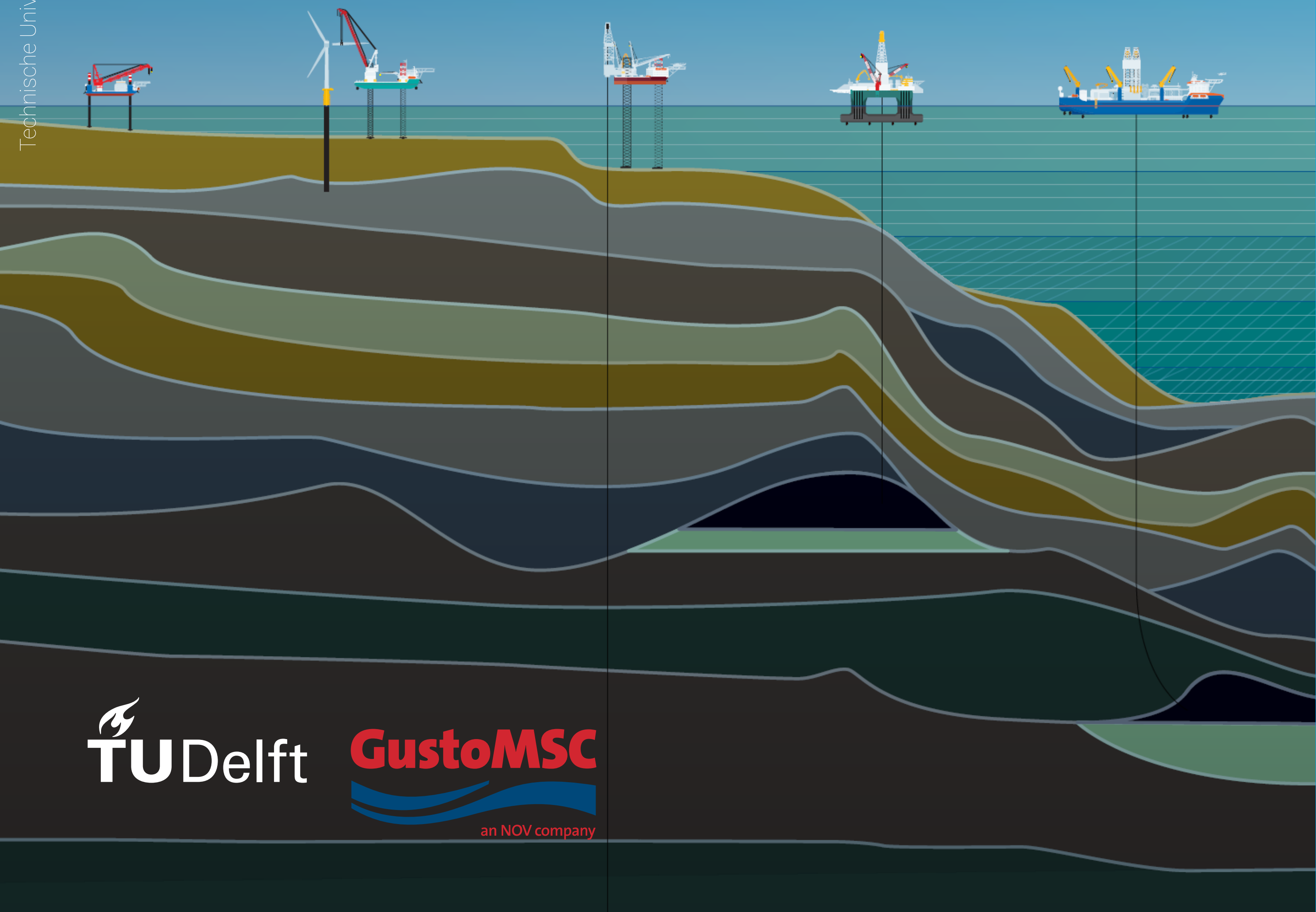
The Jack-up frame

A novel installation method for large offshore wind turbines

A.M. Janse



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GustoMSC
an NOV company

The Jack-up frame

A novel installation method for large offshore wind turbines

by

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Preface

Dear reader,

This report is the result of nine months of thinking, talking, writing and discussing. It is written as partial fulfilment of the master Offshore and Dredging Engineering at Delft University of Technology and developed in close cooperation with the design and engineering company GustoMSC, based in Schiedam. In the past two years, I learned a lot about offshore engineering and my interest in the offshore energy sector and in particular the offshore wind sector has been ever growing since. It was this relative young but extremely rapid growing industry, in which I saw room for innovation and improvement, which was confirmed by GustoMSC.

Completing this thesis would not have been possible without my supervising committee. First of all, I would like to thank Frank Sliggers, as chairman of my committee, for showing his practical knowledge and expertise and who assured that I always kept the overall goal in mind and who, by being critical about the decisions I made, helped me set out a convincing concept. Secondly, I want to thank Yang Qu who, despite his own PhD research, was always happy to help me if I needed input from a different point of view. Moreover, I would like to express my utmost gratitude to Andries Hofman, thank you for your enthusiasm and motivation, your excellent engineering knowledge and the drive to make my work better during my graduation process.

In addition, I would like to thank some colleagues from GustoMSC: Fons Huijs for introducing me to GustoMSC and for his role in the origin of this subject and Jan-Mark Meeuwisse as commercial director at GustoMSC for introducing me to his contacts within Siemens, VanOord and Mammoet, where I conducted interviews to get a better understanding about the needs and wishes from the industry.

Besides the people who helped me realising my thesis, I had many who supported me during this final phase and especially the the years that have passed. Thanks to you all.

I hope you enjoy reading my report.

Arnout Janse
Delft, September 2018

Abstract

The offshore wind industry is entering a new level of maturity. Announcements of bigger offshore wind turbines, the interest in new locations for offshore wind farms in harsher environments and the appearance of zero subsidy bids are proof of a rapid development. The next generation turbines are expected to be significantly larger and heavier compared with the current operating turbines. This poses new requirements for safe and efficient installation, requirements that go beyond the capabilities of existing jack-up installation vessels and equipment. Therefore, to avoid bottlenecks for future development, new installation equipment is needed. The goal of this thesis is to find an efficient way for installation of future offshore wind turbines with a rated power of up to $20MW$.

The characteristics of these large size turbines were studied by examining the relation between the rated power and the rotor diameter of operating offshore wind turbines. The derived dependencies between the desired power and the required area of the rotor were validated with data from announced turbines. Extrapolating these dependencies has resulted in a prediction for the $20MW$ turbine of a rotor diameter of 250 metres, a hub height of 160 metres above sea level and a nacelle with a mass of around 1100 tonnes.

To be able to develop new concepts for the installation of these turbines, interviews were conducted with industry experts and criteria were derived. Next, upscaling of the equipment of the current jack-up vessel was investigated, already existing concepts were reviewed and new concepts were developed. Based on the set criteria, a suitable installation concept was chosen.

The chosen concept eliminates the need for lifting the heaviest component (the nacelle) to the highest height (hub height) by dividing the tower of the turbine into several segments. It consists of a temporary installation frame that can be placed from a jack-up vessel on top of the foundation of an offshore wind turbine. While installing the frame on the foundation with a crane, the nacelle, hub and blades are mounted together on the deck of the jack-up vessel, forming the rotor nacelle assembly (RNA). Then, the RNA together with the first segment of the tower is placed in the frame, skidded sideways and brought up by a built-in jacking mechanism in the frame. It needs to be brought up 45 metres, so the following segment of 40 metres can be skidded underneath. While jacking the first segment, the following segment is placed next to the lift frame and prepared to be skidded. After the skidding of the next segment is finished, the previous segment is lowered on top of the other segment and they are mounted together. While fastening the connection, the jacking mechanism is lowered so it can start lifting the next segment. This is repeated until the complete turbine has been installed. When all the tower segments are installed, the turbine can be commissioned and the frame is retrieved.

Optimisation of the concept has been performed by highlighting the logistical process regarding placement of the frame, lifting of the turbine and retrieval of the frame. A concept design is presented that can install the future offshore wind turbines with a rated power of up to $20MW$. It is able to install the large size turbines faster compared to upscaling the existing installation equipment, it can be used for several turbine sizes and it only requires small modifications on the design of an offshore wind turbine.

The concept consists of a jack-up vessel from where the installation is performed offshore. This was preferred over a floating vessel, since movement of the jack-up vessel is reduced significantly when lifted out of the water. For wider applicability of the developed concept, for example on a free floating vessel, (non jack-up), further research is required to reduce motions between the turbine and the foundation.

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Introduction

The offshore wind market is an abundant source of renewable energy. To reach the international climate goals, set by the European Commission (2015), major markets around the world have set goals to increase their percentage of renewable sources in their domestic electricity consumption. The Dutch government for example sets a goal for 2020 that 14% and for 2023 16% of all energy that is consumed is produced by renewable energy, where in 2013 only 4.5% of the consumed energy was renewable energy (Government of the Netherlands, 2015; International Energy Agency, 2014). Consequently, many offshore wind farms are currently being established not only in front of the coast of the Netherlands but as well as in the rest of the North Sea and other parts in the world (4C Offshore Ltd, 2017; Snieckus and Hopson, 2016).

To lower the costs per megawatt hour for offshore wind energy, higher efficiency is a requirement and bigger wind turbines are designed. These bigger wind turbines come with challenges regarding offshore transportation and installation due to the growing size, increasing weights and increased distance to shore (4C Offshore Ltd, 2017).

This research aims to come up with a solution for the transportation and installation of the future offshore wind turbines.

1.1. Problem definition

The common way to install offshore wind turbines is with a jack-up vessel which lifts itself out of the water to reduce the environmental impact during installation, shown in Figure 1.1. This method lifts the different components of the wind turbine one by one on top of a pre-installed foundation: first the tower, followed by the nacelle and at last the three blades separately. This results that the lift height becomes as high as the hub height of the wind turbine and as a consequence requires the crane to be able to reach well beyond that height to accommodate the sling arrangement, as can be seen in Figure 1.1.

Figure 1.1: Jack-up installing an offshore wind turbine (Offshorewind, 2017)

To increase the total capacity of an offshore wind farm, bigger and more efficient turbines are designed. This results in offshore wind turbines with a rated power up to 9.5MW which have a typically diameter of 164 meter and a hub height ranging up to 115 meter (4C Offshore Ltd, 2017; Morris, 2017; Wind turbine models, 2017).

It is expected that the rated power will grow further up to 15 or even 20MW, which will bring new challenges regarding transportation and installation (T&I) of the different components of these offshore wind turbines (Jensen et al., 2017; Niermeijer and Mast, 2017).
One of the goals of this research is to give more insights in the problems regarding increase of lifting height, increase of weight and increase of size of the different components during T&I and to come up with a suitable solution to install the components.

1.2. Research objective

From 2010 until 2016, around 2,600 turbines were installed in the North Sea of which over 75% were installed by GustoMSC designed Jack-ups (GustoMSC, 2017) (Appendix F). As market leader and as engineering company in jack-up designs and associated equipment for offshore wind installation, GustoMSC is always trying to push the boundaries by innovating and developing new methods regarding installation in the offshore wind market. The aim of this research is to come up with a design that gives an answer to the following research question:

"How can offshore wind turbines with a rated power of 15 till 20MW be transported and installed in an efficient way?"

This research question can be answered by addressing the following sub-questions:

1. What are the current methods for transportation and installation of an offshore wind turbine and what are the challenges when scaling up for larger turbines?
2. What are the characteristics of turbines with a rated power of 15 till 20MW?
3. Which criteria determine if a method for T&I of OWTs is efficient?
4. Which new methods for T&I of OWTs can be thought of and which are already in development or available?
5. When a method has been chosen, what is the technical and economical feasibility of the this solution?

By answering these sub-questions an efficient way for transportation and installation for future offshore wind turbines is tried to be found.

1.3. Research methodology

To answer the research question, a study will be performed that consists of the following stages:

1. *Literature study*
   First a literature study is performed to search for information about growth of turbines in the future and their characteristics. Moreover, the current method of transportation and installation are mapped out not only by reading literature that is found but as well as conducting interviews within the industry.

2. *Market survey and requirement analysis*
   Based on literature and the conducted interviews stakeholders are mapped out and criteria are set up regarding the transportation and installation of the future offshore wind turbines.

3. *Functional analysis and concept development*
   To develop new concepts, a distinction will be made between the different installation steps. For each step a variety of ideas will be generated that can function as sub-solutions and by combining different sub-solutions, concepts will be given. Moreover, state of the art designs and innovative methods regarding wind installation will be presented.

4. *Concept selection and initial design*
   Based on the earlier set up criteria, the most promising concept will be chosen and an initial concept design will be presented. New challenges will be highlighted and solved, resulting in an improved design.

5. *Load calculations and analysis*
   After the design has been set up, dimensioning of the different members will be performed based on rules of thumb and a first estimation of the mass will be calculated. Moreover, the governing loads during installation are determined and high level calculations will be conducted to highlight the most critical places in the design of the installation frame. After setting up the design, a preliminary estimation of the costs will be presented.

6. *Visualisation of step wise installation*
   After the improved design is completed, a stepwise storyline will be presented on how the large offshore wind turbines with a rated power up to $20MW$ can be installed with the new concept.

1.4. Thesis outline and guide for reading

The thesis consists mainly of two parts, shown in Figure 1.2. It starts with finding a new transportation and installation method for offshore wind turbines, after which it develops the selected concept further by going more into detail regarding the offshore installation.

First in chapter 2 a context study is conducted to highlight the different stakeholders, the current installation methods and where a prediction is made for the future offshore wind turbine. Then, the requirements are shown in chapter 3 which result in the criteria that later will be used in the selection of the concept. chapter 4 shows the functions regarding offshore T&I that are defined and a morphological overview is presented, where different methods are described. The different concepts are grouped and with a multi criteria analysis the best method is chosen in chapter 5. chapter 6 starts the second part of this research by presenting the initial design of the installation frame and by highlighting new challenges regarding this installation method. The design is evaluated and further developed in chapter 7 together with governing load calculations and preliminary load checks. Finally, chapter 8 contains a round up with an answer to the research question and proposed further research.

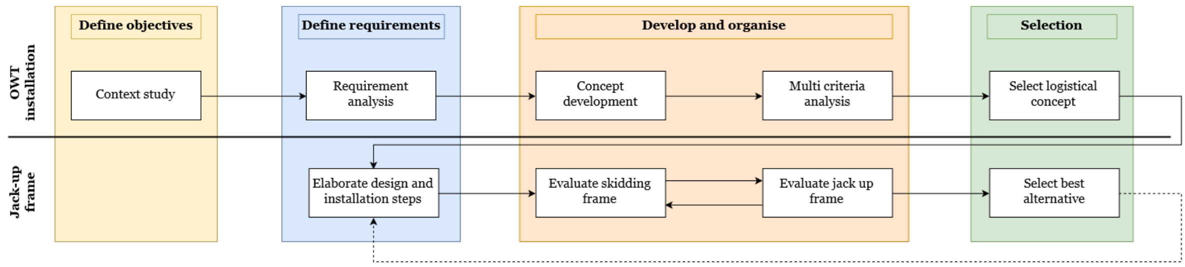


Figure 1.2: Overview of the research

2
Context study

In this chapter the context is presented, which gives general background information as well as input for the design. Section 2.1 begins with summarising previous research that is conducted by other people regarding transportation and installation (T&I) methods of offshore wind turbine (OWT)s. Then in section 2.2 analyses an OWT by listing the different components. Information about how wind is converted into energy is elaborated in section 2.3. After this an insight in the offshore wind energy market is given together with an analysis of the governing stakeholders in section 2.4, followed by an overview of the current installation methods (section 2.5). A prediction is given about the size of the future turbine components in section 2.6 which will function as input for the rest of the research. Section 2.7 concludes with the scope and assumptions bounding this project.

2.1. Previous research

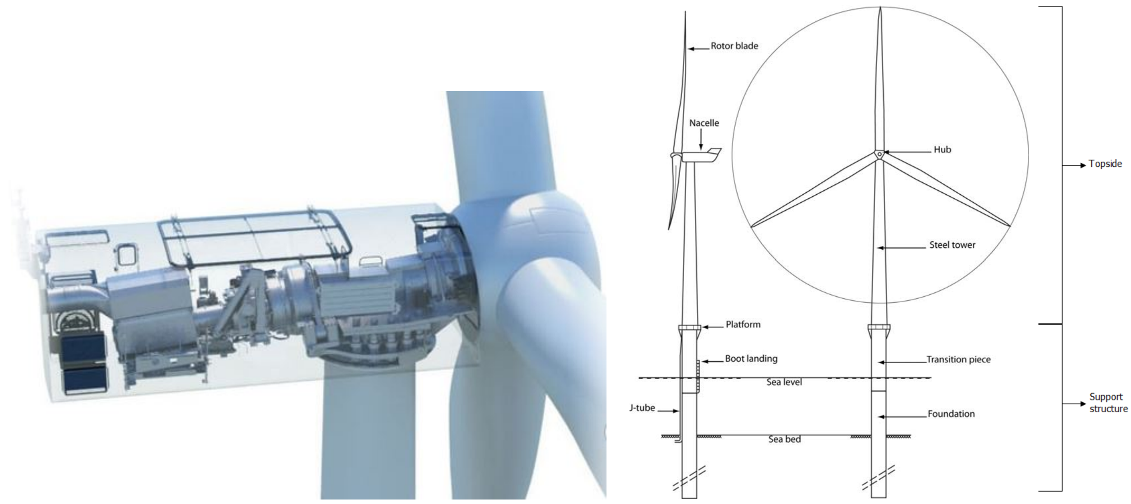
Previous research is already conducted for current methods regarding T&I of offshore wind turbines. Although this research looks into solutions for bigger turbines, it is good to know what already has been optimized or researched of the methods that are currently operating.

Stavenuiter (2009) looked into concepts of an offshore wind support vessel, which took into account the environmental influences and the need for a specified support vessel. Pieters (2010) has set up a model that could increase the efficiency of a jack-up during installation by making use of a supply barge. Avoiding of collision between cargo and supply deck is preferred but was not investigated and recognised by the offshore wind industry before. His model calculated the sea states in which the chance of collision between cargo and supply deck is acceptable and which could therefore increase the efficiency of a jack-up. Den Hamer (2011) did research for optimizing the deck arrangement design of an offshore wind turbine installation vessel (OWTIV) by looking into (1) the ship design perspective, by minimizing the deck area of the jack-up and (2) from an operational efficiency perspective, by minimizing the total length of the logistical paths on board.
Where they primarily investigated existing methods, others where trying to innovate. For example, Strien (2011) looked into the optimization of transport and installation methods for offshore wind turbines ranging from 3 up to 5 MW. He did this by first making a time estimation for the current methods, after which he later developed a new concept for these size turbines. Moreover, de Groot (2015) was looking into new methods for installation of blades, based on the sizes of a SWT6.0-154 turbine.
Kumar (2017) looked into cost optimization of the whole installation process of a complete offshore wind farm with a strict finishing date. The turbines used as reference where based on the $5MW$ reference turbine (Moné et al., 2017). Regarding the installation of these turbines, he assumed that it was installed by conventional methods like a jack-up vessel, a jack-up barge or a heavy lift vessel. Challenges during transportation were researched by Izzo (2014), focusing on sea-fastening of the tower nacelle of a ALSTOM $6MW$ turbine.

Although some of the projects are really going into depth, they are all focusing on turbines with sizes that were revolutionary for their time but are already exceeded by the current turbines. This indicates once more how fast the offshore wind industry is developing and that looking into 15 till $20MW$ turbines has to be done. The previous mentioned researches can be used as input for how they approached a problem and how some off them solved parts of the installation for the ever growing wind turbines.

2.2. Wind turbine components

This section gives a brief introduction into the different components of an offshore wind turbine (OWT). As depicted in Figure 2.1b, a general OWT can be split up into two parts: the topside and the support structure. The topside consist of the blades, hub, nacelle and tower. The blades, hub and nacelle together are called the rotor nacelle assembly (RNA), which is situated on top of the tower. The blades capture the wind and start turning, where this rotating energy is converted to electric energy in the nacelle. The support structure consist of the foundation and a transition piece (TP), which connects the tower with the foundation and corrects any obliqueness of this foundation. This separation is done for two reasons: they are normally designed and manufactured by different companies and secondly, different methods are used for the T&I of respectively the topside and the support structure.



(a) Impression of a nacelle (Siemens, 2016)

(b) Complete turbine (Strien, 2011, p.9)

Figure 2.1: Components of an offshore wind turbine

Rotor

The rotor consists of the hub and the blades of an OWT, depicted in Figure 2.1b. The blades are connected with bolts to the hub, which connects the, in general, three blades to the drive shaft in the nacelle. The diameter of the rotor has increased rapidly in the last years (Figure 2.10. Currently, the V164-8.0 of Vestas is the largest operating turbine with a rated capacity of $8MW$ and a diameter of 164 meter, where each blade measures around $80m$ in length and weights around 35 tonnes (Wind turbine models, 2017).

Nacelle

The nacelle (Figure 2.1a) houses all of the generating components in a OWT, including the generator, gearbox, drive train, and brake assembly. It converts the relative slow rotation of the rotor to a higher rotation velocity, which is necessary for the generator to produce electricity as efficient as possible. Commonly, the nacelle is able to rotate around the vertical axis (yaw), so it can turn the rotor into the wind. Becasue of different types of conversion, the dimensions and masses of nacelles vary considerable Keysan (2012). The nacelle of the V164-8.0 already has a mass of almost 400 tonnes and dimensions of approximately $12m$ length, $8m$ height and $8m$ width (4C Offshore Ltd, 2017). The nacelle is connected to the tower with a bolted flange.

Tower

The tower is a conical steel tubular structure which is commonly connected to the support structure by a bolted flange, just like the RNA on the tower. New type of connection are in development, one of them is the 'Slip Joint'. It consists of two conical cones that will form a connection based on friction (Van der Tempel and Lutje Schipholt, 2003; Segeren, 2018). Since this is still in the test phase, it is assumed for this research that the bolted connection will be used to connect the tower to its support structure.

The length and the size of the tower are site specific and depends on the wind loads, the support structure and the size and mass of the rotor. Therefore, it differs per wind farm and even per turbine in a specific wind farm. To have enough clearance between the tip of the rotor and the water surface, a minimum hub height is required. For the V164-8.0, a hub height of around 120 metres is required. This equals around 1.5 times the length of the blade. The mass of the complete tower ranges for the V164-8.0 up to 600 tonnes with a diameter of 4.5 metre at the top to 6 metre at the bottom.

Support structure

As mentioned before, the support structure is split up into two parts: the transition piece and the foundation (Figure 2.1b). The TP connects the tower and the foundation. It is equipped with a platform and boat landing so the OWT can be entered for operation and maintenance. Furthermore the power and control cables of the turbine are routed along the structure to the seabed in a J-tube. The foundation has as function to redirect the loads to the ground, where a distinction can be made between the static loads from the turbines topside, the dynamic loads introduced by the wind and the hydrodynamic loads on the foundation itself due to waves and currents.

Several foundation types are currently used, where a division can be made between bottom founded and floating foundations (Figure 2.2). The choice of the most suitable foundation will depend on water depth, soil conditions and overturning moment caused by the environmental forces. The most used foundation for intermediate water depths is the monopile foundation, where an increase of tripod and jacket foundations can be seen due to the growing size of turbines and the increase of water depth. Floating concepts are currently tested in demonstration projects and have not yet been commercialised.

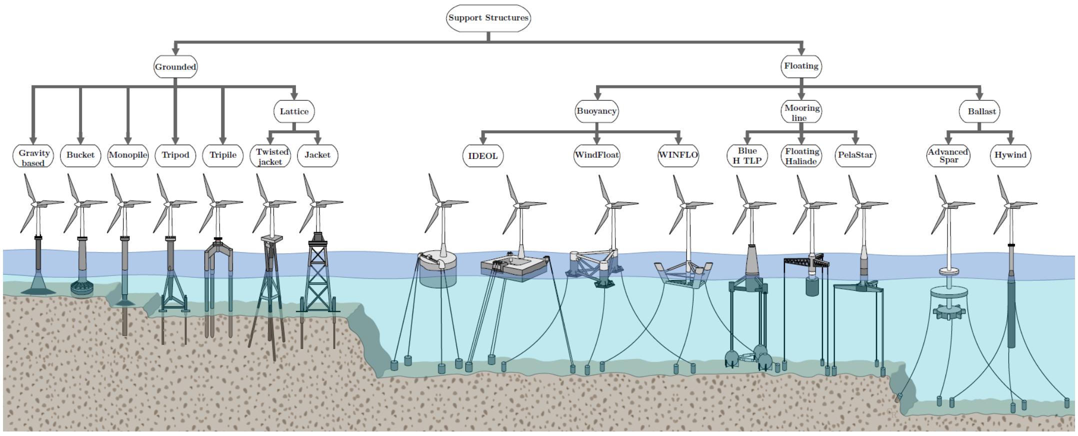


Figure 2.2: Types of support structures for OWTs (Rodrigues et al., 2016, p.14)

The structural capacity of the support structure is determined by dynamic loading of the turbine due to wind. Growth in rotor size results in higher dynamic loads due to wind which increase the overturning moment that has to be overcome by the support structure. For a MP this can be overcome to increase the moment of inertia (I), which is dependant on the diameter (D) and wall thickness (t) of the monopile (Equation 2.1).

$$I_{MP} = \frac{\pi}{4}\left((D/2)^4 - (D/2-t)^4\right) \approx \frac{1}{8}\pi \cdot D^3 \cdot t \tag{2.1}$$

The mass of the monopile is determined by multiplying the area by the length and its density.

$$Mass_{MP} = \rho_{steel} \cdot L \cdot \pi\left((D/2)^2 - (D/2-t)^2\right) \approx \rho \cdot L \cdot \pi \cdot D \cdot t \tag{2.2}$$

By keeping the length and density constant (ρ_{steel}=7950kg/m^3) and stating that for a monopile a constant D/t-ratio of 100 will be representable (van der Male and Haghi, 2017) it can be seen that an increase of diameter results in a more than linear increase of mass. Figure 2.3 shows the increase of mass due to the growing rotor diameter.

This increase of mass can already be seen by looking to the project Veja Mate where the largest monopiles until now are installed to support the respective turbine, a 6MW turbine from Siemens with a rotor diameter of 154 meter. The OWTs have a maximum hub height of 103 meter and a water depth ranging till 41 meter.

These characteristics and the soil conditions of the area results in foundations that consists of monopiles with a diameter of almost 8 meters, a length ranging to 85 meters and a maximum mass of 1300 tonnes each. To connect the tower to the monopile, a transition piece (TP) is used with a length of 25 meters and a mass of around 360 tonnes (Boskalis, 2017). Comparing this with the total topside mass of 800 tonnes (Provided by Siemens, Appendix A), results in other requirements regarding crane and guidance equipment than that of the tower.

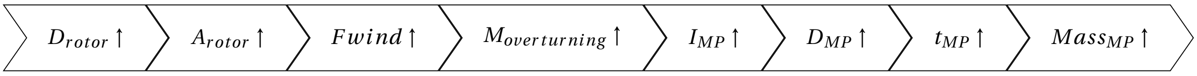


Figure 2.3: Increase mass of monopile foundation

Where a jacket foundation requires more material than a monopile for intermediate water depths, the increase of mass is less significant to overcome the increase of overturning moment than that of a monopile. This is due to the fact that the moment of inertia of a jacket is determined by among others the footprint of the structure which easily can be increased. This results not directly in a significant increase of mass since it is an open structure instead of the massive steel monopile.

For 15 till 20MW turbines it is forecast by GustoMSC that the foundations probably end up in the 2500-3000 tonnes range. After comparing this with the mass of the components of the topside and the required equipment it is therefore decided that this research will focus on the T&I of the topside, consisting of the tower, nacelle, hub and blades and not that of the support structure, namely the foundation and transition piece (TP). It is stated that the TP, and thus support structure, is ready to receive the tower.

