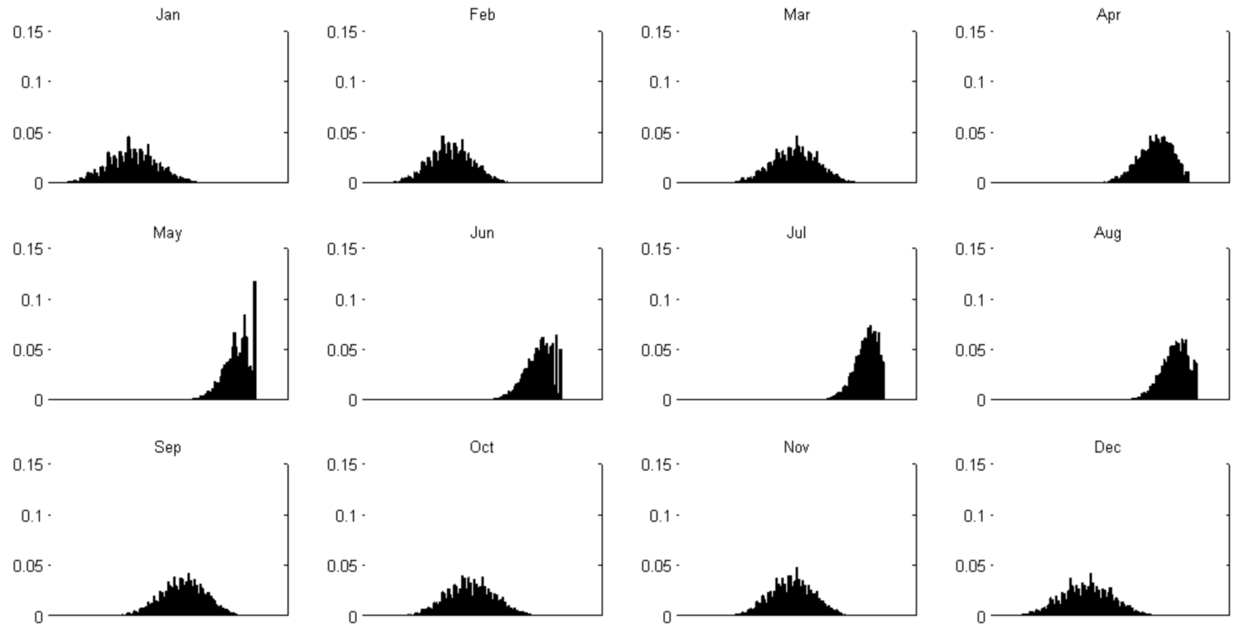

Figure 34. Monthly histograms of completed number of locations (x-label with number of locations is removed due to non-disclosure agreement.).

