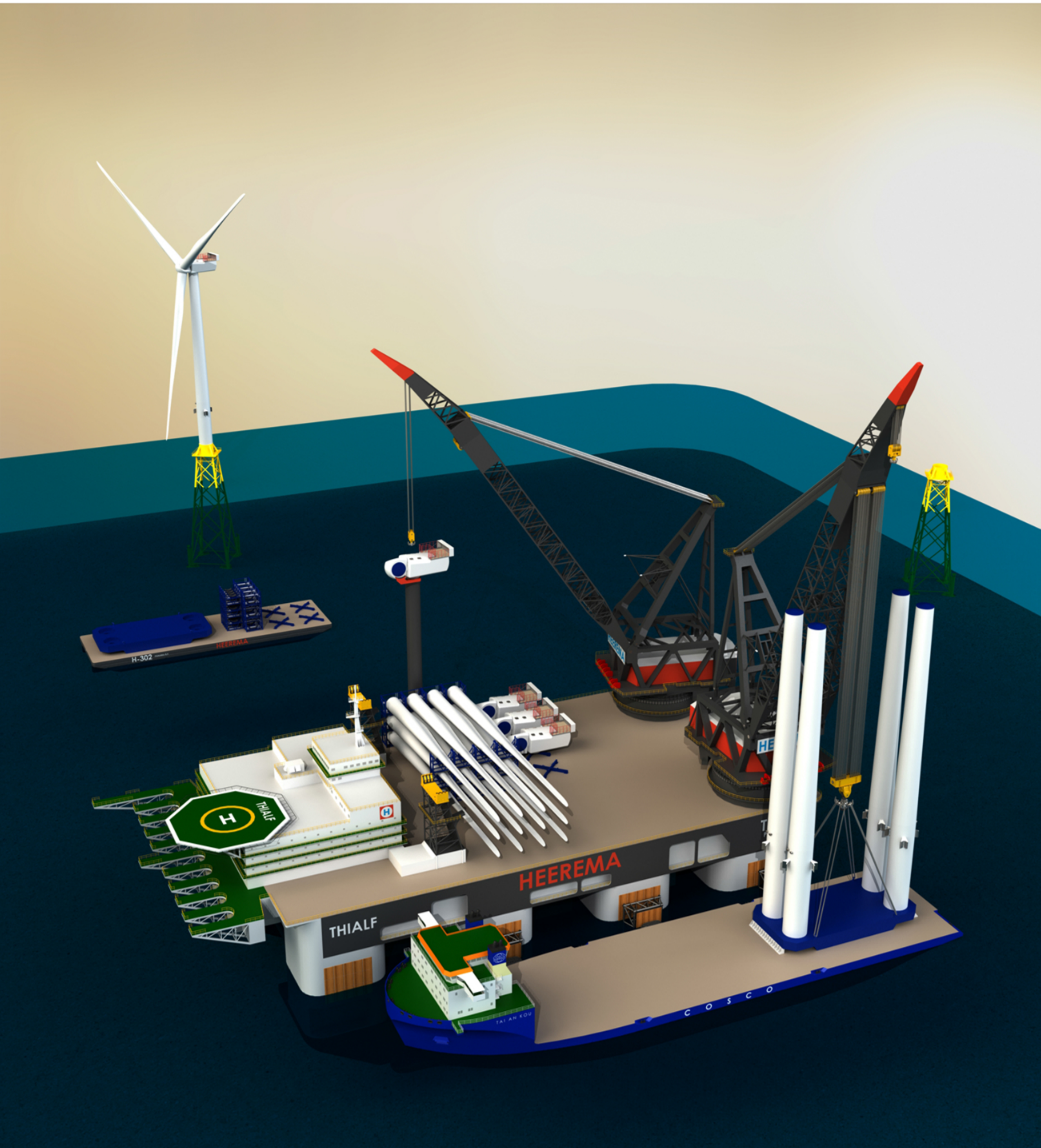
DESIGN OF A FEEDER SYSTEM FOR OFFSHORE WIND TURBINE INSTALLATION WITH AN SSCV

A THESIS BY B. X. VAN DE VEN



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Design of a Feeder System for Offshore Wind Turbine Installation with an SSCV

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Abstract

With increasing demand for renewable energy, the offshore wind industry is ever growing. Wind turbine generators (WTGs) proceed to grow in numbers and in size, wind farms are located further offshore, in deeper waters, poorer soil conditions or in areas prone to earthquakes. These changes make it increasingly difficult to find capable and affordable jack-up vessels for transport and installation of WTGs. Installing with Thialf, one of Heerema's semi-submersible crane vessels (SSCVs), would mitigate most of the problems jack-ups have today and is thus regarded promising. However, Thialf is expensive and has a low sailing velocity. To optimize its installation up-time it will stay offshore for the project duration. A feeder system is required to supply it with WTG components, which are readily available at the marshalling yard. The objective of this research is to determine the critical activities in a feeder system for installation of WTGs with an SSCV, and to improve them so Heerema can make a competitive entrance to the WTG installation market.

Turbine manufacturers demand that WTG towers are positioned vertically at all times. A qualitative assessment for all components points to transport and offloading of the turbine towers to be critical activities. A comparative motion response analysis between a barge and a heavy transport vessel (HTV) shows that during transport, both solutions perform well in sea states higher than the intended installation sea state, thus making them suitable for the task. As offloading demands stricter limits than transport, vessel motions for that activity are too severe. The natural frequency of the vessel-tower system increases with each removed turbine, moving into governing wave frequency ranges for North Sea conditions. This phenomenon shows for both vessel types, from which it is concluded that a supply vessel will be selected based on project specific parameters, rather than motion response.

During preliminary developments within Heerema, tipping of the tower when its sea fastening is released and large swinging motions of the tower after lift-off were main problems found during offloading, to which improvements are necessary. Three concept solutions are assessed: one an alteration of the existing, single tower lift solution, two others making use of the SSCV's cranes with high capacity by respectively lifting a frame with 4 towers and two frames with 8 towers. For each concept, response limits are defined at relevant locations in the system. In-house software is used to determine the RAOs, from which the heading with the highest operability is computed. The offloading and installation activity sequence for wind farms of 48 and 96 turbines are defined, followed by a weather downtime assessment.

First simulations show waiting on weather (WoW) is governed by crew transfer from a crew supply vessel to the barge for mooring operations. This can be improved by using a crew basket, motion compensated gangway or HTV. Simulations with revised limits show that using a frame with 4 towers results in significantly lower WoW days and shortest net project times, making it the most promising concept. Shorter lifting exposure and reducing motion amplification by means of a low frequency system are drivers for the decrease in weather downtime. With a lower total project duration, costs are reduced substantially.

Preface

This thesis is written in final fulfillment of my master thesis in offshore and dredging engineering at Delft University of Technology. I am pleased that I was able to combine the academic part of the thesis from a university perspective with the practical insights from my colleagues at Heerema Marine Contractors in Leiden where the research was done. The thesis covers the design of a feeder system for offshore wind turbine installation with an SSCV. I am proud to have contributed to new, floating installation solutions for the offshore wind industry and feel pleased that I was able to experience the development of this new discipline from the start and in a team atmosphere.

I would like to thank my university supervisor João, keeping me ever sharp and critical on my work. Of my professor, I vividly remember one particular sentence that changed my mindset on the research completely: "Try to think from the strengths of the Thialf". Thank you André, it was a short comment but had a huge impact. I would also like to thank all my colleagues at Heerema who have provided me with their expert insights in offshore transport and installation, taking the time to inform me even in difficult and uncertain times. A big thank you to my company supervisor, Pim, for the hours you have spent mentoring and supporting me. Anner, Bas, Chris, Kris, and Vincent, thank you for the laughs and warm company at our coffee and lunch breaks. It was always good to clear my mind with you guys.

Florian, what a pleasure to have had a mate to reflect with during all these years at university, we had a great time in Delft. Last but not least, I want to give a huge thanks to my parents, who have given me the opportunity to pursue my study goals. You have been supportive of me throughout the entire run; in my successes, but perhaps even more so when progress was slow at times. I am certain that it has shaped me to be the offshore energy engineer of the future. Let's power the world!

Bas van de Ven
Delft, February 12th 2019

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Nomenclature

Glossary

Term	Description
1T/4T/8T-Frame	Tower transfer solution in the form of a structure with a total of 1/4/8 towers on it.
48/96-WTG Farm	An offshore wind farm consisting of 48/96 wind turbine generators.
Converter station	Platform with transformers to convert alternating current to high voltage direct current.
Day rate	Daily operational cost.
Feeder system	Part of the supply chain between an onshore yard and an offshore vessel.
Fetch	Measure of distance of open sea over which waves develop due to friction between wind and the water surface.
FlexBase grillage	A grillage which can rotate in guides when lifted.
Grillage	Structure that distributes the forces induced by a transported load over the deck of a vessel.
Jack-up	Type of vessel. A jack-up can lower 'legs' to the sea bed and jack itself up above the water line, hence the name. This way, a sea bottom supported platform is created.
Marshalling yard	Harbor, often close to the installation site, where components for an offshore wind farm are collected, stored, and sometimes assembled. Also serves as pick-up point for transport of the components to the offshore installation site.
Monopile	Large diameter tube, used as a foundation for offshore wind turbines.
Nacelle	Part of the turbine containing the generator and gearbox (if present).
Snagging	Pulling sideways in pulsating fashion.
Spreader bar	Steel beam or rod used to guide cables to two or more lifting points during lifting.
Tower	Long cylindrical turbine component, connecting the nacelle to the substructure.

List of Abbreviations

Abbreviation	Description
1T	1-tower concept
1T1N	1 tower, 1 nacelle
2T2N	2 towers, 2 nacelles
3T3N	3 towers, 3 nacelles
4T	4-tower concept
4T4N	4 towers, 4 nacelles
8T	8-tower concept
Aux	Auxiliary
CAPEX	Capital expense
CoG	Center of gravity
BLT	Blade lifting tool
DCV	Deepwater Construction Vessel
DNV	Det Norske Veritas
DP	Dynamic positioning
FF	Free floating
FH	Free hanging
FR	Freely rotating
FS	Freely swinging
HMC	Heerema Marine Contractors
HTV	Heavy transport vessel
JONSWAP	Joint North Sea Wave Project
k€	Thousands of euros
M€	Millions of euros
MF	Manufacturing facility
MPM	Most probable maximum
mT	Metric tonnes
MVOW	MHI Vestas Offshore Wind
MY	Marshalling Yard
OLY	Offshore lifting yoke
OPEX	Operational expense
OWF	Offshore wind farm
POI	Point of interest
PS	Portside
PT	Partly tensioned
RAO	Response amplitude operator
Ref	Reference concept
RNA	Rotor-nacelle assembly
SB	Starboard
SPAR	Single point anchor reservoir

Abbreviation	Description
SPMT	Self propelled modular transporter
SSCV	Semi-submersible crane vessel
T&I	Transportation and installation
TP	Transition piece
UNFCCC	United Nations Framework Convention on Climate Change
ULS	Ultimate limit state
US	United States
WDT	Weather down time
WoW	Waiting on weather
WTG	Wind turbine generator

List of Symbols

Symbol	Unit	Description
$A_\perp$	[m^2]	Projected area
cap_{aux}	[mT]	Capacity of the aux hook
C_d	[-]	Shape factor
E	[-]	Environmental load factor
F_a	[N]	Force by dynamic accelerations
F_{CoG}	[N]	Sum of forces in the center of gravity
F_{dyn}	[N]	Dynamical force measured by LiftDyn
F_g	[N]	Force by gravity
F_{PS}	[N]	Force in port side support
F_s	[N]	Force in support
F_{SB}	[N]	Force in starboard support
F_w	[N]	Force by wind
g	[m/s^2]	Gravitational acceleration
G	[-]	Permanent load factor
GM	[m]	Metacentric height
H	[m]	Height of a frame
$h_{CoG,i}$	[m]	Height of the CoG of component i
$h_{CoG,system}$	[m]	Height of the CoG of the system above the frame base
H_{MPM}	[m]	Most probable maximum wave height
H_s	[m]	Significant wave height
i	[-]	Component counter
k	[N/m]	Spring stiffness
$m_{grillage}$	[mT]	Mass of the grillage
m_i	[mT]	Mass of the component i
M_P	[Nm]	Moment about point P
$m_{rigging}$	[mT]	Mass of the rigging
m_{tower}	[mT]	Mass of the tower
N	[-]	Number of waves
N_c	[-]	Number of components
N_{ship}	[-]	Number of vessels
p_{trim}	[%]	Trim percentage
$r_{day,ship}$	[€]	Vessel day rate
$r_{day,total}$	[€]	Total day rate
$SAMPM$	[various]	Single amplitude most probable maximum value of a limit
SDA	[various]	Significant double amplitude value of a limit
s_{route}	[km]	Distance of the shortest route
t_{dock}	[hrs]	Docking time
t_{return}	[hrs]	Return time
T_n	[s]	Natural period

Symbol	Unit	Description
T_p	[s]	Peak period
$T_{p,\phi=max}$	[s]	Peak period at which the highest roll motions occur
U	[-]	Outcome value of a unit check
v_s	[m/s]	Vessel velocity
v_w	[m/s]	Wind velocity
W	[m]	Width of a frame
$\boldsymbol{C}$	[Ns/m]	Damping matrix
$\boldsymbol{F}$	[N]	Force vector
$\boldsymbol{K}$	[N/m]	Stiffness matrix
$\boldsymbol{M}$	[kg]	Mass matrix
$\boldsymbol{x}$	[m]	Displacement vector
$\dot{\boldsymbol{x}}$	[m/s]	Velocity vector
$\ddot{\boldsymbol{x}}$	[m/s^2]	Acceleration vector
γ	[-]	Peakedness factor of a wave spectrum
θ	[°]	MPM roll angle due to wind and wave loads
ϕ	[°]	Roll angle
ρ_a	[kg/m^3]	Air density
ω_{dyn}	[rad/s]	Natural frequency of a matrix spring
ω_n	[rad/s]	Natural frequency

1

Introduction to Offshore Wind

1.1 Heerema Marine Contractors in a Nutshell

Following the world's offshore energy trends, Heerema Marine Contractors (HMC), or in short, "Heerema", is transitioning to offshore wind energy. With a rich track record in the oil and gas industry, HMC is an established and renowned player in the offshore heavy lifting business. To understand why it is moving to wind energy relatively late, the strengths and weaknesses of the company are addressed.

1.1.1 Heerema's history

Traditionally, HMC has been an installation service provider in the offshore oil and gas market installing platforms, substructures and subsea equipment. In the last decade, it has expanded its portfolio by executing pipelay and decomissioning projects. Throughout its history, HMC has owned multiple monohull and semi-submersible crane vessels (SSCV). All of HMC's SSCVs are equipped with a dual crane setup allowing for some of the heaviest lifts on the planet.

The current fleet of installation vessels consists of deepwater construction vessels (DCV) Balder and Aegir, as well as SSCV Thialf. A new build SSCV, Sleipnir, is in production and expected to be delivered in 2019. Equipped with two 10,000 mT cranes, Sleipnir will prolong Heerema's title of having the vessel with the highest crane lift capacity on earth. All of HMC's installation vessels have dynamic positioning (DP) capabilities, and are often supplied by barge-tug combinations delivering modules, jackets, subsea structures or equipment for the hydrocarbon energy industry.

1.1.2 Renewables on the rise

As the effect of carbon dioxide on climate change has become more recognized, political drivers push the offshore energy market towards greener sources. In 2015, the United Nations Framework Convention on Climate Change (UNFCCC) issued the Paris Agreement, which has been an accelerator for investments in renewable energy sources rather than in fossil fuels [1]. Until 2018, installation of wind turbine generators (WTGs) was never considered a great opportunity for HMC because of two main reasons:

1. The relatively lightweight components of WTGs mismatched with the high capacity cranes on their vessels, making them unable to compete with the competition.
2. Demand for installation and removal jobs in other markets, which made more profit, was high enough to provide work for HMC's vessels.

With the wind energy market rapidly expanding, however, new opportunities arise. While Europe has been at the forefront of implementing offshore wind into the energy mix and continues to expand, markets in East Asia and North America also emerge.

Installation of turbines comes with new technical and operational challenges for HMC, and a shift in mindset and approach will be necessary. Wind turbine generator (WTG) components are much lighter and differ greatly in shape from offshore platforms. Moreover, WTGs are a serial product, whereas oil and gas structures are generally unique. HMC will need to innovate so that its vessels can effectively, safely and successfully install offshore wind farms to make the company can be financially competitive in this growing market.

1.2 Earlier work in offshore wind

Before the start of 2018, HMC had already invested some of its time in the wind energy sector. Until then, jackets and topsides had been installed for converter stations, such as Dolwin Alpha (see figure 1.1). This kind of lifting operation, however, is very similar to that of an oil or gas platform module and therefore not necessarily new from a technical point of view. The company also installed over thirty jackets for wind turbines (figure 1.2), and successfully executed a pilot monopile and turbine installation for the startup company Delft Offshore Turbine in 2018.

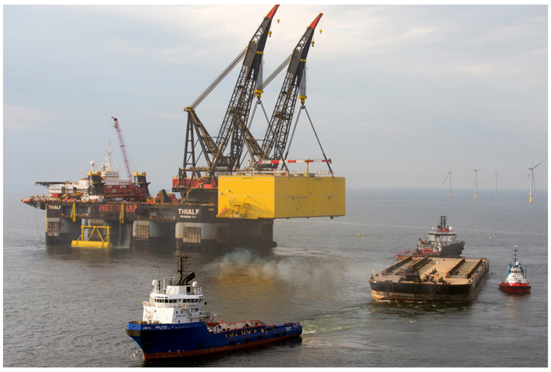

Figure 1.1: Thialf during installation of the Dolwin Alpha converter station.

Figure 1.2: Aegir installing an offshore wind turbine jacket at Aberdeen.

Additionally, small scale investigation had been done on how to use or convert Heerema's vessels for WTG installation. In May 2018, research showed that installation of WTGs with an SSCV could indeed be financially attractive for HMC [2].

1.3 Problem statement

HMC has started investigating different methods to install WTGs with its vessels. Thialf's motion behaviour in wind seas, in combination with her tall cranes, high deck and dual crane setup should make for excellent workability and a high installation rate compared to other floating installation configurations. However, Thialf's sailing speed is low, she can only dock in a select number of harbors and her day rate is very high. To maximize installation up-time and hereby press costs, Thialf will remain at the offshore wind farm (OWF) for the full duration of the project and will have to be supplied with the WTG components coming from shore.

In the past, HMC has mainly used barge and tug combinations for supply purposes. A preliminary design using a barge and tug for supply of WTG components is under development. The barges in the HMC fleet are optimized for transport of very heavy structures, therefore they may be less suitable for supply of wind turbine components. Aside from this, no solution has yet been found to safely and effectively transfer the turbine towers from the transport asset to Thialf's deck in sea states high enough to be able to compete in tenders.

1.4 Scope of work

To the aforementioned ends, there is a demand for a research into the feeder system providing an SSCV with offshore wind turbine components. The following research question must therefore be answered:

What are the critical activities in a feeder system for installation of WTGs with an SSCV and how can they be improved so that HMC can make a competitive entrance to the WTG installation market?

The transport process in its definition is limited to loading the transport asset, sailing to the offshore wind farm location, and offloading of the transport asset onto the installation vessel. Only the transport of the WTG superstructure, meaning the blades, nacelles and towers shall be assessed, as well as accompanying materials such as frames or grillages. More information about the definition of wind turbine components can be found in figure 1.3. The substructure in this figure has the form a jacket, but it may also appear in different floating or bottom founded types of constructions, the most common of which is a monopile. The type of substructure has no influence on this research. The substructure transport and installation (T&I) is assumed to be completed and ready for WTG installation and is therefore outside of the research scope.