2.3. Offshore wind energy

The growth in turbine can be explained by looking into the principles of wind and how it is converted into energy

2.3.1. Wind speed

Wind is caused by differences in pressure, which themselves are again caused by a differences in temperature and the rotation of the earth. A good estimation for the probability of occurrence of a certain wind speed can be made with the following formula, a so called Weibull distribution (Bierbooms, 2016).

$$f(v_{wind}) = \frac{k}{v_{wind}} \cdot \left(\frac{v_{wind}}{a}\right)^k \cdot e^{(v_{wind}/a)^k} \tag{2.3}$$

Where:

- $f(v_{wind})$ = probability of occurrence of a certain wind speed
- v_{wind} = wind speed
- k = shape parameter
- a = scale parameter

The shape parameter is location dependent and the lower the value, the more concentrated wind speeds occur, as is illustrated in Figure 2.4a. The scale parameter is positive dependent on the mean wind speed: the higher this parameter the higher the mean wind speed. This results in a shift of the peak towards the right. Three examples are shown in Figure 2.4a, where different values for the scale and shape parameter have been used to generate the respective distributions. The parameters are determined on measured wind speeds and their respective occurrence. The probability for the coast of North West Europe can be estimated with a shape parameter of around 2 and a scale parameter of around 8 (Bierbooms, 2016).

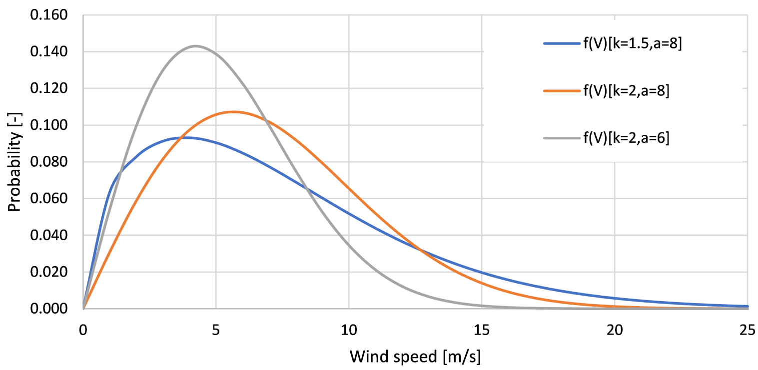
The wind speed is not uniformly distributed over the height and therefore, to calculate the wind speed on different heights the logarithmic law or the simplified power law is commonly used. It is stated by Emeis (2005) that the power law (Equation 2.4) profile provides a good description of the wind profile over the sea with respect to the height. This power law is based on a measured wind speed at a reference height ($v(z_{ref})$), which is normally around a height of 10 metres above still water level.

$$v(z) = v(z_{ref}) \cdot \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{2.4}$$

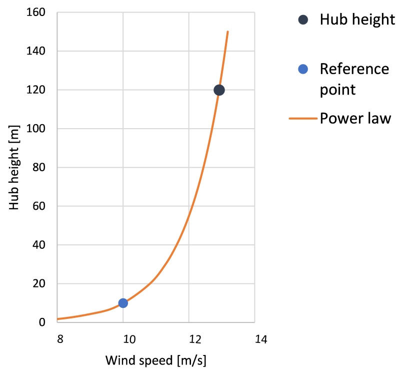
Where:

- $v(z)$ = wind speed at height z in m/s
- z = height at which wind speed is evaluated
- z_{ref} = reference height
- $v(z_{ref})$ = wind speed at reference height in m/s
- α = Hellmann exponent

The Hellmann exponent for the mean wind speed on the long term is a function of the roughness length and is in general taken as 0.11 for offshore wind locations (Kaltschmitt et al., 2007, p. 55). In Figure 2.4b an example is given, with $v(z_{ref}) = 10 m/s$, $z_{ref} = 10m$ and $\alpha = 0.11$ which results in a wind speed of $12.9 m/s$ at a hub height of $120m$.



(a) Weibull distributions



(b) Wind profile

Figure 2.4: Wind characteristics

It is stated by Emeis (2005) that extrapolations of the wind profile above the height of the surface layer (80 to 100 m) by either the logarithmic or the power law should be made with very great care because these laws are valid for the surface layer only. However, since the research of wind profiles is beyond the scope of this research, it is assumed that the power law is a good approximation of the wind speed at hub height, even for hub heights above 100 meter since it can be seen that the wind is relatively constant above 120 meter (Kaltschmitt et al., 2007, p.55). It can be concluded from Equation 2.4 and Figure 2.4b that at a higher hub height, the wind speeds are higher and the variation over the height is less. From that point of view, a higher hub height is preferred. However, a balance has to be made between the extra revenue that can be generated by producing more energy on that hub height and the rising costs regarding material of the tower and foundation.

Table 2.1 gives an overview regarding the relation between the scale of Beaufort, the mean wind speed and the significant wave height ($H_{1/3}$) for North Sea areas (Journée and Massie, 2001, p.5-50).

Table 2.1: Wind speeds and significant wave height indication

Scale of Beaufort	Wind Mean [m/s]	Limits [m/s]	Wave $H_{1/3}$[m]	Description
1	1.5	1-2	0.50	Light air
2	2.5	2-3	0.65	Light breeze
3	4.5	4-5	0.80	Gentle breeze
4	7.0	6-8	1.10	Moderate breeze
5	10.0	9-11	1.65	Fresh breeze
6	12.5	11-14	2.50	Strong breeze
7	15.5	14-17	3.60	Moderate gale
8	19.0	17-21	4.85	Gale
9	22.5	21-24	6.10	Strong gale
10	26.5	25-28	7.45	Whole gale
11	30.5	29-32	8.70	Storm
12	-	≥ 33	10.20	Hurricane

Currently, one of the most critical operations, lifting and mounting of the blade can be done till a maximum wind speed of around $10m/s$, corresponding with a wind force of 5 on the scale of Beaufort. Above this wind speed it is hard to handle the blades and therefore to have a safe and controlled installation. This can be explained by looking at the design of the blade: it is made to capture wind and they need to be installed in a windy area.

2.3.2. Wind conversion

The importance of accurate wind speed data becomes clear when one understands how the speed affects the thrust force and the power. To see how energy is retrieved from the wind, a theoretical derivation has been performed. The amount of energy that can theoretically be taken from the wind can be calculated following the actuator disc theory and by looking at the decrease of wind speed, thereby reducing the kinetic energy in the wind, due to a wind turbine (Grogg, 2005; Gundtoft, 2009). The following relations were found between wind speed and thrust force on the operating rotor (Equation 2.5) and wind speed and rated power (Equation 2.6), where a reference is made to Appendix D, section D.1 for the complete derivation.

$$F_{thrust} = \frac{1}{2}\rho_{air} \cdot C_T \cdot v_{wind}^2 \cdot \pi R^2 \tag{2.5}$$

$$P = \frac{1}{2}\rho_{air} \cdot C_P \cdot v_{wind}^3 \cdot \pi R^2 \tag{2.6}$$

With

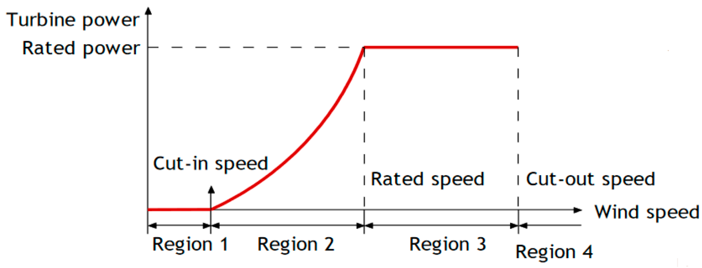
- F_{thrust} = thrust force in N
- P = theoretical power in W
- C_P = power coefficient
- C_T = thrust coefficient
- ρ_{air} = density of air, $1.225 kg/m^3$
- v_{wind} = wind speed in m/s
- πR^2 = area of rotor in m^2 where R is the radius of the rotor

where C_T and C_P are functions of the induction coefficient a, Equation 2.7 and Equation 2.8 respectively.

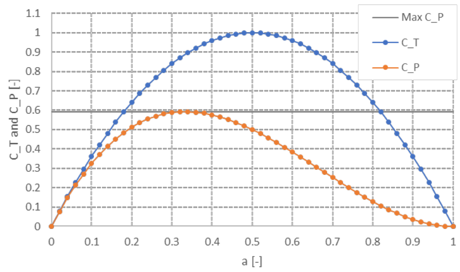
$$C_T = 4a(1-a) \tag{2.7}$$

$$C_P = 4a(1-a)^2 \tag{2.8}$$

The power coefficient indicates the efficiency of the turbine based solely on the stream tube concept, without accounting for non-ideal conditions and losses from the blades, the mechanics, and the electronics. It represents the ratio of the power in the rotor to the power in the wind as a function of the induction coefficient a, visualized in Figure 2.5b. Taking the derivative of Equation 2.8 and setting it to zero, results in a theoretical maximum C_P of 16/27 (0.593) for an a-value of 1/3. This is known as the Betz limit and is given as the solid grey line in Figure 2.5b. C_T represents the ratio of the thrust force that would act on the turbine when it was a solid disc to the thrust force that is actually acting on the turbine. This is not only influenced by the area that is covered by the blades but also the shape of the blades and the angle of attack [1]. With pitching, the blades can be turned around their length axis in such a way that they change the angle of attack and in this way it is possible to change the thrust coefficient and directly influencing the loads on the turbine during operation.



(a) Example of a power curve (Jallad et al., 2017)



(b) Thrust and power coefficient as function of the induction coefficient

Figure 2.5: Plot of a power curve, power coefficient and thrust coefficient

From Equation 2.6 it can be concluded that the theoretical power increases at the cube of wind speed, which means that small variations in wind speed have a big influence on the maximum theoretical power. Secondly, it shows that if the radius of a rotor increases, the generated power increases squared. Therefore, from a theoretical point of view the conclusion can be made that a higher wind speed and a bigger rotor are therefore preferred to produce more power with one turbine. Also here, a balance needs to be made between increasing the rotor and therefore extracting more energy from the wind and the increase of costs that comes with it.

The actual generated power is however not only determined by the power coefficient (C_P), but also by inefficiencies in conversion of kinetic energy (the rotating turbine) to electric energy. These inefficiencies are caused by losses in the rotor (η_{rotor}), the gearbox ($\eta_{gearbox}$), the generator ($\eta_{generator}$) and the converter ($\eta_{converter}$). Typical values for a three bladed rotor at nominal power are (Gundtoft, 2009):

η_{rotor}	0.833
$\eta_{gearbox}$	0.95-0.98
$\eta_{generator}$	0.95-0.97
$\eta_{converter}$	0.96-0.98

This results in a total efficiency of

$$\frac{P_{grid}}{P_{max}} = \eta_{rotor} \cdot \eta_{gearbox} \cdot \eta_{generator} \cdot \eta_{converter} \Rightarrow 0.722 \leq \frac{P_{grid}}{P_{max}} \leq 0.776 \tag{2.9}$$

Where the upper boundary is reached at rated power, where the turbine reaches its maximum possible power production, and the lower boundary when partly loaded, between cut-in wind speed and rated wind speed.

When combining the power curve (Equation 2.6 and the probability of occurrence (Equation 2.3) it can be stated that a wind that occur not that often can produce a lot of energy. But to be able to generate energy at a higher wind speed, a more expensive generator is required.

When designing an OWT, an optimum is found between capital expenditure (CAPEX) and expected generated power. A common turbine therefore has a maximum power that it can produce. In a typical power curve of an OWT, Figure 2.5a, three typical wind speeds can be distinguished:

1. Cut-in wind speed: the wind speed that is needed to start the turbine spinning so it can generate energy. It is desired to have this wind speed as low as possible.

2. Rated wind speed: the lowest wind speed where the turbine is generating its maximum power. This wind speed is among others determined by the generator. From cut-in till rated wind speed, the power curve follows the line of Equation 2.6 multiplied by an efficiency factor. Therefore, the lower the cut-in

[1] The angle that indicates in which direction the wind is blowing on the blade

wind speed, the lower the rated wind speed and the faster the turbine will be able to produce its maximum energy. Wind speeds above this wind speed, result in the turbine pitching it blades so it is still generating its rated power but will reduce the loads on the turbine.

3. Cut-out wind speed: at this speed the wind turbine stops producing energy by pitching the blades out of the wind to prevent damage of the rotor and nacelle.

Although this research is not about improving the turbine itself, it is stated that by improving the efficiency the same power can be harvested at lower rated wind speed. This results in a turbine that produces its rated power at a wind speed that occurs more often. In Figure 2.6 it can be seen that a higher efficiency results in same power at lower wind speed.

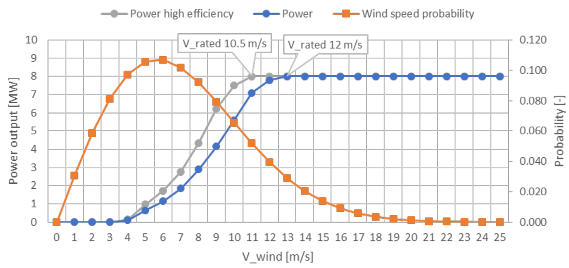


Figure 2.6: Two fictive power curves together with the probability of occurrence of the wind speed

By multiplying the power at a certain wind speed by the number of hours this respective wind speed occurs, the energy that is generated by a turbine in a certain time can be calculated in kWh. From this section, it is clear that by looking to the relation between the power and the diameter, bigger turbines are preferred to produce more energy.

2.4. Offshore wind farm development

The offshore wind market is constantly growing, not only in numbers of total installed capacity but as well as annual installed capacity, this due to bigger offshore wind farm (OWF) with higher capacity rated turbines that are being constructed (Fried, 2018). In 2017, the UK is still leader in installed annual capacity as well as cumulative capacity which among other results in a total global installed capacity of more than 18.8GW (Figure 2.7).

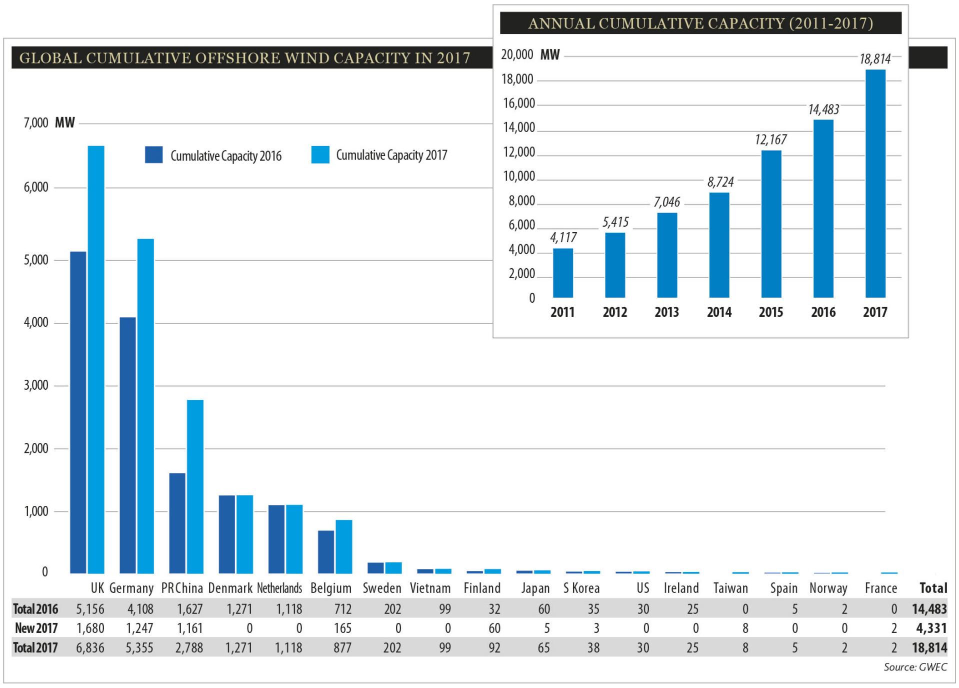


Figure 2.7: Cumulative and annual installed global offshore wind capacity (Fried, 2018)

By looking to the general development of an offshore wind farm (OWF) and identifying who is involved in which stage and how much influence they have, it can be seen who will have benefits from an improvement of the T&I-process. Interviews were held to get to know the interests, wishes and influence of different stakeholders within the offshore wind market(see Appendix A). An overview of the most important stakeholders is given in Figure 2.8 and elaborated below.

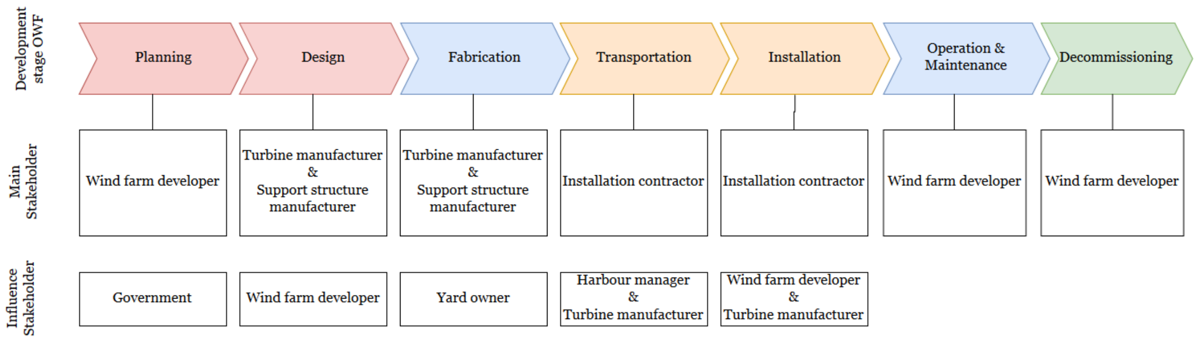


Figure 2.8: General development offshore wind farm with different stakeholders

An OWF can easily consist of up to 120 turbines (4C Offshore Ltd, 2017). Therefore, a method that improves the installation of already one turbine can have significant benefits for the reduction of costs of an OWF. When looking to the breakdown of the investment costs of a wind farm (Figure 2.9) it can be seen that the assembly and installation of the turbines match almost 20% of the total CAPEX (Moné et al., 2017). With projects already ranging up to 2 billion dollar (4C Offshore Ltd, 2017), a reduction in T&I-costs can results in a significant reduction on the total CAPEX of an offshore wind farm.

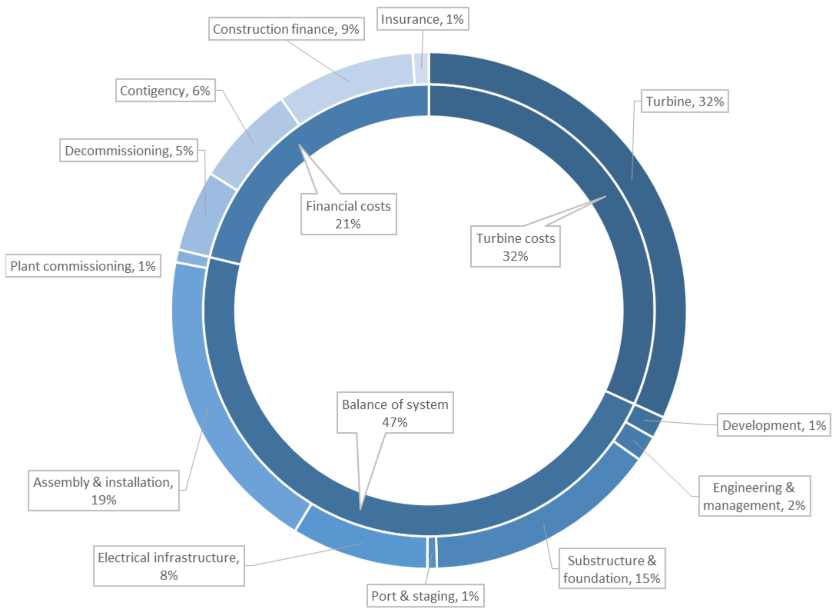


Figure 2.9: Capital expenditure breakdown of an offshore wind turbine. Data from (Moné et al., 2017, p.10)

2.4.1. Offshore wind farm developer

The wind farm developer owns, develops and operates an offshore wind farm. One of the biggest developers in Europe is Ørsted, which holds 17% of cumulative installations at the end of 2017 in Europe (WindEurope, 2018). The main goal of a developer is to lower the cost per megawatt hour (MWh), which can be among others be achieved by lowering the costs per installed MW. A long term vision is key to achieve this and optimization is one of the important elements in this vision, as also heard in an interview with VanOord (Appendix A, section A.3). One way to lower the cost per MW is by increasing the power per turbine and increasing the total installed power per wind farm. In this way, the total investment costs per turbine, the capital expenditure (CAPEX), is higher but the costs per MW is lower. This growing trend of installed power per turbine by Ørsted can be seen in Figure 2.10 and the total capacity per wind farm in database of provided by 4C Offshore Ltd (2017).

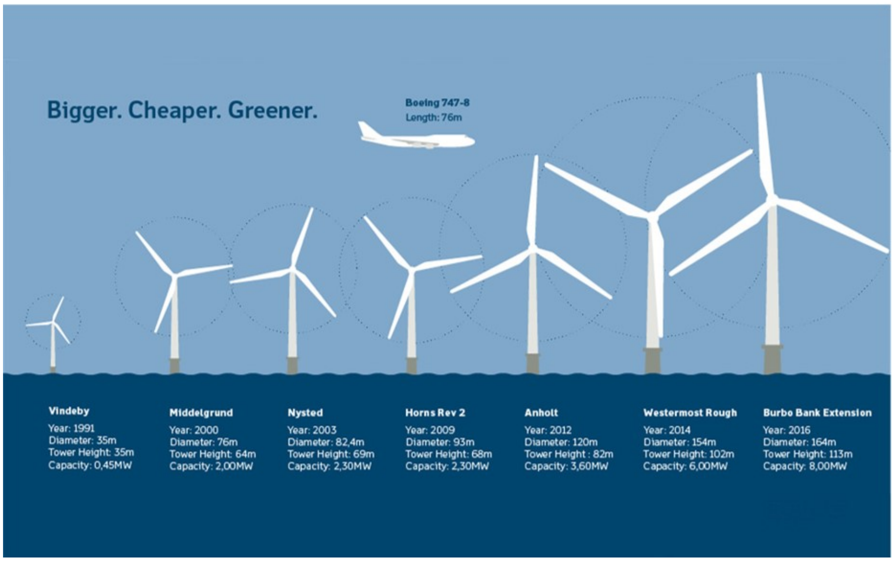


Figure 2.10: Overview of growing offshore wind turbines installed by Ørsted (Froese, 2016)

Optimizing the T&I sequence will bring an advantage to the developer since the wind farm starts operating earlier, the so called 'First wind' which indicates the time the first electricity is generated and delivered to the grid and thus when revenues are start being made. The earlier the wind farm starts producing electricity, the better. Moreover, optimising the T&I is of big interest for a developer because they are not only looking to one project but for the coming years. The developer does not own assets to install OWTs themselves and therefore are dependent on the contractor, however they are in control in which contractor they choose and with which technique so they have a rather large influence, also seen in the overview of Figure 2.8.

2.4.2. Installation contractors

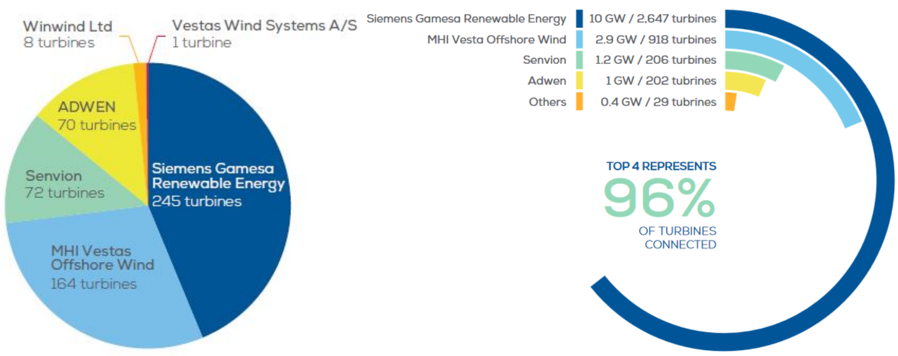
Regarding the companies that install the OWT, two different contractors can be distinguished: [1] are the companies that only rent their assets and services, like among others Fred Olsen Windcarrier, Seajacks or Geosea and [2] are the companies that also tenders the projects, such as VanOord.

The second type of contractor differs from the first in the fact that they also have a share in the development of the wind farm and therefore have a double role in the project. This is mainly done by convincing the OWF-developer for choosing them, because executing the project is not only beneficial for the main developer but also for the contractor (Appendix A, section A.3).

Both type of contractor has to make a business case for their installation vessel which is determined by the capital expenditure (CAPEX) of a vessel and the day-rate they can ask to their clients (the developers). The day-rate is determined by the time it takes to install a turbine and what the competition can do for the same price. The total income for a project as contractor is the day-rate multiplied by the days its vessel is rented. Therefore, the goal of a contractor is to make a business case where the day-rate is not too high, if so the project is awarded to the competition, and not too low, otherwise they will not able to earn back their investment or to cover the risks. Due to the bigger turbines that have to be installed, the capacity of the offshore wind turbine installation vessel (OWTIV) is rising and the CAPEX as well. A rising CAPEX brings a higher risk which is not wished by the contractors. It was also confirmed during the interview with VanOord that if a method is found that results in a higher day rate but a faster installation per MW, it can be preferred by the contractor as well as by the OWF developer.

2.4.3. Wind turbine manufactures

In Europe, a net capacity of 3148MW was connected to the grid in 2017. Where the turbines were mostly produced and installed by Siemens Gamesa Renewable Energy (51.3%) and MHI Vestas Offshore Wind (24.7%). In 2017, more manufacturers installed new wind turbines than in 2016, but Siemens Gamesa and MHI Vestas still accounted for more than 75% of the total installed capacity (WindEurope, 2018). Next to Siemens Gamesa and MHI Vestas, Goldwind is a dominating turbine manufacturer, especially in China, where in America GE is a dominant player (Bloomberg New Energy Finance, 2017). These manufacturers together keep pushing the limits of offshore wind energy by upgrading their turbines and designing even bigger ones for the future.



(a) Annual installed capacity in 2017 (b) Cumulative share at end of 2017

Figure 2.11: Share of European offshore wind turbine manufacturers in 2017 (WindEurope, 2018)

By conducting an interview at the head quarter of Siemens in the Netherlands (Appendix A, section A.2) it was heard that during the T&I of an OWT, a team of the turbine manufacturer is on board of the vessel from the contractor who will execute the complete assembly of the turbine offshore. By optimizing the current method for T&I the last years, they can now guarantee that one turbine can be up and running in 24 hours. New methods are not yet optimized and Siemens can therefore not guarantee the same speed and quality to their customers, therefore from Siemens's point of view alterations of the T&I are not directly preferred. This can be changed by proving that a significant gain can be made regarding installation time, which is also an advantage for Siemens.

Also a new method that requires alterations of the OWT design will first prove itself before it will be deployed by Siemens. It was however stated during the interview that upgrading the current installation method was maybe not possible for turbines up to $20MW$ and that there will be a need for another method in the future. This also showed that the power of a single manufacturer is somewhat limited due to the high competition between the big manufacturers and because the OWF-developers will choose which turbine and therefore which manufacturer to use.

2.4.4. Government

A stakeholder that is influencing the T&I-process indirectly but the OWT development directly, is the government. They make offshore areas available for the development for OWFs and they set guidelines and regulations. They are also financial supporting the developers by giving subsidies to ensure a minimum income per kWh, however projects has been granted and planned to be build in the Netherlands and Germany without any subsidies from the government(Maritieme Executive, 2018). The government hereby reduces their financial influence but still will have big influence on rules and regulations about environmental impact and decommissioning after the life time of a project.