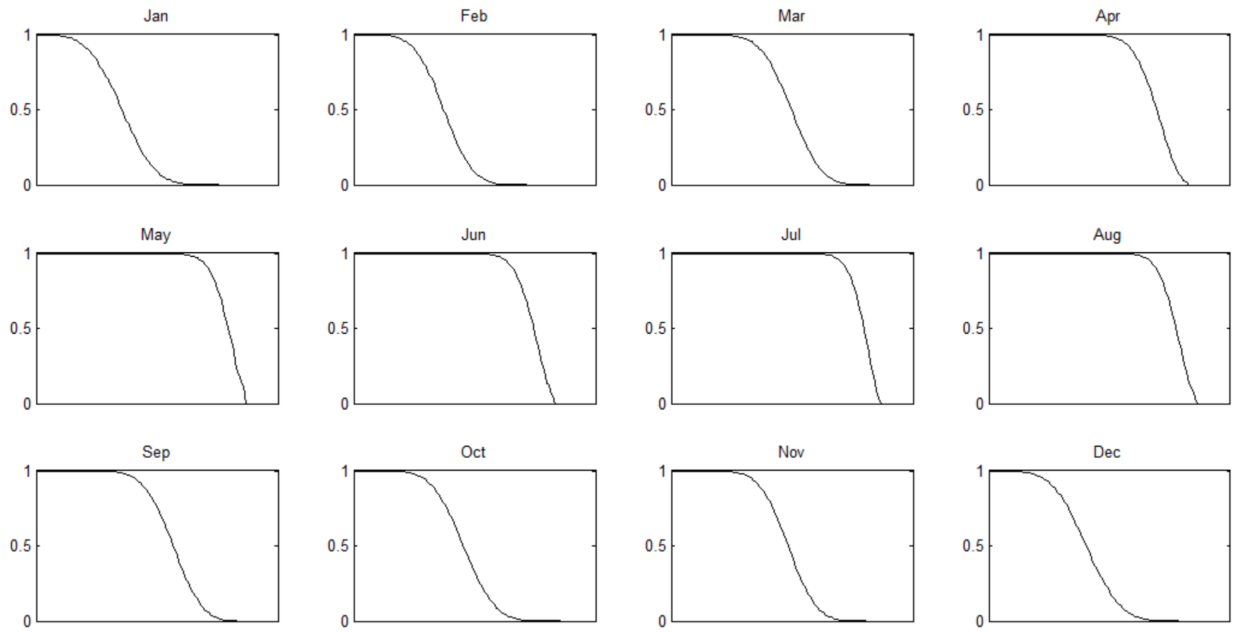

Figure 35. Monthly cumulative distribution function of the completed number of locations (x-label with number of locations is removed due to non-disclosure agreement.).

Table 5. Comparison of shape characteristics of distributions for different runs.

		Jan	Feb	May	Aug	Oct	Dec
run 1	average # locations	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	median	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	standard deviation	1,28	1,10	0,67	0,68	1,21	1,30
run 2	average # locations	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	median	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	standard deviation	1,28	1,11	0,67	0,68	1,20	1,30
run 3	average # locations	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	median	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	standard deviation	1,28	1,10	0,68	0,68	1,20	1,29
run 4	average # locations	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	median	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	standard deviation	1,28	1,10	0,68	0,68	1,19	1,30
run 5	average # locations	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	median	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]	[NDA]
	standard deviation	1,27	1,10	0,68	0,69	1,19	1,30
difference on average		**MAX**	**0,24%**				
	run 5 - 1	0,02%	-0,14%	0,05%	0,03%	-0,15%	0,11%
	run 5 - 2	-0,12%	-0,11%	-0,06%	0,05%	0,14%	0,06%
	run 5 - 3	0,04%	-0,08%	0,00%	-0,01%	-0,12%	0,05%
	run 5 - 4	-0,10%	-0,17%	0,00%	0,10%	0,03%	0,24%
difference on standard deviation		**MAX**	**0,35%**				
	run 5 - 1	0,35%	0,00%	0,04%	0,00%	-0,16%	0,00%
	run 5 - 2	0,00%	0,00%	-0,17%	0,02%	0,15%	0,10%
	run 5 - 3	0,24%	0,00%	-0,02%	0,00%	-0,08%	0,00%
	run 5 - 4	0,04%	0,02%	-0,01%	0,03%	0,06%	0,35%
difference on median		**MAX**	**1,47%**				
	run 5 - 1	0,37%	0,37%	-0,96%	-0,32%	1,01%	-0,01%
	run 5 - 2	0,38%	0,85%	-0,97%	-1,19%	0,44%	-0,51%
	run 5 - 3	0,64%	-0,27%	-0,01%	-0,86%	0,12%	-1,26%
	run 5 - 4	0,06%	0,40%	0,97%	-1,47%	-0,09%	-0,67%

5.3.1 Limitations and assumptions of the simulation

As mentioned before, only the significant wave height is considered, which underestimates the WOW, since several activities are also limited by the wind speed, and one by the wave period. The water current is not an issue in the case of OWF Baltic 2. In addition to these environmental conditions it is assumed that other environmental conditions such as temperature, rain and daylight has no influence on the work performance. Ice is also not taken into account.

The assessment of weather windows in practice is limited by the length of the weather forecast. Some activities will not be executed if it cannot be assured that the next activities can be carried out without a severe storm in between. For instance, the transfer of piles is only done if there are windows in the near future to upend, stab and hammer the piles till preliminary depth, because the conditions of the ship are much more severe in a storm with the added weight of piles on board. The duration of WOW between activities is not limited in the simulation.