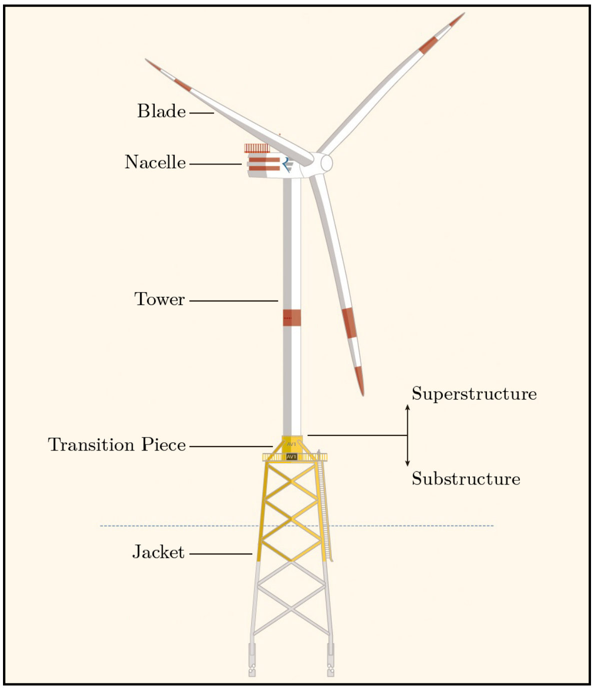

Figure 1.3: Definition of components of a WTG and its substructure.

A concept installation procedure of the WTGs is given, as later described in section 3.2.1, along with the corresponding deck layout of the installation vessel. These will be used as a point of reference, but may be subject to changes. At the start of the transport procedure, turbine components are expected to be readily available for pick-up at the quayside of a marshalling yard, as is customary in the industry. The study shall be executed using a case scenario. However, the essence of the problems as well as their solutions are to be extrapolated to different vessel and turbine models if applicable.

1.5 Layout of the study

To assist in the fulfillment of the core objective, there are a series of subquestions which must be answered. These questions are roughly representational of the chapters in this report.

1. What is modern common practice in transportation and installation of WTGs, and why is it relevant to start installing WTGs with a semi-submersible crane vessel?
2. What turbine model and wind farm location can be justified for a case study?
3. Which boundary conditions apply to the case study and what are their effects on the supply chain?
4. Which activity in the feeder system sequence is the most critical?
5. Which concept solutions can improve the most limiting activity?
6. How can the weather downtime be estimated, so that the effectiveness of a solution can be measured?
7. How can a solution be optimized to improve its workability and weather down time?
8. Which solution reduced the cost of WTG installation with an SSCV the most?
9. Can the solution be applied outside of the case study?

2

Offshore Wind Market Review

Some of HMC's competitors have been involved in offshore wind projects for almost two decades, with the first industry scale projects starting to develop around the year 2000. Since HMC lacks experience over its competitors in WTG installation, it is useful to know the competition's approach in past projects and understand their lessons learned over the years. Tools currently on the market, as well as the future competition should be known to catch up with contemporary developments and assure a competitive and profitable installation method.

2.1 Common practice in offshore wind

The layout of a wind farm consists of a number of turbines connected in arrays or loops to one or more converter stations, from which electrical energy is transported to shore by a large power cable. Prior to WTG installation, substructures for the turbines are installed. This is either done by jack-up vessel or floating heavy lift vessel; Van Oord's Aeolus and Seaway Heavy Lifting's Oleg Strashnov are respective examples. Each substructure supports one wind turbine.

2.1.1 Installation procedure

By far the most common practice to WTG installation today is by means of an offshore wind dedicated jack-up vessel (short: jack-up). The supply (figure 2.1) and installation (figure 2.2) are typically done in sequence by the same vessel. The basic steps of a T&I cycle with a jack-up are depicted in figure 2.3. All components for a limited number of turbines are loaded onto the vessel in a marshalling yard.

Figure 2.1: Jack-up Seajacks Scylla in transit mode, on its way to a wind farm.

Figure 2.2: Wind turbine blade installation by jack-up Seajacks Scylla.

Per wind turbine generator, the components include:

- One tower;
- One nacelle;
- Three blades.

The components are transported and seafastened on frames or grillages. Aside from the above listed, tools needed for offshore installation occupy a part of the deck space.

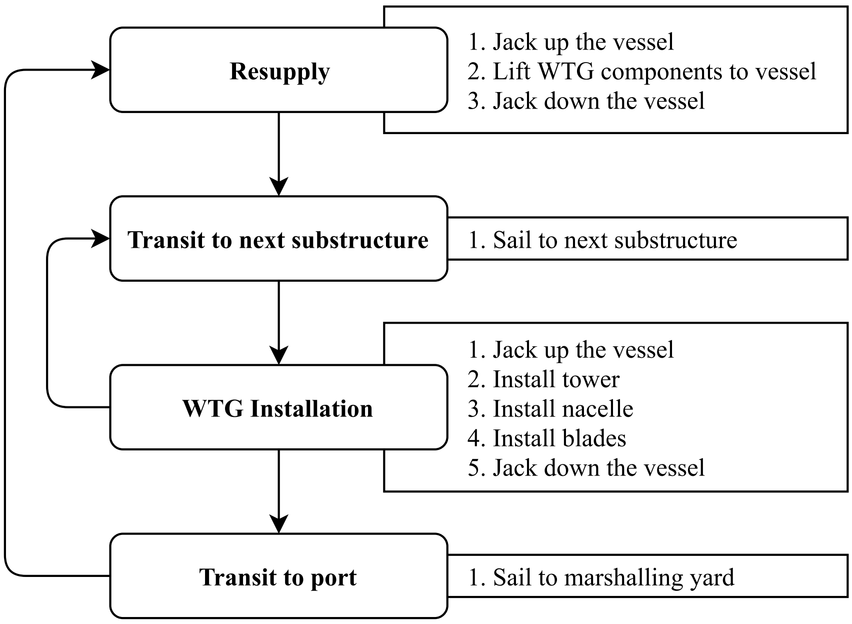

Figure 2.3: WTG installation process with a jack-up vessel.

Notably, the vessel is always in jacked up position whenever a lift is performed. This means that ship motions due to waves, wind or current can be largely mitigated and high workability is obtained. Different configurations have been used in the past, but modern-day practice is to transport the blades separated from the hub and nacelle. Three tower subsections are pre-assembled in a marshalling yard and transported as a one-piece tower. This configuration results in five major offshore lifts; tower, nacelle, and three blades. Previously used T&I methods such as the "rotor star" and "bunny ear" compositions, as discussed by Vis and Ursavas (2016) [3], are in decline due to infeasibility with increasing turbine sizes.

WTG installation is a repeating process with number of cycles depending on the amount of turbines that can be carried on board. When the installation vessel runs out of components, it returns to the marshalling yard to resupply and repeats until the wind farm has been completed. Today, some of the wind farms with the highest number of turbines are London Array and Gemini in the North Sea (175 and 150 turbines respectively) [4][5], and Gwynt y Môr in the Irish Sea (160 turbines) [6]. The currently most common deck space configurations allow four sets of turbine components on board at a time. Depending on vessel size and turbine model, up to eight sets would fit on deck in the past, wheres sometimes only two sets can be carried today. Although very much project dependent, a number of some 15 to 20 voyages from the marshalling yard to the wind park and back throughout the entire project are not uncommon [7].

2.1.2 Jack-up vessel developments

Over time, WTGs have grown in size and installation has moved to deeper waters. Naturally, installation vessels have developed to accommodate these changes. The development of GeoSea's fleet is an exemplary overview and can be seen in figure 2.4. First, jack-up barges such as Buzzard used mobile cranes for installation, sometimes mounted on an elevated structure. With Goliath, the crane was integrated as a fixed component of the vessel superstructure. Larger, tubular structures were used as jack-up legs. Later, leg-encircling cranes were introduced and quickly gained popularity because of their smaller footprint, facilitating more deck space. The most modern jack-up vessels in the wind sector, such as Apollo, are equipped with lattice structure legs rather than steel tubulars. This allows installation in deeper waters as becomes apparent in table 2.1 [8]. Trends similar to the GeoSea fleet can bee seen throughout the entire industry. The latest developments focus on installing with a floating vessel such as Orion, which is expected to be delivered in 2019.

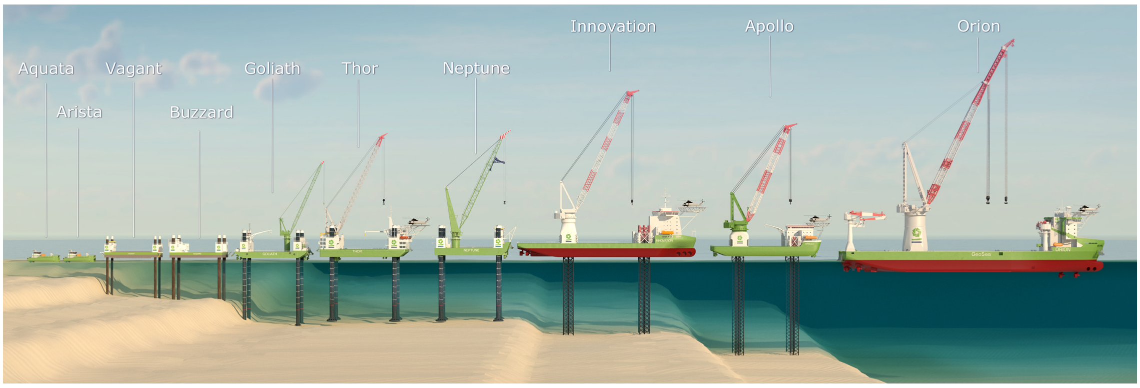

Figure 2.4: GeoSea's WTG installation vessel fleet development over time.

2.2 An alternative supply method

Rather than using the installation vessel to pick up components, an alternative method for supply is to transport the WTG components by a supply vessel. There is one known project where this solution has been used; Block Island Wind Farm, located in the Atlantic Ocean south of Rhode Island, US. Tower sections and blades were supplied by two small jack-up barges owned by Montco Offshore (figure 2.5), and installed by Fred Olsen Windcarrier's Bold Tern (figure 2.6) [9][10].

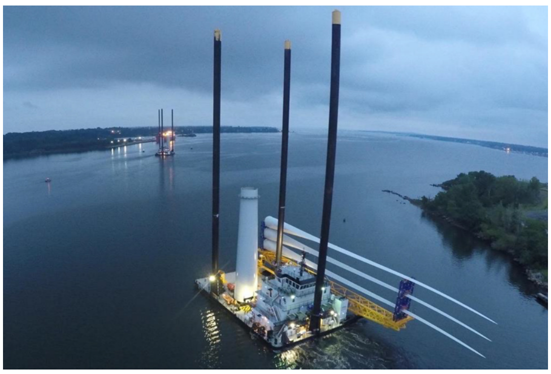

Figure 2.5: Turbine component supply by jack-up vessel.

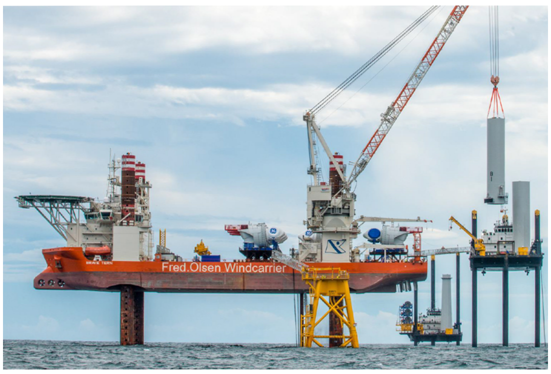

Figure 2.6: Bold Tern installing tower sections for Block Island.

The nacelles were carried directly from Europe to the OWF by Bold Tern. This was possible in one single voyage because the farm consists of just five WTGs. Turbine tower parts were delivered in three separate sections and the blades in sets of three. The two supply jack-ups together had the capacity to transport the components, nacelle excluded, for only one single turbine per voyage.

Because the first wind farms in the US are just emerging, approaches for T&I are still in development. For modern-day industry scale projects, a different solution will be necessary to make the projects economically feasible. The solution for Block Island Wind Farm is clearly politically driven, rather than being the most effective from a technical or logistical point of view.

The Jones Act prevents ships flagged outside the US to ship components from US-based marshalling yards. It can be said with confidence that this federal law will play a large role in the supply chain structure of US wind projects. Along US coastlines, there are also a number of fixed, immovable bridges that lie between the countries ports and open ocean, such as the Francis Scott Key Bridge in Baltimore. This is another limitation for transport, because large jack-up vessels may not be able to pass underneath and vertical tower transport may not be possible. However, expectations are that when there is a higher demand for offshore wind in the US, marshalling yards will be built at strategic locations and more Jones-act compliant vessels may be built to specifically serve the wind market, releasing some of these constraints.

2.3 Turbine installation with a floating vessel

Only three instances are known where WTGs have been installed with a floating installation vessel. All three were pilot projects for proof-of-concept purposes. The first project is the installation of relatively small sized WTGs onto jackets by Scaldis' sheerleg barge Rambiz for the Beatrice project. A voluminous interface was constructed between the tower and the transition piece (TP) to make this operation possible [11].

The second project was executed by HMC for Delft Offshore Turbine, during which a turbine was directly placed (without transition piece) on a tapered monopile with a slip-joint connection as in figure 2.7. The installation was on open sea at the Prinses Amaliawindpark, but involved a small turbine model and short sailing distance. This allowed for the turbine to be lifted by Aegir in a dock, after which it was sailed, freely hanging from the crane, to the offshore site and installed.

Figure 2.7: Installation of a WTG with a slip joint by a floating monohull.

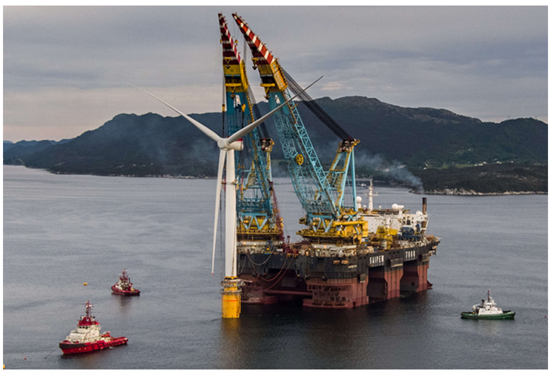

Figure 2.8: In-shore WTG installation onto a floating SPAR with an SSCV.

The third case consists of installation onto a floating SPAR-like structure by SSCV Saipem 7000 (figure 2.8) for Equinor's Hywind project. This larger turbine was lifted from the quayside and installed in-shore. After installation, the WTG-SPAR assemblies were towed out to sea. A large advantage for this specific lift operation is that the weather conditions in-shore are generally much more forgiving than at an offshore location. This can be seen by comparing the waves in figure 2.7 and figure 2.8.

With all three examples, the turbines were already assembled on-shore and lifted, transported and installed in one piece. With Beatrice and Hywind, two crane booms were used simultaneously for the lift, with a frame around the tower to stabilize the turbine at height. At the Princess Amalia Wind Farm, only a single crane was used for the lift. The turbine was small with respect to the vessel and it would not have been possible to install this way without the slip-joint. All three projects were small scale, accommodating two, one and five turbine respectively, and executed in very favorable weather conditions. WTG installation by means of a floating vessel has not yet been performed on a large, industry scale.

2.4 Problems and opportunities in the near future

The market review in this chapter shows that common practice for WTG installation relies on a stable platform in the form of a jack-up vessel. Delays in projects of 2018 however show that jack-up vessels are experiencing a significant amount of problems, which are expected to increase in the near future. Some reasons are discussed in this section.

2.4.1 Deeper waters and larger turbines

Moving to deeper waters raises the question if jack-up vessels remain the optimal solution for installation. As can be seen in table 2.1, only a handful of the most capable jack-up installation vessels are able to operate in waters of more than 60 meters. Developments show that some companies invest in lengthening their jack-up legs [12], while others invest in new vessels with increased water depth capability [13][14]. Environmental loading, especially current, causes greater horizontal movements of the bottom of the legs with increased water depth during set-down. This makes the set-down of the legs increasingly difficult. For example, a vessel roll angle of 5 degrees causes some 5 meters excursion of the spudcans at 60 meters water depth. The maximum excursion during set-down is a limiting factor for the workability of the vessel. With numerous jack-up instances over the duration of the project, this can greatly delay installation times.

The increasing turbine size also pushes companies to reconsider their vessel capabilities. A jack-up can extend its height by jacking up higher above the water line in shallow locations, but for deeper waters crane upgrades are necessary [12][15][16]. Deck space also is becoming more limited as turbines grow in size, resulting in less turbines on board at once, thus more transit time.

2.4.2 Sea floor conditions

Although not always the case, deeper waters tend to correlate with softer soil types. The relation between soil type, water depth and the location of wind farms can be seen when comparing sediment, bathymetry, and site maps of the North Sea (see appendix A) [17][18][19]. Until now, wind farms tend to be built on sandy sea floors and in shallow waters. Particularly the muddy field in the Oyster Ground and strip in the German Bight have clearly been avoided, even though these locations have relatively shallow water. Scotland and Taiwan have the ambition to invest in offshore wind energy [20][21], but are also limited in site selection because of muddy sea floor in their surrounding areas.

Table 2.1: Most capable vessels known to be involved in WTG installation.

Company	Vessel name	Ship type	Leg type	Depth [m]	Crane capacity [mT]
Jan de Nul	Vole Au Vent	Jack-up	Tubular	50	1500
A2Sea	Challenger/Installer	Jack-up	Tubular	55	900
Van Oord	Aeolus	Jack-up	Tubular	55	1600
FOW	Brave/Bold Tern	Jack-up	Tubular	60	800
SPO	Pacific Orca/Osprey	Jack-up	Lattice	60	1200
Seafox	Seafox 5	Jack-up	Lattice	65	1200
GeoSea	Innovation	Jack-up	Lattice	65	1500
Seajacks	Scylla	Jack-up	Lattice	65	1500
GeoSea	Apollo	Jack-up	Lattice	70	800
HMC	Balder	Semi-sub	N/A	∞	3000
Boskalis	Bokalift 1	Monohull	N/A	∞	3000
HMC	Aegir	Monohull	N/A	∞	4000
GeoSea	Orion	Monohull	N/A	∞	5000
Saipem	Saipem 7000	Semi-sub	N/A	∞	7000
HMC	Thialf	Semi-sub	N/A	∞	7100

Working in soft soil types with jack-up vessels poses increased risk. Legs tend to sink further into soft soils than in sandy soils. This decreases the maximum height above water level of the vessel and its crane. Cases are known where a jack-up has sunk so far into the soil, that it had gotten stuck, unable to free itself. This can compromise the safety of operation if bad weather strikes. Another risk is that of a punch-through, in which case a leg suddenly loses support during preloading due to an unstable soil layer located underneath a weight-bearing soil layer. In addition, chance of an earthquake is a serious issue and can be a deal breaker for jack-up vessels in the recently awarded wind farms in Taiwan.

2.4.3 Moving further offshore

With wind farms moving further offshore, installation vessels have to travel longer distances to and from the installation site. This has an increasingly negative effect on project costs, if nothing is about the supply chain. With installation vessels being the most expensive assets of the installation procedure, transport from marshalling yard to the OWF is becoming a very costly element in the supply chain.

2.4.4 Opportunities for HMC

Installing WTGs with a floating vessel rather than with a jack-up would be a great solution to the above-mentioned problems. By doing so, installation procedures would become a much less limiting factor in choosing sites for OWFs. Moreover, using dedicated supply vessels would eliminate undesirable critical sailing hours with the installation vessel from and to the marshalling yard. Aside from this, offshore wind projects are becoming simply too massive for the jack-ups to keep up with installation demand [22]. Due to both the vast size and number of turbines per wind farm, capable jack-up vessels are becoming scarce. With its two cranes working simultaneously and its floating nature, Heerema's Thialf may become an interesting vessel to overcome these problems. Investing in methods to make floating T&I possible on a large, industry scale is therefore necessary. Opportunities for HMC are most prominent in locations either far offshore, in difficult soil types, at projects with a very limited time schedule and especially in the US where the Jones Act applies, making working with US flagged feeder vessels mandatory.

3

Research Specifics and Critical Activities

For the case study of this research, a selection has to be made on which turbine, vessel and location are to be used. This choice needs to be well-grounded to obtain relevant results. Constraints, guidelines and assumptions define the boundaries of the research.