2.4.5. Harbour management

The harbour management indirectly influences the T&I-process. The geographical locations can play an important role in terms of free shipping height and water depth. If a route has a maximum water depth, it can result that some vessels can not enter the harbour to pick up the components of the turbine. Also if the route is crossed by a bridge, it can limit the shipping height and therefore not be able to transport the tower from harbour to the location of the OWF. Moreover, the loading capacity of the quay can be a limiting factor with the increase of mass of the components. This will especially be of importance when options with complete turbines are considered.

The T&I offshore is one part of the total logistics regarding the construction of an offshore wind farm. The whole logistical chain is influencing the offshore part. This is not a part of this research, however if needed, it will be taken into account if concepts need requirements regarding logistics.

2.5. Current installation methods

The current common way for T&I of the OWT is that it is separated in two parts, where the same division is made as mentioned in section 2.2: the T&I of the OWT and the support structure respectively. First, all the support structures of a wind farm are installed, subsequently, all the topsides are installed on top of them. The process is visualised in Figure 2.12

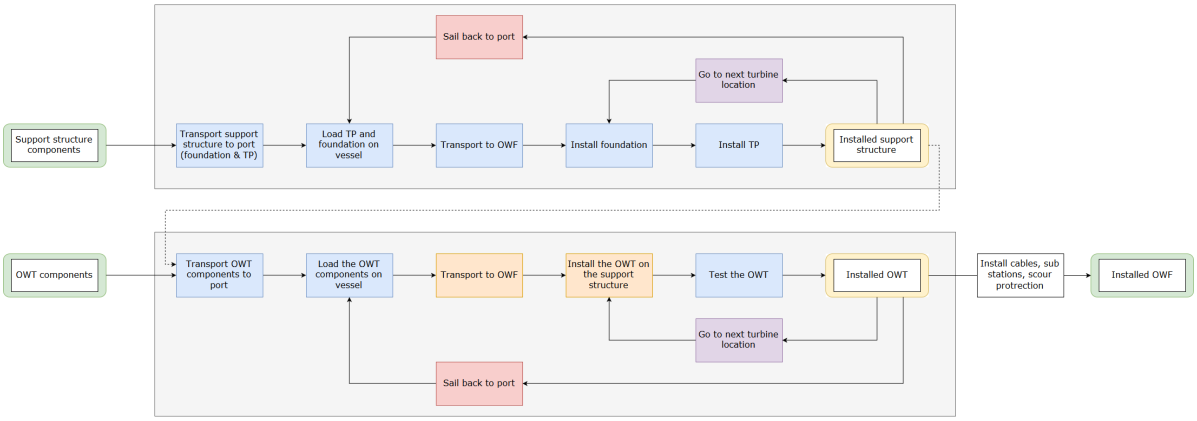


Figure 2.12: Flowchart of T& I of an offshore wind farm

This thesis focusses on the transport and installation of the OWT, indicated in orange. As described, structurally a wind turbine itself consists of six main components such as tower, nacelle, hub, and three blades. These components of the wind turbine can partly or completely be pre assembled onshore (in the port) for transporting them to the offshore site. This situation creates many different alternative assembly configurations that can increase or decrease the T&I performances (Figure 2.13).

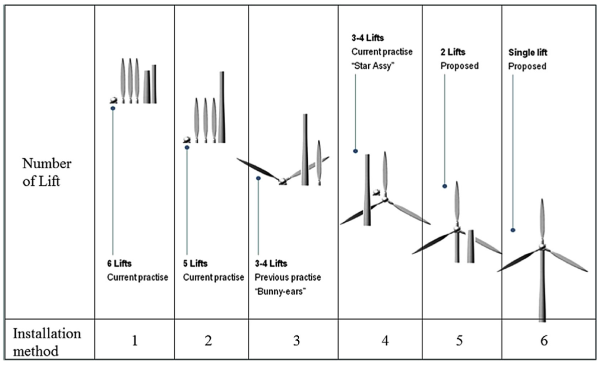


Figure 2.13: Different installation sequences (Ahn et al., 2017, p. 48)

By exploring the different methods for transportation and installation that are currently on the market, a better understanding is formed about the already existing methods and comparison with new concepts can be made later in this research.

Jack-up vessel

A jack-up vessel is a special purpose built vessel for transportation and installation (T&I) of offshore wind turbine, an OWTIV. It has a large capacity crane, large deck space and a high loading capacity. It is self propelled, has a jacking system and normally a dynamic positioning (DP) system to stay positioned. It has a day rate between $150.000 and $250.000, depending on it's capacity and capabilities (Ahn et al., 2017, p.47). A jack-up vessel is currently the most common way for T&I of OWT and GustoMSC is market leader when it comes to designing and engineering of these vessels (GustoMSC, 2017).See Appendix F for two of the biggest jack-up vessels. Looking to the current installation method with a jack-up by lifting everything, room of improvement can be found. In the case of 6 components that need to be lifted separately, with different tools needed for lifting the tower, nacelle and blades, the hook of the crane needs to go to the hub height of 150 and back at least 6 times. This vertical distance travelled by the hook alone already consists of 1800 meters in this case. With a hoisting speed of around $6 m/min$ this results in already 5 hours of pure hoisting, disregarding the times it takes to attach the tools and the different components. By extrapolating this to a complete wind farm, this has a big influence on the costs for a total wind farm project.

Figure 2.14: Jack-up vessel Seajacks Scylla. Courtesy of Seajacks

Floating crane vessels

A floating crane vessel is commonly used for the installation of foundations for OWTs or installation of topsides of oil and gas projects due to their big crane capacity. The Oleg Strashnov is one of the biggest floating crane vessels(Figure 2.15a) and has a high capacity crane located at the aft of the vessel. It has a maximum lifting capacity of $5000t$ at $100m$ height and a radius of $32m$ for the main hook and a maximum lifting capacity for the auxiliary hook of $800t$ at $132m$ height and a radius of $72m$. It has a DP-system which damp out motions in the horizontal plane. Other floating crane vessels are under construction, like the Orion of DEME's subsidiary GeoSea which will be equipped with a crane that can lift up to 3000 tonnes and a maximum lifting height of $170m$ above sea level. Deck space has been maximized to provide high transport and load capacity, so it can take monopiles, jackets, wind turbine components and structures in a single shipment (Cosemans, 2017).
A sheerleg crane vessel is another type of floating crane vessel where the whole ship is a type of floating crane. Due to almost no deck space for variable load and the fact that their crane can not hoist from their own deck, it is mainly used for installation and if it is used for transportation, the load can only be transported in the hook which brings challenges with them regarding the acceptable weather window.

(a) Foundation installation with heavy lift vessel Oleg Strashnov (Gadella, 2011)

(b) Sheerleg crane vessel (4C Offshore Ltd, 2017)

Figure 2.15: Two floating crane vessels

Semi-submersible

As last option, semi-submersible is given. Due to the large crane capacity, it is possible to transport and install the offshore wind turbine in one go, even the biggest currently operating turbines. By constructing and testing the turbine onshore, less installation time offshore is required. As described earlier, this requires a quay that can handle the loads of the complete turbine and a direct shipping route to open sea. With a day rate of around $500.000, capable of only lifting one turbine per trip and a limiting weather window for T&I makes this not a preferred option. It has however once been done for the Hywind demonstrator project, an OWF consisting of five $6MW$ turbines with a diameter of $154m$, which have been installed separately by the Saipem7000 (Figure 2.16).

Figure 2.16: Saipem 7000 transporting a wind turbine (Offshorewind, 2017)

2.6. Prediction turbine components

The characteristics of the large size turbines with a rated power of 15 till 20MW were studied by examining the relation between the rated power and the rotor diameter of operating offshore wind turbines from (Siemens, 2016; Wind turbine models, 2017; 4C Offshore Ltd, 2017). Figure 2.17 shows the outcome of this examination, where in white the operating turbines are plotted and in grey the announced and theoretical turbines. From this figure, two things were found:

- The currently operating turbines are bounded by two orange lines, depicted in the figure. The upper one represents a minimum energy per square meter of 300W/m^2 that is extracted from the wind and the lower line a maximum of 450W/m^2.
- Turbine manufacturers are able to upgrade a model to a certain extend. They do this by improving the blade technology and the efficiencies of the different parts in the nacelle. This is reflected in the graph by the turbines V164-7.0, V164-8.0 and V164-9.5, which concern turbines of Vestas. First they announced the V164-7.0, a turbine with a rated power of 7MW and a rotor diameter of 164m, and later on the V164-9.5, with the same rotor diameter but a higher rated power (Wind turbine models, 2017).

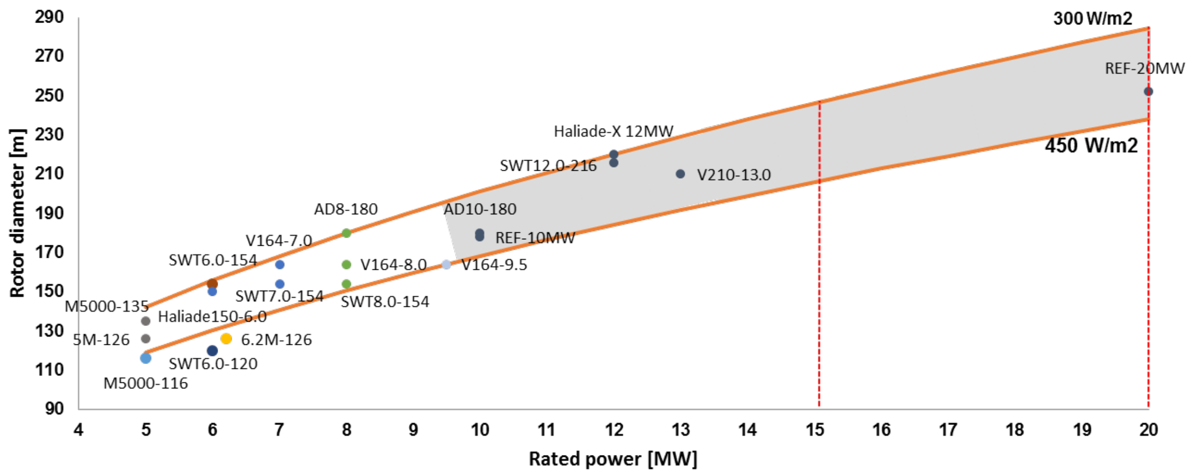


Figure 2.17: The rotor diameter plotted against the rated power, together with energy density lines of 300 and 450 W/m^2. The red dotted lines represent the desired rated power of 15 and 20MW

In the grey area turbines are plotted that are used for theoretical research, like the REF-10MW and REF-20MW, and that were recently announced, for example the Haliade-X 12MW. REF-10MW and REF-20MW are theoretical turbines from the Upwind project which are used to see which innovation in techniques are required with respect to turbine technology to keep innovating and improving offshore wind turbines and are not real produced turbines (Jensen et al., 2017, p.49), where the HaliadeX-12MW is confirmed by a pres release on the 1st of March by GE Renewable Energy (2018). It concerns the development of a 12MW turbine with a 220m diameter rotor and a tip height of 260m above sea level. It is stated by GE Renewable Energy (2018) that the first nacelle will be demonstrated in 2019 and they strive to have an operating turbine in 2021.

Using the boundaries found in Figure 2.17 and the data from several turbines regarding mass and size, obtained from 4C Offshore Ltd (2017), Table 2.2 shows the elaborated data of two of the biggest operating turbines, the SWT8.0-154 from Siemens and the V164-9.5 from Vestas, two reference turbines from the Upwind project, REF-10MW and REF-20MW and a prediction for a turbine with a rated power of 20MW, Future. The prediction of the size and mass of the different components of a 20MW OWT are presented in a range since it is based on data of different turbines.

Table 2.2: Characteristics of operating turbines SWT8.0-154(Siemens, 2016) V164-9.5 (Morris, 2017), two reference turbines from Inwind (Jensen et al., 2017, p.29) and future prediction

Model	SWT8.0-154	V164-9.5	REF 10MW	REF 20MW	**Prediction**
Producer	Siemens	Vestas	Upwind	Upwind	
Rated power [MW]	8	9.5	10	20	20
Rotor diameter [m]	154	164	178.3	252	238 - 270
Blade length [m]	75	80	86.4	122	115 - 130
Hub height tower from LAT [m]	122	105	119	168	160 - 200
Surface area [m^2]	18627	21124	24969	49955	44488 - 57256
Energy density [W/m^2]	429	450	401	400	350 - 450
Mass nacelle [t]	n.g.	390	446	1098	900 - 1100
Mass hub [t]	n.g.	n.g.	105.5	278	100 - 300
Mass blade [t]	n.g.	35	42	110	60 - 100
Mass tower [t]	n.g.	n.g.	628	1600-1780	1200 - 1600

This prediction is used in the next chapter when determining the characteristics of the $20MW$ OWT that needs to be installed. Looking to the T&I of these large turbines, challenges are expected for installation regarding lift height, lift capacity and handling and for transportation regarding deck space and logistics.

2.7. Conclusion context study

After this context study, it can be seen that not only from a industrial point of view bigger turbines are desired, but also from a theoretical point of view due to the higher and more constant wind velocity at a greater height. It is confirmed by industry, Siemens, Mammoet and VanOord (see Appendix A), that a new solution is required if the size, mass and height of the OWT is growing. Reasons for this are on one hand the rising CAPEX of the needed equipment and on the other hand the wish to install faster and cheaper.

The scope of this research has been further defined:

- The solution found will be focusing on world wide application and not be targeting a specific wind farm or location.
- The solution will mainly be focusing on the installation of a topside of an OWT, not the support structure.
- The solution will not look into cable installation.
- The solution will not look into options to improve the wind turbine itself.
- This research is mainly focusing on improving the transportation and installation and not specifically on operation and maintenance.
- The solution will look into solutions that can install OWTs with a rated power of 15 till $20MW$.

Under the assumptions that:

- The geographical locations of the harbours will not be a limiting factor for T&I.
- The support structure is ready to receive the topside.

3
Requirement analysis

This chapter define the requirement to which the solution needs to conform. By defining these requirements early on, separate functions for the design can be derived. Furthermore, it is possible to return to them later for evaluation purpose. By doing a criteria analysis, performance of the solution is ensured.

Requirements are divided in design constraints (section 3.1), which have to be complied, design wishes (section 3.2) which are not essentially to be fulfilled but which are desired for a higher final viability of the concept and technical requirements (section 3.3) which have to be fulfilled no matter what type of concept. In section 3.4 the criteria are determined which later will be be used for the comparison of the different concepts.

3.1. Design constraints

The goal of this research is to install an offshore wind turbine with a rated power of $20MW$. The characteristics of these large size turbines were studied in section 2.6 by examining the relation between the rated power and the rotor diameter of operating offshore wind turbines. The derived dependencies between the desired power and the required area of the rotor were validated with data from announced turbines. Extrapolating these dependencies has resulted in a prediction for the $20MW$ turbine.

A rotor diameter has been chosen of $250m$, with a blade length of $120m$ which results in a diameter of the hub of $10m$. To calculate the length of the tower, a blade clearance between the tip of the blade and the platform of the TP of $20m$ is chosen. This results in a tower length of $140m$. Together with an air gap of $20m$ between the platform of the TP and half the diameter of the hub, a hub height of $165m$ above sea is obtained. The diameter and wall thickness of the tower are calculated based on the expected stresses introduced on the tower during operation and rules of thumb, elaborated in Appendix D, section D.2. The characteristics of the different components are summarized in Table 3.1 and will be used as input for one of the design constraints.

Table 3.1: 20MW Turbine input for design

Description	Length [m]	Width [m]	Height [m]	Mass [t]
Blade	120	6.6	9	80
Hub	10	10	10	98
Nacelle	25	15	15	1000
Tower	5.5-8	5.5-8	140	1561

Constraints explain what has to be done by identifying the necessary task, action or activity that must be accomplished. For this design the following constraints are set:

- The solution must be able to install the tower, nacelle, hub and blades of a $20MW$ offshore wind turbine with the characteristics listed in Table 3.1.
- The solution must comply with health, safety and environment regulations, stated by DNVGL (2017).

3.2. Design wishes

Design wishes can be seen as requirements that, when fulfilled, can higher the viability of the final solution but are not necessary to be functional.

- The solution may be applicable to be used for smaller wind turbines as well.
- The solution may be based on already, not patented[1], proven technology.
- The solution may be able to be used in existing ports.
- The solution may also be used for maintenance of the offshore wind turbine.

3.3. Technical requirements

The solution that will be found has to not only fulfil design constraints, but also fulfil technical constraints to be able to function within its environment. These constraints will be tested when the design has been set up by setting out a stepwise installation and by performing governing load calculations.

In subsection 2.3.1 it was stated that current methods are capable of installing up to a wind speed of $10m/s$ and that new methods are already investigating for installation in wind speeds up to $15m/s$, corresponding to a moderate gale (confirmed by interviews with Siemens and Vanoord, see Appendix A). Above this wind force it is not safe any more to install OWTs offshore. Therefore, to have a competitive design but still be able to operate safely, a wind speed of $15m/s$ has been chosen as maximum to be able to continue installation of an OWT.

- The solution should be able to withstand loads with a wind speed of $15m/s$.
- The solution will be stable during transport over sea.
- The solution must withstand the loads introduced by the OWT during installation.

3.4. Criteria

To evaluate the T&I-concepts, a set of criteria are defined based on conducted interviews with industry experts (see Appendix A), the constraints defined in section 3.1 and the wishes defined in section 3.2.

1. *Technical complexity*
   Technical complexity of a concept is defined by the type of technology the concept requires. A score can be given by asking if the concept uses a technology that is already developed or that it require new technology to be developed. Since new concepts for T&I can introduce new technologies to the offshore wind industry, this criteria is seen as important.
2. *Installation time*
   The installation time is defined as the time that is required to install the tower, nacelle, hub and blades. This not only includes offshore installation time but also the time that is required for load out of the components from quay to vessel and the required offshore transportation time. A score can be given by estimating the total required time.
3. *Modification to OWT design*
   Modification to OWT design is defined as required extensions on the current design of an OWT. Based on interviews with Siemens it is found that modifications are not preferred from a turbine manufacturers point of view. VanOord stated however that from a developers point of view modifications on the OWT design are possible if significant profit can be made on the transportation and installation process. A score can be given based on the required modification.
4. *Adaptability for different size turbines*
   This criterion is defined as the ability to install other turbines than the expected $20MW$ turbines. When significant modifications of the T&I-concept are required to install different size OWTs, the concept is not efficient. Also, when full capacity of equipment is always present, the concept is not efficient as well. This criterion can be scored by looking to the required modifications of the T&I-concept to be able to install smaller or even bigger turbines.

A criterion that is not listed separately, is the cost for installation per MW. This is done, since it is needed to have independent criteria and costs per MW are interwoven in the otherwise independent criteria. For example, if it takes more time to install a turbine or if modifications are required on the OWT design the costs

[1] This is not a decisive requirement for this research, however for GustoMSC to be able to further develop a design it is required that the solution is not using technology that is patented by another company than GustoMSC.

will rise for the installation of a turbine. Moreover, if the concept requires new technology to be developed or if the concept require modifications to be able to install other turbines, the investment costs of the concept will rise.

To stress the importance of the different criteria with respect to each other, they are compared to each other individually. When two factors are compared, the most important factor receives a 1 and the less important factor receives a 0. If the criteria are equally important, they are both valued with a 1. By adding the scores, every criterion has a value between 0 to 4. Subsequently, this value is divided through the sum of all values to calculate the respective weight factor (see Table 3.2).

Table 3.2: Weight factor determination

Criteria	Technical complexity	Installation time	Modification to OWT design	Adaptability for different size turbines	Total	Weight factor
Technical complexity	-	0	1	1	2	**0.250**
Installation time	1	-	1	1	3	**0.375**
Modification to OWT design	1	0	-	0	1	**0.125**
Adaptability for different size turbines	1	0	1	-	2	**0.250**
Sum					8	**1**

From this table it is concluded that the most important criterion is installation time, followed by technical complexity and adaptability for different size turbines and lastly by modification to OWT design. This weight factor is used when evaluating the T&I-concepts.

4

Functional analysis

To be able to come up with a complete solution for the installation of a $20MW$ offshore wind turbine, a functional analysis has been conducted. This is achieved by splitting up the goal of the system in several functions (section 4.1), based on the different installation steps described in section 2.4 and the requirements stated in chapter 3. Using a morphological chart (section 4.2), as many solutions as possible are then identified for each separate function. By combining these separate solutions per function, concepts are generated and described in section 4.3. To know what type of other installation concepts are already in development, section 4.4 gives an overview of concepts from other companies than GustoMSC. section 4.5 groups the different concepts from this chapter which are used for the evaluation in the next chapter.

4.1. Definition of functions

From the different installation steps described in section 2.4 and the requirements as defined in the previous chapter, a number of functions are derived for the system. The purpose of dividing the goal of the system up into a number of functions enables the design of subsolutions. These will afterwards be unified in an integrated design. The following functions in the T&I-process for the OWT are distinguished:

- Load out of OWT from quay
- Offshore transport of OWT
- Eliminate motion between vessel and support structure
- Installation sequence of the OWT
- Installation method of the OWT
- Handling of OWT components during installation

4.2. Morphological overview

The functions defined in section 4.1 are used to generate a number of ideas. This is summarised in a morphological chart, where the different functions are listed below each other and solutions to fulfil these functions are listed horizontally. Below the different functions are explained and ideas to fulfil them are given. In Appendix E the complete list of generated ideas are displayed.

4.2.1. Load out of OWT from quay

Load out is the sub-operation within the transport phase, during which the different components of an OWT is transferred from the quay onto the deck of a barge, jack-up vessel, semi-submersible or other water craft. This can be done by means of lifting the components with a crane, by means of rolling the components on the ship by means of self-propelled modular transporter (SPMT)s or by means of flipping the components with a frame.

4.2.2. Offshore transport of OWT

The components of the OWT requires to be transported from the harbour to the location of the offshore wind farm before they can be installed. Different types of transport can be distinguished where a division is made between offshore transportation on the installation vessel itself, transportation done by a feeder barge, transportation due to floating capability of the OWT itself or transportation through air by using a helicopter for multiple components or a drone for separate components.

4.2.3. Eliminate motion between vessel and support structure

The installation vessel is loaded by waves, currents and wind and is therefore moving with respect to the support structure. To have a safe installation environment, the relative motions between the vessel and the already installed support structure have to be eliminated. Eliminating these motions also results in a reduction of installation time of an OWT. A jack-up vessel is eliminating the influence of the environmental loads by putting its legs on the sea bed and lifting itself out of the water. Another option is to make a fixed connection which in that case has to be able to withstand the forces introduced on it caused by the relative motion. Another option is by making use of tug lines. This however is not able to withstand compressing forces and is only assuring a maximum relative distance. The relative motion can also be eliminated by using global positioning system (GPS) where the support structure function as reference point or by using manual corrections. However, relative vertical motion caused by waves is hard to eliminate with GPS.

4.2.4. Installation sequence of the OWT

The different possibilities for the installation sequence are mentioned in the context study already in Figure 2.13. The type of installation sequence results in a number of required lifts. The different sequences that can be distinguished are:

- Single blade and two tower segments
- Single blade with one tower segment
- Bunny ear method
- Complete rotor lift, nacelle and tower separate
- Complete RNA including part of tower
- Complete turbine lift

4.2.5. Installation method of the OWT

The installation method consists of the technique that is used for installing the various components offshore. This is the function where innovation can be made by looking into new possibilities of getting the components to the immense height for the future OWTs. A jack-up vessel lifts the different components to their required height by making use of a crane with high loading capacity and a great lifting height. If the different components can be brought to their required height by other techniques, the great lifting height can be eliminated. Techniques that are thought of are: pushing the different components from underneath; pulling the components by making use of cables and a pulley system; a float over system that can position itself above the support structure and lower the turbine; a turbine that already includes its foundation as transported to its location and which is ballasted with water to let the support structure settle on the seabed.

4.2.6. Handling of OWT components during installation

The components are subjected to wind loads during installation and need to be guided to have a safe installation. This can be done by making use of tug lines, which can be used to adjust the position of the components. Another option is a temporarily fixed guidance systems that can be placed on the support structure or a guidance system that is installed on the tower.

Combining the above mentioned solutions for the separate functions, the morphological overview of Table 4.1 is obtained.

Table 4.1: Morpohological chart

Function	Sub-solutions				
Load out from quay	Crane from ship	Roll-on/roll-off	Flipping	Crane from quay	
Transport	Barge	On installation ship	Floating turbine	Helicopter	Drones
Eliminate motions	(D)GPS	Manual	Tug lines	Rigid connection with heave compensation	Stand on seabed
Installation sequence	Single blade (5 lifts)	Bunny ear (4 lifts)	Complete rotor (3 lifts)	RNA (2 lifts)	Complete turbine (1 lift)
Installation method	Lift	Push	Pull up	Float over	Ballasting
Handling of OWT components	Tug lines	Rail on tower	Drones	Extra structure	None

4.3. Concept generation

Concepts can now be generated by picking one solution for each function from the morphological chart and by combining these separate solutions to a complete concept. An example is shown in Figure 4.1 for the current jack-up vessel. For the illustration of the other generated concepts, a reference is made to Appendix E. The different generated concepts are briefly discussed in this section by addressing their advantages, their disadvantages and points for further research.

Function	Sub-solutions				
Load out from quay	**Crane from ship**	Roll-on/roll-off	Flipping	Crane from quay	
Transport	Barge	**On installation ship**	Floating turbine	Helicopter	Drones
Eliminate motions	(D)GPS	Manual	Tug lines	Rigid connection with heave compensation	**Stand on seabed**
Installation sequence	**Single blade (5 lifts)**	Bunny ear (4 lifts)	Complete rotor (3 lifts)	RNA (2 lifts)	Complete turbine (1 lift)
Installation method	**Lift**	Push	Pull up	Float over	Ballasting
Handling of OWT components	**Tug lines**	Rail on tower	Drones	Extra structure	None

Figure 4.1: Example of using the morphological chart to generate an installation method

Up scaling jack-up method

Installation of current size turbines are most commonly done by a jack-up vessel, see section 2.5 for more information. To make it possible to install the different components of the 20MW offshore wind turbine, upgrading of equipment is required.

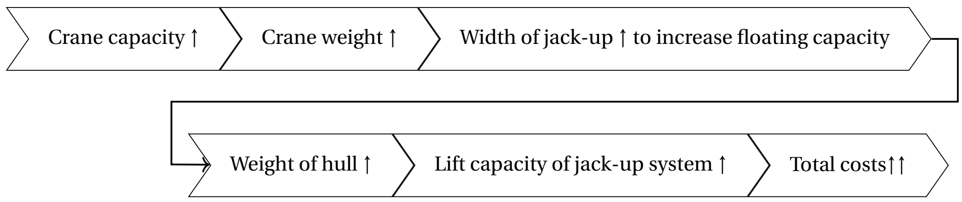
A comparison between three of the biggest jack-up vessel designs of GustoMSC (the NG9000C, the NG14000X and the NG20000X) is made to see if making the jack-ups bigger, results in a lower price per kilogram. The following parameters are used as input for this comparison: the maximum weight that can be elevated by the legs, the elevated weight, the maximum variable load the vessel can carry, the weight of the legs and the total CAPEX. By subtracting the variable load from the maximum elevated weight, the elevated light ship weight can be calculated. Subsequently, the weight of the legs are added to get the light ship weight (LSW). This LSW is used to estimate the price per kilogram by dividing the total CAPEX of the vessel by the LSW.