There is not extra time included for sheltering for WOW. It is assumed that the JUP is in survival mode after each completion of an activity. Huge storms may force the JUP to relocate to a survival location, where e.g. the risk of a punch through is lower and the airgap is sufficient to survive a 50 year storm, or even sailing back to port may be the only option. Such events are not considered in the algorithm.

In this first set-up of the code, the variability of the activity duration is not included. However, this can be implemented by generating a second random number that selects a duration in the CDF of the activity duration. Attention should be paid to the contingency time, which should not be exceeded, since the weather window is not assured anymore. Other events could also be simulated by generating a third or even a fourth random number to include operational standby and technical breakdown. Note that the WOW intervals already foresee some of the operational standby activities.

In the contingency time of the ‘JUP transit and positioning’ the ‘template lowering’ could be executed, but this would not be valid if the variability of ‘JUP transit and positioning’ is implemented. However, the code could be implemented to determine the weather window duration and in that way be able to check whether next activities can be carried out during the same weather window, but this is not straightforward since next activities can have different weather limits. Therefore it was decided to re-assess the available weather window after each activity. Moreover, the CDF of the weather window is not enough developed. Another approach to determine the expected cycle time is expressed as follows:

$$\sum_{i}^{n} \frac{t_{\text{acitivity i}}}{P(< H_s; \geq \tau)}$$

this is the sum of the time per activity divided by the probability of a weather window. The probability is determined as the ratio of the time of appropriate weather by the total time. E.g. two weather windows of 9 h in the time series count for three 6 h weather windows, whilst in reality these provided only two useful 6 h long weather windows, overestimating the appropriate weather windows. The monte carlo simulation uses the same probabilities, nevertheless, the monte carlo simulation emphasizes the simulation of waiting on weather by the interaction of WOW with intervals. Table 6 shows the calculation of the number of finished locations for the month January by the above formula. Comparing this result with the average number of locations from Table 5, only 30 % of the WOW-days are estimated.

As a final remark, the monte carlo simulation is as accurate as the accuracy of the probability input. The accuracy of the time series analysis is important. Shifting the extrapolated point in Figure 28 affects the simulation output as can be observed from Figure 36. Therefore further research of the shape of CDFs is recommended.

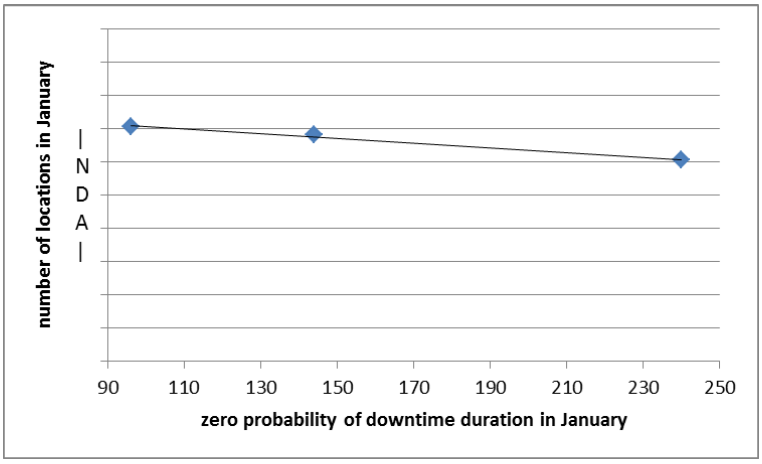

Figure 36. Sensitivity analysis of extrapolated point in Figure 28.

Table 6. Example of alternative calculation of expected number of finished locations per month.

Activity	**time [h]**	**WW length**	**P_Hs Jan**	**time/P_Hs**
JUP transit & positioning	NDA	NDA	0,85	NDA
Template lowering	NDA	NDA	0,87	NDA
Pile transfer	NDA	NDA	0,68	NDA
Upending & stabbing	NDA	NDA	0,84	NDA
Piling to preliminary depth	NDA	NDA	0,85	NDA
Dredging	NDA	NDA	0,83	NDA
Piling to final depth	NDA	NDA	0,85	NDA
Survey / measurement	NDA	NDA	0,87	NDA
Template recovery	NDA	NDA	0,87	NDA
SUM	NDA			
# of WOW days*	NDA	**# of locations in Jan****		NDA

* WOW days = 31 – (NDA x NDA)/24; ** number of locations = 31 x 24 / NDA; 31 is the number of days in January, 24 is a conversion factor from days to hours.