3.1 Case study setup

MHI Vestas Offshore Wind (MVOW) is one of two market leading companies in the WTG market [23]. MVOW has designed and as of 2014 started manufacturing the most powerful WTG: the V164. This turbine model has been selected for a notable number of OWFs in the coming years and has the highest output power ratings and available on industry scale, making it exemplary for modern WTGs. The V164 is therefore a logical choice as turbine model for this research. For reasons mentioned in sections 1.3 and 2.4.4, SSCV Thialf will be used as installation vessel. The choice for an OWF location is Halfdan, a part of the Eastern section of Dogger Bank in the Danish North Sea. Extensive environmental data from the oil and gas industry is available to HMC, which is needed for reliable research results. Far offshore and with muddy soil conditions, this would typically be a area where HMC would be a good contender for WTG installation (see appendix A). Hence, Halfdan is a suitable location for this research.

3.2 Boundary conditions

Boundary conditions and limiting criteria conform modern wind industry standards apply, as well as HMC in-house rules, the most important of which are discussed and reviewed in this section. The criteria by HMC are based on limits of the oil and gas industry, as no track record on WTG installation has yet been obtained. If valid safety and reliability of operation can be shown, they may be reconsidered. Standard rule sets for marine operations by Det Norske Veritas (DNV) are taken as a reference point for the T&I process.

3.2.1 Installation method

For the T&I scope in this research, it is assumed that the towers, nacelles and blades are ready for transport at the quayside of the marshalling yard (MY), as per common practice. The SSCV remains offshore for the duration of the project, and should be supplied with the turbine components. Offshore, the components will have to be transfered from the supply asset to the SSCV, and placed on deck. The deck layout as in appendix B will be used, serving as a reference point for HMC's installation method. There is deck space available for components of a total of four turbines.

Prior to placement on the substructure, Thialf's WTG installation method includes partial assembly of the components on board. A nacelle is placed onto a vertical steel cylinder, the "dummy tower", which enables Thialf to mate the blades with the nacelle on the ship deck. While the blades are installed by the starboard (SB) crane, the tower will be installed onto the substructure by the portside (PS) crane. Lastly, the complete rotor-nacelle assembly (RNA) will be lifted onto the tower in a single lift by the SB crane. An impression can be seen in figure 3.1 and figure 3.2.

Figure 3.1: Proposed installation method: RNA assembly and tower installation.

Figure 3.2: Proposed installation method: RNA installation on tower.

To allow Thialf to work at its maximum rate, it should never have to wait on new components, meaning that a new supply should be readily available when demanded. With a target time of 12 hours per turbine, new supplies need to be ready every 48 hours. Transfer of the WTG parts to deck should have the same statistical workability as Thialf during installation, to avoid hold-up.

3.2.2 Turbine properties and restrictions

The case turbine's dimensions and specifications are given in table 3.1. Once assembled, the rotor diameter is 164 meters. The nacelle is elevated to heights within a range of 100 to 120 meters above sea level, with the blade tip reaching up to 200 meters above sea level once installed.

The T&I of the V164 turbine is subject to boundary conditions in accordance with modern wind industry standards. No welds are to be made to any of the components. The towers and nacelles are to be transported in a vertical manner. Blades shall be transported in dedicated blade saddles and may be batched in stacks of three blades high. The nacelles are brought to the marshalling yard on an X-frame, which may be used as seafastening during transport.

Table 3.1: Dimensions and specifications of the MVOW V164 wind turbine.

Component	Length [m]	Width [m]	Height [m]	Mass [mT]	CoG - above base [m]
Tower	6.5	6.5	87.0	465.0	40.0
Nacelle	20.5	8.0	8.0	386.0	4.0
Blade stack of 3	82.1	6.5	15.6	169.5	7.8

Grillage design is undefined but during transport, at least half of the tower's bottom flange bolts must be fastened, or a system ensuring equivalent force may be used. The components are limited to single amplitude displacements and accelerations in their center of gravity (CoG) in accordance with table 3.2.

Table 3.2: Limiting single amplitude motions of WTG components during T&I.

Component	Roll [°]	Pitch [°]	Surge [g]	Sway [g]	Heave [g]
Tower	10.0	10.0	4.0	8.0	8.0
Nacelle	10.0	10.0	4.0	8.0	8.0
Blade stack of 3	20.0	12.5	4.0	8.0	2.0

MVOW grants a combined tower-nacelle tool called an offshore lifting yoke (OLY), spreader bar for lifting the blade stacks and a blade lifting tool (BLT) for installation. All these tools are purpose built for the V164 model, but alternatives may be suggested by the installation contractor.

3.3 Shaping the supply chain

Shaping the supply chain for offshore wind projects is logistically challenging and dependent on many factors. It is mainly influenced by turbine type, location of the wind farm, locations of manufacturing facilities (MFs), asset availability and cost. These variables result in a vast number of logistic possibilities, of which the financially optimal solution will differ per project. Regardless, the overall process can be divided into six separate though dependent subprocesses.

1. Loadout of components onto the transport asset at a marshalling yard;
2. Transit to the offshore wind farm;
3. Offloading components from the transport asset to the SSCV;
4. Backloading frames and tools from the SSCV to the transport asset;
5. Transit back to shore for resupply;
6. Offloading frames and tools from the transport asset to the yard.

The last three subprocesses are roughly the reverse execution of the first three subprocesses. Since the WTG components will have been transferred to the SSCV at this stage, these steps will be much less restricted than the first three. While some thought should be given to the deck layout and planning of subprocess 4 and after, they will not be discussed in much detail.

3.3.1 The marshalling yard

The marshalling yard serves two purposes in the supply chain; buffer storage and a location for partial assembly of the WTGs. Blades, nacelles and tower sections are brought here by ship or truck from their manufacturing facilities. An impression of the world's largest marshalling yard in Esbjerg, Denmark is found in figure 3.3. Esbjerg has a nacelle assembly facility and tower sections, of which three unique pieces are required per tower, are assembled here. A large crawler crane, typically a Liebherr LR-11350 or similar, assembles the towers. When ready for transport, they are placed on the quayside. Blades and nacelles are transported throughout the yard by self-propelled modular transporter (SMPT) and also placed at the quayside before loadout onto a vessel.

The marshalling yard is a significant contributor to project cost. Since Heerema's SSCV remains offshore and has no need for a centralized location to pick up components, it was investigated if direct transport from the manufacturing facilities would be possible. This could either be done by separate vessels shuttling between OWF and manufacturing

Figure 3.3: Impression of the world's largest marshalling yard in Esbjerg, Denmark.

facility, or by one vessel sailing to all three facilities and returning to the OWF. In either case, it was found that in most scenarios, the distance from a MF to the OWF would be greater than from a MY to the OWF, as marshalling yards are chosen as close to the OWF as possible.

It can be argued that, when using a marshalling yard, the components will still need to be transported from the MFs to the MY. This is true, but with a marshalling yard the transport from MF to MY is in non-critical time, as it can be done well before T&I starts. The MY then functions as a buffer area. Moreover, some manufacturing plants are located inland, not directly allowing for seagoing transport. Aside from this, tower sections may come from different locations, or tower MFs may not have capacity to assemble the towers on-site. Despite the cost, it is therefore logical to keep the marshalling yard a part of the supply chain. Esbjerg is the marshalling yard of choice for the Halfdan wind farm, resulting in a 250km supply route to the OWF.

3.3.2 Loadout of the components

Traditionally, wind installation vessels jack up in the marshalling yard before hoisting WTG components on board. Now that a transport vessel is to be used, a different way of loadout is required. Three common options in the offshore industry are skidding, roll-on by SPMT and lifting. Roll-on can be used for the blades and nacelles, using the SPMTs that are already used in the yard. However, this limits the selection of a vessel to flush deck vessels. Alternatively, the crane used for tower assembly has the capacity to lift the components on board. If a large base frame is provided, roll-on of the towers may be an option as well. Skidding is a slow process and mainly used for very large and heavy constructions such as platform modules and jackets, therefore likely being less suitable for the lighter turbine components.

3.3.3 Transport vessel options

An investigation was done on vessels available on the market judging by deck space, sailing speed and estimated cost. Balancing these parameters with the total number and frequency of voyages defines the transport solution. A reference point was found in the Wikinger project (figure 3.4), in which the heavy transport vessel (HTV) Dockwise Swan transported loads of four 59-meter high jackets at a time. This was considered a comparative load to the turbine towers, because of similar masses and high CoG.

For the range of ships to choose from, the vessel breadth was considered leading because of the static stability and righting moment it provides. The vessels in table 3.3 came out as sensible options for transport. If more than one vessel of a type is needed, it should

Figure 3.4: Dockwise Swan carrying four jackets.

be known that identical sister vessels exist for each type. Additionally, all ships have a flush deck and a ballasting system, making them suitable for roll-on, roll-off operations. They do have diverse bows and stern profiles, which could influence positioning options and clearances during the loading and offloading processes.

Table 3.3: Contender vessels for transport purposes.

Name	Type	Sailing speed [kts]	Length [m]	Breadth [m]	Day rate [€]
H-404	Barge + Tug	6.0	110.0	36.6	18k-24k
H-541	Barge + Tug	6.0	145.0	42.0	25k-36k
Swan	HTV	12.0	126.6	31.6	20k-50k
Tai An Kou	HTV (DP2)	12.0	126.0	36.0	32k-80k
Baffin	HTV (DP Ready)	12.0	125.0	42.0	32k-80k

3.4 Critical activities

To put into perspective where the most time can be gained throughout T&I, a qualitative assessment was made of limiting weather conditions for all of the activities.

Table 3.4: Activity limits for WTG T&I

Activity	Component	Method	Limiting criterion
Loading	Blades	Lift/SPMT	Strong winds/Height of tide
	Nacelles	Lift/SPMT	Strong winds/Height of tide
	Towers	Lift/SPMT	Strong winds/Height of tide
Transit	Blades	Barge/HTV	Large waves
	Nacelles	Barge/HTV	Large waves
	Towers	Barge/HTV	Small to medium sized waves
Offloading	Blades	Crane lift	Medium sized waves
	Nacelles	Crane lift	Medium sized waves
	Towers	Crane lift	Small waves

Looking at the limiting criteria in table 3.4, offloading and transport of the towers looks to be most critical. Both activities should therefore be assessed more closely.

3.4.1 Offshore offloading

Offshore transfer of WTG components between a supply vessel and SSCV, or rather between two floating vessels of any kind, has yet never been done. Hence, no standard procedure yet exists. The transfer procedure as currently envisioned by HMC prescribes individual offloading of the towers from a barge. The rest of the WTG components are transported on another vessel. The auxiliary (in short 'aux') hook of the Thialf has the height and capacity necessary to lift the tower overhead. A spreaderbar and diverterframe are used to keep slings clear from the tower and transfer the lift forces to a grillage, to which the tower is attached at its base as shown in figure 3.5 (1).

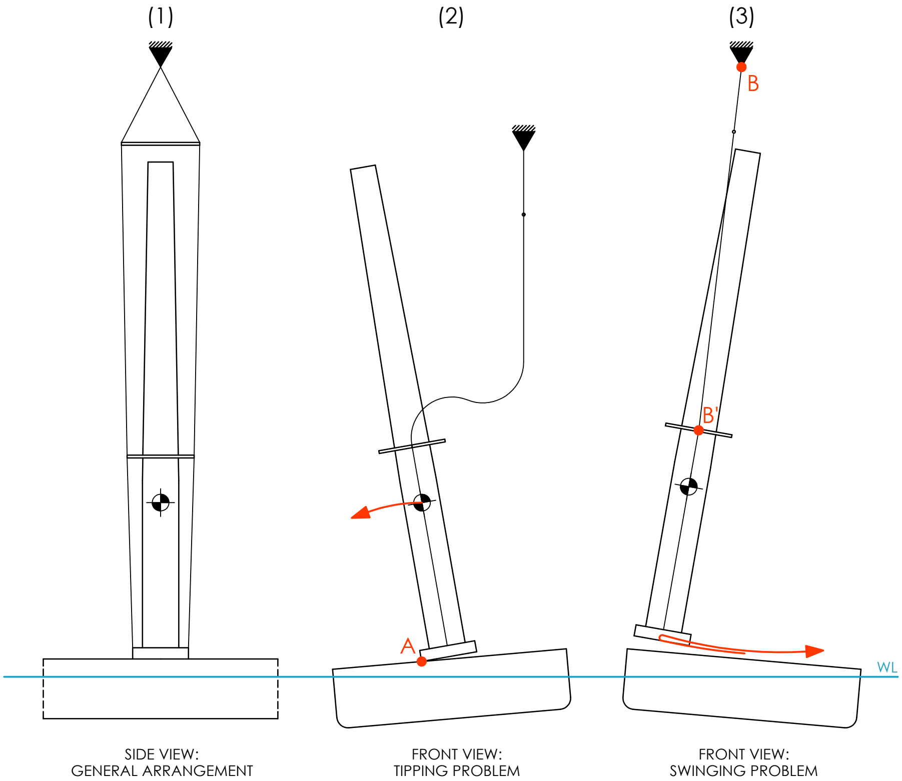

Figure 3.5: Setup for turbine tower offloading by HMC with (1): General Arrangement, (2): The tipping problem and (3): The swinging problem.

An offshore crew, together with marine engineering experts tested the offloading procedure in the Heerema Simulation Center. Two main problems arose:

- The stability of the tower after its grillage is released from sea fastening cannot be guaranteed for the desired operational sea states 3.5 (2). The dynamic forces in the CoG of the tower-grillage combination become so large that the moment around point A exceeds the righting moment by gravity, resulting in the tower falling over.
- Already in lower sea states, the tower base swings over deck just after lift-off, because it is difficult for a crane operator to keep the crane tip over the center of gravity of the tower-grillage combination 3.5 (3), especially with the tower snagging on the crane tip. The tower swings around point B and B', in a double pendulum fashion.

Both problems contribute to a currently unworkable scenario for a desired sea state of North Sea conditions with a significant wave height H_s of 2.0 meters and peak period T_p of 8.0 seconds. For further reference in this report, let's respectively call the problems the 'tipping problem' and the 'swinging problem'.

3.4.2 Transport limitations

Different boundary conditions apply for transport of the towers than for offloading. The environmental conditions not only differ over time, but also over the traveled trajectory. Moreover, for restricted operations, DNV dictates that the planned operational time should be at most 72 hours, to ensure a sufficiently reliable weather window. This means that for every shipment, all carried components should be shipped and offloaded within this time span. Alternatively, an operation may be put on hold and the supply vessel should be able to sail to a harbor within that period. This must be avoided, because it stagnates the project flow, increasing cost. Choice of heading during transport is limited because the route has a fixed starting and ending location. Were the transport to be executed in the shortest distance possible, a direct line from MY to OWF, the motion response with the worst possible heading should be considered.

It must be kept in mind that the definition of a sufficiently reliable weather window does not only depend on the motion response of a vessel and its cargo, but also on other capabilities such as heading control. Use of an HTV with DP, or a heading controlled tow by using a tug on both the bow and the stern of a barge are methods to avoid adverse wave directions. In such a case, approval to start a transport in compliance with DNV can be granted at higher sea states.

4

Tower Transport and Offloading Analyses

In the previous chapter it was established that tower transport and offloading are two activities which require further assessment for feasibility. In this chapter, motion response analyses of both these activities are explained and discussed.

4.1 Motion response analysis of tower transport

In order to find the limits of tower transport, an analysis is done of the motion response for two types of vessels; a barge and a heavy transport vessel (HTV) with similar dimensional characteristics. The vessels H-404 and Tai An Kou from table 3.3 are chosen, each carrying four turbine towers and four nacelles. A priori, the towers are positioned over the vessel centerline in the front, whereas the nacelles are placed on the aft of the ship (layout 1). An impression can be found in figures 4.1 and 4.2.

Figure 4.1: Layout 1: Starting deck layout on planar bow barge H-404.

Figure 4.2: Layout 1: Starting deck layout on HTV Tai An Kou.

The goal of the analysis is to find the effects of the following parameters on the vessel's motion response in terms of roll angle (ϕ).

- Position and number of components;
- Ballasting and draft;
- Heading of the vessel;
- Hull shape.

Ultimately, the analysis should give insight in optima of these parameters and a limiting sea state. To find this, in-house software package Sinai is used, which is a graphical user interface pushing input to offshore simulation software Bentley MOSES. This software uses integrated solvers to compute hydrostatic and hydrodynamic roll angles [24]. As input, a panel mesh of the vessel is loaded and geometry and masses of the cargo are defined by the user. All components are considered infinitely rigid and connected, as if they were a single body. Then, the filled volume of ballast tanks is defined, optimized so that the vessel experiences ideal trim and heel while in static equilibrium. If possible, only the outer ballast tanks should be used to increase inertia. For vessels with a ship-shaped bow, the trim should be zero degrees at all times. However, for barges with a flat, planar bow and shoe box shaped stern such as H-404, vortex shedding causes sway and yaw motions during sailing. Experience has shown that a trim percentage p_{trim} equal to inequality 4.1 should be used to ensure better course stability [25]. This does result in slightly poorer roll motion response than sailing with zero trim.

$$0.5 \leq p_{trim} \leq 0.8 \tag{4.1}$$

In addition, a wave spectrum with a significant wave height H_s and a wind velocity v_w are defined. A standard JONSWAP spectrum is chosen with a peakedness of $\gamma = 3.3$. This spectrum is suitable for fetch limited, developing seas in shallow waters such as the North Sea [25]. The wind forces on structures are conservative because the full cross sectional area of each body are taken into account and structure-to-structure effects are neglected. The wind profile is of uniform shape over the height. The program computes the system's response amplitude operator (RAO) for roll and matching natural period for the given environmental input. Next, a selection of peak periods is chosen for which the motion response should be evaluated. For climates in which the seas are predominantly wind-driven, DNV dictates that at least peak periods T_p defined by equation 4.2 must be assessed [26].

$$\sqrt{13H_s} \leq T_p \leq \sqrt{30H_s} \tag{4.2}$$

DNV also prescribes a minimum range of stability defined by equation 4.3 for large barges. The range of stability is the range of angles of rotation in degrees for which the vessel will automatically right itself or, in more technical terms, the range of angles for which it has a positive metacentric height (GM).

$$0 \leq \phi \leq 36 \tag{4.3}$$

If inequality 4.3 does not hold, alternatively inequality 4.4 may be used:

$$0 \leq \phi \leq 15 + \frac{15}{GM} + \theta \tag{4.4}$$

Here, θ is the most probable maximum (MPM) rotational motion due to waves in the vessel's worst heading, plus a static heel angle due to wind loads. The MPM roll motion for a defined sea state H_s and period range in accordance with inequality 4.2 is the main output of Sinai. A heading convention of the software can be found in appendix C.

Sinai computes all motion responses with the ship being stationary ($v_s = 0$). In reality, this will not be the case as this would disregard the definition of transport. A rule of thumb in marine engineering states that the motion response of a stationary vessel in beam waves is roughly equivalent to that of a sailing vessel in bow quartering waves. This way, results from Sinai can be used to say something about the sailing behaviour of the vessel.

Lastly, roll damping must be accounted for. Since this is a non-linear phenomenon and MOSES is based on linearized systems, damping parameters should be tuned to obtain accurate results. MOSES applies viscous roll damping using formulation from a paper by R.T. Schmitke [27] which is referred to as Tanaka damping. The response from MOSES is compared to scale model test results from HMC, to which the damping input can be tuned [25].

4.1.1 A comparison between a sailing barge and a sailing HTV

In the first assessment, the motion behaviour of a barge and an HTV are compared. The list below summarizes the relevant input parameters for the simulations.

H_s	=	0.5 - 3.5m
v_w	=	30kts
Draft	=	50%
Trim	=	0.71% for H-404, 0% for Tai An Kou
Cargo	=	4 nacelles and 4 towers

It was found that for beam waves and while fully loaded, the HTV performs slightly better than the barge. In its worst heading, a barge can sail in a maximum sea state of $H_s = 2.60$m, whereas the HTV can operate to a maximum of $H_s = 2.95$m, see figure 4.3. For all the simulated sea states, the roll angle limit of 10° was reached before the sway acceleration limit of 0.8g from table 3.2 was reached. This makes the roll angle most critical, thus most interesting to look at.