Table 4.2: Price comparison of three jack-up vessle designs by GustoMSC, confidential by GustoMSC

	Unit	NG9000C	NG14000X	NG20000X
Maximum Elevated weight	tonne	18000	28000	46000
Variable Load	tonne	6000	8500	16000
Elevated Light Ship Weight	tonne	12000	19500	30000
Mas legs	tonne	4000	3500	4000
Light Ship Weight	tonne	16000	23000	34000
CAPEX	million $	160	250	350
costs/kg	$	10.00	10.87	10.29

It can be concluded that the price per kg of around $10-11[1] is not decreasing by upgrading the equipment. The upscaling of the current jack-up vessel results in a higher CAPEX which brings higher risks that has to be carried by the installation contractor. This all results in a higher day rate, as also described in subsection 2.4.2. Moreover, to be able to install a turbine of $20MW$ in the same installation sequence as currently is used, a not yet existing crane needs to be designed to be able to lift the nacelle to hub height. This not only requires higher investment of equipment of the crane but also in required vessel equipment. The influence of the increased crane capacity on the jack-up vessel is visualised in Figure 4.2. Moreover, the increased mass and hub height result in longer offshore installation time and together with the increased day-rate of the jack-up vessel increases the costs for installing one turbine. Taking into account that multiple turbines are installed for one offshore wind farm (OWF), this increase of installation time introduce significant increase of total installation costs of an OWF.

Figure 4.2: Increase of investment costs of Jack-up vessel



RNA on deck

This concept makes use of a traditional jack-up vessel which transports the components of an OWT to its location. After lifting itself out of the water the installation of the different components can begin. It consists of a frame in which the nacelle and hub can be placed vertically and which make it possible to attach the blades separatly on deck of the vessel by rotating the nacelle. It reduces the numbers of lifts to hub height and thus decreases offshore installation time. The frame that rotates the nacelle and hub should be placed just next to the blade rack. The hub can be aligned with the first blade, where subsequently the blade is connected to the hub. By rotating the nacelle and hub by 120 degrees, the second blade can be attached. The last blade can be attached by rotating the hub, the nacelle and the two already attached blades again by 120 degrees. While assembling the hub, nacelle and blades, the tower is installed on top of the support structure. Lastly, the complete RNA is lifted and placed on top of the installed tower by a crane. The required frame has to be capable of carrying the total load of the RNA. Moreover, it should have a rotating platform that can align the hub with the blades. To attach the blades to the hub, a type of firing line is needed, which can be integrated in the blade rack. Since the total rotor has to be assembled on deck, large deck space is required as well. However, the blades can be assembled at the aft of the ship, so they can hang over the water as sketched in Figure 4.3a.

Things for further research

- Location of the frame on the deck.
- Possibility for vertical placement of the nacelle.
- Methods of attaching the blade to the hub.
- Combination with other ideas.

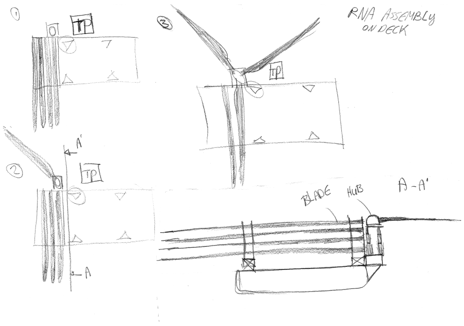
Advantages

- Only one heavy lift to hub height is required to install the RNA.
- No separate blade handling is required at hub height.
- Total RNA lift is already a known lift.
- Assembly of RNA on deck can be done in parallel with the installation of the tower on the support structure.

Disadvantages

- Rather large deck space is needed for the assembly.
- The nacelle is placed vertically, so some nacelles have to be altered to be lifted.
- A crane is needed which can lift a load of 1340 tonnes to 145 meters height.
- The components of the RNA are loaded during installation in a way for which they are not designed, namely bending moments in the blades, hub and nacelle when placed in the frame.

[1] Based on data provided by GustoMSC



(a) Drawing of RNA on deck

(b) Rotor with blades assembly by Fred Olsen Windcarrier (2013)

Figure 4.3: RNA on deck

Monopile lift

This concept is mainly focusing on reducing the required lift height of the nacelle, the hub and the blades and therefore reducing the required capacity of the crane. By lowering the lift height, offshore installation time can be reduced. The concept consist of a self propelled jack-up vessel that can lift the separate components from the quay on the vessel by its own crane. The jack-up vessel transports the components to the offshore location and by lifting itself out of the water before installation starts, motions due to environmental loads are eliminated.

The concept makes use of the monopile (MP) foundation by lowering the tower inside the MP with equipment that is temporarily installed on the MP. In Figure 4.4 an short impression is presented of the offshore installation steps. When the jack-up vessel is lifted out of the water, first equipment is installed consisting of winches on top of the MP and a frame that is lowered with cables via the winches in the MP(Figure 4.4, upper left). The tower is placed on top of this frame (Figure 4.4, upper right) and the frame together with the tower is further lowered in the MP. Subsequently, the tower is lowered and the RNA is installed on top (Figure 4.4, bottom left). Then, the RNAis bolted to the tower and the complete OWT is lifted to its desired height by the winch system that is installed on top of the MP. When finished, the tower can be mounted to the support structure and the winches together with the other equipment can be retrieved (Figure 4.4, bottom right).

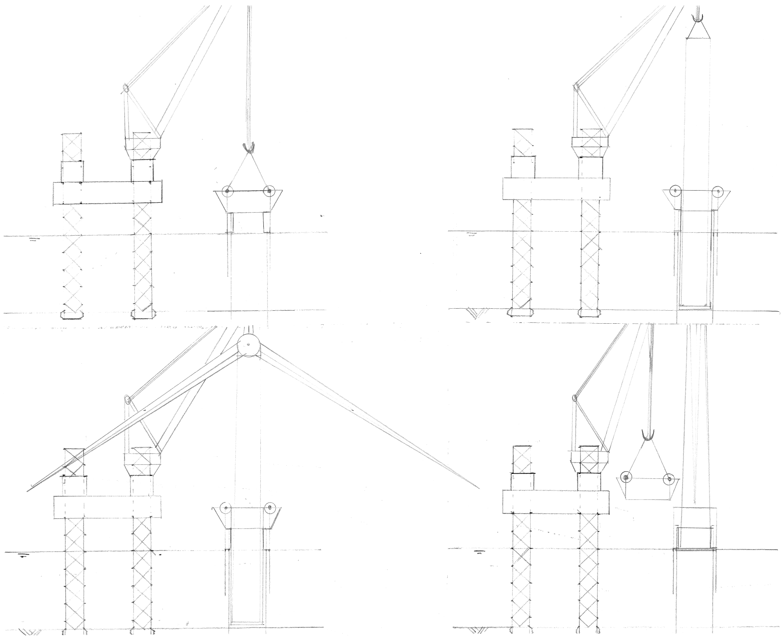


Figure 4.4: Drawings of lifting the turbine out of the monopile

To reduce the lifting height for the tower, it can be split up into two segments. The lower segment is put on the frame and lowered into the monopile while the next segment with the RNA is assembled. The tower segment together with the RNA is subsequently placed on top of the lowered segment after which everything is lifted out of the MP. This not only reduces the required lift height but also reduces installation time by making it possible to do two processes, installing the frame and lower tower segment while assembling the next tower segment and the RNA at the same time.

Things for further research

- Tolerance between diameter of tower and monopile
- Forces on monopile due to lifting the tower
- Fastening of the platform
- How the cable from the tool will be retrieved
- The final connection between the tower and the MP.
- Adjustment of connection due to changing diameter of the tower.

Advantages

- The RNA does not have to be lifted to hub height.
- Reduces number of lifts.
- Reducing time since two processes can be done parallel.
- The RNA can be assembled on deck, which reduces the relative motion of the blades, hub and nacelle since it is all installed on the same platform and at a lower height.

Disadvantages

- The electrical components of the OWT are not allowed to get wet, therefore the tube where the tower is in retrieved can not be full of water. The water in the MP has to be pumped out before the frame can be lowered.
- It can only be used on turbines with monopile foundations or a huge tube has to be installed under the jacket foundation. This results in more loads on the jacket foundation since the water is blocked by this tube.
- Construction work has to be done offshore to construct a solid connection between the tower and the monopile.
- The loads on the monopile will differ and probably will be higher since the vertical loads from the tower are not directly transported to the wall of the monopile any more.
- Extra lifts are required to mount and dismount the winches.
- Instability of topside of OWT during installation.

Everything separate

Looking to the already separation regarding T&I of the support structure and the topside, the idea came up to separate the T&I of the different components of the topside as well. This introduces the option to have more specialised vessels for the different offshore operations. However, this option requires three different vessels which will require a high investment. Moer vessels will also bring challenges regarding logistics and can result in longer installation time per turbine. Moreover, all three vessels needs to eliminate relative motions between vessel and support structure and equipment needs to be prepared on each vessel before installation can start. This results in later operating turbines and therefore later production of 'first wind'. This concept does not solve the problem of lifting the heaviest part (the nacelle) to the greatest height (hub height).

Things for further research

- Demands of wind farm operators for 'First wind'.
- Cost balance between separate vessels

Advantages

- Specialized vessels engineered for the different demands of components, so no overcapacity will be used.
- The different components do not have to be transported over land to one port to be placed on the vessel. Different ports can be used as offloading location.

Disadvantages

- Time of 'first wind' will be later.
- Higher capital expenditure (CAPEX).

- Multiple good weather windows needed for the different vessels to begin their lifting operations.
- The different vessels are dependent on each other which can bring logistical challenges and delay. If the first vessel is delayed, the other ones are as well.

Jack-up frame

Just like the monopile lift, this concept is mainly focusing on reducing the required lift height of the nacelle, the hub and the blades and therefore reducing the required capacity of the crane. By lowering the lift height, offshore installation time can be reduced. The concept consist of a self propelled jack-up vessel that can lift the separate components from the quay on the vessel by its own crane. The jack-up vessel transports the components to the offshore location and by lifting itself out of the water before installation starts, motions due to environmental loads are eliminated.

Moreover, the concept includes a frame that can be placed on top of the transition piece (TP) that is able to push the components to their desired height. In Figure 4.5 and 4.6 impressions are presented of the concept with some installation steps. When the jack-up vessel is lifted out of the water, the frame will be installed on top of the TP. The first tower segment is placed on top of the frame (Figure 4.5 step 1) and four hydraulic cylinders pushes the frame and tower segment up (Figure 4.5 step 2). When the maximum position has been reached by the cylinders the next tower segment is placed underneath (Figure 4.5 step 3). Then the frame is lowered and the installation steps can start again (Figure 4.5 step 4). The RNA can be executed on deck of the vessel, so it can be installed on top of the tower when a height has been reached so that the blades will not touch the water surface. When the complete OWT has been installed, the jack-up frame is retrieved and the turbine is tested.

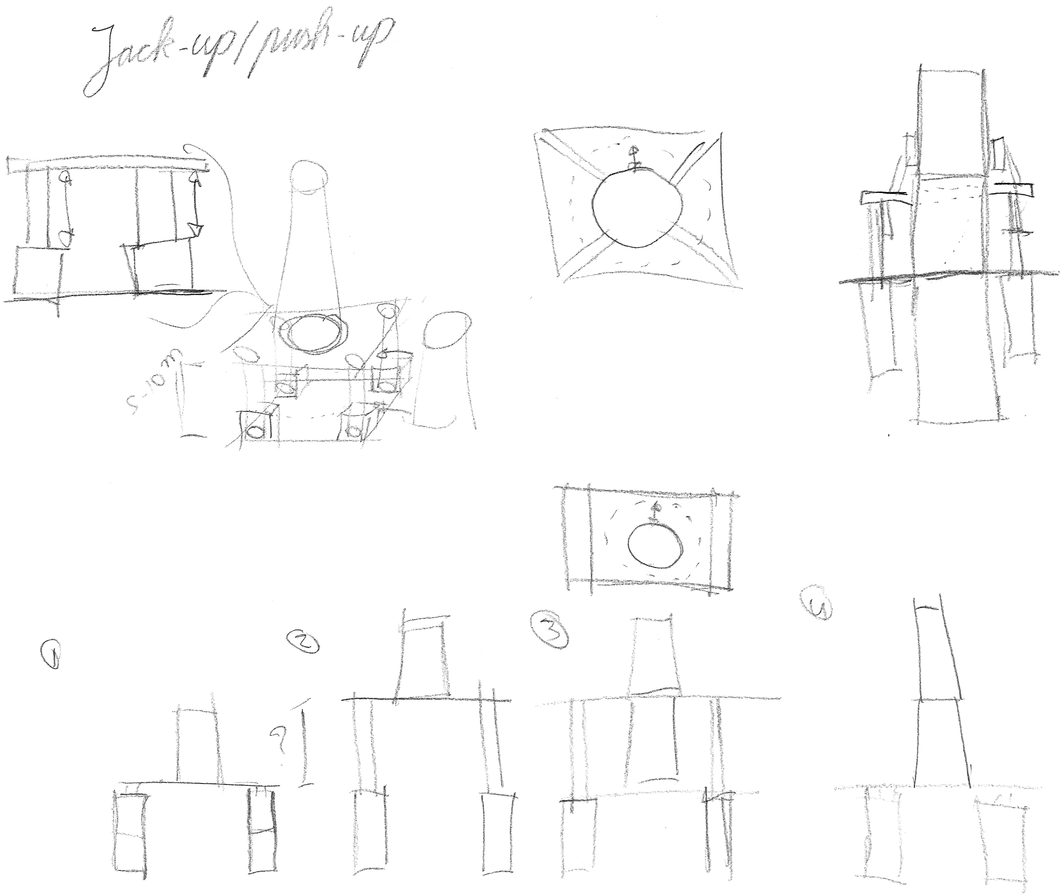


Figure 4.5: First idea, jack-up frame

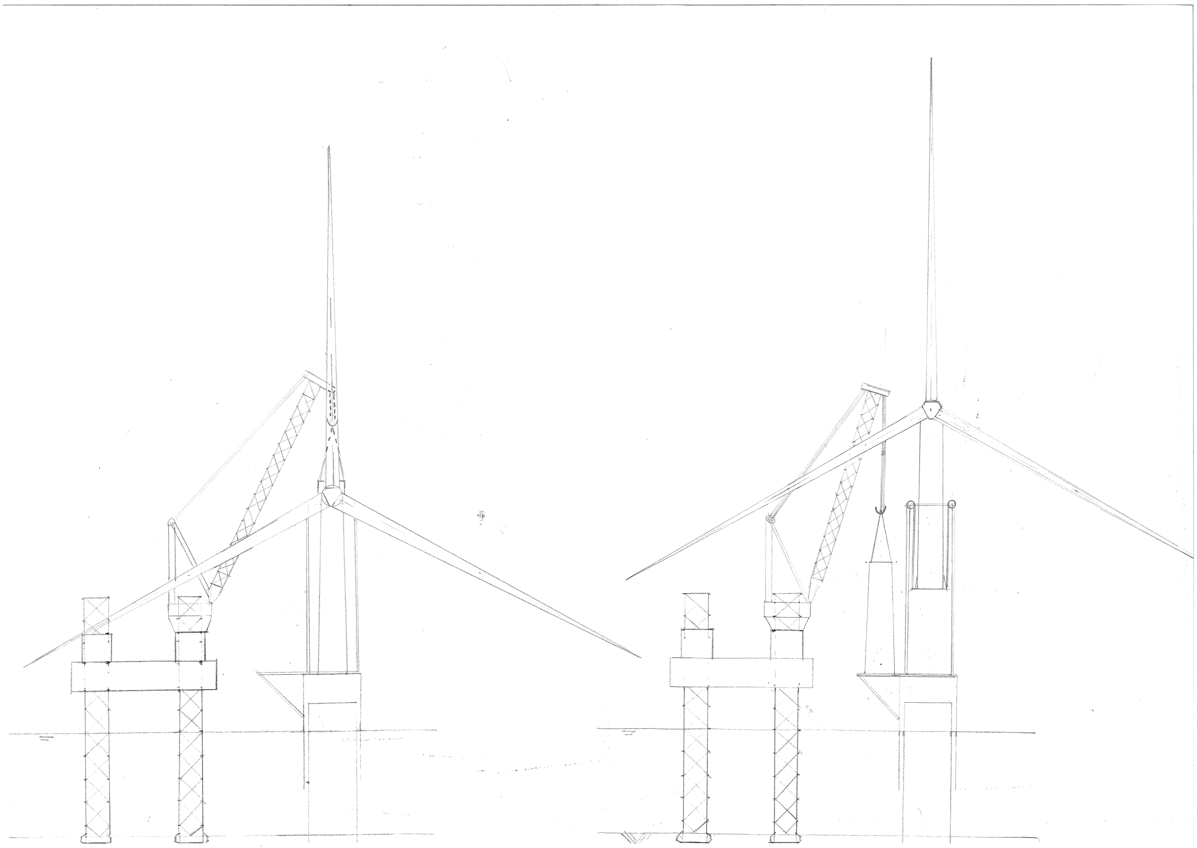


Figure 4.6: Visualisation of installation steps of bringing up tower

Things for further research

- Connection between tool and tower.
- Time to jack-up the different parts.
- The maximum height of the segments of the tower that have to be installed per time.
- Type of jack-up system: pushing or pin system.
- How the tower can be pushed up while not obstructing the path underneath
- If tool will be placed on support structure or that it is held by a type of rigging system

Advantages

- Jack-up technology which will be used in the frame is already existing technology within the offshore wind industry.
- Crane has to lift to lower heights. Smaller crane capacity is needed.
- RNA and first part of tower can already be installed on deck.
- Reduced lifting time, since lifting height is reduced.
- Several installation steps can be excuted parallel, while installing the jack-up frame and tower segments, the RNA can be conducted on deck of the vessel, resulting in lower installation time.

Disadvantages

- More installation steps offshore because of installation and removal of temporary jack-up frame
- Although it is proven technology, it is used for a new application.
- Connection has to be strong enough to with stand the loads
- Modifications on tower of OWT are required.

4.4. Installation concepts by other companies

In the past years, different concepts are created by companies, where some of them are listed below.

SOUL

SOUL is a collaboration between the companies SeaOwls and Ulstein. They saw a disproportional weight increase compared to gain in variable deck load in the development of a jack-up. They designed a jack-up vessel that could install offshore wind turbines of 10-15MW with a weight reduction up to 10% compared to conventional jack-up designs due to its cruciform structural lay-out. More information about for example the sailing speed and installation time is not yet given (Ulstein, 2017). Although this is an impressive development regarding weight reduction, the design is not yet constructed and it is not suitable for installing the 15-20MW turbines. However, a valuable lesson that can be learned from this concept is that redesigning the structural lay-out can already save weight.

(a) SOUL Jack-up vessel design (b) Shuttle with two turbines (c) Clamping mechanism on shuttle

Figure 4.7: Artist impression of Soul (Ulstein, 2017) and Wind Turbine Shuttle (Huisman Equipment BV, 2015)

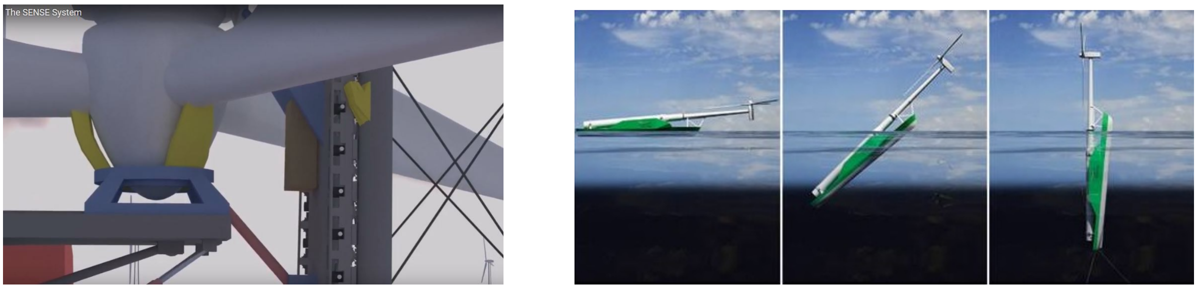
Wind Turbine Shuttle

The wind turbine shuttle is a catamaran design from Huisman Equipment BV (2015) which can transport two complete turbines in one go and which can install the turbine directly on top of the support structure with a specialised crane frame. This concept can install in large water depths since it is a floating solution and it requires only one lift to install the complete turbine. The origin of this concept can already be found 8 years ago but it has not been developed further. To be able to transport and install the 20MW OWTs, it requires a complex crane system that can lift up in total around 6000 tonne. Moreover, it has to withstand the loads introduced on the turbine during transportation which require an immense compensation system. This concepts indirectly require severe harbour requirements since the harbour needs to be able to withstand the load of a complete commissioned OWT of almost 3000 tonnes.

SENSE

It is stated by Sensewind (2017) that the this concept can be transported to site using a standard construction vessel. For offshore turbines the RNA, fitted with a special carriage, is transported. When close to the tower, the RNA is transferred to the base of the tower in one operation where the special carriage attaches to the tower under automatic control, allowing the transport vessel to move away. Once the RNA is attached on the tower the special carriage, equipped with power supply and automatic controls, lifts it to the top of the tower and rotates it into position and hold it until bolted down to the tower. Once installed, the special carriage is retrieved and can be used for the next turbine.

This concept is only focussing on the transportation and installation (T&I) of the RNA and does not specify anything about transportation and installation (T&I) of the tower, Moreover, it require severe modifications to the tower to be able to transport the RNA up and the nacelle is kept vertical which require severe modifications on the nacelle as well, heard from Siemens.



(a) Sense lifting method from vessel to carriage (Sensewind, 2017)

(b) Artist impression of the Windflip (Liggett, 2011)

Figure 4.8: Artist impression of Sense and Windflip

WindFlip

The WindFlip is designed to carry turbines out to sea at an almost horizontal position which minimizes draft and allows the barge to motor along at about eight knots. The Windflip measures 100 meters long and 30 meters wide, and it is stated that the barge is capable of carrying a 65 meter tall 15MW turbine fully assembled. Figure 4.8b shows an artist impression of the WindFlip barge. Once on site the WindFlip starts to fill 27 interior ballasts with water sequentially from the stern aft-ward which tips the WindFlip vertically with the turbine in tow. The barge then backs away from the turbine allowing it to be anchored in place while injecting compressed air back into its ballasts, tipping horizontally and readying itself for the next tow Liggett (2011).

By only using a barge which installs the turbine by ballasting and not using a big crane, a significant effort can be made. However, from a logistical point of view, the complete turbine has to be assembled onshore and loaded out on the barge. Moreover, by transporting the turbine horizontally, alterations are needed with respect to the structural capacity of the turbine since the tower is not designed to take such a load. Also, the nacelle needs to be adjusted in such a way that no liquids will be spilled. It is stated by turbine manufacturers that this is not preferred. Looking to stability, during transport it will be difficult to keep the barge stable with high waves, since it is close to the water level. Another disadvantage is that only one turbine can be taken and installed per time, this will play a significant role with wind farms located far offshore. Although there is some potential, disadvantages are present and no further development is presented since its revelation in 2011.

4.5. Concept families

Where the already existing concepts look quite different from each other, similarities can be found with regards to installation method, transportation and stabilisation. Based on the initial ad- and disadvantages and by checking if the concepts meat the constraints described in section 3.1, two most promising concepts were chosen to be evaluated later on, These concepts are both using a jack-up vessel and are mainly focussing on changing the installation method rather than the complete transportation and installation process. This results in four groups which will be evaluated in the next chapter based on the criteria set in section 3.4.

4.5.1. Upgrading of jack-up method

This group consist of the SOUL concept and upgrading of the jack-up vessels designed by GustoMSC. They use the same equipment and require the same technology upgrade from the jack-up legs, the jacking system, the crane and the floating capabilities. Although the SOUL concept is considered to be less expansive than the designed jack-ups from GustoMSC, regarding installation steps of an OWT not much difference is found.

4.5.2. Installation with floating solutions

This group consists is characterised by concepts or methods that stay in the water during installation. In this way no time is needed to lift the vessel out of the water and installation time can be reduced. However, during installation, the vessel is more influenced by the sea state and this waiting on weather (WOW) can result in longer total transport and installation time. To eliminate the influences of the waves, the vessels are equiped with a dynamic positioning-system or with anchoring lines. Since heave compensation is difficult with these systems, this has to be taken into account and a compensation system needs to be designed. To overcome the problem of WOW, the floating solutions are installing the complete OWT in one go. This brings some limitations regarding onshore logistics since the quay needs to be able to handle the loads of a complete turbine; transportation is bounded, since a complete $20MW$ turbine has a minimum height of around 200 metres and sailing in waterways which are crossed by bridges are not possible or require to have a clearance height of 200 metres and lastly during offshore transport, the loads that are acting on the turbine needs to be compensated by the vessel. The concepts that are covered are the 'Wind Turbine Shuttle' from huisman and the 'WindFlip'. Also installation with semi-submersibles are considered to be part of this group.

4.5.3. Jack-up frame

As described in section 4.3, this concept is mainly focusing on reducing the required lift height of the nacelle, the hub and the blades and therefore reducing the required capacity of the crane. By lowering the lift height, offshore installation time can be reduced. The concept consist of a self propelled jack-up vessel and a frame that can be placed on top of the transition piece (TP) that is able to push the components to their desired height.

4.5.4. Monopile lift

As described in section 4.3, this concept is mainly focusing on reducing the required lift height of the nacelle, the hub and the blades and therefore reducing the required capacity of the crane. By lowering the lift height, offshore installation time can be reduced. The concept consist of a self propelled jack-up vessel and a new lifting mechanism that uses the monopile foundation.

5

Concept evaluation

This chapter elaborates on the evaluation of the different concept families as presented in section 4.5 after which the best chosen concept can be worked out in more detail. The evaluation, as described in section 5.1, is based on criteria set in chapter 3 and concludes with a multi criteria analysis (MCA) of the different concept families. A basic design of the concept with the highest MCA-score is elaborated in section 5.2.

5.1. Concept selection

This section first describes the four different criteria as stated in section 3.4, then shows the score for each concept family on each criterion and finishes with the MCA.

5.1.1. Technical complexity

Technical complexity of a concept is defined by the type of technology the concept requires. A score can be given by asking if the concept uses a technology that is already developed or that it require new technology to be developed.

Summarised for the concept families:

- Upscaling of jack-up method: based on a proven method, but new specialised crane needs to be developed.
- Installation with floating solutions: require complex heave compensation system and a specialised crane that can lift the total turbine during transportation
- Jack-up frame: new application and requires developed heavy lift crane, new clamp connection with tower is required.
- Monopile lift: requires complex fixation system and stabilising system and new technology

5.1.2. Installation time

The installation time is defined as the time that is required to install the tower, nacelle, hub and blades. This not only includes offshore installation time but also the time that is required for load out of the components from quay to vessel and the required offshore transportation time. A score can be given by estimating the total required time.

A tool has been developed to calculate how long a certain installation method occupies. By first identifying all the different steps that have to be taken, secondly estimating how much time each step takes and saying if processes can be done parallel and subsequently verifying the steps and time by known data and expert knowledge, a valid estimation has been made for each concept regarding offshore installation. Although this gives a good indication of the offshore installation, it has to be taken into account that this is not the only step within the total T&I process of an OWT and OWF, as already described in section 2.4.

For the tool, the input required per step consists only of the duration and how the start or finish time is related to the previous task. After this input is given, the tool provides the start and finish time per task and visualises this directly. In this way it is able to automatically show the start and finish time per task and that of the total offshore installation per turbine, see Table 5.1. The options that can be given for the relation between the previous task are as follows:

- 0 if the next task can only be done if the previous task is finished (default).
- 1 if the next task has the same finish time as the previous task, with the constraint that it could not start earlier than the previous task.
- 2 if the next task has the same start time as the previous task.
- 3 if it is neither one of the above. This is the only case that the start time has to be filled in manually.