5.4 Planning and decision making

The output of the WOW simulation is the probability distribution of the number of finished locations per month (Figure 34). With the expected number of locations per month (average) the expected completion date can be calculated for a given start date and number of to be installed locations, illustrated in Table 7. The average number of locations in a month is subtracted from the total until the left locations drops below zero. The amount below zero is proportionally compensated to determine the completion day. The completion date and start date determine the total number of construction days, which is related to the overall cost of the project. This provides a methodology to compare two scenarios, i.e. different activities, and helps to decide whether an investment will be profitable.

Table 7. Calculation example of completion date for 41 locations.

Start date	**Completion date**	**Number of days**
May 10th	NDA	NDA
Number of locations finished in …		**Locations to go (/41)**
May	NDA*	NDA
June	NDA	NDA
July	NDA	NDA
August	NDA	NDA
Completion day	NDA	

* $\left(\frac{Days_{May} - start\ day + 1}{Days_{May}}\right) \cdot \overline{\text{Locations}_{\text{May}}}$

Figure 37 presents the influence of the starting date on the total number of construction days. The most productive proven starting dates are situated in end of April and beginning of May, the least ones are situated around first of October. The difference is relevant in terms of time and cost. This demonstrates the impact of a delay of the starting date or even a delay during the project due to breakdowns. The prolongation of a project due to a delay will deteriorate by additional WOW days or be tempered by decreasing WOW days, depending the season wherein the delay occurs.

Figure 37 displays also the number of construction days based on the 5th percentile and 95th percentile, derived from the CDFs in Figure 35. The largest deviation is observed around first of September, when the starting dates are also the worst. The least deviation is observed around first of May, when the best starting dates are. Starting a project in the end of the summer leads to longer project duration and involves both higher risks and costs.

The 95th percentile provides a more conservative approach to determine the completion date to avoid delays of next projects. The drawback is a non-optimum occupation of the JUP, since a non-active period between two project is then more likely. The 5th percentile is a conservative approach to decide on an investment to increase productivity, since the WOW days will have less influence. In addition the 5th percentile provides earliest possible dates to plan and mobilize subcontractors.

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Figure 37. Seasonal influence of starting date on number of days for OWF Baltic 2 (41 locations).

6 RESULTS AND DISCUSSION

Figure 38 presents the cumulative operational hours per finished location for the five pre-piling projects presented in chapter 0. The time difference between projects at the same earned value, i.e. finished locations, is useful to estimate the performance, but caution should be paid when analysing the graph. Obviously, Borkum West II and Baltic 2 have less piles to drive per location, which implies a faster progress. However, a.o. dredging has slowed down significantly the progress at Baltic 2. At Ormonde dredging of the piles was an additional task as a preparation for the installation of the jacket structures later, whilst at Baltic 2 dredging of the piles was a necessary activity to complete the pre-piling job. Due to the dredging at Ormonde as an extension of the scope of work, dredging is left out of the Ormonde data to compare the projects side to side in Figure 38.

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Figure 38. Cumulative operational time per location.

Figure 38 represents only the operational time, and not the WOW days, technical breakdown nor operational standby, still considerable variation is present. In the first part of this chapter the variation between projects is discussed by benchmarking the SPC charts of the five pre-piling projects with the seven activity groups proposed in section 3.4. Possible correlations and histograms are discussed too. In the second part of this chapter some concrete examples are demonstrated of the combined use of a SPC and a monte carlo simulation on a project level. The currently ongoing project Baltic 2 has been chosen as case study.

6.1 Changes and variation in production cycle

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6.2 Influence on total service time by weather conditions

This section demonstrates the impact of a change on the completion date, taking into account the WOW days. Operational standby and technical breakdown have not been considered, because the failure rate of equipment is not known. Each project uses different equipment for distinct situations, of which the history is not known, and therefore cannot be analysed through a benchmark comparison with other solutions. Three cases are considered: (i) base case, (ii) a case with deployment of roller stands and (iii) a case with a new lifting arrangement. The input for the monte carlo simulation can be found in Table 8. The two last cases are compared to the base case in the following subsections.