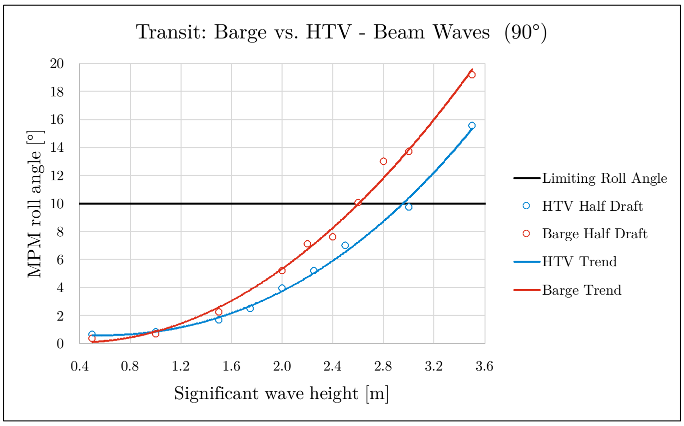

Figure 4.3: Barge and HTV roll motion response plots during transit.

Changing the draft to the minimum, 35%, increases roll motions for the barge, but lowers them for the HTV. The maximum draft, 70%, marginally decreases roll motions for the barge, but also causes a negative effect on fuel consumption due to higher water displacement. The HTV performs worse while operating with maximum draft. A draft of 50% for the barge and 35% for the HTV are therefore appropriate while the vessel is in sailing mode.

Figure 4.4: Layout 2: Towers moved to the stern of the vessel.

Figure 4.5: Layout 3: Nacelles moved to the sides of the vessel.

An experiment with alternative deck layouts with towers at the stern of the vessel (layout 2) and with nacelles on the sides of the vessel (layout 3) were analyzed (figures 4.4 and 4.5). The idea behind these layouts is to find out if there is any influence on component placement configurations, and to increase the moment of inertia around the vessels longitudinal axis, respectively. Maximum roll motion responses for these alternative deck layouts in seas of $H_s = 2.0$m can be found in table 4.1.

Table 4.1: Vessel motions compared to reference for different deck layouts.

	Layout 1	Layout 2	Layout 3
MPM roll in $H_s = 2.0$m	3.7°	4.0°	3.5°

Layout 2 worsens the motion response, and is therefore not recommended. Granted, layout 3 slightly improves the roll motions, but the nacelles undergo larger vertical displacements and accelerations because they are more distant from roll axis of rotation. This may be of influence during offloading, so whether this layout is better than layout 1 can be disputed.

4.1.2 The influence of travel routes

Both vessel types perform sufficiently up to and exceeding the intended installation H_s of 2.0 meters in their worst heading. However, if they encounter a greater significant wave height than 2.6 meters on their route, the roll angle may exceed the limit. In this scenario, the transport activity would stagnate or an alternative route may be chosen to avoid exposure to sea states higher than the limit.

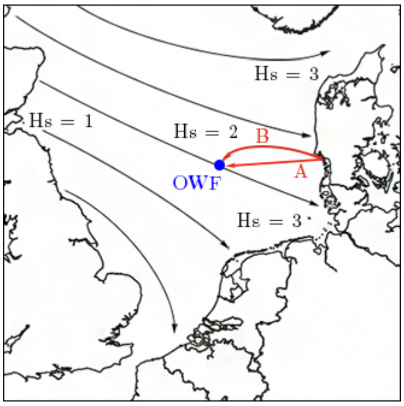

Figure 4.6: Rerouting for more beneficial roll motion response.

For the Halfdan case, a scenario with Northwestern wind is drawn in figure 4.6. The black arrows represent the wave direction, with their respective significant wave heights. The wave height increases with greater fetch. Route A is the shortest route and would normally be a logical choice to sail. It cannot be sailed in this scenario however, due to the combination of $H_s = 3.0$m at the Danish coast and bow quartering waves in the direction of travel. Rerouting to route B could, even though slower, still make transport possible in these weather conditions. The change to head waves in $H_s = 3.0$m would make the motion response more favourable in that section of the route. The part at which the vessel has to sail in bow quartering waves and beam waves is minimized, and only executed in sea states of $H_s \approx 2.5$m and lower. In the project execution phase, adapting to weather in this way can be beneficial for transport activities, avoiding delays. In an emergency situation, methods as described in section 3.4.2 may be applied.

4.1.3 Cost calculation and conclusion on transport

The analysis shows that transport will not be limiting in sea states up to $H_s = 2.5$m. From the results in table 3.3 and figure 4.3, an HTV wins out not only on motion response in higher sea states, but also in sailing speed.

To find out if transport with an HTV it is also more cost-efficient, it should be determined how many vessels N_{ship} are needed. Equation 4.5 prescribes the time it takes to sail from the OWF to the marshalling yard, resupply and return fully loaded, named the return time t_{return}. A docking and loading time t_{dock} of 10 hours is assumed. With sailing speed v_s and the shortest route s_{route}, the return time then becomes:

$$t_{return} = 2 * \frac{s_{route}}{v_s} + t_{dock} \tag{4.5}$$

It was mentioned in section 3.4.1 that a new supply needs to be available when the SSCV has finished installation; every 48 hours. But since the blades need to be offloaded from another supply vessel first, roughly 6 hours must be added, resulting in a maximum return time of 54 hours. For location Halfdan with a route distance of 220km, it is then found that one vessel is enough for either the barge or the HTV to supply the towers and nacelles in time. The total day rate $r_{day,total}$ for every vessel type is computed:

$$r_{day,total} = N_{ship} * r_{day,ship} \tag{4.6}$$

A cheap 300ft barge with the same sailing velocity as H-404 is chosen to serve as blade transport asset. A preliminary cost calculation with an example day rate is done, the results of which are to be found in table 4.2.

Table 4.2: Transport cost calculation of towers and nacelles for Halfdan wind farm.

Vessel	v_s [kts]	v_s [km/h]	t_{return} [h]	N_{ship} [-]	$r_{day,ship}$ [€]	$r_{day,total}$ [€]
H-302 + Tug	6	11.1	49.6	1	16k	16k
H-404 + Tug	6	11.1	49.6	1	20k	20k
Baffin	12	22.2	29.8	1	40k	40k

The velocity of the barges in combination with the 220km route makes them just fast enough to deliver and resupply within the 54-hour time window. Cost wise, the barges therefore win over the HTV, but it should be stressed that this result is highly dependent on project parameters. Were the sailing distance a bit greater, an extra barge of each type would be needed and the HTV would have been more cost-effective. The barge is more sensitive to weather delays as it can sail in lower sea states. If this causes too many delays for the SSCV, it may become more expensive then the HTV regardless. Mobilization costs have also not yet been taken into account, which vary with a vessel's global position prior to the start of the project. Moreover, with the price ranges depending on market demand as in table 3.3, the outcome is likely to differ substantially in time.

Because of these project and time dependencies, it is difficult to point to a clear general winner between the cargo vessels from a transport viewpoint. Yet, transport is not the only criterion for vessel selection.

4.2 Motion response analysis of tower offloading

With a crane vessel trying to attach its hook and lift the towers, a transport vessels motion behaviour during offloading may be even more defining than transport itself in making a decision for a supply vessel. Again, an analysis was done in Sinai as explained in section 4.1. Layout 1 as in figure 4.1 and 4.2 was chosen, but this time the number of components was varied as if they were being removed by Thialf's cranes. For each iteration, one nacelle and one tower were removed from the transport asset, working from the outside inwards. This is abbreviated as '4T4N', '3T3N', '2T2N' and '1T1N', referring to the number of towers (T) and nacelles (N) on board of the transport asset.

4.2.1 Offloading a barge in beam waves

To determine the effects of component offloading, a number of simulations were done with the barge in beam waves. It was discovered in section 4.1 that a large draft resulted in slightly better performance than half draft. Nevertheless, that was disregarded because of increasing fuel costs. During offloading the transport asset is stationary, making a large draft permissible. A check was done to determine whether a large draft was also the best option with fewer components on board. For H-404, a total of 12 simulations were executed; maximum, half and minimum draft for all offloading iterations. In general, operating under large draft prevailed. Motion response results of the barge with a large draft in beam waves are shown in figure 4.7. The scatter data are exact points of measurement, whereas the lines represent a trend for each cargo scenario.

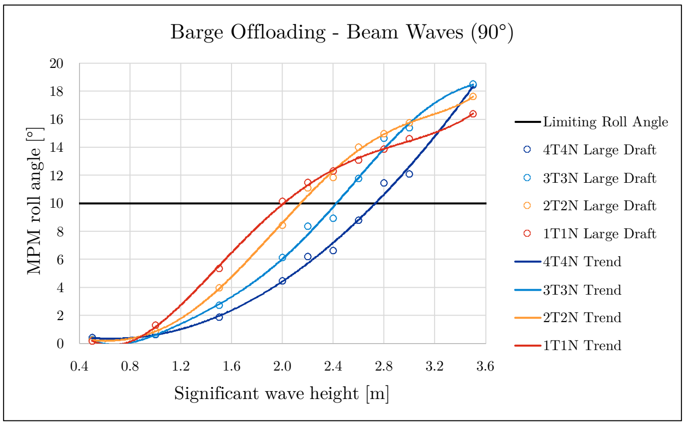

Figure 4.7: Motion response of a barge during offloading in beam waves.

From this plot, the differences in response between varying amounts of cargo can be clearly observed. With decreasing numbers of nacelles and towers on board, the maximum roll angle increases significantly, causing the limiting sea state to decrease. When fully loaded, the limiting sea state is $H_s = 2.7$m. But when only one tower and nacelle are left, the limiting sea state is just under $H_s = 2.0$m. The roll angle increase is greater with respect to H_s with less cargo for sea states up to $H_s \approx 2.0$m, which is the H_s range in which offloading will take place.

To establish what causes these effects, a closer look is taken at the influence of the systems natural roll period T_n on the motion response. In table 4.3, T_n for each cargo scenario is displayed, along with the simulated peak period at which the highest roll motions occur ($T_{p,\phi=max}$).

Due to the high center of gravity of the turbine towers, the natural roll period changes significantly every time a tower is removed. This change in T_n is the cause of the different responses in figure 4.7. Practically, this means that it will become increasingly harder to

Table 4.3: Natural roll period for each cargo scenario.

Scenario	T_n [s]	$T_{p,\phi=max}$ [s]
4T4N	11.0	10.5
3T3N	10.1	10.0
2T2N	9.2	9.5
1T1N	8.4	8.5

offload the towers with every offloaded component. It is no surprise that the maximum roll angle is experienced at peak periods close to T_n of the system. If the highest wave density in a spectrum has a frequency close to the natural period of the system, there is a high likelihood that a wave excites the vessel motion. In fact, $T_{p,\phi=max}$ should therefore correspond exactly to T_n, but due to the 0.5s increments in the wave period input, there is a small error. The 1T1N scenario is addressed in more detail to see how the wave period at which the maximum roll occurs relates to H_s and its T_n of 8.4 seconds.

Table 4.4: Dependency of $T_{p,\phi=max}$ on the T_p input range.

H_s [m]	T_p range [s]	$T_{p,\phi=max}$ [s]
0.5	$2.5 \leq T_p \leq 4.0$	4.0
1.0	$3.5 \leq T_p \leq 5.5$	5.5
1.5	$4.0 \leq T_p \leq 7.0$	7.0
2.0	$5.0 \leq T_p \leq 8.0$	8.0
2.5	$5.5 \leq T_p \leq 9.0$	8.5
3.0	$6.0 \leq T_p \leq 9.5$	8.5
3.5	$6.5 \leq T_p \leq 10.5$	8.5

It becomes clear that $T_{p,\phi=max}$ corresponds with the maximum value of the T_p range, which is directly related to H_s as prescribed by equation 4.2. However, the increase of $T_{p,\phi=max}$ stops as soon as the natural period is reached. For peak periods higher than the natural period, namely, less resonance occurs, meaning that even with higher waves, the roll response will be smaller. The increase behaviour of the maximum roll angle can therefore be split in three parts:

1. H_s increases and $T_{p,\phi=max}$ increases, resulting in an exponential ϕ increase.
2. H_s increases and $T_{p,\phi=max} = T_n =$ constant, resulting in a linear ϕ increase.
3. H_s increases and $T_{p,\phi=max}$ decreases, for which the roll response is unknown.

The first two parts correspond neatly to figure 4.7. Part 3 is never reached as it only occurs outside workable wave heights, for which the lower bound of the T_p range is larger than T_n. Therefore, it is not necessary to simulate this scenario.

4.2.2 Improving the offloading motion response

In section 4.7, the roll motion limit of 10° is reached for the operational target sea state of H_s=2.0m and T_p=8.0s when the last tower and nacelle are to be offloaded. This roll motion limit is a standard limit from the wind industry, based on the component motions during T&I with a jack-up. A roll motion of 10° is acceptable for transport, but absolutely unworkable during offloading with an SSCV. With the top of the tower some 90 meters above the water line, the horizontal excursions of the tower top would be 15 meters single amplitude, making crane operations uncontrollable and clashes inevitable.

Thialf's DP system can be of use to improve barge motions. Since the barge will be moored to the SSCV during offloading, it can benefit from Thialf's heading control, which has a single amplitude accuracy of 15°. Positioning the vessel into head waves generally results in the lowest roll motions, meaning that the worst motion response of the barge should be experienced at a heading of 165°. Sinai computes responses to incoming wave directions with increments of 45°, so an analysis of 165° is not possible with this software. Instead, simulations with a heading of 135° and 180° were run to obtain an indication of the influence of heading control for both H-404 and Tai An Kou. It should also be noted that no ship-to-ship interaction or shielding effects are taken into account yet.

Because Sanai does not make use of wave spreading, only true head waves are induced to the system for an angle of 180°. As a consequence, vessels with symmetry about their longitudinal plane do not experience any roll motions, as is the case with the barge and the HTV. No conclusions can be drawn from this, but the simulations with bow quartering waves give some surprising results, displayed in figures 4.8 and 4.9.

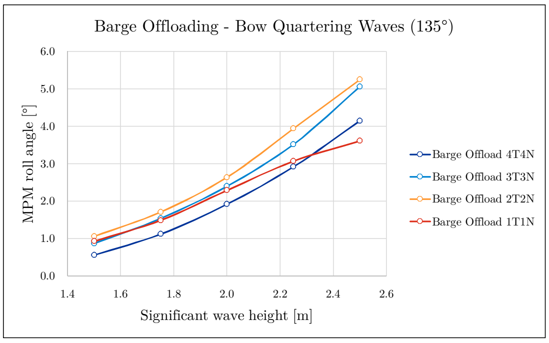

Figure 4.8: Motion response of a barge during offloading in bow quartering waves.

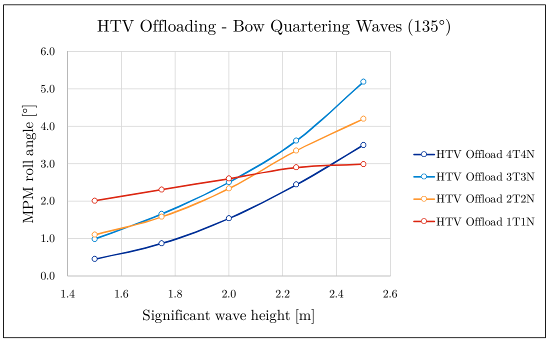

Figure 4.9: Motion response of an HTV during offloading in bow quartering waves.

Figure 4.8 shows that, already for an incoming wave angle of 135°, the motions are drastically reduced. For H_s=2.0m, the worst roll angle is now 2.65°, compared with 10.0° in beam waves as in figure 4.7; a reduction of 73.5%. Notably, the maximum roll angle in bow quartering waves occurs in the 2T2N scenario. This change can be addressed to a different mode of excitation, with the governing wave period being closer to the natural period of the 2T2N case. The change in natural period is related to the vessel's axis of rotation, which is inherently different in bow quartering waves than in beam waves.

There are some similarities and some differences when comparing the results of a barge in figure 4.8 with those of an HTV in figure 4.9. The motion response for the 2T2N and 3T3N cases are almost identical, especially for sea states H_s=2.2 and lower. On the other hand, the HTV performs better than the barge for the 4T4N scenario and worse for the 1T1N scenario. Since hull shape is the only different input parameter, the dissimilarities in the response are directly related to the variation of the hull shape.

Overall, the barge performs more consistently, particularly in sea states up to H_s=2.0m in which the vessels will operate the majority of the time. Conclusively, the barge has a slight edge over the HTV, offloading wise. Nonetheless, roll motions around $\phi = 2.0°$ are still on the high side to perform a safe offloading operation and should therefore be improved.

4.3 Remarks on supply vessel selection

By changing different parameters sequentially it has become clear that the motions in both sailing and non-sailing condition are largely governed by the inertia coming from the high tower CoG, and the number of towers on board contributing to this inertia. As a consequence, the motion response results between a similar sized barge and HTV do not diverge substantially. It must be acknowledged that the barge performs slightly better during offloading than the HTV. Contrarily, the HTV makes up for it by performing better in sailing condition. Eventually, both options are suitable as a supply vessel. For further reference in this research, a barge with a ship shaped bow will be used as a supply vessel. This vessel can sail with zero trim like the HTV, but preserves the benefit of a lower day rate. Use of such a barge also means HMC can use their own equipment, rather than relying on a subcontractor.

Ultimately, the decision on which ship to use will be dictated by its project-specific price tag and vessel availability as discussed in 4.1.3. The conclusion to be drawn is that the decision will be more dependent on specific project parameters rather than the differences in vessel performance.

5

Concept Solutions for Tower Offloading

In chapter 4, a motion response analysis showed that transport of the WTG towers was not the most limiting activity in the supply chain from marshalling yard to OWF. The high mass and CoG of the towers, however, generated large enough motions to be cause of concern during offloading of the towers. This activity must therefore be improved.

5.1 Market-ready solutions

In marine engineering, vessel roll motions have been a long time problem. Many roll mitigation systems exist, one of which already widely implemented on ships: bilge keels (figure 5.1). A bilge keel is a fin that runs longitudinally over the outside of the vessel hull, underneath the waterline. When a vessel rolls, a bilge keel will disturb the transversal flow over the hull, thereby dampening the vessel's roll motion. Many HTVs, such as the BigRoll Baffin, already have bilge keels on them. Applying bilge keels to an HMC barge can be considered, but would be a costly operation as it requires dry docking of the barge.

To transfer crew or cargo between vessels in high seas, active motion compensation systems can be used. Examples are solutions by Ampelmann or Bargemaster. These systems do not reduce the motions of the vessel, but of the items that are to be transferred offshore. The BM-T700 is a heavy duty platform able to support 700mT (figure 5.2), meaning that one unit would be needed per turbine tower. It is however costly, and the performance when carrying components with such a high CoG is unknown.

Figure 5.1: Bilge keel on the bottom of a ship hull.

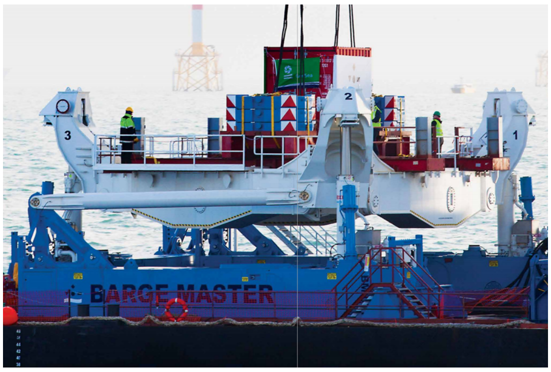

Figure 5.2: Bargemaster's BM-T700 motion compensation system.

An alternative passive solution would simply be to use a larger, especially wider, vessel. The roll motions will be reduced, but the system's natural frequency will increase due to a higher stiffness. It is a more expensive solution, too. Hence, whether this would be a good alternative can be questioned.

A new solution is thus to be found, preferably one which better uses the strengths of the SSCV rather than looking for a solution from a supply vessel viewpoint. The tipping problem and swinging problem of figure 3.5 should be mitigated and the workability should be improved to an acceptable level. In the next sections, three new concepts are presented that have been designed in an attempt to make tower offloading a practicable activity.