For the overview, a TaskID is also given to every step and the tool categorises to which component the task is related. This results in an input of every step that looks like the following:

Table 5.1: Input example installation tool

	TaskID	Task name	Duration	Parallel	Start time	Finsih time
Tower	1	Install rigging tower	20.00	0	0.00	20.00
	2	Release seafasting	20.00	1	0.00	20.00
	3	Lift tower segment to platform	30.00	0	20.00	50.00

The validation of this tool is done based on previous research of Strien (2011) where the different tasks regarding installation were identified and verified by experts from Siemens and GustoMSC for a $5MW$ turbine with the 'single blade' method, see Appendix B for all the installation steps and an overview generated per concept.

For the new concepts, assumptions had to be made about tasks that have to be executed. Depicted below:

1. Installation of the tool on the TP: it is not exactly known how long this take, since this operation has not been done before. However, looking to the tasks that have to be performed, mounting the bolts, attaching the clamps, attaching electricity, it can be concluded that they are somehow similar to the actions that are required to mount the tower of an OWT a reference can be made to objects that

2. Mounting the bolts of the tower/nacelle/blades: this is based on the required actions: get bolt, place bolt, get tool to screw bolt and finally use machine to pretension bolt. Assumptions: all the tasks take around 30 seconds, and multiple bolts can be done simultaneously, 96 bolts required so 48 minutes is assumed.

3. Jacking up in frame: $1m/minute$. Time effectively based on 40% of 1m/min to account for recycling of cylinders, putting pins in and out.

4. Removing frames. This has to be done with care, tool can not be damaged just like the turbine.

Overview of the total offshore installation time per concept family is given below, where a reference is made to Appendix B for a more elaborated overview. It needs to be stated that the complete turbine installation is not shown here. Based on research of Strien (2011) it was stated that the total installation time including load out and offshore transportation for a complete turbine installation was slower if the total transportation and installation of an OWF was taken in consideration. To have a conservative selection it was assumed that the installation time is as fast as that of the proven single blade method.

Table 5.2: Total installation time per method

	Single blade 5MW	Single blade 20MW	Jack-up frame 20MW	Monopile lift 20MW
Installation time [hh:mm]	15:45	28:10	23:20	24:15
Total handling time [hh:mm]	24:25	38:05	39:10	38:10

5.1.3. Modification to OWT design

Modification to OWT design is defined as required adjustments on the current design of an OWT. Based on interviews with Siemens it is found that modifications are not preferred from a turbine manufacturers point of view. VanOord stated however that from a developers point of view modifications to the OWT design are possible if significant profit can be made on the transportation and installation process. A score can be given based on the required modification.

Summarised for the concept families:

- Upscaling of jack-up method: no modifications are required since it uses the same method as now is used.
- Installation with floating solutions: new lifting point and required frame. adjustments are needed in such a way that the turbine can be lifted from the quay with a crane or a frame that is mounted on the vessel. This result in new forces in the turbine which require some modifications to keep it in place during transport.
- Jack-up frame: it will need a change in the design of the tower in such a way that it is able to be lifted in different segments instead of 1. This has already been done in other projects and it only requires an extra flange inside to bolt the different segments together. Also, adjustments are needed in such a way that it is possible to lift the segments from the bottom. Although, this will require some material, it is expected that it will not has a big influence on the design. Therefore it scores lower than the previous two families.
- Monopile lift: over the total length of the tower, not a lot of alterations are required. Although, changes are needed in such a way that forces can be taken by the tower that are induced by the stabiliser frame during installation/lifting out of the MP. On the bottom however, a new connection needs to be designed, which is able to connect the tower permanently to the MP. The design of the TP needs to be altered significantly since it has to be able to receive a tower that can be lowered in the MP. The design of the MP also has to be altered because the tower with electrical equipment is not allowed to be lowered in the water. However, by looking only to the topside, the same score is given as the 'Jack-up frame'.

5.1.4. Adaptability for different size turbines

This criterion is defined as the ability to install other turbines than the expected $20MW$ turbines. When significant modifications of the T&I-concept are required to install different size OWTs, the concept is not efficient. Also, when full capacity of equipment is always present, the concept is not efficient as well. This criterion can be scored by looking to the required modifications of the T&I-concept to be able to install smaller or even bigger turbines.

Summarised for the concept families:

- Upscaling of jack-up method: since the design of the crane is determined by the mass of the nacelle and the hub height, the total capacity of the crane is always designed for this. Turbines can be installed, but the full capacity of the crane and other equipment is always present. Therefore it will score not high on this criterion.
- Installation with floating solutions: since the crane is designed to lift the complete $20MW$ OWT a smaller turbine is still lifted with the same capacity. Also seen in the Hywind project (descirbed in section 2.5) where the full capacity of 14000 tonne is used for one turbine. It will score the same as the upscaling of the jack-up method.
- Jack-up frame: the installation frame that pushes the segment to the required height can easily be altered for smaller or even bigger turbines. However, the crane is designed to lift the complete RNA which is the governing mass and can not easily be altered. In comparison with the previous families, it is not designed to lift to hub height and therefore a changing hub height will have less influence on the concept and it can be adapted more easily. Therefore it will score higher than upscaling of the jack-up method and the installation with floating solutions.
- Monopile lift: the installation frame that lifts the tower to the required height can easily be altered for lighter or even heavier turbines. However, the crane is designed to lift the complete RNA which is the governing mass and can not easily be altered. In comparison with the previous families, it is not designed to lift to hub height and therefore a changing hub height will have less influence on the concept and it can be adapted more easily. Therefore it will score the same as the jack-up frame for this criterion.

5.1.5. Outcome Multi Criteria Analaysis

Based on the information given above a score between 1 and 5 was given to each of the criteria where the respective score represents the following per criterion:

Table 5.3: Qualitative score per criteria

Criteria	Score description		
Technical complexity	complex or new technology	1- 5	not complex or already developed technology
Installation time	slow transport and installation	1 - 5	fast transport and installation
Modification to OWT design	no influence	1 - 5	big influence
Adaptability for different size turbines	not adaptable	1 - 5	adaptable

The four concept families are scored on each criterion. To get a result from the MCA, the different scores are multiplied by each weight factor respectively and added together. The result of this analysis is shown in Table 5.4 and it can be seen that the 'Jack-up frame' is the most preferred concept based on the MCA.

Table 5.4: MCA score per concept

Criterion	Weight factor	Upscaling of jack-up method	Installation with floating solutions	Jack-up frame	Monopile lift
Technical complexity	0.250	4	3	3	2
Installation time	0.375	3	3	4	4
Modification to OWT design	0.125	5	4	3	3
Adaptability for different size turbines	0.250	3	3	4	4
Total	1	3.50	3.13	3.63	3.38

Finally, a sensitivity analysis is conducted to determine what happens if one of the criteria increases in weight factor. An increase of 25% has been chosen. If this factor is used for all criteria, and another concept is the most feasible, it might be the case that the concept is not the best in all options and should be re-evaluated. The results are shown in Appendix C where it is concluded that even if the weight factor of one of the criteria increases by 25%, that the 'Jack-up frame' is still the preferred concept.

5.2. Basic design

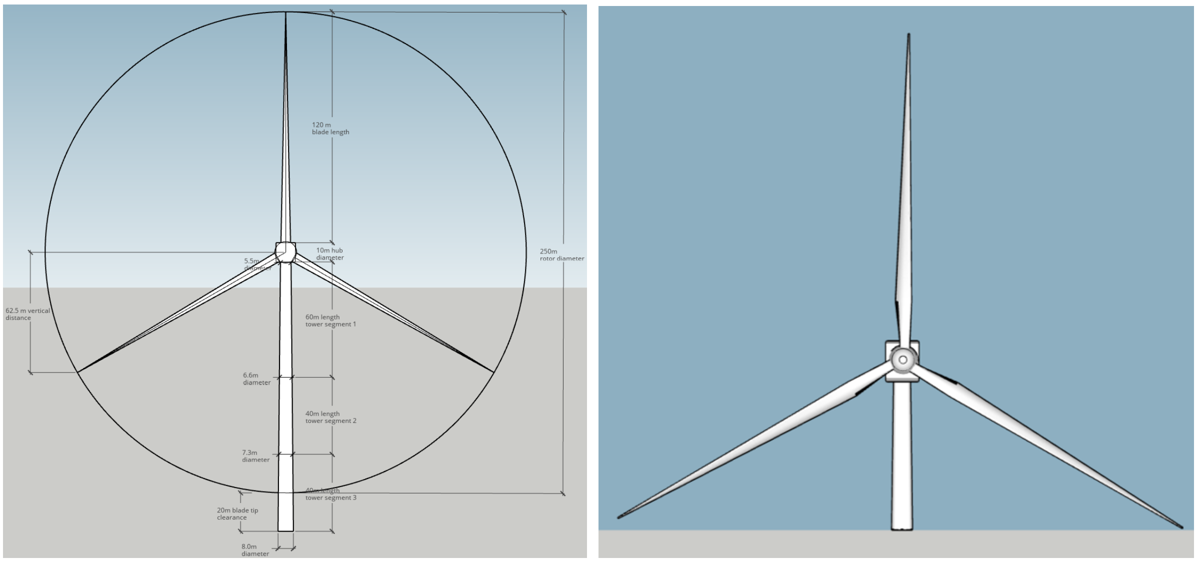
It is stated that the most preferred method for installation is from a platform that is out of the water line. Therefore it is chosen to use the design of a jack-up vessel, to eliminate the motions due to wave loading on the ship, by lifting it out of the water with four legs. The solution focus in more detail about changing the method of installation, by looking to other techniques than lifting with a crane to a hub height of $160m$ above sea level. By making use of a frame which will jack-up the tower in segments to its desired height, the need of a specialised new developed crane with a lift capacity of over 1100 tonnes to a height of over $160m$ has been eliminated.

5.2.1. Initial geometry

The height of the frame is obtained by looking to the height of the different segments of the tower. The length of the first tower segment is determined based on the minimum required vertical height of the rotor so that the tip of the blade will not come in contact with the water, see Figure 5.1b. With goniometry rules, knowing that every blade is rotated with respect to each other with 120 degrees and a distance of $125m$ from the center of the rotor to the tip, a minimum vertical distance of $62.5m$ was calculated. Taking into account that this is from the center of the hub, which will be $5m$ above the tip of the tower, a height of $60m$ has been chosen for the first tower segment. By determining the number of other segments, it is taken into account that the more segments there are, the more activities have to be executed offshore what is undesired. Keeping the offshore activities as low as possible would result in only one segment of $80m$. However, to not lift higher than necessary, the remaining tower is split up into 2 segments of $40m$. By using the diameters determined for the top and bottom of tower and using rules of thumb for the D/t-ratio, the characteristics of the different tower segments are calculated and listed in Table 5.5. The OWT is presented in Figure 5.1a. This segmentation of the tower reduces the maximum required lift height, including sling arrangement, by a factor 2 from 160m to roughly 80m.

Table 5.5: Tower segment characteristics

Segment	Length [m]	D [m]	t [mm]	W [tonne]
1	60	5.5-6.6	62.9	515
2	40	6.6-7.3	71.4	467
3	40	7.3-8.0	80	579
Tower	140	5.5-8.0	60-80	1561



(a) Key dimensions

(b) Complete RNA together with first tower segment

Figure 5.1: Visual impression of a 20MW offshore wind turbine

The chosen method of installation requires that the tower is split up in several parts. Although dividing the tower in several parts is not common, it is already been done before in offshore wind installation projects. For example, the Global Tech I offshore wind farm consists of 80 OWTs with towers of around 80 metres length which were installed in two segments (Fred Olsen Windcarrier, 2015). Looking to the increase of tower length and weight for a 20MW turbine, installing the tower in several segments will be almost inevitable. Therefore this is not seen as adjustment of the design of the OWT.

Based on the length of the first tower segment, a frame with an initial height of 60m will be used that is installed on the foundation. It will receive the tower segments and bring them to their desired height. To minimise the moment in the connection, it was initial desired to have the frame as close to the tower as possible. Secondly, to let the frame fit on the foundation, a small area was desired, resulting in the dimensions of Figure 5.2 and Figure 5.3.

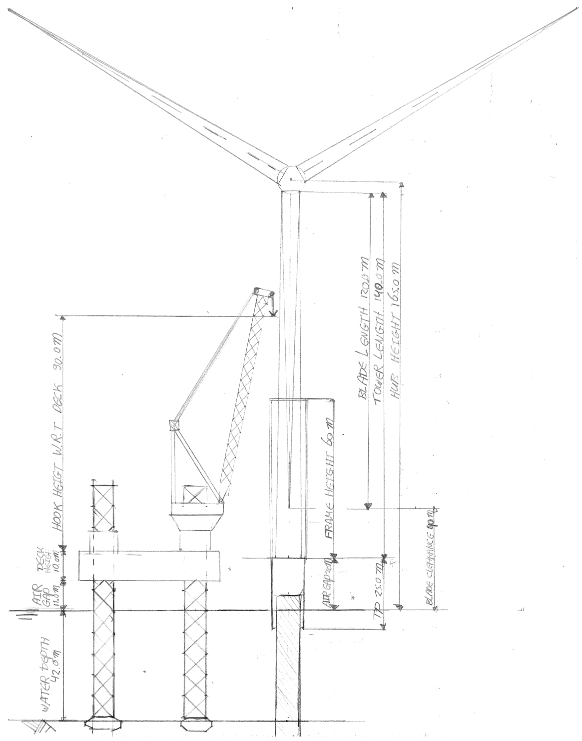


Figure 5.2: Jack-up system with height indication

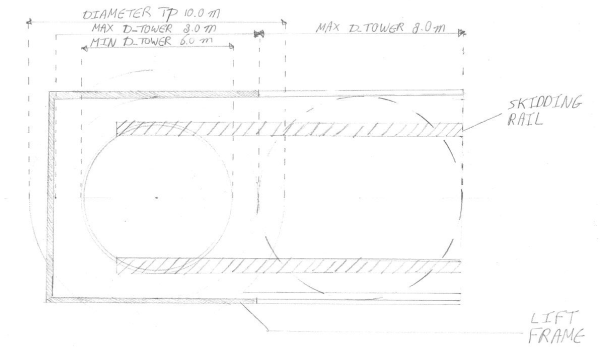


Figure 5.3: Top view of total frame, with lift frame left and skid part right

5.2.2. RNA on deck

Where the lift height is decreased by splitting up the tower, the goal to eliminate mutual movement between the blades and hub during installation still had to be covered. This is done by making use of the idea of assembling the complete rotor on deck. The idea of Strien (2011), the assembly tower for 5MW turbines, eliminates these movements by making use of a guidance frame on deck of the vessel. It was stated that this solution will be faster than the conventional way, and especially when looking to 20MW turbines where the lift height and size of the blades only further increase. This results in higher wind loads at hub height (see section 2.3 and more loading of the blade respectively. Moreover, when conducting the RNA on deck, simultaneously the skid and lift frame can be installed on the TP.

Strien (2011) used the width of the vessel to install the rotor on deck, however that would not be possible with the dimensions of the 20MW turbine. Therefore, the steps that have to be undertaken are similar to that of Strien (2011)(Figure 5.4) but the orientation with respect to the vessel will be in the longitudinal direction of the vessel.

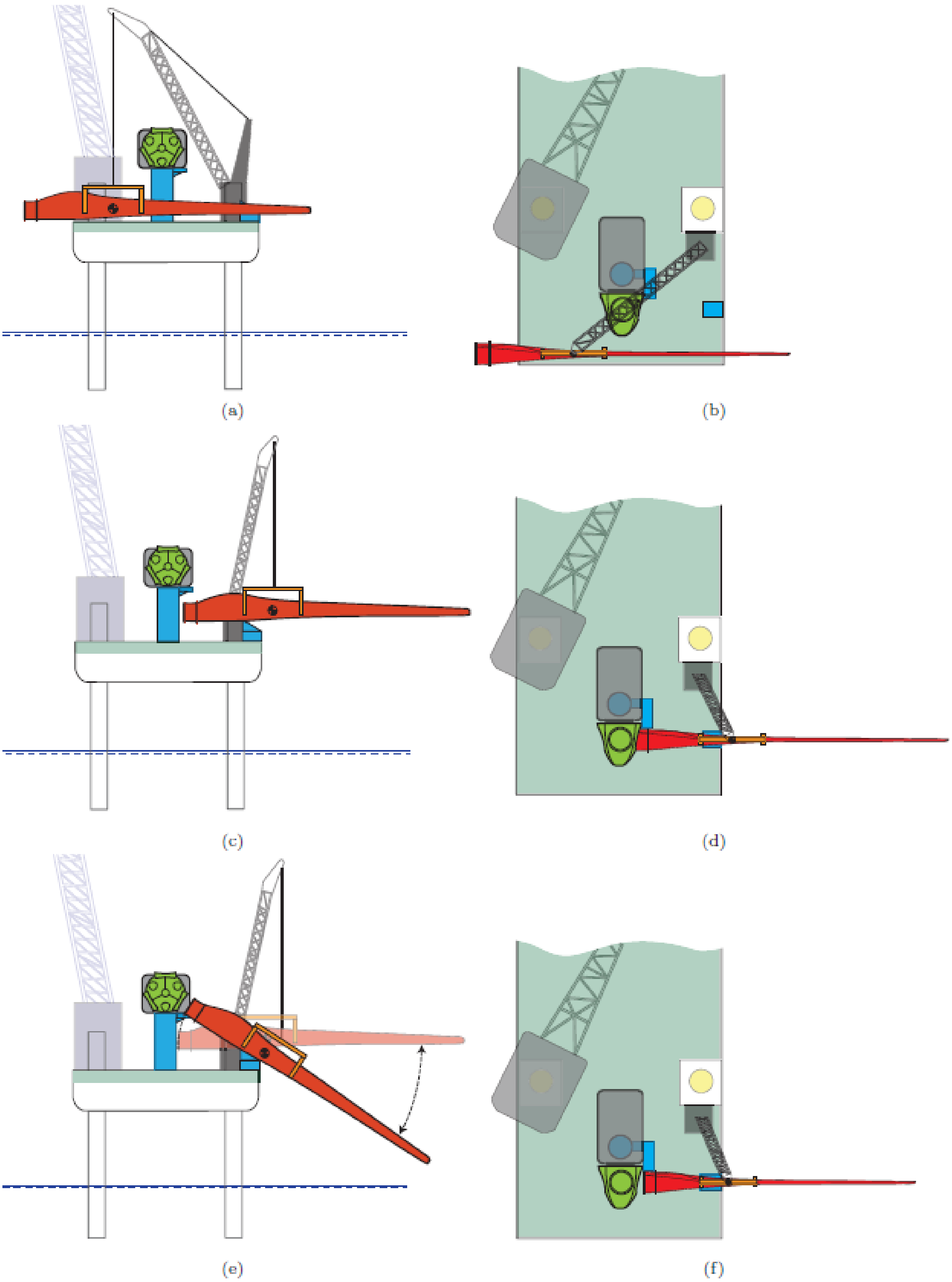


Figure 5.4: Assembly tower of (Strien, 2011, p.141). Steps of manipulation of the blade towards the pre-assembly of hub and nacelle by use of blade handling tools. [left] Front view [right] Top view. (a,b) Pick up from stack position. (c,d) Move to the starboard of the vessel. (e,f) Tilt to the desired angle of 30 degrees by using the guidance frame

6

Initial concept

After the concept has been chosen, innovation and improvement was expected to be found by focusing on the frame that will install the turbine. This also starts the second part of this research as discussed in the approach in section 1.4. This chapter elaborates more on the initial design of the frame and the technical challenges that have to be solved. To have a viable solution, the installation steps are written down in section 6.1 and the first challenges are introduced. section 6.2 highlights parts of the frame that solve these challenges, which results in a 3D model presented in section 6.3.

6.1. Installation steps

The installation steps that are set out in the time sheets in Appendix B for installing the OWT with the jack-up frame can be summarised to the following:

1. The RNA is assembled on deck
2. Simultaneously, the frame to move the tower sideways and to push the tower upwards are temporarily installed on top of the TP.
3. The first tower segment together with the RNA is placed on top of the already installed frame.
4. The segment is temporarily fixated to withstand the forces during installation
5. The segment is pushed upwards by the lift frame.
6. When the segment is pushed high enough, a new segment is placed underneath it.
7. While the new frame is temporarily fixated, the previous segment is lowered and placed on top of the new segment and they are mounted together.
8. This is repeated until the last segment is installed.
9. After the last segment is placed it is mounted to the TP.
10. The previous segment is lowered and mounted on top of this segment.
11. Now the installation frame will be retrieved and the OWT can be tested.

Based on the installation steps described, it was stated that an important part of the design will be focussing on how to lift the turbine from the bottom and still be able to place the next segment underneath. This sets the following requirements for the interface between the segments of the tower and the lift frame:

- It has to be strong enough to bring the tower segments to its desired height.
- It has to be able to fixate the tower segments temporarily so it can withstand the loads acting on the turbine during installation.
- It has to be designed in such a way that it is not restricting the connection between the different segments, so it is possible to lower the upper tower segment on top of the next tower segment.

6.2. First design cycle: the U-shape frame

The installation frame is discussed below by dividing it in the following: the clamp connection, the lift connection, the lift frame and the skid frame. The clamp connection will mainly fixate the tower temporarily and therefore has to transfer the loads acting on the turbine during installation. The lift connection will redirect the loads from the clamp connection to the lift frame and will need to ensure it can bring the tower segments to their desired height. Both the clamp and lift connection needs to be situated in such a way that they ensure a clear path between the flanges of the tower segments. The lift frame needs to be strong enough to guide the lift connection that brings the segments to their desired height and to transfer the loads to the support structure. The skid frame needs to be able to receive the next tower segment and to move it into the lift frame.

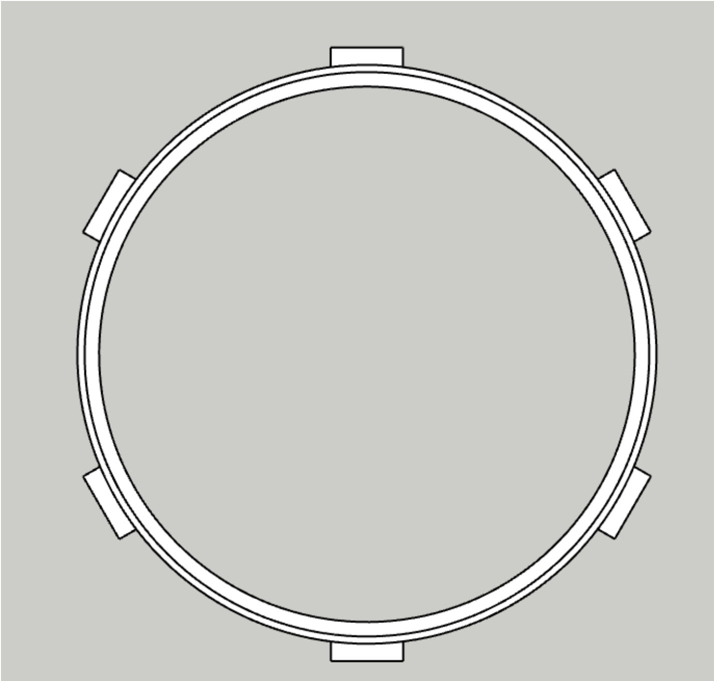
6.2.1. Clamp connection

The clamp connections require some additions to the tower. As said before, these are necessary to be able to lift the tower segments from underneath while not obstructing the flanges which are used to connect the different tower segments together. The following options were considered:

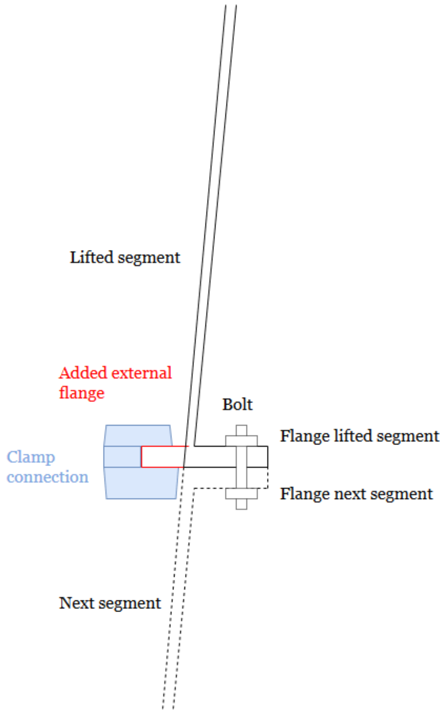
1. Making holes in the tower so it can be moved up just like the leg of a jack up vessel now is done, depicted in Figure 6.2. These holes will disrupt the path of how the loads are transferred to the support structure and this requires an increase of wall thickness or an additional structure within the tower to still be able to transfer the loads during installation and operation.
2. Ears can be mounted on the outside of the tower. The lift connection requires a pin system that can connect with the ears and in this way will be able to lift the different tower segments to their required heights. The ears will be situated at the bottom of the tower, so lift height is kept as low as possible. Also, this will introduce the loads in the tower via the flanges that are already designed to withstand loads during operation. This solution requires an extra stabilisation frame in the lift frame since the ears can not be used to prevent the tower from rotating when loaded sideways by the wind. An internal frame in the tower is probably required since the height of ears will be higher than the thickness of the flange of the different segments.
3. Solid extensions are made at the bottom of the tower that will be clamped. This can be achieved by extending the flange on the outside of the tower. This will introduce the loads that have to be withstand at a place designed for it. However a clamping mechanism must be developed that can withstand the loads during installation and that can keep the tower in place.

Since minimal adjustments are required, the third option was chosen. An advantage of this option was that the loads will be transferred to places which are already designed to transfer loads during operation phase, namely the flanges. From a stability point of view, three extensions are required around the outside of the tower where the clamp connection can clamp the tower before starting to lift. Also for skidding the tower, three extensions are required. These extensions can not be the same, since the tower needs to be clamped during skidding and can only be released after the clamp connection has secured the tower. Therefore, in total six extensions are required around the tower which are distributed equally around the outside of the tower, one every 60 degrees, depicted in Figure 6.1a. A cross section of such a section is shown in Figure 6.1b, where the extensions are depicted in red and the clamps in blue. The extensions to the tower will be the only adjustments on the design of the tower. However, since the tower of the OWT is split up in three segments, these extensions need to be added to all three segments. The clamp connection will support the extension of the tower, so it can lift the tower to its desired height.

When looking to the offshore transport of the different components of an OWT, these extensions can also be used for sea fastening. This can reduce the time that is required to prepare the different tower segments for installation and can also reduce time for sea fastening after load out from the quay.



(a) Top view towersegment with flange extensions



(b) Cros section of clamp connection

Figure 6.1: Illustrations of interface between tower segment and lift mechanism

6.2.2. Lift connection

As stated, the lift connections will redirect the loads from the clamp connections to the lift towers and will need to ensure it can bring the tower segments to their desired height. Since there are three clamp connections for lifting, situated 120 degrees with respect to each other, three lift connections are required on the same position. The choice has been made to use a jack-up mechanism for every lift connection, inspired by the jack-up mechanisms which are already used by jack-up vessels to lift itself out of the water and which is based on the pin-in-the-hole principle (Figure 6.2). The current jack-up vessel uses four of these jack-up systems. The conventional technique of a jack-up system consist of first moving the leg down to the seabed after which it is lifting the vessel out of the water by climbing up around the legs, so moving the frame upwards with respect to the leg. This new application is different in such a way that the tower is lifted up and the lift connection will climb up via a stationary lift frame.