Table 8. Input for base case, case with new lifting arrangement and the case with roller stands.

			Base case		New lifting arrangement		Roller stands	
	sequence	max Hs [m]	duration [h]	required WW length [h]	duration [h]	required WW length [h]	duration [h]	required WW length [h]
JUP transit & positioning	1	NDA	NDA	NDA	NDA	NDA	NDA	NDA
template lowering	2	NDA	NDA	NDA	NDA	NDA	NDA	NDA
pile transfer	3	NDA	NDA	NDA	NDA	NDA	NDA	NDA
upending & stabbing	4	NDA	NDA	NDA	NDA	NDA	NDA	NDA
piling to preliminary depth	5	NDA	NDA	NDA	NDA	NDA	NDA	NDA
Dredging	6	NDA	NDA	NDA	NDA	NDA	NDA	NDA
piling to final depth	7	NDA	NDA	NDA	NDA	NDA	NDA	NDA
survey/measurement	8	NDA	NDA	NDA	NDA	NDA	NDA	NDA
template recovery	9	NDA	NDA	NDA	NDA	NDA	NDA	NDA

6.2.1 Reduction in 'Upending and stabbing of pile'

To reduce the time of moving the pile horizontally in the upending frame to attach shackles and hooks roller stands are proposed, see Figure 39. The roller stands are estimated to be faster than the crane and additionally the crane hook becomes available to connect immediately the crane to the shackles without disconnecting the spreader beam first. A time saving of 53 min. is estimated.

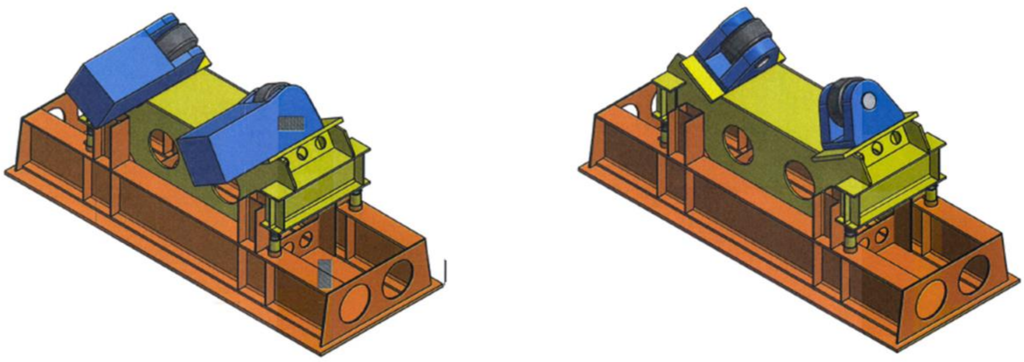

Figure 39. Roller stands.

Assume 37 locations need to be done on the 1st of May, the total gain (incl. WOW) is 33.4 h, whilst the total net gain (w/o WOW) is 32.9 h. There is almost no difference. When instead of the 1st of May the 1st of October is taken, the monte carlo simulation results in a gain of 33.6, also a small difference with the net gain.

6.2.2 Reduction in 'Pile transfer'

After a pile transfer the slings has to be disconnected from the crane tackle. Disconnecting slings at both sides of the pile can be done without lifting and lowering the connection point alternately at one side of the pile thanks to another lifting arrangement, see Figure 40.