5.2 Modifying the existing design

The first concept is a modification of the HMC reference design. The grillage, connected to the bottom flange of the tower, serves as a connection point for the rigging as well as a source of stabilization when the tower is free standing. The footprint of the grillage is 9x9 meters, corresponding to the spacing of the barge bulkheads through which the forces are to be introduced on deck. Rather than making the grillage larger dimension wise and occupying large amounts of space on deck and in the marshalling yard, the mass of it is maximized, resulting in a lower CoG of the tower-grillage system. This can be done by adding enclosed volumes in the grillage which can be filled with sea water. This should lower the CoG and reduce the risk of the tower tipping over when it is in free standing position, just before lift-off. During lifting, the tower with grillage, spreader bar and rigging accumulates to a height of 106 meters. This relates to a maximum outreach of 72 meters. According to the auxiliary (aux) hook load-clearance curve, the capacity cap_{aux} is a constant 900mT up to and including an outreach of 80 meters. The mass of the spreaderbar, diverter frame, slings and other possible add-ons is yet unknown, but the mass of the grillage should be chosen conservatively so that inequality 5.1 should hold.

$$m_{grillage} + m_{tower} + m_{rigging} \leq cap_{aux} \tag{5.1}$$

With a tower mass from section 3.2.2 of m_{tower} = 465mT and a grillage of $m_{grillage}$ = 300mT, there is still 135mT of margin for the rigging. This leaves enough margin any design alterations later on, but does not compromise the idea behind the concept. The new center of gravity can be calculated by means of the masses and CoG's of the attached components. Since the construction has symmetry in mass over the two vertical planes, the CoG will remain coincident with the tower centerline, but shift in vertical direction. The new CoG height above the frame base, $h_{CoG,system}$, is calculated through equation 5.2.

$$h_{CoG,system} = \frac{\sum_{i=1}^{N_c}(h_{CoG,i} * m_i)}{\sum_{i=1}^{N_c} m_i} \tag{5.2}$$

With i = 1 to N_c being the number of structural components and all heights $h_{CoG,i}$ measured from the bottom of the grillage. Increasing $m_{grillage}$ to 300mT results in a CoG of the system of 25.9 meters above the grillage base, which is a great improvement over the tower CoG at 40 meters above the tower flange.

Increasing the mass of the grillage improves the limitations of the tipping problem, but the swinging problem is not yet resolved. The motions in the swinging problem may even increase with the heavier base. To mitigate swinging of the tower base altogether, the grillage is again altered, to form a solution called the FlexBase grillage.

A large tube is added to each side of the grillage, sliding in guiders which are welded to the barge deck. An impression is given in figure 5.4 and 5.3. During sailing, the grillage is pressed to the deck by hydraulic pistons as a form of sea fastening (not shown). Once the barge is moored to the SSCV and the rigging is connected to the aux hook, the sea

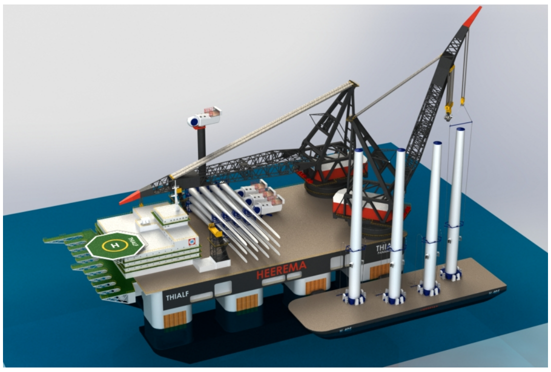

Figure 5.3: Offloading of the Flexbase grillage concept.

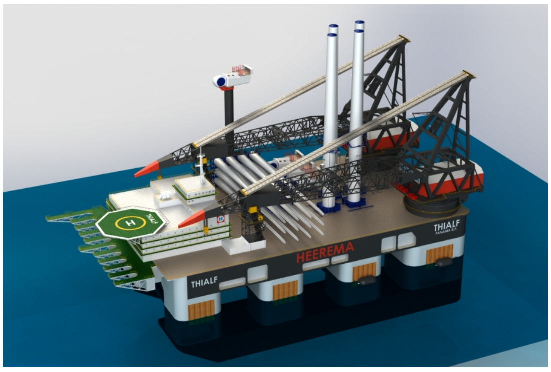

Figure 5.4: Deck layout of the FlexBase grillage concept, cranes boomed down.

fastening is released, and the spreader bar will be hoisted over the tower top. At this moment, the tower stands freely on the barge deck. The tower is then slightly lifted, some 2 meters above the barge deck and held there for a period of time. During this activity, the grillage can freely rotate in the guides but horizontal motions and rotation about the vertical axis are constrained. The crane driver can take a considerable time to let the tower motions dampen out before he lifts the tower out of the guiders completely and sets it down aboard the SSCV deck.

Removing the fixed connection at the vessel deck and replacing it with a double axis hinge mitigates the tugging effects of the turbine to the crane tip when the slings are tensioned and allows for a more controlled liftoff thereafter. Also will the pistons be protected from any clashes with the grillage as the guides project higher over the barge deck than the pistons. The most critical part in the sequence will remain the moment when a tower stands freely on the deck, just before lift-off.

5.3 Offloading multiple towers in a single lift

A disadvantage of the reference concept, as with the FlexBase grillage concept, is that the towers are lifted overhead. This principle is based on conventional procedures in the wind industry, where tall cranes with relatively low capacity are used (see table 2.1). As a consequence, an increasingly larger hook height is needed as the towers increase in size. For Thialf, this means only the aux hooks have enough height, while its primary strength, the main hooks, go unused. Thialf's main hooks have a maximum capacity of 7100mT each, which would be more than enough to lift all four towers on board at once. Because of its height restriction, use of a main hook has been disregarded already at an early stage of the development process for installation of WTGs. Since achieving a good workability by mimicking existing installation methods has now shown to be difficult, the preliminary deck layout and the use of the main hook were reconsidered.

5.3.1 A heavy lift with maximum capacity

When lifting multiple towers in a single lift, the lifting exposure time per tower is much lower when compared to lifting all towers separately. The definition of the lifting exposure time is the time it takes to execute an offshore lift. Optimizing towards exposure time means the amount of towers per frame should be maximized, so that as few as possible lifts need to be performed. First, the area at which towers can be placed on deck was determined. This is based on a number of parameters:

- Projected area blocked by the crane booms while they are in boomed down position for emergency purposes;
- Swept projected area of the winch house at the back of the cranes;
- Load-clearance curve of the main hook for offloading purposes;
- Load-clearance curve of the aux hook for installation purposes.

From the above, the area feasible for turbine placement can be found in figure 5.5, in which the minimum and maximum lift radii describe the workable limits of the aux hook. The turbine towers are allowed to be tangent to the limit area perimeter, but may not exceed it.

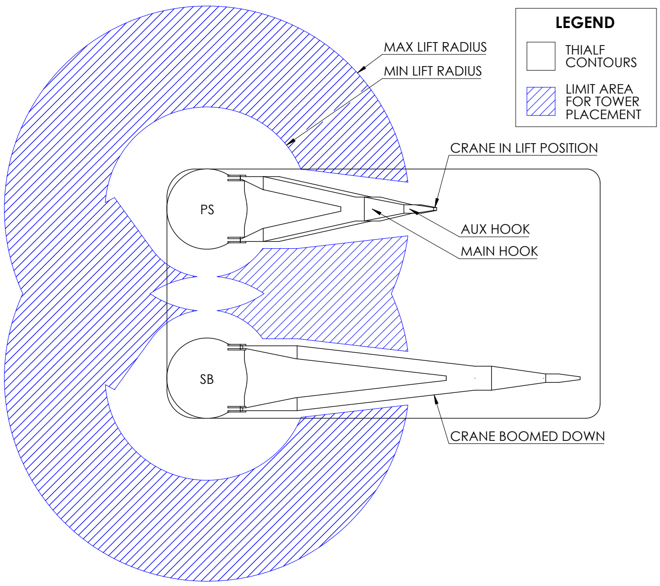

Figure 5.5: Area feasible for turbine placement.

Aside from the above mentioned, the mass of a frame proportionate to its dimensions was determined by informing with an experienced structural engineer. Thialf's deck strength was also assessed, as well as a number of clearance limits apply to ensure safe lifting operations:

- Clearance between tower centerlines of 10 meters.
- Clearance between the crane boom and the towers during offloading, consisting of:
  - 3 meters standard boom clearance;
  - Expected displacement during offloading.
- Clearance between the towers and fixed structures on deck, such as:
  - Boom rests;
  - Dummy tower.

With all these limitations in mind, the first logical step is to check whether a dual crane lift is possible. A dual crane lift is normally done from the stern of the vessel as in figure 1.1, provided that the lifted object does not have to be placed on Thialf's deck. Since the contrary is true for the turbine towers, the load would have to be maneuvered between the two cranes, a risky operation. Since the crane booms cannot move over the load, it would result in complex and inconvenient crane movements leading to, surprisingly, only a small number of towers on a frame possible due to inevitable clashes. An alternative dual crane lift could be performed from either side of the vessel, for example the starboard side. This would mean that the portside crane would have to reach over the deck to a radius of approximately 92 meters, at which point the capacity has reduced to a bare 800mT and the advantage of having a second hook has become near worthless.

By using a single crane, there is room for many other options. An iterative process as in appendix D resulted in defining a maximum amount of towers on a frame. Notably, two parameters were dominating in defining the general shape of a multi-tower frame:

- The projected area blocked by the crane booms while in boomed down position;
- Having the CoG of the solution vertically in-line with the crane hook, making symmetry a logical choice.

The result of a series of iterations is a wide, partly overhanging frame, with eight towers on either side of the crane boom (the '8T-Frame'). The frame has symmetry over the vertical plane running in longitudinal direction of the boom. The mass of a frame is estimated at 2000mT. The total mass of this solution then equates to 5720mT. The frames are just narrow enough to not cross the SSCV centerline. This makes it possible to lift and store a frame on both sides of the SSCV, totaling to a number of 16 towers on deck at once (see figure 5.7). A simple static moment check was done to make sure the frame would not tumble over the side of the vessel if towers are being removed from the frame and installed onto the substructure. This check passed with sufficient margins, as long as towers will be taken off alternating between the sides of the frame. The main hooks have the capacity to lift the frames at a maximum radius of 45 meters, providing enough clearance to lift and maneuver the closest towers by the aux hook during installation. The length and width of the frame are respectively 30m and 57m, providing stability against the tipping problem for the duration that the structure is free standing on the barge.

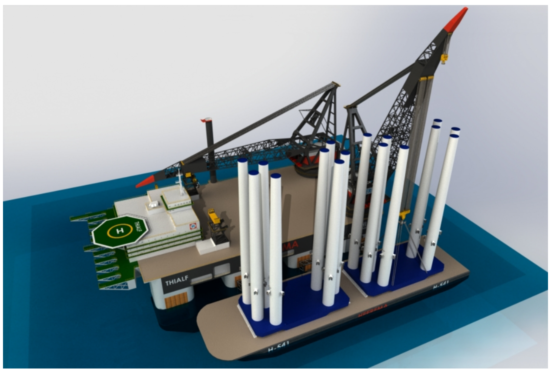

Figure 5.6: Offloading of the 8T-Frame concept on portside.

Figure 5.7: Deck layout of the 8T-Frame concept, cranes boomed down.

A consequence of using all the deck space for tower placement is that there is little space left aboard for the nacelles and blades, all of which is has become unreachable for the SSCV's cranes. The intent of 8T-Frame concept is therefore to split WTG installation into two separate campaigns. In the first campaign, all the towers in an OWF are installed. Once completed, the SSCV needs to be re-outfitted and prepared for the RNA installation. This requires exchange of lifting tools and removal of the starboard main hook, last of which is needed to avoid clashes during the RNA installation procedure. There is room for six sets of blades and nacelles on board during the second campaign. Such a fundamental change in installation sequence affects activities outside the scope of this research, such as fabrication and logistics in the marshalling yard. A discussion on this topic with involved third parties is therefore essential, already starting from the tender phase of a project.

5.3.2 A heavy lift in-line with current installation procedures

A solution more in line with HMC's deck layout and with industry procedures is found in scaling down the multi-tower frame concept. Where previously most towers per frame was the target, the solution should now work with the already envisioned deck layout and installation sequence. The result is a frame carrying four towers, two on either side of the crane boom, hereafter called the '4T-Frame'. With dimensions of 20m length and 42m width, it fits between the crane and blades as in figure 5.9. The mass of this frame is estimated at 1000mT. It can dimension wise be transported on a relatively small sized barge, together with four nacelles if logistically practical.

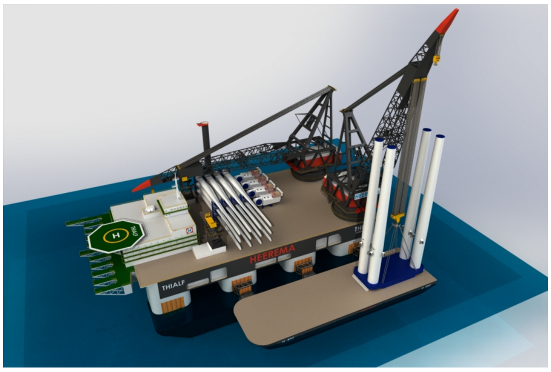

Figure 5.8: Offloading of the 4T-Frame concept.

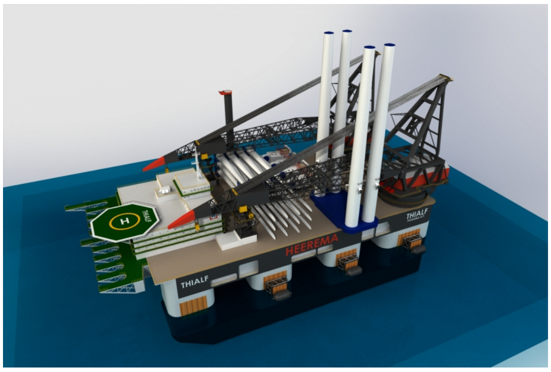

Figure 5.9: Deck layout of the 4T-Frame concept, cranes boomed down.

5.3.3 Design characteristics of multi-tower frame lifts

The potentially most valuable advantage of lifting multiple towers on a frame, is that the number of lifts and thereby the lifting exposure time is drastically reduced. Secondly, the worst scenarios of section 4.2, simply do not occur when offloading all towers at once. Thirdly, the high mass of the frames lowers the CoG of the system. For both the 4T-Frame and the 8T-Frame solution, it is reduced to 29.5 meters above the base of the frame. This positively contributes to the tipping problem, similar to the heavy grillage of the FlexBase concept. Conveniently, the lift of a large, heavy frame with WTG towers on it is not too different from a lift of a platform module with a crane extending outward close to the boom of the SSCV, a type of lift for which Thialf was originally made. Such a lift has been performed many times in the past, the advantage of which is having an experienced crew for such an operation.

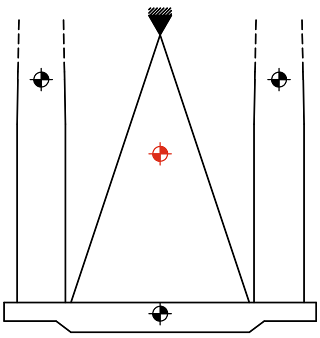

Figure 5.10: Front view of the system with its CoG (red) located within the pyramid-shaped volume.

Choosing an appropriate hook height in case of a multi-tower lift is essential. The slings, which connect the frame to the hook, enclose a pyramid shaped volume with its four connection points on the edges of the frame. The system CoG has to remain within this volume at all times as moving outside it would cause the frame, and the towers with it, to flip over [28]. The CoG can move through the pyramid shape when the slings extend in length when loaded for which reason the pyramid should be as stiff as possible. To assure minimal shifting of the CoG, short slings made of steel are chosen, with a diameter based on standard criteria [29]. The main hook is located 40m above the frame base. A front view is portrayed in 5.10.

When the frame is on Thialf's deck, the load is transferred to the vessel's bulkheads. The overhanging side is not supported by any means. In its simplest form, the loads and supports on the frame can be modeled as a four-point load test of a beam in bending, see figure 5.11. This model is not only true for the frame when it is on deck, but also when it is suspended from the main hook as in figure 5.10. The red line in figure 5.11 corresponds to the bending moment in the frame.

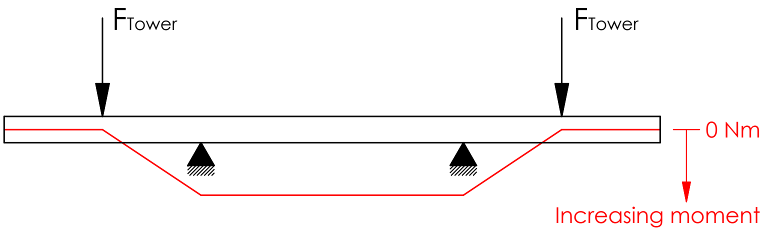

Figure 5.11: Four point load test of a beam with corresponding bending moment line.

From structural engineering, it is known that the bending moment line relates to the height profile of a beam necessary to carry the induced loads. This means that the shape of it can be used as a basis for the design of the frame. On the quayside, this offers opportunities. More specifically, the fact that the frame is allowed be less high on both ends is an advantage for roll-on operations. The notches at the lower side of the frame ends create a void into which an SPMT can be maneuvered, making for an elegant solution without any extra grillage needed to roll the load on board during load-out. The large footprint and lower CoG of the frame also help in making this operation more feasible than with a single tower. A detail of the left side of the frame is shown in figure 5.12.

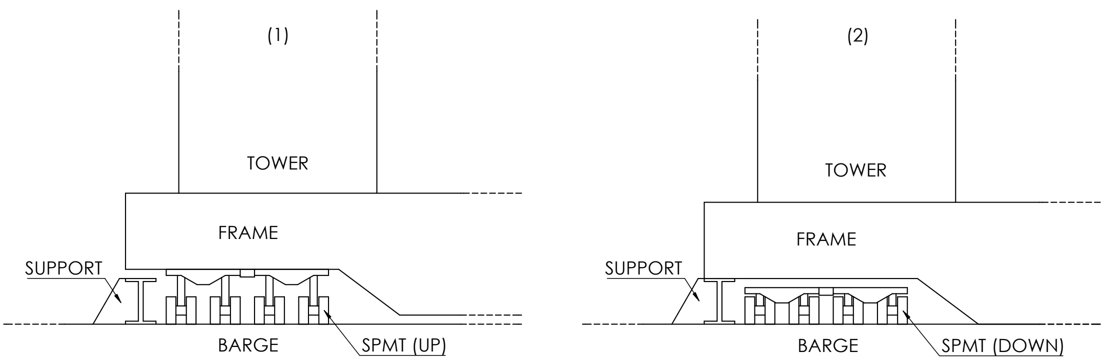

Figure 5.12: SPMT load-out of the 4T-Frame with (1): Roll-on of the frame onto a barge and (2): SPMT moving from underneath the frame after set-down.

Supporting beams should be welded as shown to the barge deck, to maintain maximum stability of the frame, especially in the free standing condition during offloading.

5.3.4 Disadvantages of multi-tower frame lifts

A possible negative effect of this method will be noticed if the number of turbines in a farm is not a multitude of the amount of towers on board the supply vessel. This can best be explained by using an example. Say, a wind farm consists of 50 WTGs. Knowing that two frames fit on one barge, just three voyages are required to bring 48 towers offshore with the 8T-Frame. For the last two turbines, a massive frame is transported and lifted, while serving only the two left over turbines. This makes the last voyage, and as a consequence 25% of the tower transport voyages very cost inefficient. A perhaps even worse scenario exists when the wind farm consists of an odd number of turbines, in which case one frame will be unevenly loaded, resulting in tilt or likely even a flip when suspended from a crane hook. A solution for this could be to add a lump of dead weight (in whichever form) on the opposite side of the frame to balance it, but it is clear that this fix is not ideal.

5.4 Remarks on offloading concepts

After considering a number of market ready solutions, it was decided that alternatives for offloading should be sought which would better make use of the strengths of a semi-submersible crane vessel. By iteration, three concepts for tower offloading have been given their primary dimensions and carry enough potential to be further researched. These three concepts are dubbed: the FlexBase grillage, the 8T-Frame and the 4T-Frame, each with their own strengths and weaknesses. The FlexBase grillage is an improvement of the reference procedure. The 8T-Frame exploits Thialf's crane capacity to its fullest, but demands a radical change in working procedures. The 4T-Frame effectively uses the SSCV's crane capacity, without interfering with market practices. Figure 5.13 shows an overview of the three concepts. A feasibility analysis of these three concepts are discussed in the next chapter.