It was decided to climb up by use of hydraulic cylinders, each connection housing two cylinders. The cylinders are connected with a yoke at the top and the bottom, where the bottom yoke also houses the clamp connection in between the cylinders. In this way, the cylinders are only loaded vertically. The lift connection is placed between two towers each, which are used to climb up based on the pin-in-the-hole principle. Both the bottom and the top yoke are equipped with pins which will be brought into the holes in the towers. The pins in the top yoke will ensure that the system is fixated while the cylinders are retracted. Then the pins in the bottom yoke will pinch the holes of the tower, ensuring a fixed connection, so the top yoke can be released and the cylinders can push it up. Repeating this sequence results in a jacking system that can bring the tower segments to the top of the frame.

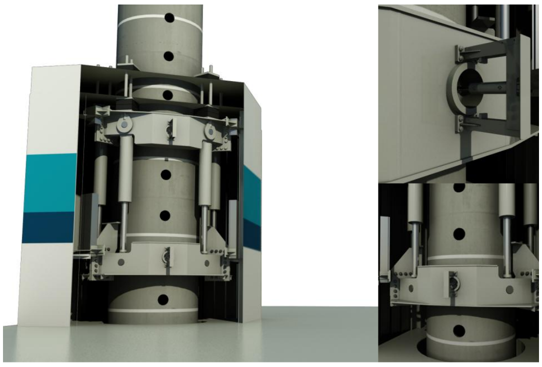


Figure 6.2: Jacking system, courtesy of GustoMSC

6.2.3. Lift frame

The lift frame consist of the lift towers that are used by the lift connection to climb and an external frame that connects the towers at the bottom and that will redirect the loads to the foundation. A frame is required in which a jacking system can climb up as described above.

6.2.4. Skid frame

The skid frame has as function to receive the next tower segment and to move it into the lift frame. To do that, it consist of skid cars that are moved on skidding rails. The amount of skid cars are based on the amount of clamp connections required for stable skidding, namely three. The skid cars house the clamp connection on top to be able to withstand loads during skidding. A construction is designed so the loads can be redirected via the rails to the support structure.

6.3. Initial dimensions

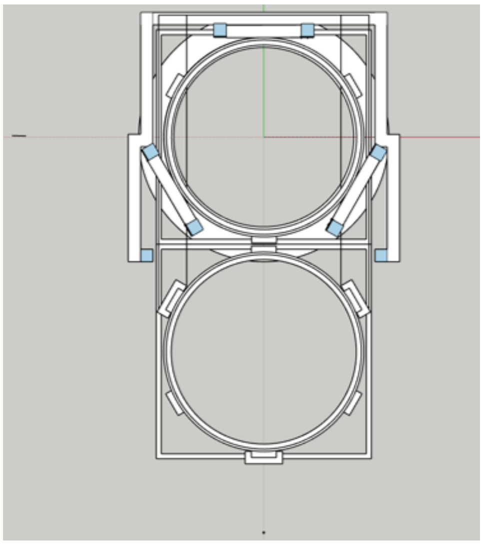
The height of the lift frame, as calculated in section 5.2, measures 60 metres based on the length of the first tower segment. Secondly, to reduce moments in the lift frame, the choice was made to keep the lifting towers close to the turbine. This results in a slender frame that can be temporarily installed on top of the support structure. Moreover, one side needs to be open to be able to skid the next tower segment into the lift frame. This results in a u-shaped frame with a footprint area of 9 by 9 meters. For the skid frame, an outreach is needed that can the same dimensions are kept as presented in section 5.2 which equal a platform that has an outreach of around 9 metres to be able to receive the next tower segment while the other one is lifted.

6.3.1. Visualisation

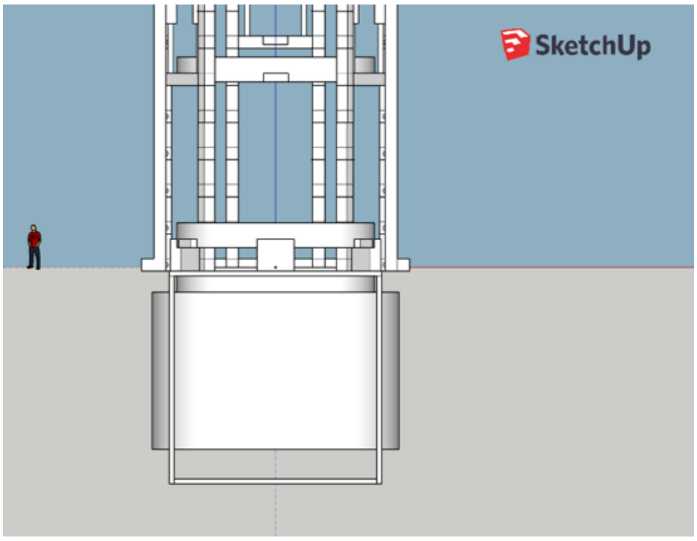
To have a better visualisation of the concept, a 3D model for the turbine and the frame was set up. The design is set up and presented below, based on the specifications already given in section 5.2. The goal was to be able to identify any challenges with regard to the installation steps. It was known that the total lift frame required more members to have a good structural design.

The input of the turbine corresponds with the data as determined with the design constraints in Table 3.1. For the support structure, it was assumed that the top of the TP has the same diameter as the bottom of the tower ($8m$), since they need to be connected with each other.

Elaborating on the design, results in challenges that require a solution to have a viable concept. The most important one was considering the lifting towers that were blocking the skidding path which hinders the next segment to be placed underneath (Figure 6.3). Secondly, because of keeping the footprint of the frame as small as possible, the lift frame looks too slender with respect to the total turbine (Figure 6.4). Also, looking from a logistic point of view, the retrieval of the skidding bars will be hard since they are under the last segment of the tower.

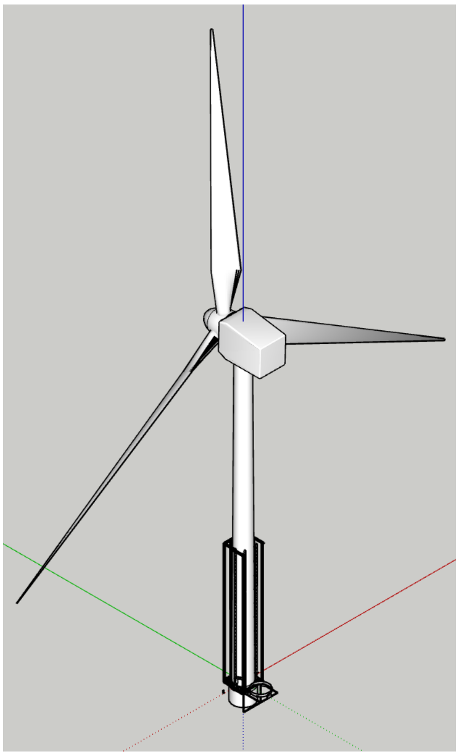


(a) Top view

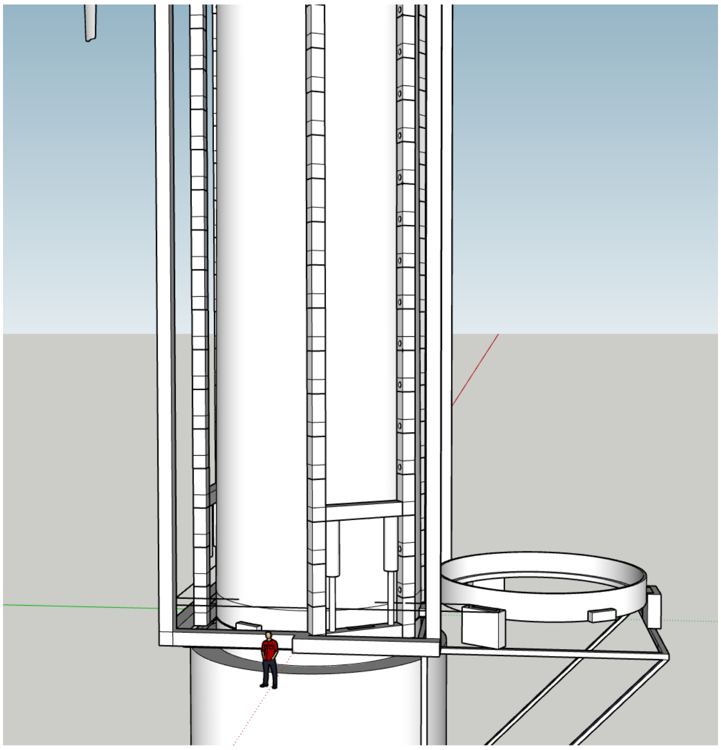


(b) Side view

Figure 6.3: U-shape frame. The tower segments are not displayed completely so the different components of the lift frame are still visible



(a) U-shape frame with complete turbine



(b) Zoomed in on lower part of frame

Figure 6.4: 3D impression of the U-shape frame

7
Improved concept

After the first 3D model was made, problems were found regarding skidding and a design iteration has been performed to solve the found problems and to have a logistical possible solution.

The chapter has been removed from the report because of the non disclosure agreement (NDA) that has been signed between GustoMSC and the TU Delft. This NDA sets an embargo of 10 years on the report, which is longer than the standard embargo of the TU Delft repository of 4 years. If you want to see this chapter, please contact the author by the email address as stated on the title page.

8 Conclusion

The goal of this project was to develop an efficient installation method for future offshore wind turbines with a rated capacity of 15 till 20 megawatt. This chapter is meant to reflect on whether this goal was achieved. First, the main research question will be answered after which suggestions for further research are listed.

8.1. Conclusions

Mapping out the current installation methods and sequences resulted in the conclusion that an offshore wind turbine (OWT) is commonly installed with a jack-up vessel which lifts itself out of the water to reduce the environmental impact during installation. The different components of the wind turbine are lifted with one by one on top of a pre-installed foundation: first the tower, followed by the nacelle and at last the three blades separately. This results that the lift height becomes as high as the hub height of the wind turbine and as a consequence requires the crane to be able to reach well beyond that height to accommodate the sling arrangement. In only one known case the installation of a complete OWT was executed by a semi-submersible.

The characteristics of large size turbines were studied by examining the relation between the rated power and the rotor diameter of operating offshore wind turbines. The derived dependencies between the desired power and the required area of the rotor were validated with data from announced turbines. Extrapolating these dependencies has resulted in a prediction for the $20MW$ turbine of a rotor diameter of 250 metres, a hub height of 160 metres above sea level and a nacelle with a mass of around 1100 tonnes.

These next generation turbines are significantly larger and heavier compared with the current operating turbines. This poses new requirements for safe and efficient installation, requirements that go beyond the capabilities of existing jack-up installation vessels and equipment regarding lift capacity and lift height of the crane. To be able to install a turbine of $20MW$ in the same installation sequence as currently is used, a not yet existing crane needs to be designed to be able to lift the nacelle to hub height. This not only requires higher investment of equipment of the crane but also in the jack-up vessel which is supporting the heavier crane. Upscaling of the current jack-up vessels requires a higher capital expenditure, which brings higher risks that have to be carried by the installation contractor, resulting in higher day rates. Moreover, the increased mass and hub height result in longer offshore installation time and together with the increased day-rate of the jack-up vessel increases the costs for installing one turbine.

Interviews were conducted with industry experts and requirements were set to be able to develop new concepts for the installation of the $20MW$ turbines, resulting in criteria to determine an efficient installation method. For each of the criteria, weight factors have been derived. This has resulted in a criteria ranking as follows (most important first): the total installation time of an OWT, technical complexity, the adaptability for different size OWTs and required modifications on the OWT design. New concepts were developed and based on the set criteria, a suitable installation concept was chosen.

The chosen concept eliminates the need for lifting the heaviest component (the nacelle) to the highest height (hub height) by dividing the tower of the turbine into several segments. It consists of a temporary installation frame that can be placed from a jack-up vessel on top of the foundation of an offshore wind turbine. While installing the frame on the foundation with a crane, the nacelle, hub and blades are mounted together on the deck of the jack-up vessel, forming the rotor nacelle assembly (RNA). Because of simultaneously operations, considerable time can be gained. Then, the RNA together with the first tower segment, measuring 60 meter, is placed in the frame, skidded sideways and brought up by a built-in jacking mechanism in the frame. It needs to be brought up 45 metres, so the following segment of 40 metres can be skidded underneath. While jacking the first segment, the following segment is placed next to the lift frame and prepared to be skidded. After the skidding of the next segment is finished, the previous segment is lowered on top of the other segment and they are mounted together. While fastening the connection, the jacking mechanism is lowered to the base of the installation frame, so it can start lifting the next segment. This is repeated until the complete turbine has been installed. When all the tower segments are installed, the turbine can be commissioned and the frame is retrieved.

Optimisation of the concept has been performed by highlighting the logistical process regarding placement of the frame, lifting of the turbine and retrieval of the frame. Initial dimensioning has been executed and preliminary load checks are performed. The result is a conceptual design of the frame with a mass of around 1100 tonnes and a first estimated material cost of 7.1 million. It is able to install the future offshore wind turbines with a rated power of up to 20MW faster compared to upscaling the existing installation equipment, it can be used for several turbine sizes and it only requires small modifications on the design of an offshore wind turbine.

8.2. Future work

In this thesis a conceptual design of the Jack-up frame is presented. The detailed design phase is left for further research. The detailed design will comprise more elaboration on load calculations, more detailed dimensioning and a design for fabrication. The load transfer from the installation frame to the support structure is not yet addressed and requires attention. Moreover, the clamp mechanism still needs to be designed that can clamp the turbine and withstand the loads introduced on it. The skid cars are not elaborated but can be based on already existing skid cars that are used on- and offshore. All the components of the installation frame should be designed in lines with the rules and regulations of the relevant certifying authorities (e.g. DNVGL).

The concept consists of a jack-up vessel from where the installation is performed offshore. This was preferred over a floating vessel, since movement of the jack-up vessel is reduced significantly when lifted out of the water. Due to the high crane tip, small vessel motions already result in significant motions of the turbine and the frame, which is not desired. Turbine manufacturers only allow minimum movement and impact, since the components are sensitive to impact loads and damaged easily. For wider applicability of the jack-up frame, further research is required to reduce motions between the turbine and the foundation during installation from a floating vessel.

This thesis focused on the offshore installation logistics. As stated in section 2.4, the offshore transportation and the onshore logistic chain is of significant importance. For example, the onshore supply of components from different manufactures, the port area and equipment required for onshore pre-assembly are only discussed briefly. These are important aspects that have to be taken into account when looking at the impact that this installation frame can make on the transportation and installation process of a complete offshore wind farm.

The installation time of the 20MW turbine with the Jack-up frame has been based on extrapolation of current installation time of an 8MW turbine where possible. For as far as the jack-up frame deviates from the current installation methodologies, time estimates have been based on the knowledge of existing jacking techniques (such as applied in the jacking systems in regular jack-up vessels. These estimates have to be validated in the next development phase. Next, a sensitivity analysis is recommended to see how a change of the indicated duration time per step will influence the total installation time of an offshore wind turbine.

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A
Interviews

During the research period, a number of interviews were conducted, were the validation of found results was tested, challenges regarding transport and installation were discussed and valuable information was gathered.
At each interview, a short introduction in the subject is given and the problems found regarding T&I will be addressed. To the different companies, different questions were asked regarding the challenges of T&I of future offshore wind.

A.1. Interview Mammoet - 08 March 2018

The interview was held at Mammoet Europe B.V. located at Karel Doormanweg 47, Schiedam and was focused on the challenges that Mammoet sees in the current and future offshore wind market. The men that was interviewed:

- Richard van Looij, Senior Commercial Manager Offshore at Mammoet Europe B.V.

Richard is roughly working 8 years at Mammoet and is since 2017 the head of department of offshore operations of Mammoet. The following questions were answered.

What do you think about the future wind energy, both onshore as well as offshore?
The growth that can be seen is almost exponential, both onshore and offshore. Technical it is feasible, but I think it is going too fast: the subsidy is gone and the companies are taking huge risks since the costs per wind farm are growing with the growing size in total installed capacity per wind farm. For innovation regarding T&I and maintenance, more collaboration is needed between the contractors, the wind turbine manufacturers and the designers of equipment. Collaboration can already be seen, like the Rotterdam Offshore Wind Coalition[1], but this is only till a certain depth. Companies are not open enough to each other, which results in less innovation than can be reached, which is necessary if the turbines keeps on growing.

Till what extend is Mammoet involved in offshore wind installation?
Mammoet is more focusing on the engineering and has sold most of her assets in offshore wind. They only have three barges with which they can participate in projects in only relative calm and shallow waters. Moreover, the cranes and equipment of Mammoet are not designed to operate offshore and the capacity can not be guaranteed by the manufacturer if used offshore. Mammoet only poses three barges for offshore operations and is therefore helping with float overs of for example substations but not focusing on the installation of offshore wind turbines.

Last February, there was an article published about using onshore techniques in an offshore environment in Flevoland, why not extend that?
From Mammoet's point of view, these projects are seen as special projects, where conventional methods are not able to install due to its relative shallow water depth of only 15 meters and its limited access caused by the geographical location. Therefore, not a lot of competitors are tendering on these projects and Mammoet can use their expertise to execute these projects. This is not extended to further offshore because of the heavy competition, the fact that Mammoet does not own the assets to do so and stricter rules have to be taken into

[1]ROWC is a coalition of Ampelmann, Boskalis, Damen, Eneco, Falck, Huisman, Jules Dock, Mammoet, Marsh, Peterson, Port of Rotterdam, Rabobank, Seaway Heavy Lifting, Sif, STC-group, STC-KNRM, Tennet, VanOord, Visser & Smit Hanab

account when transporting over sea than over rivers.
Things to keep in mind
Furthermore, it was mentioned by Richard that Mammoet is working on two cranes: one can be used for maintenance and one for installation of the different components of the RNA. Both cranes use guidance rails that are placed to the tower and the tower itself to climb up. The capacity of the cranes are however limited, 100 tonne and 250 tonne, respectively for maintenance and installation.

A.2. Interview Siemens - 09 March 2018

The intention of this interview is to see what challenges Siemens see in bigger turbines regarding, logistics, transport and installation and if these aspects are also taken into consideration in the design of the wind turbine components. The interview was conducted at Siemens Dutch head quarter in The Hague, Princes Beatrixlaan 800. The men that was interviewed:

- Sven Overmeeren, Head of Primary Structure Design, Offshore Support Structures at Siemens

After a short introduction the following questions were answered.

What do you see as the biggest challenge in T&I of future turbines? And how to overcome this?
Closing the business case and taking all the risks in consideration are the most important drivers. Regarding T&I, I agree that the lifting height and weight of the nacelle are one of the biggest challenges. To overcome these problems, maybe splitting up the nacelle is an option, in this way the weight and size are reduced. However, an extra lift is needed and extra actions have to be done offshore at height, which are not desirable.

During the design of a turbine, how are T&I and maintenance taken into account?
Maintenance is really important, because you want to have as low as possible downtime, since you loose earnings when a turbine is not operating. Looking to T&I, it accounts for around 15% of the total CAPEX of a wind farm and it occurs only once in a life time. However, the faster a turbine is installed, the faster he starts earning money. Therefore Siemens has set up a 24-1 policy which means that we promise to install, test and commission one turbine in 24 hours. We do this by lifting the different components of a turbine separately and this is also why we prefer to keep the single blade installation sequence, since we optimized it for our clients.

Looking to Hywind project, where the topside of the turbine was installed in one lift, do you think that is possible for the bigger turbines?
This project was according to my information conducted because Statoil already hired the Saipem 7000 for a job for the installation of two topsides for oil and gas. Therefore, they had reduced costs for the ship, otherwise, installing turbines with a semi-submersible is too expensive. In general, if a turbine needs to be placed in one go, it first has to be constructed on a quay side and with the future turbines you therefore need a specialized built port with quay side. Furthermore, if it is transported, the workable weather window will go down since less movement is desired, which both results in even longer installation time since the wind farms move further offshore. Moreover, someone has to be accountable for the risks that have to be taken with the installation of a complete turbine. For Siemens, this is not the preferred way.

What do you think about floating vessel concepts in general for T&I?
This can be solution, the only thing is the stability. If you look to Boskalis, they just released the Bokalift 1 which can be used for offshore wind installation but more focusing on the foundation and not the height you need with the tower and nacelle.

If needed for stability or structural integrity during T&I, are alterations of the design of the tower/turbine possible?
Yes, but it has to be proven that it is beneficial for every project and not only one. As mentioned before, maybe alterations in the design of the nacelle can be made so it can be lifted in different lifts.
Another option is maybe to look into the split of foundation-transition piece-tower. This is still based on the oil and gas industry and maybe it is preferred to spread the sizes and weight more proportionally instead of a relative heavy foundation, light transition piece and tower. An example where it is the other way around, can be seen regarding the tower. During transport it is placed vertically on a frame which fits the flange perfectly which is designed for the connection with the transition piece.
So alterations are possible on the design but not preferred since we have start optimizing again from the beginning for design, construction and in the end also for T&I.

Things to keep in mind
The blades and hub are directly installed after the tower and nacelle since idling of the turbine can otherwise

result in damage on the bearings. And as mentioned before, the faster you can produce energy, the faster you start earning money.

A.3. Interview VanOord - 16 March 2018

The main goal of this meeting was to discuss ideas and challenges from the contractor's point of view regarding T&I. The men that was interviewed:

- Paul Vernimmen, Advisor Offshore Energy at VanOord

After a short introduction the following questions were answered.

Do you think that the current jack-ups are reaching their limits when, when thinking about the just announced turbine from GE, with a diameter of 220 meters and a hub height of around 150 meters?
Yes, maybe new concepts have to be developed to make it more stable, like a combination of a semi-submersible and a jack-up. There can be seen that the costs per MW to install a turbine is rising because of the immense capacity that is needed. However, I don't think the turbines will develop to 20MW. The current methods for installation can not guarantee that it still can be installed and although it is only a small part of the CAPEX, the installation still has to be done.

How are contractors looking into new methods, since the development of offshore wind is growing so rapidly?
Look to the idea of Seaway Heavy Lifting that consist of a mechanism that mounts the blades to the tower with a frame, to exclude the problems that blades give while lifting them to hub height. Only the tower has to be installed with the blades attached to it and the nacelle has to be placed on top. Subsequently, the blades can be installed without an extra crane, since the system can attach the blades via hydraulic pumps for example where after the nacelle is lined up with the next blade and the hub is turned in such a way that the second blade can be attached. "I think floating foundation is the future and maybe you will need total other concepts compared with the bottom founded support structures, I don't know exactly".

How are new ideas or concepts implemented in the offshore wind energy?
"The most difficult part is to make up a good business case. For example, Europe wants to install 4-5GW of offshore wind power per year, this consists of 250 turbines per year, where a ship nowadays needs 1 day to install a complete turbine plus one for the foundation and some days for transit. This results in 1 or 2 vessels if this number of turbines is indeed produced. Therefore, specialized vessels for 20MW turbines will bring a high risk since the investments costs will be around 300 million, which roughly results in a day rate of 300.000."

Things to keep in mind
"Partnerships with other companies will increase effective production and installation of offshore wind turbines. Due to this partnership, agreements can be made for a complete year where it is assured that all year long a certain amount of turbines and support structures need to be produced. In this case, support structure manufacturers, like SIF for monopiles or BEFAB for jackets (which approximately take one week each), knows they can fabricate support structures, the turbine manufacturer can produce a certain amount of turbines and a contractor knows that his ship has an order all year long. If the different manufacturers are assured they have a continuous demand all year long, they can produce more efficient."

"For example: if Siemens wants to produce 1GW of offshore wind energy per year, you need around 50 turbines of 20MW. This results in 1 turbine and 1 support structure per week on average. An upgraded Aeolus which can take 4 turbines per shipment, has to come by on average every month to pick up those turbines and install them. Since the Aeolus does not need 4 weeks to install 4 turbines, in the meantime it can install the support for the next four turbines"

B
Installation time sheets

The time that is required for a 20MW wind turbine to be installed offshore is determined by looking to the different tasks that are needed. The change in technique of lifting the different components reduces the height of lifting but requires more tasks to be done offshore. By preassembling as much as possible onshore reduces the number of lifts, but can increase the amount of tasks offshore as well. Based on the time analysis done by Strien (2011), a model has been set up to assess the different T&I concepts. Where Strien (2011) looked into the T&I of a 5MW turbine, an extrapolation is made to make it applicable for the 20MW turbines, where the used time steps are verified based on engineering knowledge within GustoMSC
In the sheets, an overview is given off all the tasks needed per concept, where it can be seen that some tasks are concept specific while others are coming back in every concept. A distinguish has been made between tasks that can only be performed after the previous task is finished and between tasks that can be performed simultaneously. This results in the installation time that is needed to install the turbine per concept. However, this does not take into account the offshore transport to the harbour and location.
It should be noted that time savings on the total installation time of an OWT can be achieved by executing as much as possible simultaneously, still taking into account the safety of the people.
The following time sheets are presented

1. Time sheet for the offshore installation process of a 5MW OWT with the 'Single Blade' method, based on values of (Strien, 2011, p.155).
2. Conversion table for the installation with the single blade method from a 5MW to a 20MW turbine.
3. Time sheet for the offshore installation process of a 20MW OWT with the 'Single Blade' method.
4. Time sheet for the offshore installation process of a 20MW OWT with the 'Jack-up frame'.

The time sheets have been removed from the report because of the non disclosure agreement (NDA) that has been signed between GustoMSC and the TU Delft. This NDA sets an embargo of 10 years on the report, which is longer than the standard embargo of the TU Delft repository of 4 years. If you want to see this section, please contact the author by the email address as stated on the title page.

C

Multi Criteria Analysis

This appendix gives more elaboration on the scores of the multi criteria analysis. Also a sensitivity analysis is conducted to see if the choice for the best concept will be changed if one of the criterion will be given a higher weighting factor.

This appendix gives more elaboration on the sensitivity analysis which is conducted to see if the choice for the best concept will be changed if one of the criteria will be given a higher weighting factor.

The different criteria are scored all between 1 and 5

Table C.1: Qualitative score per criteria

Criteria	Score description		
Technical complexity	complex or new technology	1- 5	not complex or already developed technology
Installation time	slow transport and installation	1 - 5	fast transport and installation
Modification to OWT design	no influence	1 - 5	big influence
Adaptability for different size turbines	not adaptable	1 - 5	adaptable

Based on the information presented in chapter 5, the score of the multi criteria analysis is presented in Table C.2.

Table C.2: MCA score

Criterion	Weight factor	Upscaling of jack-up method	Installation with floating solutions	Jack-up frame	Monopile lift
Technical complexity	0.250	4	3	3	2
Installation time	0.375	3	3	4	4
Modification to OWT design	0.125	5	4	3	3
Adaptability for different size turbines	0.250	3	3	4	4
Total	1	3.50	3.13	3.63	3.38

The four concept families are scored on each criterion. To get a result from the MCA, the different scores are multiplied by each weight factor respectively and added together. The result of this analysis is shown in Table C.2 and it can be seen that the 'Jack-up frame' is the most preferred concept based on the MCA.