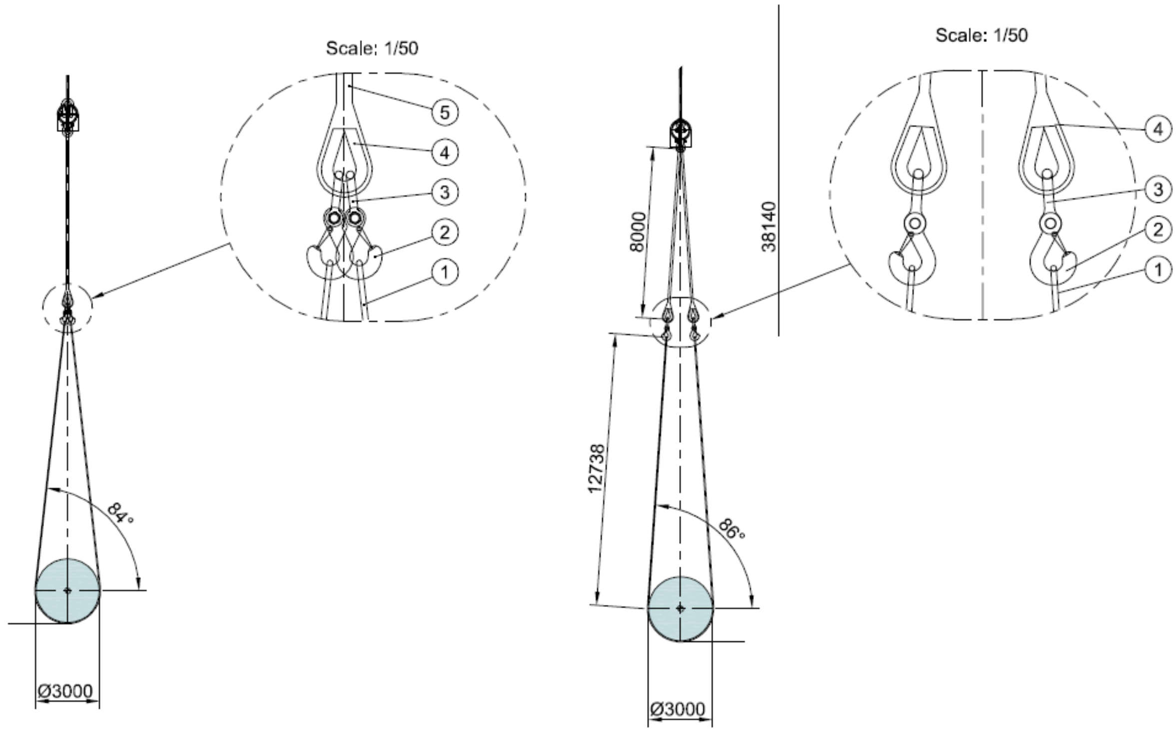

Figure 40. Change in lifting arrangement.

Figure 41 presents the time gain of the change in lifting arrangement, approx.. 53 min.. Assuming 37 locations have to be done after this change starting on the 1st of May, the monte carlo simulation results in a gain of 33.6 h. Compared with the 32.9 h net gain, the WOW has almost no influence. Assuming the starting date is the 1st of October instead, the time gain incl.WOW is 38.6 h, an increase of 17 % w.r.t. the net gain of 32.9 h.

This last result leads to two conclusions. Firstly, the gain is higher when more WOW is expected. Secondly, although ‘Upending and stabbing’ take more time and would be assigned as a bigger bottleneck in a Pareto graph, an equal time saving in a shorter lasting ‘Pile Transfer’ results in a bigger gain due to its more critical weather limits (1 m Hs instead of 1.5 m Hs).

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Figure 41. Impact in time of new lifting arrangement.

7 CONCLUSIONS

The analysis of the reported time data confirmed the influences of technology, weather and soil conditions on the installation of a series of foundation piles. A pronounced learning curve at the start of each pre-piling project can be observed. The most improvements are realized after the first pre-piling project and were especially technology driven (new conceptual design of the piling template in combination with moon pools). After two projects the metrology was integrated in the piling template, resulting in a reduction of the installation spread. The seasonal influence of the start date of a pre-piling project was proven. Projects starting at the end of the summer involves both higher risks and costs. The soil conditions at offshore wind farm Baltic 2 caused additional dredging works during pre-piling due to rising soil plug in the pile.

A tool based on a monte carlo simulation is proposed to account for the weather downtime, which has as output a prognosis of the completion date. Different scenarios can be compared by means of the completion date prognosis. The day rate of the installation spread multiplied by the time difference determines whether an investment is profitable.

It was demonstrated that pareto diagrams can be misleading when the weather sensitivity of the activities are not taken into account.

7.1 Future work

The proposed tool that makes a prognosis of the completion date forms a base to include other variability than weather downtime, such as the variation of the production time. Events of operational standby and technical breakdown can also be implemented. The tool can be further developed with an appropriate graphical user interface.

More research in distribution functions of weather data is recommended. The relation between probabilities of excess of wind speed and wave height would provide a higher accuracy of the monte carlo simulation. The historical data could also be tested for decadal trends to estimate whether the current decade situates more above the average weather downtime or below.