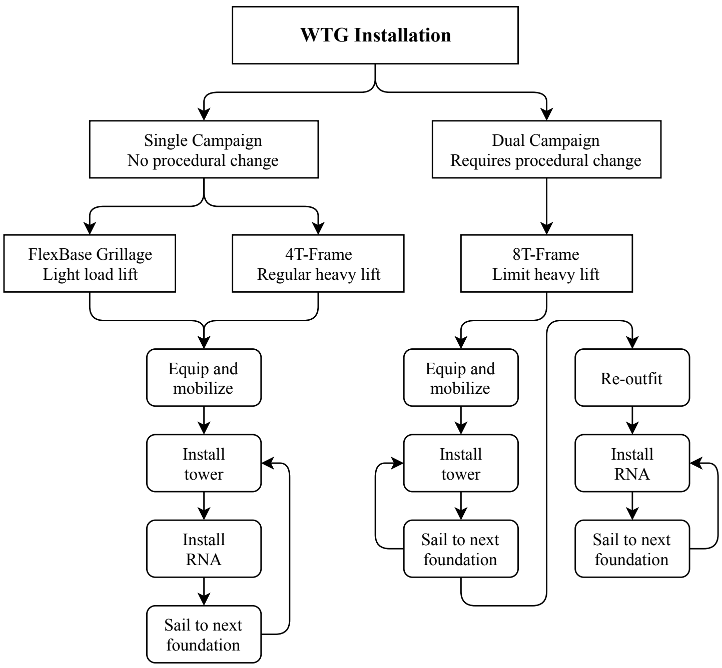

Figure 5.13: Overview of the concepts and their effect on installation procedures.

6

A Study on Concept Effectiveness

The cost of a T&I project is primarily driven by the operational costs of the used vessels, and therefore strongly corresponds to the duration these vessels have to be hired. The project duration typically depends on the net transport and installation time and the weather down time (WDT). The weather down time, expressed in hours or in days, is a time window during which project execution is stagnated due to environmental conditions greater than allowable for a pending activity in the operational sequence. The net installation time is outside of the scope of this research and is already minimized by HMC's engineers. A good feeder system solution should therefore minimize the net offloading time and especially the WDT. Experience shows that WDT is strongly correlated to relative motions between bodies and their corresponding limits. The approach to determine the total project duration including weather down time is presented in this chapter.

6.1 Offshore lift types and test cases

The net offloading time can easily be computed by assigning a duration to every activity in the offloading sequence and adding them together, taking into account that some activities may occur simultaneously. This cannot directly be said of the WDT, for which an in-depth analysis is required.

For the offloading solutions, different lift types have to be distinguished. The 8T-Frame and 4T-Frame are categorized as 'heavy lift'. With a heavy lift, ballasting the SSCV is typically used to lift a frame of a supply vessel, resulting in a relatively long duration lift. This results in a significant time span during which the load is in part carried by the supply vessel and in part by Thialf's crane; the partly tensioned (PT) scenario. The slings connecting the main hook to the frame act as a pretensioned spring between two floating bodies, which may result in unexpected behaviour. The FlexBase grillage is a 'light lift'. The use of the aux hook, with much fewer reevings than the main hook, allows for a quick lift with an insignificant pretension time. Instead of the PT case, a scenario just after lift-off is analyzed; the grillage freely rotating (FR) in the guide rails. The HMC guidelines prescribe that two other steps must be analyzed with each lift: a free floating (FF) scenario with the the barge aside the installation vessel prior to connecting the rigging, and a free hanging (FH) scenario when the load is completely free from contact with the barge.

It was found in section 4.2 that the number of towers on a frame significantly changed the roll amplitude of a supply vessel. It is necessary to consider this in the detailed analysis as well. To simulate a full lift sequence, the scenarios with a check mark in table 6.1 should thus be simulated. This equates to a total of 21 geometrically different scenarios.

Table 6.1: Scenarios to be simulated.

Concept	Cargo	FF	FR	PT	FH
FlexBase Grillage	4 x 1 Tower	✓	✓	✗	✓
	3 x 1 Tower	✓	✓	✗	✓
	2 x 1 Tower	✓	✓	✗	✓
	1 x 1 Tower	✓	✓	✗	✓
4T-Frame	1 x 4T-Frame	✓	✗	✓	✓
8T-Frame	2 x 8T-Frame	✓	✗	✓	✓
	1 x 8T-Frame	✓	✗	✓	✓

6.2 Overview of used software packages

A series of in-house software programs is used to determine the expected WDT of the three concepts, as set out in the flow chart of figure 6.1.

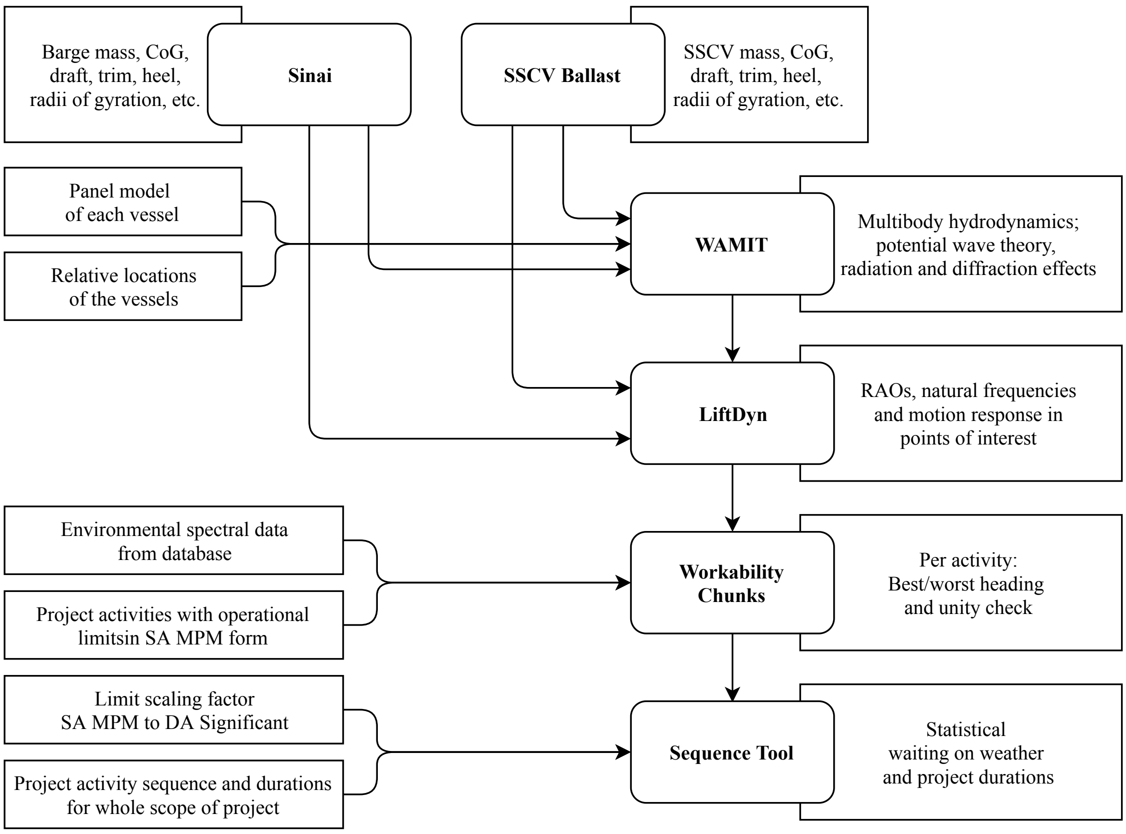

Figure 6.1: Flowchart of the programs used to determine the expected project duration per concept.

All of the above are mature programs for different applications within Heerema, used before in several projects over the course of history. Some of the programs have been validated by model testing prior to their launch and all of them have been updated and improved where necessary, based on experience gained during executed projects in full scale. The programs have been used in line with standard company procedures and have therefore been assumed valid for this research.

6.3 Sequence of simulations

In this section, the sequence of simulations through the software programs is explained, as well as the relationships between them. In essence, this is the approach on how to obtain statistical weather down time for each of the concepts.

6.3.1 Sinai

The working principle of Sinai has earlier been explained in chapter 4. It should be noted that for all 21 scenarios, a barge with a ship-shaped bow is used as a result of section 4.3, with a trim of zero degrees and a draft of 70%, which is the maximum allowed draft. It was found earlier that this would give the best motion response for offloading. A single run with a JONSWAP spectrum with $H_s = 2.0$ is enough to determine the natural frequency, mass and radii of gyration for every scenario.

It was found that the stability criteria of inequalities 4.3 and 4.4 did not hold if two 8T-Frames were put on barge a 400ft barge. A larger, 540ft barge from HMC's fleet is chosen to improve stability. Indeed, with two 8-tower frames on barge H-541, the stability and motion response of the system are sufficient. Therefore, barge H-541 is used for transport in the further analysis of the 8T-Frames scenarios.

6.3.2 SSCV Ballast

SSCV Ballast is a tool in which the CoG, draft, transverse and longitudinal metacentric height, trim and heel of Thialf can be defined. For each scenario, the radius of both cranes with their suspended loads have been used as input. The masses and locations of the components on deck are also taken into account. The vessel is then ballasted so that it experiences zero trim and heel, with an operational draft of 26.6 meters. This is a standard draft for lifting operations, in line with [30] and selected after consultation with a marine engineering expert. The lower and outer ballast tanks are filled first to create extra inertia.

6.3.3 WAMIT

WAMIT is a program which computes the body-to-body interaction between vessels due to inertial forces such as radiation and diffraction. It does so by making use of potential wave theory. Panel models, with the appropriate drafts from the prior two programs, were generated from the barge and the SSCV with a mesh size of at most 4 by 4 meters, see figure 6.2. The panels are impenetrable, resulting in zero flow in the direction normal to each panel.

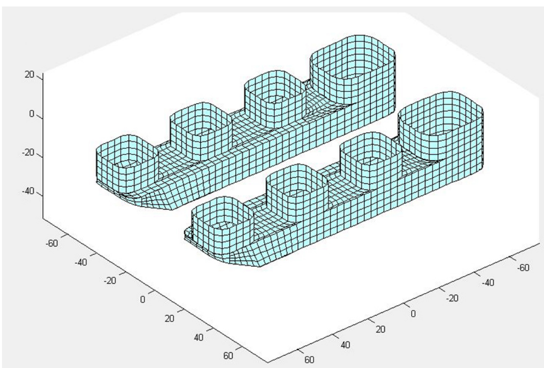

Figure 6.2: WAMIT panel model of the SSCV.

Next, a script is run with as input relative distances between the two bodies for every scenario with their corresponding panel model data. At location Halfdan the water depth is approximately 40 meters, which is also taken into account for bottom surface effects. The ship-to-ship interactions for waves in 24 headings are computed; from 0° to 345° with increments of 15°. The heading convention for WAMIT and other software is found in appendix C.

6.3.4 LiftDyn

LiftDyn uses information resulting from WAMIT, Sinai and SSCV Ballast to compute a system's natural periods or frequencies, along with RAOs in any point of interest (POI). The vessel bodies, as well as cranes and components on deck of both the SSCV and barge are defined. LiftDyn runs a vibration analysis in the frequency domain with six degrees of freedom (DOF); three translations and three rotations. The differential equation 6.1 is solved.

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{F} \tag{6.1}$$

The mass matrix **M** is defined by a vessels mass and radii of gyration. The output of WAMIT, in the form of a text file, is coupled to the relevant wetted bodies, adding a hydrostatic spring matrix **K**. In case of the SSCV, a standard spring matrix which represents the stiffness of the DP system is added to **K**. Thialf's damping matrix **C** is barely influenced by shifting loads or surrounding vessels and therefore taken from a standard table. Roll damping of the barge is tuned to the response from Sinai, by computing the roll motions under the same loading conditions; a JONSWAP spectrum with $H_s = 2.0$. Iteratively, the damping matrix is altered until a roll motion response for each period is obtained sufficiently close to that from Sinai. A slight error therein is that in Sinai, no ship-to-ship interaction or bottom surface effects are taken into consideration. Heave and pitch damping is dominated by radiation and diffraction effects, and therefore largely captured by the model data from WAMIT.

Aside from this, the interface conditions between any two POIs on any two bodies can be defined. This can be done in the form of a joint, in which a fixture in any of the 6 DOFs is determined. An example of this is the connection between the towers and their grillages, in which case all DOFs are fixed. Another interface type is a connector, in which case both a spring and a damper can be added. Among other things, this is used for the slings, connecting the hook to the frames.

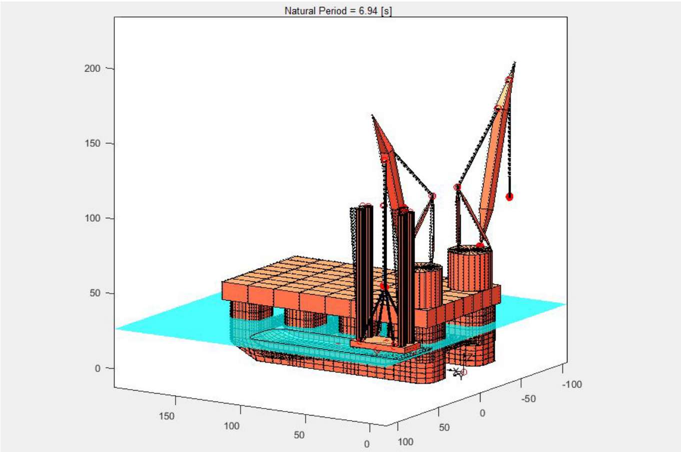

Figure 6.3: LiftDyn displaying a pitch mode shape of the 4T-Frame in the PT scenario.

When this all is done appropriately, the bodies will interact much like they would in real life, even if they are not directly linked through a physical connection as in the free-floating scenarios. It is of the essence that coordinate consistency is properly executed to obtain accurate results. Since the coordinate system in WAMIT can have a different origin than in LiftDyn, coordinate shifting may apply. To verify if the input is correct, a graphical representation of every mode shape with its natural period can be displayed. This information serves as a visual check, but can also be used to get a first sense of feasibility of the concept.

To extract useful RAOs from LiftDyn, specified POIs in the system are chosen in which operational limits will later be defined. These limits can take the form of forces, velocities, accelerations, or displacements both rotational and translational, and are based primarily on criteria mentioned in chapters 3 and 5. POIs can be added to measure a parameter at a location which was not earlier defined. The RAOs are saved in a file which will be used by the next program in the sequence. There is one particular criterion which cannot be captured in an obvious way with the abovementioned limit forms; the criterion for the tipping problem.

As discussed in section 3.4.1, the tipping problem arises due to dynamic forcing in the CoG of a tower-grillage combination causing a moment about the side of the grillage which is greater than the restoring moment due to gravity. This also applies for the tower-frame systems of the 4T and 8T concepts. The hinging interface between the grillage and the barge cannot be modeled with the available constraints in LiftDyn. A way to solve this is by modeling the support of the frame or grillage as four matrix springs; one in the middle of each side of the structure. A matrix spring experiences a virtual displacement when loaded, and has a certain stiffness from which the support reaction force can be computed by LiftDyn. If all four matrix springs remain in compression, it is certain that no side of the frame will come loose from the barge, hence no tipping will occur. The limits of the reaction forces in the spring can be derived in accordance with appendix E. The stiffness of the matrix spring should be chosen with care, so that:

- No resonance occurs, for which $\omega_{dyn} \ll \omega_n$ or $\omega_{dyn} \gg \omega_n$ should hold, with ω_{dyn} the frequency of the system's motion and ω_n its natural frequency;
- The spring emulates a stiff support, so the motions of the frame or grillage should be identical to the barge motions.

Choice of a very high spring stiffness k will satisfy both criteria. A value of $k = 10^9$ kN/m was used and found appropriate by checking the motion response in relevant POIs in LiftDyn. These springs have no physical meaning, but only serve to model a rigid connection from which a force can be extracted from LiftDyn.

6.3.5 Workability Chunks

Workability Chunks is a Matlab script that determines the optimal heading for separate scenarios, as a response to given environmental data. As a source, a database with 20-year weather measurements of locations on the North Sea is consulted. For location Halfdan, an energy density spectrum has been generated every three hours, based on measurements of waves for every frequency, and in all directions with increments of 15 °. For every event in the offloading and installation sequence (for example a PT scenario), the RAO files from LiftDyn are loaded and limit values in the point to which the RAO applies must be defined. A large part of this, such as offloading the blades and nacelles and installation of the tower and RNA have yet been defined by other engineers within Heerema.

Any energy density spectrum, defined by H_s and T_p, is a statistical representation of the sea state. Due to its statistical nature, no theoretical maximum exist for the wave height. The same applies to any linear motion response as a consequence of the surface elevation. One can imagine, however, that with a longer exposure time or, more accurately, the exposure to an amount of wave cycles, the chance of exceeding a certain motion increases [31]. Ocean wave theory dictates that the number of waves N in wind drive sea states over a period of 3 hours is equal to $N = 1000$ [25]. In wind industry standards, a minimum exposure time for an activity of 30 minutes is applied, relating to $N = 167$. By coupling the number of wave cycles to every limit in Workability Chunks, the script can compute the most probable maximum wave height, according to equation 6.2.

$$H_{MPM} = H_s \sqrt{\frac{\ln(N)}{2}} \tag{6.2}$$

The response in each POI to the most probable maximum wave load is then computed, based on the corresponding RAO and the energy density spectrum for every incoming wave angle. The script then performs a unity check, comparing the response to the defined limit:

$$U = \frac{Response}{Limit} \tag{6.3}$$

In equation 6.3, U is the value of the unity check. If U is smaller than 1, the response in the POI will not be limiting and operation can start or continue safely. The heading with the lowest unity check is the best operational heading, because in this case the response is the most beneficial. It can occur that for one of the checks U is greater than 1 for all headings. In this case, the response in the POI is limiting and delaying the operation.

In one scenario, the lowest unity check may result from different angles in different points of interest. Because a vessel can only have one orientation at a moment in time, an average unity check value over all POIs is computed for each wave direction. From this can be derived that the heading with the lowest average unity check is the best heading for a specific activity. However, since the SSCV cannot maintain its heading with a 100% accuracy, the second best heading is taken, 15° off the best heading. This heading is written to the matching sea state in the environmental database file. Again, some limits may have a unity check higher than 1 even in this optimal heading. The crew will have to wait for a sea state in which U $\leq$ 1 for all limits in the optimal heading before continuing the installation sequence.

6.3.6 Sequence Tool

With the sequence tool, statistical weather down time can be computed for a project. The environmental database file with the headings and RAO data for each activity is loaded. Then, all offloading and installation activities for a complete wind park have to be defined. From section 5.3.4, it is known that to effectively exploit the potential of the concepts, an OWF size of a multitude of turbine components per transport should be chosen. To fairly compare all three solutions, the OWF size should also be a multitude of the transported cargo of all three concepts. Table 6.2 shows the different cargoes and number of voyages of each configuration, totaling to 48 WTGs for a small wind farm and 96 WTGs for a large wind farm.

For every activity in the sequence, a duration needed to complete the activity must be defined. Most durations are based on experience from oil & gas and pipelay projects or expected values determined in consultation with installation engineers and crew. Certain actions may be time dependent on prior activities, which can be accounted for. For example, the FF scenario and its corresponding limits relate to motions of the bodies when a crew is attaching the rigging. In principle, the crew can wait as long as they like for a good weather window before they start doing so, independent of the prior task.

Table 6.2: Components per cycle and cycles per wind farm for each concept.

	Case	Components per cycle	Cycles per farm	
			48 WTGs	96 WTGs
Towers	1T	4	12	24
	4T	4	12	24
	8T	16	3	6
Blades & Nacelles	1T	4	12	24
	4T	4	12	24
	8T	6	8	16

The PT and FH scenario which follow are time dependent on their previous scenarios, because once the rigging is connected, the frame should be lifted and set down on deck as quickly as possible. When determining a suitable time window, the script takes this into consideration. If activities are practically difficult to execute, a time window greater than the net time frame for that activity may be assigned, to account for any practical hold-up. This is applied to the major lifts, such as the lift of a frame during offloading and the lift of the RNA during installation. Furthermore, activities which require no limits, or activities with standard limitations in the form of significant wave height or wind speed may be added.