Table C.3: Add caption

SENSITIVITY ANALYSIS							
sensitivity_factor			1.25				
WF_Technical complexity increase 25 %				Upscaling current method	Floating	Jack-up frame	Lifting out of MP
Old		New	Normalised				
	0.25	0.31	0.29	4	3	3	2
	0.38	0.38	0.35	3	3	4	4
	0.13	0.13	0.12	5	4	3	3
	0.25	0.25	0.24	3	3	4	4
	1.00	1.06	1.00	3.53	3.12	3.59	3.29
WF_Time efficient increase 25 %							
Old		New	Normalised				
	0.25	0.25	0.23	4	3	3	2
	0.38	0.47	0.43	3	3	4	4
	0.13	0.13	0.11	5	4	3	3
	0.25	0.25	0.23	3	3	4	4
	1.00	1.09	1.00	3.46	3.11	3.66	3.43
WF_Influence on design increase 25 %							
Old		New	Normalised				
	0.25	0.25	0.24	4	3	3	2
	0.38	0.38	0.36	3	3	4	4
	0.13	0.16	0.15	5	4	3	3
	0.25	0.25	0.24	3	3	4	4
	1.00	1.03	1.00	3.55	3.15	3.61	3.36
WF_Adaptability increase 25 %							
Old		New	Normalised				
	0.25	0.25	0.24	4	3	3	2
	0.38	0.38	0.35	3	3	4	4
	0.13	0.13	0.12	5	4	3	3
	0.25	0.31	0.29	3	3	4	4
	1.00	1.06	1.00	3.47	3.12	3.65	3.41

C.1. Sensitivity analysis

To see the influence of heightening the weighting factor, each criteria will be increased with 25% separately. After one criteria has been increased, all the criteria are normalised in such a way that the sum of weighting factors are still 1. Subsequently, the total score per concept is calculated and the outcome is presented below.

Now the result is known for increasing the different weighting factors, the results of the MCA's are listed together in Figure C.1 and it can be concluded that the jack-up frame is still the preferred concept, even if the weighting factors will change with 25%.

	Upscaling current method	Floating	Jack-up frame	Lifting out of MP
Original	3,50	3,13	3,63	3,38
WF_Technical complexity increase 25 %	3,53	3,12	3,59	3,29
WF_Time efficient increase 25 %	3,46	3,11	3,66	3,43
WF_Influence on design increase 25 %	3,55	3,15	3,61	3,36
WF_Adaptability increase 25 %	3,47	3,12	3,65	3,41

Figure C.1: Multi criteria analysis compared

D

Calculations

This appendix gives a more elaborated calculations and derivations which are used within the report. First the derivation of the thrust force and power formula is given in section D.1, used in chapter 2, section 2.3. section D.2 and section D.3 are elaborating on the sizing of the tower and the center of gravity of the OWT, used in chapter 2, section 2.6. section D.5 and D.4 provide more detailed information regarding the load and weight calculations presented in chapter 7.

D.1. Thrust force and power output

To see how energy is retrieved from the wind, a theoretical derivation has been performed. The amount of energy that can theoretically be taken from the wind can be calculated following the actuator disc theory and by looking to the decrease of wind speed, thereby reducing the kinetic energy in the wind, due to a wind turbine (Grogg, 2005; Gundtoft, 2009).
For simplicity, the following values for the wind speed are introduced:

- Far in front of the rotor, the wind speed is v_1.
- In the rotor plane the wind speed is v.
- After passing the rotor the wind speed is reduced to v_3.

The pressure distribution is changing as follow: the initial pressure is p_1, where as the air moves towards the rotor, the pressure rises to a pressure p_+, while passing the rotor the pressure directly drops with an amount Δp to p_- ($=p_+ - \Delta p$). After passing the rotor, the pressure stabilizes to p_3 which is again equal to p_1. The pressure curve is globally shown in Figure D.1.

To find a relation between the pressure p and wind speed v for the wind moving towards the rotor plane, Bernoulli's equation from fluid dynamics (D.1) can be used, assuming that the flow is frictionless, and a constant total pressure p_{total}.

$$\frac{1}{2}\rho v^2 + p = p_{total} \tag{D.1}$$

From this equation it can be stated that if the speed of the flow goes down, the pressure goes up and the other way around.

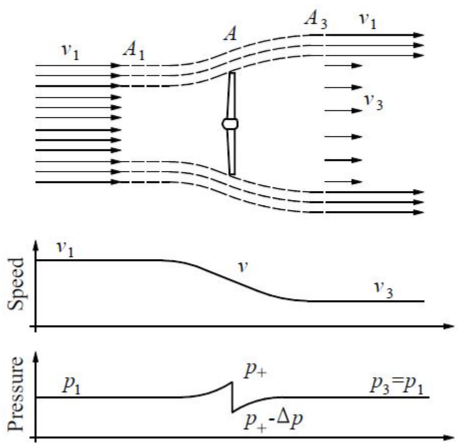


Figure D.1: Stream tube around a rotor, change in wind speed and pressure difference (Gundtoft, 2009, p.3).

It is assumed that the density ρ is constant, because of the relative small change in pressure compared with the pressure of the flow. Under this assumption and using (D.1), the pressure for the flow up stream (in front of the turbine) (D.2) and down stream (behind the turbine) (D.3) can be calculated

$$p_1 + \frac{1}{2}\rho v_1^2 = p_+ + \frac{1}{2}\rho v^2 \tag{D.2}$$

$$p_+ - \Delta p + \frac{1}{2}\rho v^2 = p_1 + \frac{1}{2}\rho v_3^2 \tag{D.3}$$

To find an expression for difference in pressure (Δp), (D.3) is subtracted from (D.2)

$$\Delta p = \frac{1}{2}\rho(v_1^2 - v_3^2) \tag{D.4}$$

Change of momentum on a particle can be written as

$$p = mv \tag{D.5}$$

where m is the mass and v is the speed of the particle.

Following Newtons second law for the force:

$$F = \frac{dp}{dt} \tag{D.6}$$

and combining it with the assumption that the mass stays equal and (D.5)

$$F = m\frac{dv}{dt} = ma \tag{D.7}$$

where a is the acceleration of the particle. Introducing the mass flowing per unit time, q_m, which equals the total mass flowing through an area with a certain speed and density for some duration, the force that is needed to slow the wind down from v_1 to v_3 can be calculated:

$$F = q_m(v_1 - v_3) \tag{D.8}$$

where

$$q_m = Av\rho \tag{D.9}$$

Combining (D.8) with the fact that the force is equal to the change in pressure divided by the area it follows that:

$$\Delta p = \frac{q_m(v_1 - v_3)}{A} = \rho v(v_1 - v_3) \tag{D.10}$$

From combining Equation D.4 and (D.10) and that $v_1^2 - v_3^2 = (v_1 - v_3)(v_1 + v_3)$ it can be concluded that

$$v = \frac{1}{2}(v_1 + v_3) \tag{D.11}$$

which shows that the wind speed at the rotor plan is equal to the mean value of the wind speed up stream and down stream.

To calculate the thrust force on the rotor, F_{thrust}, the change of pressure (D.10) can be multiplied by the area of the rotor, A_{rotor}

$$F_{thrust} = \Delta p A_{rotor} = v\rho(v_1^2 - v_3^2)A_{rotor} = \frac{1}{2}\rho A_{rotor}(v_1^2 - v_3^2) \quad \text{(D.12)}$$

The power of the turbine can be calculated by multiplying F_{thrust} with v_{wind} at the rotor plane (Grogg, 2005, p.9)

$$P = F_{thrust}v = \frac{1}{2}\rho A_{rotor}v(v_1^2 - v_3^2) \quad \text{(D.13)}$$

In order to characterize OWT's, an induction factor a is introduced (Grogg, 2005; Gundtoft, 2009) which is the fractional decrease in wind velocity when it reaches the rotor:

$$a = \frac{v_1 - v}{v_1} \quad \text{(D.14)}$$

Using Equation D.11, an expression can be found for v_1 and v_3, respectively:

$$v = v_1(1-a) \quad \text{(D.15)}$$

$$v_3 = v_1(1-2a) \quad \text{(D.16)}$$

Using (D.16) results that (D.13) and (D.12) can be rewritten:

$$P = 2\rho a(1-a)^2 v_1^3 A \quad \text{(D.17)}$$

$$F_{thrust} = 2\rho a(1-a)v_1^2 A \quad \text{(D.18)}$$

Subsequently by defining two coefficients, one for the power, C_P, and one for the thrust force, C_T, which can be written as a function of the induction factor and are visualized in Figure D.2:

$$C_T = 4a(1-a) \quad \text{(D.19)}$$

$$C_P = 4a(1-a)^2 \quad \text{(D.20)}$$

(D.18) and (D.17) become

$$F_{thrust} = \frac{1}{2}\rho C_T v_1^2 A \quad \text{(D.21)}$$

$$P = \frac{1}{2}\rho C_P v_1^3 A \quad \text{(D.22)}$$

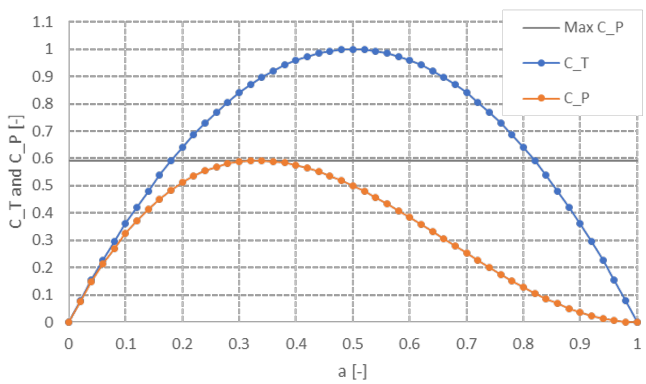
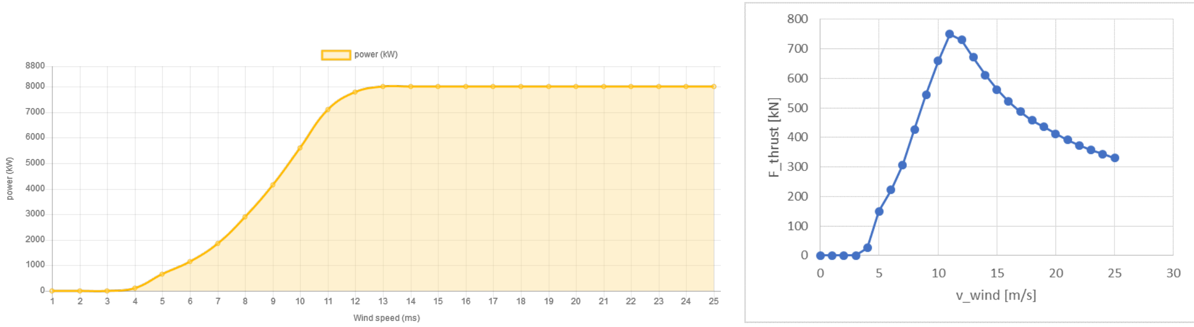


Figure D.2: Thrust and power coefficient as function of the induction coefficient

By comparing the theoretical power curve to the one of the V164-8.0, currently one of the biggest installed and operational OWT, it can be seen that the power curve is kept constant after a certain wind speed, the so called rated wind speed (13m/s for the V164-8.0).



(a) Power curve (Wind turbine models, 2017)

(b) Thrust force

Figure D.3: Power curve and thrust force V164-8.0 plotted against wind speed

It be concluded that the theoretical value for C_P and a, and therefore C_T, are not as presented in Figure D.2 for a operating turbine. This is the result of pitching the blades in such a way that the rated power is kept constant above the rated wind speed. As a result, the thrust force is at its maximum at rated wind speed and after that gradually decreases with increasing wind speed, until the cut-out wind speed of 25m/s has been reached. When the cut-out wind speed is exceeded, the turbine stops generating energy and is pitched out of the wind completely to prevent the turbine from breaking down. The force generated by the wind is kept as low as possible and it can be assumed that it is lower than the thrust force at rated wind speed.

D.2. Stresses in tower

The diameter and wall thickness of the tower are determined by taking into account the maximum allowable stress in the tower and the loads that are acting on it. The OWT is not only loaded by the thrust force but also by the wind that is acting on the tower and by the weight of the RNA and the tower.

This horizontal load created by the wind is dominated by drag and can be calculated following Equation D.28. For the stress calculation in the tower, a wind speed of 15m/s is used and a value of 1.5 for the drag coefficient (C_D) (van der Male and Haghi, 2017, p.51). The horizontal forces create an overturning moment in the tower that is growing from hub height to the base of the tower. The vertical loading is directly transferred to the support structure via the tower. Both are creating stresses in the tower which are not allowed to exceed 55% of the yield stress (195.25N/mm^2) to have a safe OWT.

The following iteration has been performed to determine the diameter and wall thickness of the tower:

1. A diameter and wall thickness for the top and bottom of the tower have been chosen based on extrapolation of the towers of current OWTs.. As first input, for the top a diameter of 5m and wall thickness of 50mm has been chosen and for the bottom a diameter of 7m with a wall thickness of 70mm has been chosen, resulting in a D/t ratio of 1/100.
2. The tower is segmented into pieces of 10m to take into account the growth in diameter and wall thickness over the height linearly
3. The area is calculated based on the average diameter and wall thickness of each segment.

$$A_{segment} = \frac{1}{4}\pi((D_{average}+t)^2 - (D_{average}-t)^2) \quad (D.23)$$

4. The moment of inertia is calculated.

$$I_{tower} = \frac{1}{64}\pi((D_{average}+t)^4 - (D_{average}-t)^4) \quad (D.24)$$

5. The mass per segment is calculated by multiplying the area with the segment length and the density of steel.

$$W_{segment} = A_{segment} l_{segment} \rho_{steel} \tag{D.25}$$

6. The vertical force of each segment is calculated by multiplying the weight per segment by the gravity acceleration. The total vertical force per segment is calculated by summing the mass of all the segments above plus the mass of the RNA.

$$F_z = (W_{RNA} + \sum W_{segment}) * g \tag{D.26}$$

7. The vertical force is divided by the cross sectional area to get the axial stresses due to the vertical force in the tower.

$$\sigma_{axial} = \frac{F_z}{A_{segment}} \tag{D.27}$$

8. The loads due to wind per segment is calculated (Equation D.28) and by multiplying it with the length of each segment, the moment is obtained. Where the diameter of the tower, D_{tower} is changing over the height of the tower.

$$F_{wind} = \frac{1}{2} C_D \rho_{air} v_{wind}^2 D_{tower}(z) l_{segment} \tag{D.28}$$

9. To calculate the total moment in a segment, the thrust force on the RNA is multiplied by its respective arm to that segment and the moments generated by the wind are added together per segment (Equation D.29). l(z) represents the distance from the hub to the respective segment. In the last segment this is equal to the hub height.

$$M_{overturning} = F_{thrust} l(z) + F_{wind} l_{segment} \tag{D.29}$$

10. The bending stress is calculated, following Equation D.30.

$$\sigma_{bending} = \frac{M_{overturning} D_{segment}}{2I} \tag{D.30}$$

11. The axial and bending stress are added together to see what the total stress per segment will be (Table D.1).
12. By changing the diameter and wall thickness of the tower in such a way that the total stress is lower than the maximum allowable stress, the final D and t were found.

In Table D.1 the outcome of the final iteration is shown, resulting in a tower with a bottom diameter of $8m$ and wall thickness of $80mm$ and gradually decreasing to the top with a diameter of $5.5m$ and a wall thickness of $50mm$. Growth in turbine capacity leads to growth in dimensions and mass of the tower, which is also confirmed by looking into previous data of turbines provided by turbine manufacturers. However, the diameter and wall thickness of the tower is not only determined by the loads it has to withstand, but also by requirements on how to react on the different loads [1]. They are influenced by the structural dynamics of the tower, which is characterized by among others the natural frequency and mass of the tower, which is in his turn influenced by the diameter, wall thickness, length and type of material of the tower. This is something that is not taken into account when making an estimation for the mass since it is site specific, a complicated process, influenced by the support structure and since it is more into optimizing the turbine itself instead of the T&I methods, which is out of the scope of this research.

D.3. Dimensions of OWT components

The characteristics of the $20MW$ turbine are listed in Table D.2 following the axis convention depicted in Figure D.4. The tower segments are given with their average diameter.

[1] This was substantiated in an interview with Maël Gormand, a colleague within GustoMSC and an expert on load calculations on turbine and tower by wind

Table D.1: Weight and stresses in tower

Segment	zbot [m]	length [m]	ztop [m]	Dbot [m]	Dtop [m]	Daverage [m]	t [m]	D/t [-]	A [m^2]	mass [kg]	M_RNA [Nm]	F_wind_tower [N]	M_wind [Nm]	M_total [Nm]	F_z [N]	I [m^4]	sig_ax [N/mm^2]	sig_bend [N/mm^2]	sig [N/mm^2]	sig(bend/tot) [N/mm^2]	Max stress [N/mm^2]
1	130	10	140	5.68	5.50	5.59	0.0521	107	0.916	71874	2.44E+07	1.16E+04	1.16E+05	2.45E+07	1.35E+07	3.576	14.78	19.43	34.21	0.57	195.25
2	120	10	130	5.86	5.68	5.77	0.0543	106	0.984	77218	4.87E+07	1.19E+04	1.19E+05	4.89E+07	1.43E+07	4.091	14.53	35.04	49.57	0.71	195.25
3	110	10	120	6.04	5.86	5.95	0.0564	105	1.054	82751	7.31E+07	1.23E+04	1.23E+05	7.34E+07	1.51E+07	4.660	14.33	47.55	61.88	0.77	195.25
4	100	10	110	6.21	6.04	6.13	0.0586	105	1.127	88473	9.74E+07	1.27E+04	1.27E+05	9.79E+07	1.60E+07	5.286	14.17	57.55	71.72	0.80	195.25
5	90	10	100	6.39	6.21	6.30	0.0607	104	1.202	94384	1.22E+08	1.30E+04	1.30E+05	1.22E+08	1.69E+07	5.972	14.06	65.50	79.55	0.82	195.25
6	80	10	90	6.57	6.39	6.48	0.0629	103	1.280	100483	1.46E+08	1.34E+04	1.34E+05	1.47E+08	1.79E+07	6.724	13.97	71.77	85.74	0.84	195.25
7	70	10	80	6.75	6.57	6.66	0.0650	102	1.360	106771	1.70E+08	1.38E+04	1.38E+05	1.71E+08	1.89E+07	7.544	13.92	76.67	90.59	0.85	195.25
8	60	10	70	6.93	6.75	6.84	0.0671	102	1.443	113248	1.95E+08	1.41E+04	1.41E+05	1.96E+08	2.00E+07	8.436	13.89	80.43	94.32	0.85	195.25
9	50	10	60	7.11	6.93	7.02	0.0693	101	1.528	119913	2.19E+08	1.45E+04	1.45E+05	2.20E+08	2.12E+07	9.405	13.89	83.26	97.15	0.86	195.25
10	40	10	50	7.29	7.11	7.20	0.0714	101	1.615	126768	2.44E+08	1.49E+04	1.49E+05	2.45E+08	2.25E+07	10.455	13.91	85.32	99.23	0.86	195.25
11	30	10	40	7.46	7.29	7.38	0.0736	100	1.705	133811	2.68E+08	1.52E+04	1.52E+05	2.69E+08	2.38E+07	11.590	13.95	86.74	100.68	0.86	195.25
12	20	10	30	7.64	7.46	7.55	0.0757	100	1.797	141042	2.92E+08	1.56E+04	1.56E+05	2.94E+08	2.52E+07	12.816	14.00	87.63	101.63	0.86	195.25
13	10	10	20	7.82	7.64	7.73	0.0779	99	1.891	148463	3.17E+08	1.60E+04	1.60E+05	3.18E+08	2.66E+07	14.135	14.07	88.09	102.16	0.86	195.25
14	0	10	10	8.00	7.82	7.91	0.0800	99	1.988	156072	3.41E+08	1.64E+04	1.64E+05	3.43E+08	2.81E+07	15.554	14.16	88.18	102.34	0.86	195.25
												1.95E+05									

Table D.2: Dimensions turbine components, axis according Figure D.4

Component	Mass [t]	x [m]	y [m]	z [m]
Blade (x3)	80	120	6.6	9
Hub	98	10	10	10
Nacelle	1000	20	15	15
Tower s1	515	6	6	60
Tower s2	467	7	7	40
Tower s3	579	7.8	7.8	40

The center of gravity (CoG) of the different components in their local axis system and in the global axis system is listed in Table D.3. The CoG of the RNA and total turbine can be calculated based on the local CoGs of the components. The distance of the x-coordinate of the CoG of the RNA is calculated using Equation D.31 and is with respect to the axis convention of the nacelle (see bottom two pictures of Figure D.4). First the masses of each component is multiplied by its respective distance to the z-axis and then the total is divided by the total mass of the RNA. The assumption was made that the z-coordinate of the CoG of the rotor is in the CoG of the hub. This can differ, but since the mass of the blades is small with respect to that of the nacelle, it will not have a big influence on the final outcome. The nacelle has its CoG not in the middle of the component, but more shifted towards the sight were the hub is connected, this because of the heavy shaft and components that connect the components to each other.

$$x = \Big(1000 \cdot 15 + 98 \cdot (20+5) + 3 \cdot 80 \cdot (20+5)\Big)/1338 = 17.52 \tag{D.31}$$

The RNA is mounted on the tower in such a way that the CoG is just in front of the tower. In this way, if the turbine is operating, it is located approximately above that of the tower. The CoG of the total OWT has been calculated following Equation D.32: multiplying each of the masses of the components by its respective vertical distance to the base of the tower (last column in Table D.3) and dividing it by the total mass.

$$z = \Big(515 \cdot 20 + 467 \cdot 60 + 579 \cdot 110 + 1000 \cdot 145 + 98 \cdot 145 + 3 \cdot 80 \cdot 145\Big)/2899 = 100.12 \tag{D.32}$$

Table D.3: Center of gravity of component, axis according to Figure D.4 and D.5a

Component	Mass [t]	x [m]	y [m]	z [m]	z (w.r.t. base tower)
Blade (x3)	80	37	0	3.6	-
Hub	98	5	0	5	145
Nacelle	1000	15	0	5	145
Tower s1	515	0	0	30	110
Tower s2	467	0	0	20	60
Tower s3	579	0	0	20	20
RNA	1338	17.52	-	5	145
Total OWT	2899	-	-	100.12	100.12

Assuming that the weight of the nacelle is positioned above the tower, the RNA has an eccentricity of $2.52m$ with respect to the CoG of the tower.

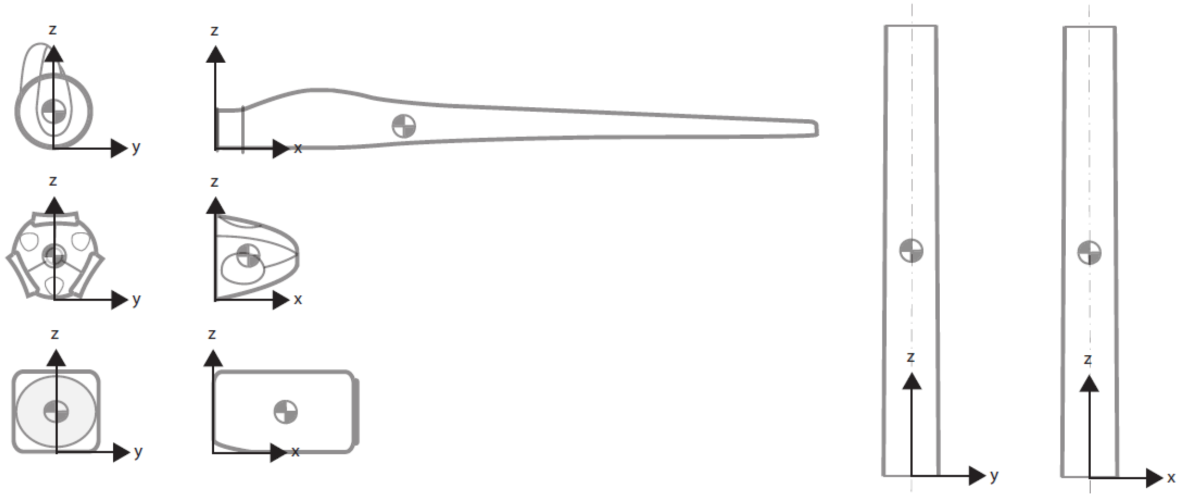
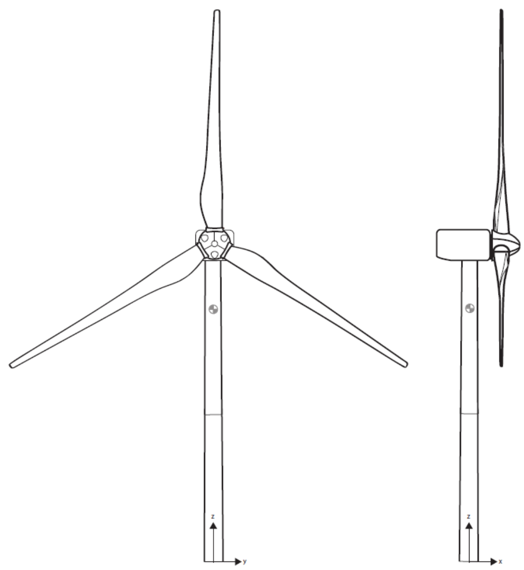
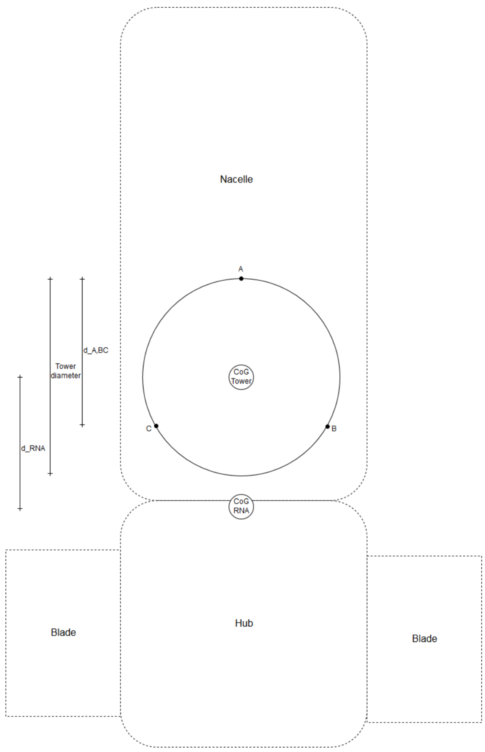


Figure D.4: Axis convention of the different components



(a) Axis convention of the total offshore wind turbine



(b) Topside tower with CoG of tower and RNA

Figure D.5: CoG configurations

In Figure D.5b the governing distances are named which later will be used for calculating the loads in the clamp connections A, B and C.

D.4. Weight estimation

This section has been removed from the report because of the non disclosure agreement (NDA) that has been signed between GustoMSC and the TU Delft. This NDA sets an embargo of 10 years on the report, which is longer than the standard embargo of the TU Delft repository of 4 years. If you want to see this section, please contact the author by the email address as stated on the title page.

D.5. Load calculation

The loads acting on the OWT during installation are calculated to be able to give an estimation regarding the loads that have to be withstand. The loads that are acting on the lift frame caused by the OWT can mainly be split up in four components:

1. Loads due to the mass of the tower
2. Loads due to wind acting on the tower
3. Loads due to wind acting on the RNA
4. Loads due to mass of the RNA

A brief elaboration on each of the loads is given below

Loads due to mass of turbine

The load of the turbine consist of the parts that are jacked up by the lift frame. The governing case is when the total turbine is lifted with a mass of 2899 tonne, calculated in Table D.3. With a gravity acceleration of $9.81 m/s^2$ this results in a vertical force of $28.4 MN$.

Loads due to wind on tower

The loads acting on the tower are calculated already when determining the diameter and wall thickness of the tower, see Table D.1. By multiplying the wind force on each segment with the distance to the bottom of the tower, a total overturning moment of 12.8 MNm at the bottom of the tower is obtained. A constant wind speed of $15 m/s$ is assumed. This is a little bit conservative since the wind speed will be a little bit lower closer to the sea surface, based on the wind principles explained in section 2.3.