The activity groups could be tested for more parameters than water depth and pile length. Especially soil conditions are not elaborately discussed in the present study.

8 ACKNOWLEDGEMENTS

I wish to thank Professor Robert Bronsart, my supervisor, for the guidance and encouragement. I would also like to offer my special thanks to Mr. Stefaan Van Velthoven, my supervisor during the internship, for the constructive discussions and valuable insights in offshore works. His willingness to answers all my questions has been very much appreciated. My grateful thanks are also extended to various people; to Mr. Pedro Pereira to review a part of my thesis, to give advice about presenting graphs and to show his token of interest; to Mr. Ruben Loos and Mr. Jeroen Daems for the information about lean six sigma and SPC charts; to Mr. Ruben Stevens, Mr. Klaas Van Varenbergh and Mr. Christopher Maguire for their helpful explanations and interesting thoughts on the pre-piling process; to Mr. Alfonso Alvarez and Mr. Robert Kawczyk who appreciated me for my work and motivated me.

I would like to thank GeoSea nv, and in particular Mr. Geert Linthout, deputy project manager of Baltic 2, for the opportunities and support during my internship which led to the creation of this thesis. I would also like to thank the complete staff at Baltic 2 for enabling me to experience their daily operations.

Last but not least, I wish to pay tribute to my parents and brothers for their unconditional support and encouragement throughout my study.

This thesis was developed in the frame of the European Master Course in “Integrated Advanced Ship Design” named “EMSHIP” for “European Education in Advanced Ship Design”, Ref.: 159652-1-2009-1-BE-ERA MUNDUS-EMMC.

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10 APPENDICES

10.1 Appendix A – Statistical weather data of OWF Baltic 2

Removed due to non-disclosure agreement.

10.2 Appendix B – Comparison different runs of monte carlo simulation

Table 9. Continuation of Table 5.

			Mar	Apr	Jun	Jul	Sep	Nov	Dec
run 1	average # locations		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	median		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	standard deviation		NDA	NDA	NDA	NDA	NDA	NDA	NDA
run 2	average # locations		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	median		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	standard deviation		NDA	NDA	NDA	NDA	NDA	NDA	NDA
run 3	average # locations		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	median		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	standard deviation		NDA	NDA	NDA	NDA	NDA	NDA	NDA
run 4	average # locations		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	median		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	standard deviation		NDA	NDA	NDA	NDA	NDA	NDA	NDA
run 5	average # locations		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	median		NDA	NDA	NDA	NDA	NDA	NDA	NDA
	standard deviation		NDA	NDA	NDA	NDA	NDA	NDA	NDA
difference on average									
	run 5 - 1		-0,17%	0,06%	-0,02%	-0,04%	-0,05%	0,04%	0,11%
	run 5 - 2		-0,02%	0,03%	-0,06%	-0,03%	0,00%	-0,08%	0,06%
	run 5 - 3		-0,15%	-0,01%	-0,02%	-0,01%	-0,22%	-0,02%	0,05%
	run 5 - 4		-0,01%	-0,01%	-0,01%	-0,12%	-0,05%	0,02%	0,24%
difference on standard deviation									
	run 5 - 1		0,04%	0,13%	0,06%	-0,04%	-0,23%	0,04%	0,00%
	run 5 - 2		0,23%	0,03%	-0,06%	-0,04%	-0,01%	-0,10%	0,10%
	run 5 - 3		0,02%	0,16%	0,02%	-0,05%	-0,24%	0,04%	0,00%
	run 5 - 4		0,09%	0,03%	-0,03%	-0,13%	-0,10%	-0,04%	0,35%
difference on median									
	run 5 - 1		-0,32%	0,18%	0,21%	0,02%	-1,41%	-0,22%	-0,01%
	run 5 - 2		-0,20%	-0,68%	-0,41%	-0,26%	-0,49%	-0,49%	-0,51%
	run 5 - 3		0,33%	0,02%	-0,47%	-0,09%	-0,24%	0,54%	-1,26%
	run 5 - 4		0,03%	0,55%	-0,76%	1,26%	-0,87%	-0,44%	-0,67%