To determine the weather down time, a limit for each RAO has to be defined again. These limits are the same ones as used earlier for Workability Chunks, but scaled to match Sequence Tool's calculation method. Sequence Tool calculates the responses based on H_s and expressed in significant double amplitude (SDA), while the operability limits were earlier defined as a single amplitude most probable maximum (SAMPM). For this reason, the limits have to be scaled according to equation 6.4, with N again the exposure time in number of wave cycles.

$$SDA = \frac{2 * SAMPM}{\sqrt{\frac{1}{2}\ln(N)}} \tag{6.4}$$

For $N = 1000$ this equates to:

$$SDA = \frac{SAMPM}{0.93} \tag{6.5}$$

And for $N = 167$ it becomes:

$$SDA = \frac{SAMPM}{0.80} \tag{6.6}$$

Sequence Tool computes responses for the weather data from the environmental database file, with the vessels in their most optimal heading for every step. On an arbitrary day in the year, it starts the installation sequence. For every activity, the response is computed. If a response exceeds its limit condition, the operation stops and will only continue when the all responses for the activity have dropped under their limit. The time between stopping and resuming operations due to bad weather is added to the weather down time. With the net durations for every step known, the total project time including waiting on weather (WoW) is computed. The Sequence Tool computes the total project time on every day of every year, with a starting interval of 3 hours. The measured data in the environmental database ranges from January 4th 1992 until July 31st 2010, resulting in a plentiful amount of project duration estimates to obtain a statistically reliable output.

6.4 Activities and their limits in the points of interest

The number of activities per cycle of each concept, along with the net cycle time, can be found in table 6.3. At first sight, the net cycle times seem greater than the estimated 48 hours for installation of four WTGs mentioned in section 4.1.3. This is partly due to an estimation error, and partly because the cycle times of table 6.3 include offloading the turbine components, which is a substantial part of the total cycle time. In Sequence Tool, the activities are multiplied by the number of cycles of table 6.2 to obtain a total number of activities per project.

Table 6.3: Number of activities per cycle.

	Reference	FlexBase	4T-Frame	8T: Towers	8T: RNAs
Activities per cycle	94	94	83	119	102
Net cycle time [hrs]	79.3	79.3	76.6	91.8	94.4

Due to the great number of activities, they will not all be discussed in detail here. Many activities, especially the ones defining the installation procedure, are a direct copy of the reference case and defined by HMC's engineers. They should be included in the sequence to determine the total WoW days, but have little other relevance to the objective of this research. In the next section, attention is given to some of the new activities, corresponding to offloading of the concept solutions.

Table 6.4: SAMPM limits some scenarios of the new concepts.

	FlexBase		4T-Frame		8T-Frame		
Limit	FF	FR	FF	FH	FF	FH	
Crane vessel motions							
Roll-pitch SSCV	0.5	0.5	0.5	0.5	0.5	0.5	[°]
Tower limits							
Transverse acceleration tower	3.924	3.924	3.924	3.924	3.924	3.924	[m/s^2]
Longitudinal acceleration tower	7.848	7.848	7.848	7.848	7.848	7.848	[m/s^2]
Vertical acceleration tower	7.848	7.848	7.848	7.848	7.848	7.848	[m/s^2]
Roll-pitch of tower	10	10	10	10	10	10	[°]
Rigging attachment							
Hor. motions crane tip/rigging	1.5	-	1.5	-	1.5	-	[m]
Ver. motions crane tip/rigging	1.0	-	1.0	-	1.0	-	[m]
Clearances							
Motions crane boom/top tower	-	-	4.63	5.75	8.15	6.31	[m]
Motions crane boom/CL tower	-	-	-	4.63	-	8.15	[m]
Hor. motions hook/diverter frame	1.6	-	-	-	-	-	[m]
Ver. motions hook/diverter frame	1.0	-	-	-	-	-	[m]
Hor. motions spreaderbar/CL tower	-	3.0	-	-	-	-	[m]
Ver. motions grillage/guiderail	-	1.5	-	-	-	-	[m]
Support reactions							
Force in transverse support	1354	-	5214	-	10549	-	[kN]
Force in longitudinal support	1354	-	5309	-	10663	-	[kN]

6.4.1 Limit values in offloading activities

To get an impression of the types of limits that are put on the system, the limits in some of the new scenarios of table 6.1 are shown in table 6.4. The values are defined as a single amplitude most probable maximum. Relative motions between two bodies are indicated by a forward slash.

Table 6.4 covers most of the new limits, but some of the scenarios are not presented. The missing scenarios FH for the FlexBase grillage and PT for the frames can be fully defined by the limits from table 6.4, although not all mentioned limits apply. Next to these exact limits, a maximum allowable sea state of $H_s = 2.0$ meters and a wind velocity of v_w = 12.9 m/s are applied to all barge-related activities. The wind limit is also applied to all lifting activities during installation. These limits follow from HMC standard procedures for barge offloading and crane operations from the oil and gas industry.

6.4.2 Pinpointing the limiting parameter

The specific limit within an activity causing a high weather down time in the sequence tool can be determined. In liftDyn, a JONSWAP spectrum can be added as load and SDA limits as are also entered in the sequence tool can be added. The operability for each motion, force or acceleration is then computed by LiftDyn, in terms of maximum allowable wave height for a certain wave period. For each heading, the most limiting POI is determined. This way, the most critical limit can be found for each heading.

6.4.3 Comparison to the reference case

Judging how the concepts compare to the reference case is fairly easy. To really see how the hinging base contributes to the weather down time, the grillage mass of the reference case is changed to match the FlexBase grillage. Other than that, there is only one difference between the reference case and the Flexbase grillage which is the joint constraint in LiftDyn during the freely rotating scenario. For the reference case, the joint is removed and replaced by an SAMPM limit of 2.0 meters horizontal excursion in the grillage CoG, so that the bottom of the tower will not swing too far over deck. Elsewise, the reference case was put through the same procedure as described in section 6.3.

7

Results and Discussion

The results following the simulations of chapter 6 are presented in this chapter, along with a number of findings that followed from analyzing these results. Based on those findings, some parameters were changed to improve the model limiting criteria after which a second run was executed, the effects of which are also discussed.

7.1 Results of the first simulation iteration

The average waiting on weather for a full project, expressed in days, is presented for every concept solution in figure 7.1. The total project time, consisting of the net project time plus the waiting on weather is shown in figure 7.2. The results shown are based on a wind farm size of 48 WTGs. The months on the horizontal axis represent the month in which the project is started. The abbreviations Ref, 1T, 4T and 8T again stand for the reference case, the FlexBase grillage, the 4-tower frame and the 8-tower frame respectively. As an example: with a project start in March for the reference case, the WoW over the whole project is 18 days. Adding the net project duration of 40 days, the total project duration becomes 58 days.

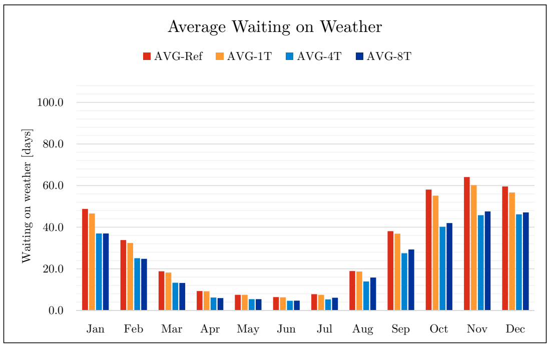

Figure 7.1: Average waiting on weather for a 48-WTG Farm.

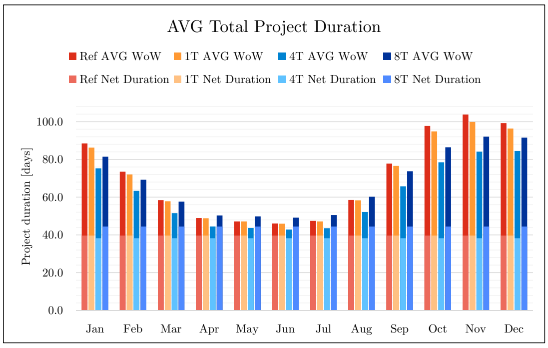

Figure 7.2: Average total project duration for a 48-WTG Farm.

In figure 7.1 it can be seen that the waiting on weather time varies over the year for all cases. The multi-tower frames perform considerably better than the concepts in which the towers are offloaded individually. The extent to which they perform better varies over per starting month, which is no surprise. It is generally known that the North Sea is subjected to high sea states in the winter months, increasing the waiting on weather time. An example, for which the FlexBase grillage concept is assessed, can give insight in why the starting month has an influence on the WoW:

A WTG T&I project is started at the end of May. There are few WoW days in this period due to the generally low sea states in May and the months shortly thereafter. With a net project time of some 40 days and delays of around perhaps 2 days in May, 4 in June and 2 in July, the total WoW equates to 8 days. If work starts early November, the best case scenario would be a project duration equal to the net project duration, resulting a finish halfway through December. However, the high sea states in November cause much weather downtime, pushing work to December. In December the weather is statistically even worse, causing many more delays, and so on through the winter. As can be seen, the WoW days with a project start in November are equal to 60, making for a total of some 100 days for the project and finishing only in February. This shows that starting a project of 48 WTGs in autumn is a poor choice, as a small delay can result in increasingly larger delays in the months that follow. This is also the reason that the ideal starting month shifts to earlier in the year for larger projects, which have a longer duration. This 'shift to the left' can be clearly seen when the results in figures 7.1 and 7.2 for the 96-WTG farm are compared to figures 7.3 and 7.4 for the 48-WTG farm.

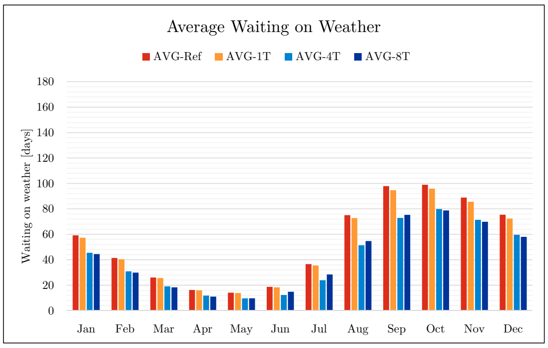

Figure 7.3: Average waiting on weather for a 96-WTG Farm.

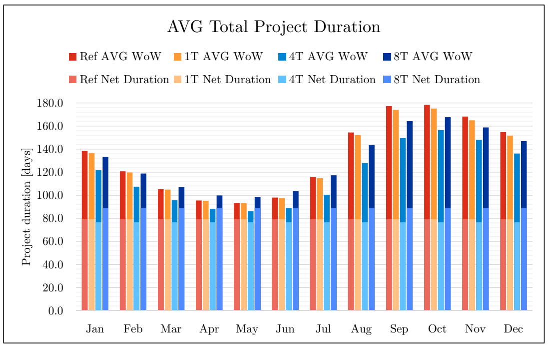

Figure 7.4: Average total project duration for a 96-WTG Farm.

Above, the concepts are compared in an absolute sense. Their performance can however be more clearly identified when normalized to the reference case. These results for a 48-WTG farm are shown in figure 7.5 and 7.6.

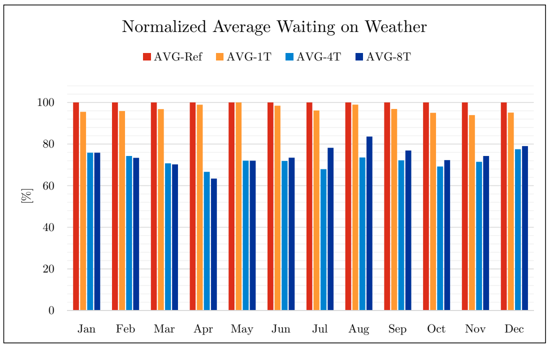

Figure 7.5: Average waiting on weather normalized to the reference case for a 48-WTG Farm.

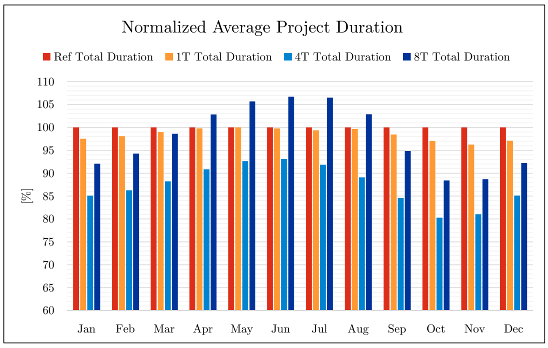

Figure 7.6: Average project duration normalized to the reference case for a 48-WTG Farm.

The Flexbase grillage performs only marginally better than the reference case regarding WoW. Since the swinging of the tower over deck is the only different limit, it is suggested that that is not the most limiting criterion. The 4T- and 8T-frames perform considerably better regarding weather downtime.

A surprising result is found in the total project duration plots. The 8T-frame performs worst of all cases in the summer months. The explanation for this can be found by relating back to figure 7.2. In the summer months, the WoW of all concepts is low, only consisting of a couple of days. However, the net project time of the 8T-concept is higher than that of the other concepts. This is due to many barge movements around the SSCV, re-equipping Thialf between the two cycles and visiting every foundation twice, resulting in notably more sailing activity and putting down a bridge to the foundation twice as often. The reduction in WoW is not enough to compensate for this increase in net duration. Therefore, the 8T-Frame does not seem a promising option.

The 4T frame scores high both WoW wise and in project duration wise, making it a winner. The largest improvements are booked in the winter months, with a start in October being the best with a project duration reduction of almost 20%. This looks promising, but in absolute sense the WoW is responsible for 50% of the total project duration when starting in October. A project taking twice longer than intended due to weather down time is not acceptable, hence months ranging from March to August are more realistic to start in. Unfortunately, these are also the months where the relative gain is the lowest, ranging from 7% to 12% duration reduction. This may be able to improve by changing input parameters. Consequently, a closer look was taken which activities are main contributors to the weather down time.

7.2 Assessment of limiting activity limits

The Sequence Tool output gives a WoW duration for every separate activity. For every case, it is found that the first activity with a weather related limit, mooring of a barge, is hugely governing in the weather downtime. In fact, the differences between the actual offloading concepts are lower than expected due to this. The weather for mooring the barge has to be so mild that, due to weather persistence, the offloading activities shortly thereafter are likely to be performed in mild weather as well. This results in relatively low WoW for offloading, and high WoW spikes for barge mooring activities. The limit was defined as $H_s = 2.0$m and $v_w = 12.9$m/s as mentioned in section 6.4.1, of which the H_s limit was responsible for the high weather downtime.

7.2.1 Improving barge operations

The limit for barge operations originates from the 1970s and is based on experience on the transfer of crew from a small supply vessel to a barge anywhere in the North Sea, following from standard procedures as described in 6.4.1. During topside or jacket installations, HMC's vessels normally work in very low seas. Therefore, this limit was rarely critical in the past. With the new-type installations of WTGs in much higher wind seas though, this limit does show to be critical. Since many barge operations need to be executed in a project, it is of absolute importance to evaluate and improve this limit. There are a number of options considered to achieve this:

1. Have a crew member on a support tugboat throw a bridle around a fixed object on the barge deck to control the barge with two tugs and position it close to the Thialf. Then, a crew basket can be used to hoist crew from the SSCV on board of the barge and moor it;
2. Use a crew supply vessel with a motion compensated bridge such as an Ampelmann to transfer crew;
3. Use an HTV which already has a crew on board instead of a barge, making the crew transfer operation non-existent.

According to operation engineering experts at HMC, all three solutions can be a feasible alternative to work up to a sea state of at most $H_s = 3.0$ meters. This allows for a second iteration of the sequence tool with the barge limits changed to $H_s = 3.0$ meters.

7.3 Results of the second simulation iteration

The results of the second simulation iteration are shown in the following sections. From here on, a barge operational limit of $H_s = 3.0$ meters applies. The wind limit remains at $v_w = 12.9$m/s. The 3D plots below show the average waiting on weather per activity for a complete cycle in hours, computed for a wind farm consisting of 48 WTGs. While more activities are present, only the names of the activities with significant delays are shown on the horizontal axis. Exact values for all activities can be found in appendix F.

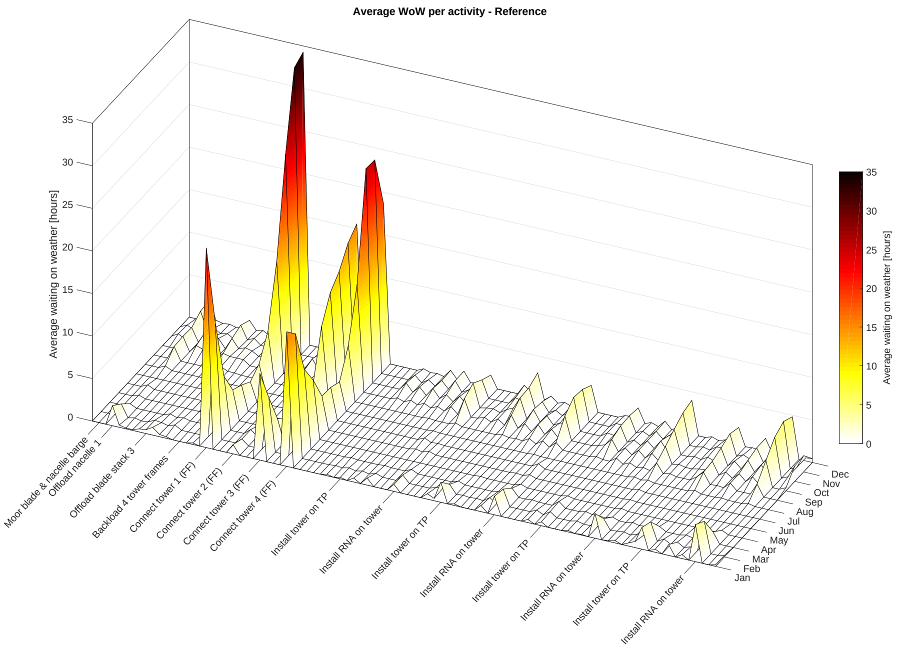

Figure 7.7: Number of hours of WoW per activity in the reference case.

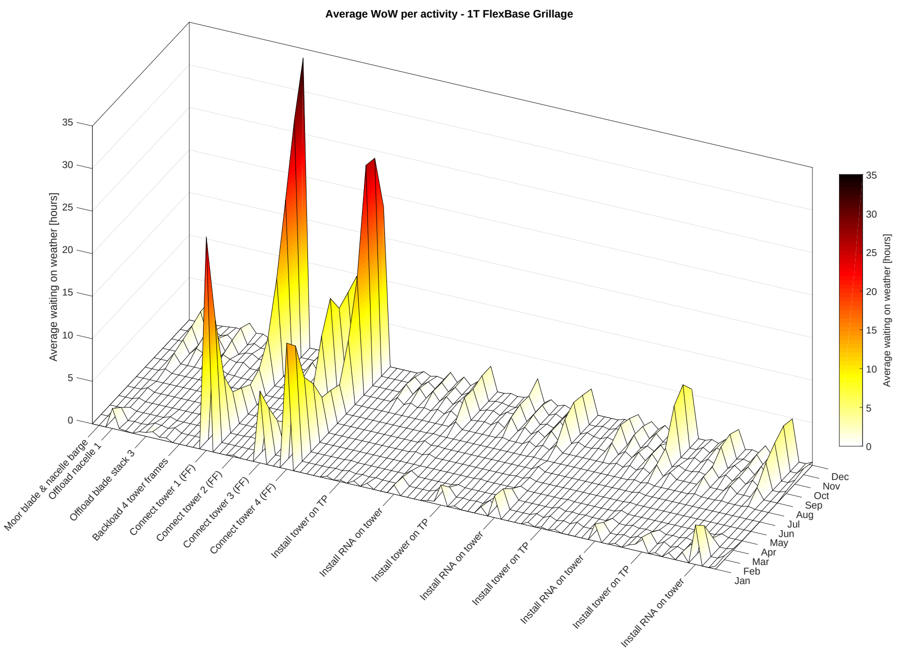

Figure 7.8: Number of hours of WoW per activity in the Flexbase grillage case.