Loads due to wind on RNA

During installation, the load acting on the RNA is not equal to the thrust force, since the rotor is not yet rotating and therefore no dynamic forces are generated. Therefore, not the force calculated for determining the diameter and wall thickness of the tower can be used, since this would be too conservative. To have a good estimation of the wind load on the RNA, the following steps were made:

1. The blades are represented by triangles that have the length of the blade ($120m$) as height and the width of the chord diameter ($9m$) as base.
2. The hub is represented by a disc with a diameter that is the same as that of the hub ($10m$)
3. The total area is calculated by the following equation:

$$Area_{rotor} = 3 \cdot \frac{1}{2} \cdot l_{blade} \cdot w_{blade} + \frac{1}{4}\pi \cdot D_{hub}^2 = 1698.54 m^2 \tag{D.33}$$

4. The wind force is calculated with

$$F_{wind} = \frac{1}{2} C_D \cdot \rho_{air} \cdot v_{wind}^2 \cdot Area_{rotor} = 0.35 MN \tag{D.34}$$

   Where

   - A value of 1.5 has been chosen for C_D, based on (van der Male and Haghi, 2017, p.51).
   - A wind speed has been chosen of 15 m/s ,based on the input stated in the context study in chapter 2.

5. By multiplying this force by the hub height ($145m$) a moment at the bottom of the tower is calculated of 50.91 MNm

Loads due to mass of RNA

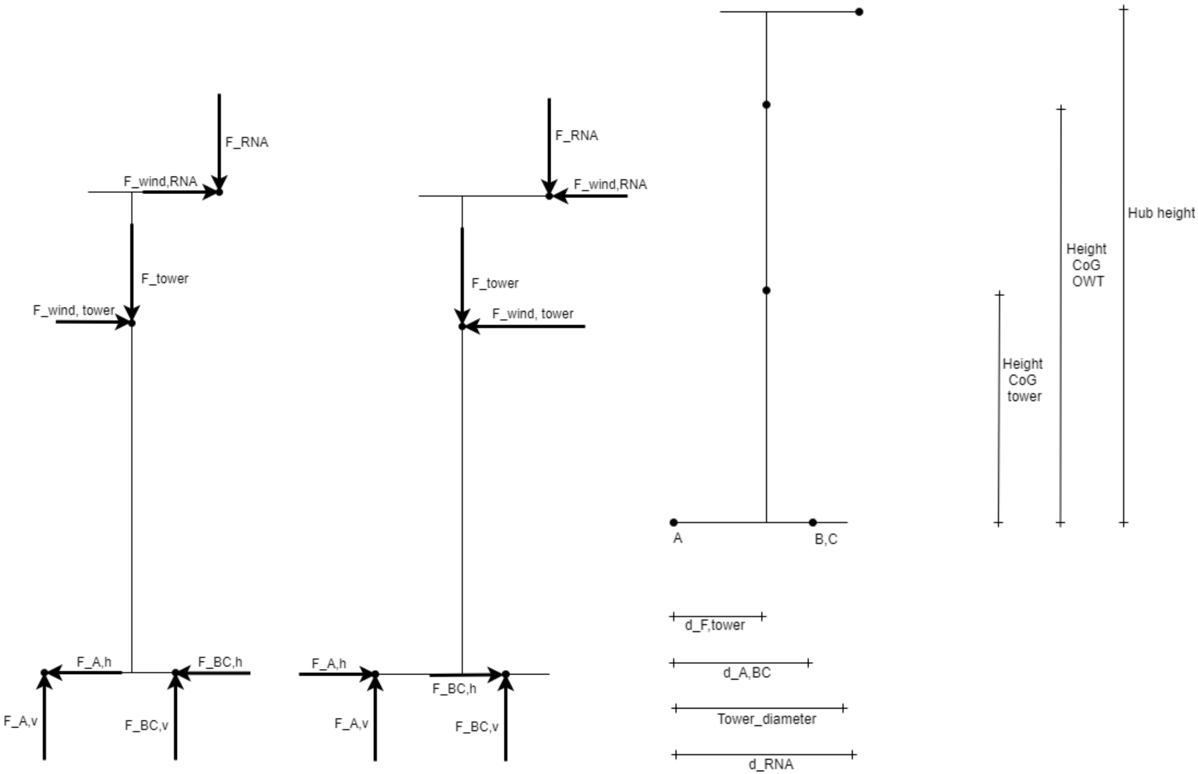
Not only the gravitational force has to be taken into account, also the moment due to eccentricity of the CoG of the RNA with respect to the CoG of the OWT. The arm of this moment is equal to this eccentricity, which was calculated in section D.3 and equals $2.52m$, where the load is equal to the mass of the RNA (1388 $tonne$) multiplied by $9.81 m/s^2$. Resulting in a moment of $13.13 MNm$

D.6. Loads in clamp connection

To calculate the maximum force in the lift frame, two load cases are considered as most extreme:

1. The wind is acting from the south when the complete OWT is lifted, where the wind loads acting on the RNA and tower are creating a moment in the same direction of the moment that is created by the eccentricity of the RNA, depicted in Figure D.6a.
   Since the tower will try to rotate around a line that goes through connection B and C, a maximum vertical loading downwards is expected in clamp connection B and C.
2. The wind is acting from the north when the complete OWT is lifted, where the wind loads result in a moment that is countering the moment introduced due to eccentricity of the mass of the RNA, depicted in Figure D.6b.
   Since the tower will try to rotate around clamp connection A, a maximum vertical loading downwards is expected in clamp connection A.

In Figure D.6a and D.6b the wind is shown as point load, however in the calculation the wind on the tower is calculated in segments and multiplied by its respective length to the bottom of the tower to get the overturning moment.



(a) Loadcase 1 (b) Loadcase 2 (c) Governing distances

Figure D.6: Free body diagrams of governing load cases

For both load cases, the addition of the different loads can be downwards or upwards, resulting in a force pushing on or pulling at the clamp connection respectively. Resulting in Table D.4 and D.5 for load case one and two respectively.

Table D.4: Addition of loads on clamp connection for load case 1, + is pull − is push

Connection	F_{OWT}	F_{RNA}	$F_{wind,tower}$	$F_{wind,RNA}$
A	-	+	+	+
B	-	-	-	-
C	-	-	-	-

Table D.5: Addition of loads on clamp connection for load case 2, + is pull − is push

Connection	F_{OWT}	F_{RNA}	$F_{wind,tower}$	$F_{wind,RNA}$
A	-	+	-	-
B	-	-	+	+
C	-	-	+	+

For load case 1, the moment equation around connection BC is calculated and set to 0, together with the the sum of vertical forces had to equal 0. For load case 2, the moment equation around connection A is calculated and set to 0 and here the sum of vertical forces had to equal 0 as well. Resulting in the following reaction forces in the clamp connections for load case 1 and load case 2 (Table D.6). For both load cases a wind speed of 15 m/s is used as input, based on the input stated in section 2.7.

Table D.6: Reaction forces in the clamp connection for load case 1 and 2 in MN with a wind speed of 15m/s

Load case	$F_{a,v}$	$F_{b,v}$	$F_{c,v}$
1	+7.79	-18.12	-18.12
2	-15.70	-6.37	-6.37

From here it can be concluded that load case 1 is governing. What is remarkable, is that the wind loads and the eccentricity of the mass of the RNA exceed the force introduced by the mass of the tower in load case 1. This results in a required pull force in clamp connection A. This requires therefore a restriction not only at the bottom of the external flange, but also at the top of the flange to prevent the total turbine from rotating during installation. The load of 18.12 MN in connection B and C is taken as governing during installation for all the clamp connections.

For survival conditions, a wind speed of 20 m/s is used as input for the loading of the turbine. It is stated that lifting operations can be stopped at this wind speed, but the installation frame still needs to be able to keep the tower stable. This resulted in Table D.7.

Table D.7: Reaction forces in the clamp connection for load case 1 and 2 in MN with a wind speed of 20m/s

Load case	$F_{a,v}$	$F_{b,v}$	$F_{c,v}$
1	+16.93	-22.68	-22.68
2	-24.83	-1.80	-1.80

For survival conditions, load case 2 becomes governing, resulting in a reaction force required in connection A of 24.83 MN. This can be explained, by the increase of wind speed and therefore an increase of overturning moment caused by the wind loads while the mass of the tower does not change. Moreover, while clamping connection B and C are dividing the required reaction force, clamp connection A has to take all the force by its own and in this case this exceeds that of connection B and C.

To see if the tower needs to be restrained in the horizontal plane by the clamp connection, a check is performed based on friction. If the horizontal wind loads exceed the friction introduced by the total mass of the OWT, a restrain is required. The mass of 2899 t results that the horizontal loads introduced by a wind speed of 15 m/s exceed the 2.85 MN only if the friction coefficient is lower than 0.02. This is far lower than the friction coefficient for steel on steel of 0.5 and therefore, horizontal restriction is not necessary based on this calculation.

D.7. Load checks

This section has been removed from the report because of the non disclosure agreement (NDA) that has been signed between GustoMSC and the TU Delft. This NDA sets an embargo of 10 years on the report, which is longer than the standard embargo of the TU Delft repository of 4 years. If you want to see this section, please contact the author by the email address as stated on the title page.

E

Idea and concept generation

This appendix gives an overview of first ideas that came up in the beginning of the research. Some of them are used in the development of sub solutions for the functions of the morphological chart. In

E.1. Idea generation

During the project, the following ideas where generated as solutions for different sub functions of the T&I process.

Load out from quay

1. Roll-on/roll-of: ride the different components of the turbine on the ship with self-propelled modular transporter instead of lifting the different components with a crane. You can elevate the ship till a certain height so you can ride everything directly in the ship.

Transport

1. Use the floating capacity of the towers to let the ship float.
2. Put the towers horizontal on the ship.
3. Put the tower inside the leg of the jack-up, or use leg as support for tower during transport
4. Flexible deck configurations
5. New blade rack design to save space. For example, during transport from fabrication yard to load out area blades are placed mirrored with respect to each other.
6. Take a cantilever jack-up with you that can be functioning as a feeder barge

Installation sequence

The different sequences that can be distinguished are:

- Single blade and two tower segments
- Single blade with one tower segment
- Bunny ear method
- Complete rotor lift, nacelle and tower separate
- Complete RNA including part of tower
- Complete turbine lift

Installation method

1. Floating installation of wind turbine. Tower partially filled with water which will submerge, then nacelle is installed with blades in horizontal plane and tower is de-ballasted slowly so the tower comes out of the water and the nacelle is turned vertically afterwards. Stability and influence of waves on structure is a challenge.
2. From a vessel. Put first tower segment together with nacelle in water, lift it by pumping in air and place next segment underneath it. Stability in water is an issue

3. Jacking up on the tower itself, install the first section together with nacelle and hub and subsequently jack up in pieces of 5 - 10 meters. No need for high hub height. Offshore activity is rather high.
4. Construct the RNA already on deck and place it in one lift (See sketches)
5. Floating turbine that is towed to the location of installation and installed by sinking the foundation to the seabed (only gravity based foundations are possible) **[also for transportation]**

Lifting with air pressure
This is based on buoyancy. If you push something in the water where there is still air inside (like a cup) it is pushed out of the water if you stop pressing it down. A problem here is that it is hard to be controlled: the buoyancy force keeps acting on the structure so the structure keeps accelerating upwards and this force is not acting in the center of gravity of the structure.
Things for further research

- If lifting is even possible with air pressure
- Influence of waves, currents and wind on this process.

Advantages

- No need of high and heavy lift

Disadvantages

- Unstable due to fluctuating pressure
- Upward pushing force from water keeps accelerating the mass.
- Tower has to be completely sealed so no air can escape.

Rail on turbine tower
This solution is mainly focusing on getting the nacelle to the top without the need of lifting the heavy mass of around 1000 tonnes to 180 meters height. The idea consists of a rails that is mountable to the tower of the turbine where a frame is attached on. This frame is pulled up by a cable that is attached at a winch in the top of the tower and is pushed from below to lower the tension force in the cable.
Things for further research

- Buckling of tower due to load.
- More detailed load calculation.
- Rotation (and if necessary lifting)of the loads at the top of the tower.
- Connection between ship and tower.

Advantages

- No heavy and high lift is needed
- The different parts are already guided and the relative movement of the different parts with respect to the turbine are terminated.

Disadvantages

- Rails have be attached and detached to and from the tower
- Winch has to be attached and detached to and from the top of the tower.
- Adjustment of tower is probably needed or new design is preferred.

Handling of OWT components

1. Drones to install or guide the blades .
2. Different tools for guiding.
3. Sliding system to overcome problems of movement with crane.
4. Guide the parts via a rails on the crane, to make the lift faster a part of the weight can be pushed.
5. Guidance by tower of turbine.

General design ideas

1. Create sleeping cabins not at one place, so more deck space is available - constraints can be noise, hallways, etc.
2. Design everything in format of containers, if something is not needed, you can replace it faster. More adaptable to changes

E.2. Concept generation

The different concepts that are generated based on the morphological chart.

Up scaling jack-up method

Function	Sub-solutions				
Load out from quay	**Crane from ship**	Roll-on/roll-off	Flipping	Crane from quay	
Transport	Barge	**On installation ship**	Floating turbine	Helicopter	Drones
Eliminate motions	(D)GPS	Manual	Tug lines	Rigid connection with heave compensation	**Stand on seabed**
Installation sequence	**Single blade (5 lifts)**	Bunny ear (4 lifts)	Complete rotor (3 lifts)	RNA (2 lifts)	Complete turbine (1 lift)
Installation method	**Lift**	Push	Pull up	Float over	Ballasting
Handling of OWT components	**Tug lines**	Rail on tower	Drones	Extra structure	None

Figure E.1: Upscaling jack-up vessel

RNA on deck

Function	Sub-solutions				
Load out from quay	**Crane from ship**	Roll-on/roll-off	Flipping	Crane from quay	
Transport	Barge	**On installation ship**	Floating turbine	Helicopter	Drones
Eliminate motions	(D)GPS	Manual	Tug lines	Rigid connection with heave compensation	**Stand on seabed**
Installation sequence	Single blade (5 lifts)	Bunny ear (4 lifts)	Complete rotor (3 lifts)	**RNA (2 lifts)**	Complete turbine (1 lift)
Installation method	**Lift**	Push	Pull up	Float over	Ballasting
Handling of OWT components	**Tug lines**	Rail on tower	Drones	Extra structure	None

Figure E.2: Concept generation of 'RNA on deck'

Monopile lift

Function	Sub-solutions				
Load out from quay	**Crane from ship**	Roll-on/roll-off	Flipping	Crane from quay	
Transport	Barge	**On installation ship**	Floating turbine	Helicopter	Drones
Eliminate motions	(D)GPS	Manual	Tug lines	**Rigid connection with heave compensation**	Stand on seabed
Installation sequence	Single blade (5 lifts)	Bunny ear (4 lifts)	Complete rotor (3 lifts)	**RNA (2 lifts)**	Complete turbine (1 lift)
Installation method	Lift	Push	**Pull up**	Float over	Ballasting
Handling of OWT components	Tug lines	Rail on tower	Drones	Extra structure	**None**

Figure E.3: Concept generation of 'Monopile lift'

Everything separate

Function	Sub-solutions				
Load out from quay	Crane from ship	Roll-on/roll-off	Flipping	Crane from quay	
Transport	Barge	On installation ship	Floating turbine	Helicopter	Drones
Eliminate motions	(D)GPS	Manual	Tug lines	Rigid connection with heave compensation	Stand on seabed
Installation sequence	Single blade (5 lifts)	Bunny ear (4 lifts)	Complete rotor (3 lifts)	RNA (2 lifts)	Complete turbine (1 lift)
Installation method	Lift	Push	Pull up	Float over	Ballasting
Handling of OWT components	Tug lines	Rail on tower	Drones	Extra structure	None

Figure E.4: Concept generation of 'everything separate'

Jack-up frame

Function	Sub-solutions				
Load out from quay	Crane from ship	Roll-on/roll-off	Flipping	Crane from quay	
Transport	Barge	On installation ship	Floating turbine	Helicopter	Drones
Eliminate motions	(D)GPS	Manual	Tug lines	Rigid connection with heave compensation	Stand on seabed
Installation sequence	Single blade (5 lifts)	Bunny ear (4 lifts)	Complete rotor (3 lifts)	RNA (2 lifts)	Complete turbine (1 lift)
Installation method	Lift	Push	Pull up	Float over	Ballasting
Handling of OWT components	Tug lines	Rail on tower	Drones	Extra structure	None

Figure E.5: Concept generation of 'Jack-up frame'

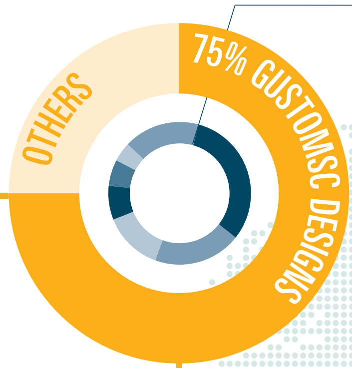
F
Data sheets

GustoMSC

NORTH SEA WIND INSTALLATION GUSTOMSC MARKET SHARE 2010 UP TO JANUARY 2018

NG-9000C 37,2%
SEA INSTALLER, SEA CHALLENGER
BRAVE TERN AND BOLD TERN

NG-20000X

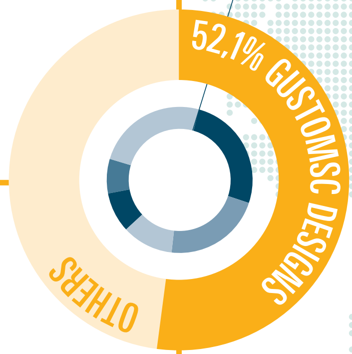


INSTALLATION OF OFFSHORE WIND TURBINES BY CONTRACTOR

31% A2SEA
20% MPI Offshore
14% Fred. Olsen Windcarrier
7% Seajacks
6% Van Oord
5% GeoSea
17% Others

OLEG STRASHNOV

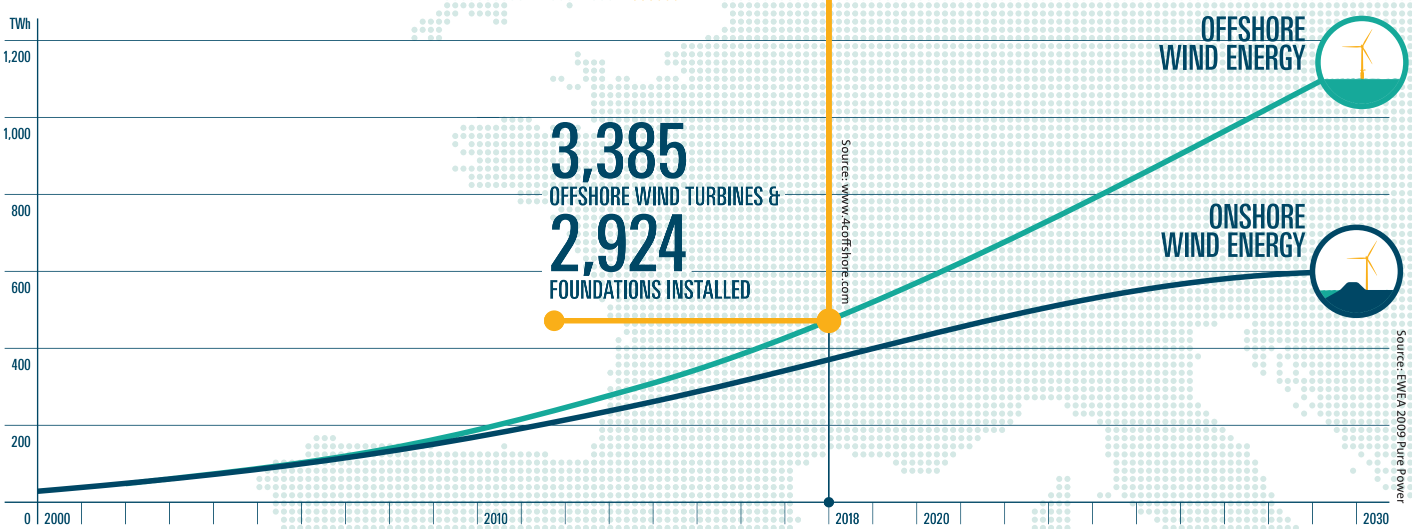
ENSIS



INSTALLATION OF TURBINE FOUNDATIONS BY CONTRACTOR

26% GeoSea
22% Van Oord
11% Seaway Heavy Lifting
9% MPI Offshore
8% Boskalis
24% Others

DEVELOPMENT AND PROJECTION OF ON- AND OFFSHORE WIND FARMS



SEAJACKS SCYLLA

seajacks.com

SEAJACKS SCYLLA

The newest member of the Seajacks fleet, delivered in October 2015, is a state of the art wind turbine foundation & installation vessel. With the largest deck space, leg length and lifting capacity of our fleet, Scylla has been specifically designed for deeper water larger wind farm components.

CLASSIFICATION AND RULES

Type: GustoMSC NG14000X
Built: Q4 2015
Yard: Samsung Heavy Industries
Class: ABS A1 Self-elevating Unit + AMS + ACCU + DPS 2, Self Propelled, Helideck + Wind IMR
Flag: Panama

MAIN DIMENSIONS

Hull

Length (Maindeck:	139m
Width:	50m
Hull depth:	11m
Draft:	6m to hull (7.8m inc. Spudcan Pins)
Main deck area:	4600m²
Main deck load capacity:	10t/m²

Helideck

Helicoptr type:	Sikorsky S92 (12.8t) Sikorsky S61 or equivalent
Diameter:	22.2m

Legs and Spudcans

Number/Type:	4/triangular truss
Footing type:	Spudcan with pin
Spudcan area:	200m²
Leg length:	105m

Jacking System

Type:	Rack and pinion
Drive:	Electric/VFD
Elevating speed:	0.8m/min
Pre-load capacity per leg:	14000t pre-load holding/leg
Maximum Jacking load:	7680t/leg

CRANES

Main crane mount wrap-around the starboard aft leg.

Boom length:	105m(approx)
Capacities:	1500t at 15-31.5m radii
Floating Condition:	800t at 40m radius
Aux Hoist:	600t at 15-55m radii
Whip Hoist:	(rated 5t for man-riding 100t at 17-92.8m radii)

Auxiliary crane 2 x lattice boom pedestal cranes mounted fwd and aft port side.

Boom length:	46.5m
Capacities:	Car go 50t at 10-45m radii. Man-riding, 2t at 10-45m radii.

SAFETY SYSTEMS

Fire and gas detectors throughout the whole vessel in full compliance with MODU requirements.

2 x 130 person capacity totally enclosed survival crafts located on port and starboard side (200% total complement).

Inflatable life rafts for 200% of total complement (260).

1 x MOB/Fast Rescue diesel 300hp..

PROPULSION UNITS

Thrusters:	2 x 3000kW retracable - fwd
Design Speed:	3 x aft thrusters - 10 knots 6 thrusters - 12 knots

Control Systems

Dynamic Positioning Control System (DPCS) according to ABS DPS 2.

Navigation and communication systems, according to IMO and DSI requirements.

ACCOMMODATION AND FACILITIES

Total complement:
130 persons in 67 cabins.
Cabins equipped with en-suite shower/toilet, telephone, TV/DVD and network connections.

Facilities

Galley, mess-room, stores, laundry, recreation rooms, gym, TV-rooms, radio room, change-rooms, sickbay, client meeting rooms, offices and workshops.

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seajacks

Van Oord
Marine ingenuity

Equipment

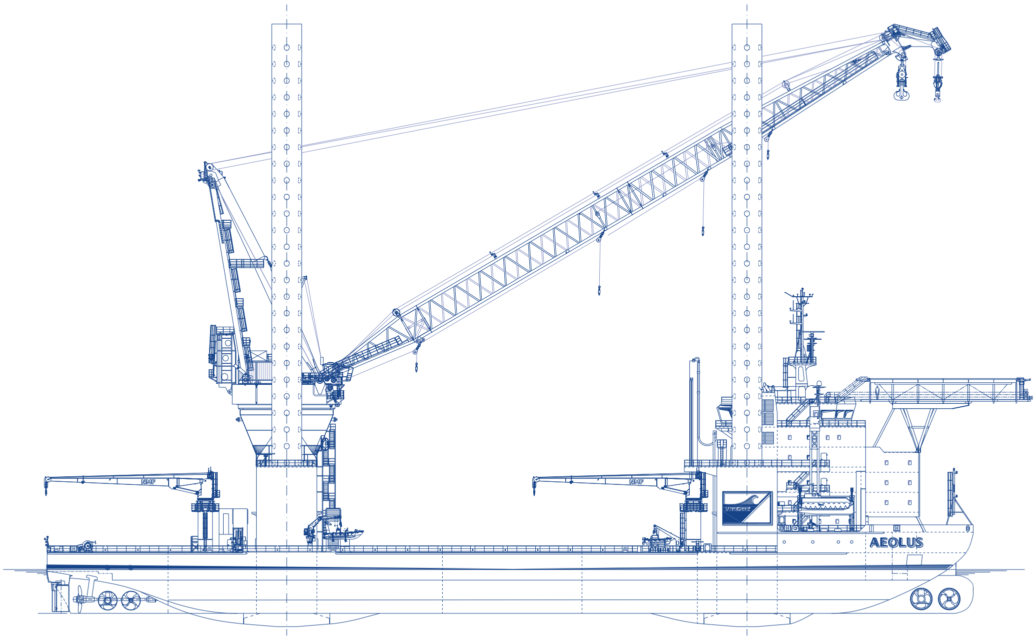
Offshore installation vessel Aeolus 2.0

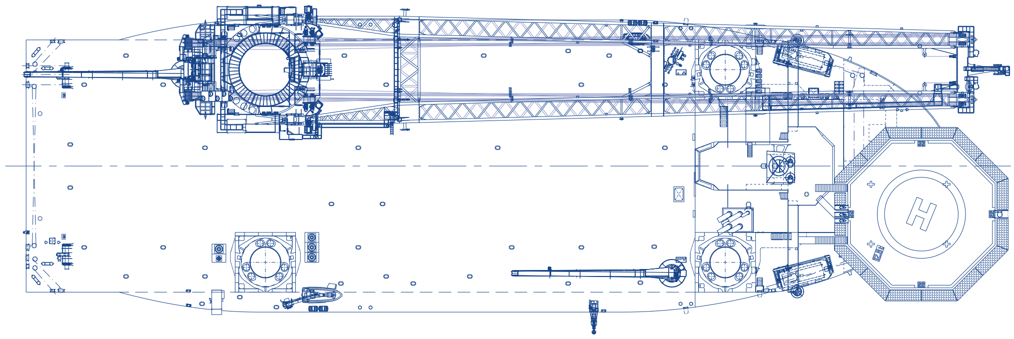
Sustainable EPC and Marine Contractors

Principal particulars

Van Oord

Marine ingenuity





Aeolus 2.0

Name	Aeolus 2.0
Type	Offshore installation vessel
Classification	DNV GL: ✠ 1A1 Self-elevating Wind Turbine Installation Unit CRANE OPP-F E0 DYNPOS-AUTR NAUT-OSV(A) CLEAN DESIGN TMON HELDK-SH
Trading area	Unrestricted
Year of construction	2014
Year of modification	2017
Dimensions	Length overall 139.40 m
	Breadth overall 44.46 m
	Depth (to maindeck) 10.12 m
	Draught 6.60 m
Tonnage	19,000 GT - 5,700 NT
Deadweight	ab. 12,000 tons
Speed	10.5 kn
Huisman offshore installation crane	Main hoist
	1600 tons / 14.00 - 32.00 m
	Auxiliary hoist
	100 tons / 16.00 - 109.00 m

Auxiliary cranes	2 x 20 tons / 24.00 m
Main engines	4 x 4,500 kW
Propulsion	10,000 kW
Bow thrusters	2 x 2,500 kW
Stern thrusters	2 x 2,500 kW
Total power installed	18,688 kW
Accommodation	99 persons
Jack-up system	4 legs - length 81.00 m - diameter 4.50 m
Clear deck area	ab. 3,775 m^2
Dynamic Positioning System	DP Class 2

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