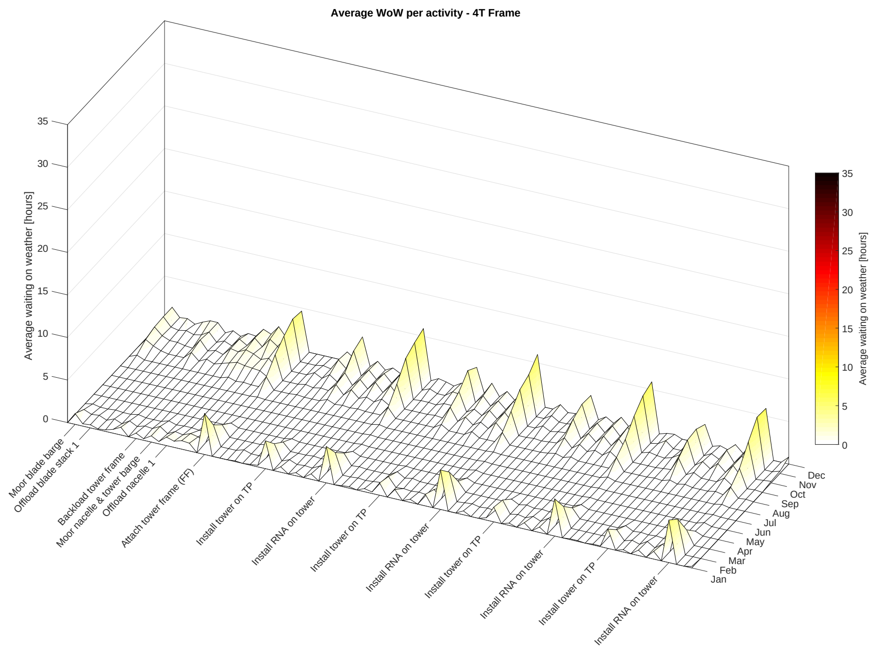

Figure 7.9: Number of hours of WoW per activity in the 4T-Frame case.

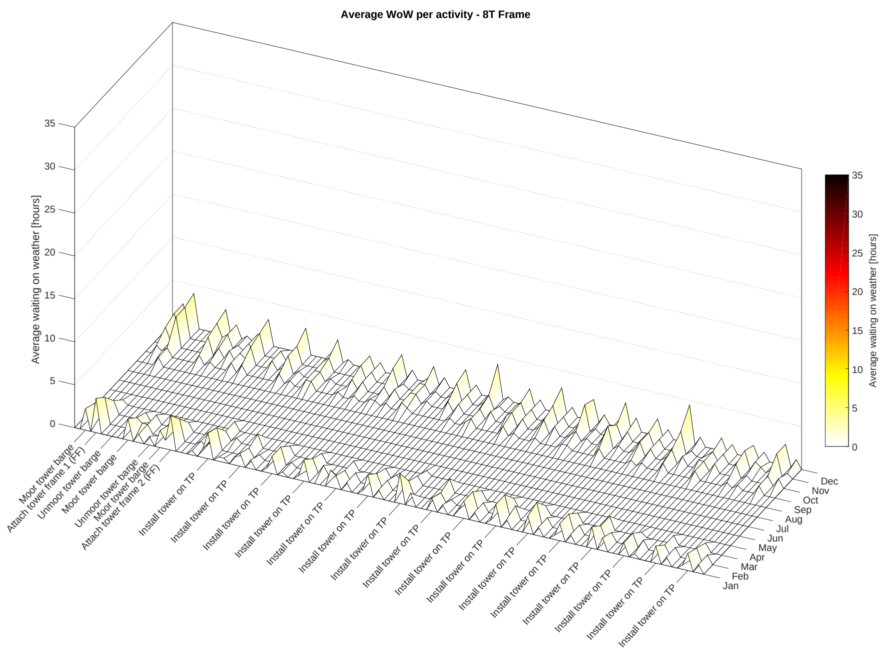

Figure 7.10: Number of hours of WoW per activity in the 8T-Frame case.

The plots show that waiting on weather for barge operations has almost disappeared, which is the desired outcome of increasing the H_s limit. With the possibility of barge operations in higher sea states, the differences between the different cases become more apparent. The observed effects are discussed in more detail.

7.3.1 FlexBase grillage

The most influential activity on the weather down time in the reference case and FlexBase grillage case is connecting the rigging to the first tower (figures 7.7 and 7.8). An interesting observation is that the WoW first decreases, then increases with every tower that is offloaded, which is a consequence of two working principles:

1. The change of the system's natural frequency with every offloaded tower;
2. The persistence of good weather decreases with time.

The first principle relates directly to the findings of section 4.2. The natural frequency of the barge-tower system increases, resulting in a frequency closer to the dominant wave frequency and thus larger motions for fewer towers on the barge deck. This, in turn, increases the weather downtime. The second principle, related to weather persistence, works as follows: the crew needs to wait a relatively long time for a weather window to appear in which they can safely remove the first tower. Once the weather is good enough, it is likely that it will be good enough for the offload of the second tower, some 2 hours later. However with time, it becomes increasingly less certain that the weather will remain sufficiently calm to work in. Notably, both of these phenomena are related to the barge, not the installation vessel.

The last tower offload suffers the most of these effects, resulting in a quite high WoW. To pinpoint what the governing limit is for the last offload in the FlexBase grillage concept, the approach in LiftDyn from section 6.4.2 is followed with a JONSWAP spectrum with $H_s = 3.0$m. The sea state is plotted against the period for which the limit of a criterion is exceeded. This is done for each of the criteria in the free floating (FF) case, with the system operating in its optimal heading. The results can be found in figure 7.11.

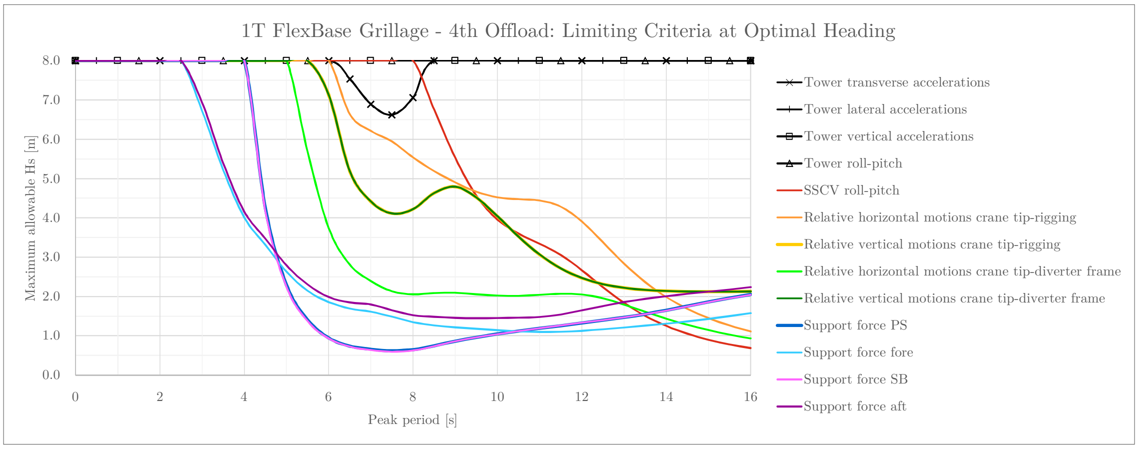

Figure 7.11: Limiting criteria for the last offloaded tower in the FlexBase grillage concept, free floating scenario.

The forces in the support reactions dominate the limiting criteria up to wave periods of 13 seconds. The maximum allowable significant wave height for a peak period of 6 to 8 seconds is just over 0.5 meters for the transverse support forces, resulting in a very poor operability. This is no surprise, as the energy in this period range for a North Sea wave spectrum is very high. The best option to improve the WoW would thus be to lower the dynamic forces in the support reactions in a way. Since the mass of the frame is already maximized as explained in chapter 5, a possible solution would be to make the grillage wider while maintaining the same mass. Of course, mass is related to the dimensions of the frame, but leaving out the water tanks in the grillage could solve the issue.

7.3.2 Multi-tower frames

For the multi-tower frame concepts, an interesting occurrence takes place in figures 7.9 and 7.10. The offloading activities are now, regarding WoW, in line the activities in the installation part of the sequence, particularly with tower and RNA installation. This means one of the fundamental goals of this research has been reached: to provide a feeder system of the WTG components with the same or a better workability than the SSCV's installation workability.

To find out where this difference comes from, the limiting criteria in the best heading are also plotted for the 4T-Frame in figure 7.12.

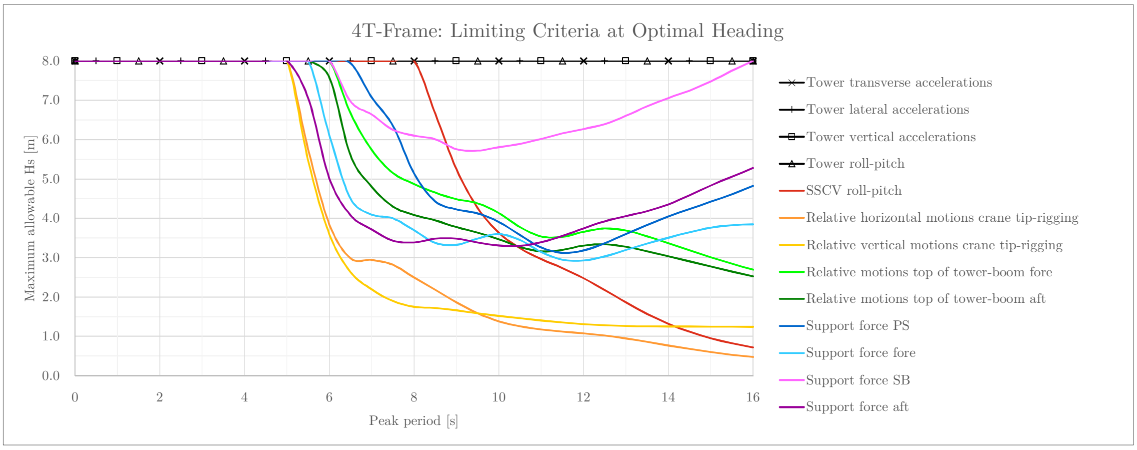

Figure 7.12: Limiting criteria for the 4T-Frame, free floating scenario.

The differences with respect to the FlexBase grillage are profound. Not only is a much higher limiting sea state achieved in the 6 to 10 second peak period range, but also is a different kind of limit now governing. The far larger footprint than for the single tower in combination with a similar CoG, results in support reactions at the edges of the frame which are much lower, preventing the system to tip over in desired sea states. The most limiting criteria are relative vertical and horizontal motions between the crane tip and the rigging, which are a result of the barge's and Thialf's motions.

With the changed barge operations limit, the effect on total WoW and project durations are more distinct. The total project durations with an $H_s = 3.0$m barge operations limit are found in figure 7.13 for a 48-WTG farm and in figure 7.14 for a 96-WTG farm.

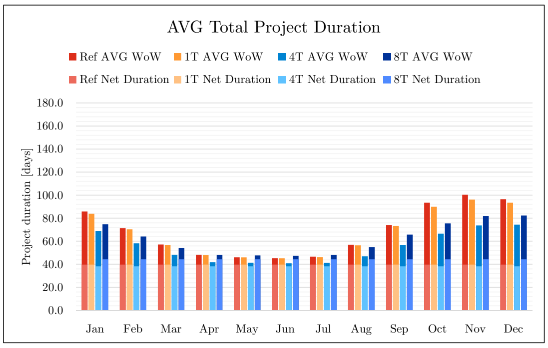

Figure 7.13: Average project duration for a 48-WTG Farm with $H_s = 3.0$m barge activity limit.

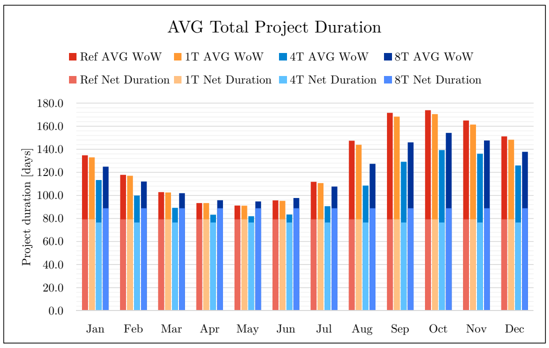

Figure 7.14: Average project duration for a 96-WTG Farm with $H_s = 3.0$m barge activity limit.

Normalised to the reference case, the project durations then become:

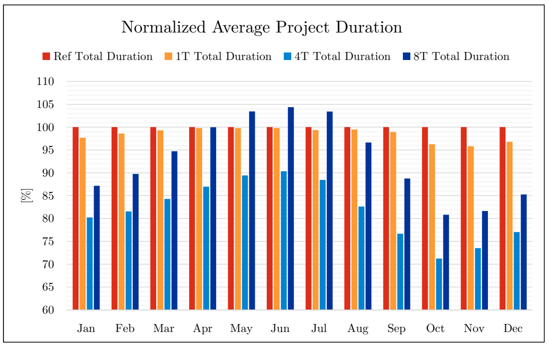

Figure 7.15: Normalized project duration for a 48-WTG Farm with $H_s = 3.0$m barge activity limit.

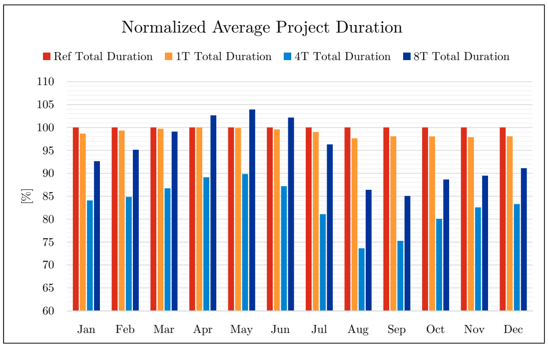

Figure 7.16: Normalized project duration for a 96-WTG Farm with $H_s = 3.0$m barge activity limit.

A number of observations can be made from these plots. By comparing figures 7.15 and 7.16, it can be seen that more benefit can be gained in winter months for a small project, whereas the relative performance is better in the summer months for a larger OWF. In general, the bigger the project, the more consistent the reduction in project duration over the year will be. Compared with the barge limit of H_s=2.0m, the 4T-Frame and 8T-Frame concepts perform significantly better as can be seen when comparing figure 7.6 with figure 7.15.

The 4T-Frame performs best cases, with project duration reductions of 9.6% up to 28.8% for the smaller wind farm and 10.1% to 26.4% for the larger wind farm. It can now be said with certainty that the 4T-frame concept is the winner regarding WoW and project duration in OWF T&I projects.

7.3.3 Confidence estimates and risk assessment

It should be realized that all conclusions drawn so far have been based on the average WoW, and on project durations which are based on historical measurements from the environmental database. In order to make a risk assessment of weather induced delays in the future, especially when applied to a specific project, a more statistical approach is needed. Indicators P10, P50 and P90 are confidence measures of under-exceedance. This means that there is a 10% chance that the P10 value will not be exceeded. Similarly, there is a 50% chance that the P50 value will not be exceeded and a 90% chance that the P90 value will not be exceeded. The P10, P50 and P90 for total project durations for the 4T-Frame concept in a 96-WTG farm are plotted in 7.17.

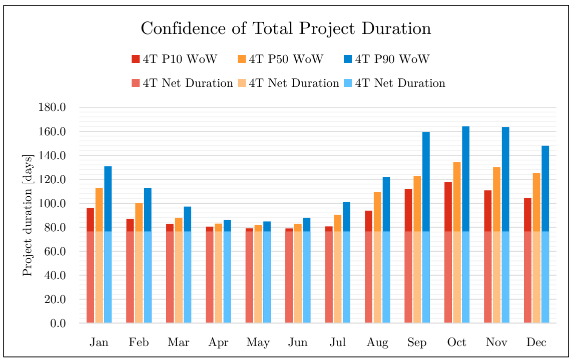

Figure 7.17: P10, P50 and P90 project durations for the 4T-concept in a 96-WTG farm.

7.4 Cost determination

Ultimately, only the price per kWh counts in the world of offshore wind. Hence, a cost comparison will decide the best concept. The cost of a project is assessed by operational expense (OPEX), which is mainly dependent on the combined day rate of the vessels used, and by capital cost (CAPEX), consisting of the buy-in and fabrication price of the required materials and tools. Costs for on-shore cranes and SPMTs are expected to be relatively low in comparison with the other OPEX and therefore left out of the assessment. Since mobilization costs are extremely project dependent, they will not add meaningfully to the cost determination and are therefore also left out.

7.4.1 Vessel costs

An overview of the number of vessels per case and their day rates are found on the left side of table 7.1 and are based on consultation with HMC's procurement department. The vessel day rates are given in terms of price on the date of publishing (early 2019), low price and high price, excluding fuel. The price ranges vary per vessel type, depending on abundance of existence of that vessel type (or lack thereof). It should be stressed that they may fluctuate considerably depending on global demand, especially for HTVs. Using the solution of support tug and crew basket is cheaper than using an HTV or fast crew supply vessel with motion compensation. Consequently, the required amount of vessels per concept for the support tug and crew basket solution are shown on the right side of table 7.1.

Table 7.1: Vessel day rates and amount per concept solution.

	Day rate [€]			No. of vessels per case			
Asset	Low	2019	High	Ref	1T	4T	8T
SSCV Thialf	400k	500k	600k	1	1	1	1
Barge 300ft	3k	4k	6k	0	0	1	0
Barge 400ft	6k	8k	12k	2	2	1	0
Barge 540ft	12k	16k	24k	0	0	0	1
Support tug	8k	8k	8k	2	2	2	1
Towing tug	12k	12k	12k	2	2	2	1
Biglift MC-Class	32k	40k	80k	0	0	0	0
Cosco K-Class	32k	40k	80k	0	0	0	0
Damen FCS 2610	5k	5k	5k	0	0	0	0
Damen FCS 5009	8k	8k	8k	0	0	0	0
Ampelmann	2k	3k	4k	0	0	0	0
			Low total day rate [€]	452k	452k	449k	432k
			2019 total day rate [€]	556k	556k	552k	536k
			High total day rate [€]	664k	664k	658k	644k

The day rates between the concepts are fairly close because they are primarily dependent on the price of the SSCV which is far higher than any other asset.

7.4.2 Steel costs

The costs of the frames and grillages now have to be determined. The cost can be split into two parts which contribute in equal fractions to the total cost; steel cost of structural members and assembly costs. Normally, HMC tries to save on the latter by re-using structural members from previous projects. For this cost calculation though, it is assumed that all steel is purchased as new. Like assets, the price of steel and of assembly may vary. After consultation with HMC's fabrication department low, current and high prices are taken as 3.0, 3.5 and 4.0 euro per kilogram.

To ensure the continuity of the transport and installation process, fabrication of the solutions has to be executed in three-fold. One set should be on the SSCV during installation, one set transported on the barge and one set restocked in the marshalling yard. An overview of the grillage and frame quantities and their costs are found in table The masses do not only cover the frames, but also an estimate of the corresponding mass of associated steel on the Thialf and barge.

Table 7.2: Costs of the frames and grillages.

Asset	Ref	1T	4T	8T
Concept steel mass [mT]	100	150	1000	2000
Associated steel mass [mT]	100	100	150	200
Total number of frames [-]	12	12	3	6
Low total cost [€]	7.2M	9.0M	10.4M	39.6M
2019 total cost [€]	8.4M	10.5M	12.1M	46.2M
High total cost [€]	9.6M	12.0M	13.8M	52.8M

The concept that jumps out in this case is the 8T-Frame. Its high mass and the fact that six frames need to be made in total, make for an exceptionally high CAPEX.

7.4.3 Project costs and savings

For both a wind farm of 48 and 96 WTGs, the average project duration over all starting months is taken to make a project cost calculation. The project duration times the total day rate from table 7.1 forms the OPEX, while the CAPEX can be directly copied from table 7.2.

Table 7.3: Average estimated project costs per concept in a low, 2019 and high market.

	48-WTG Farm				96-WTG Farm			
	Ref	1T	4T	8T	Ref	1T	4T	8T
Project duration [days]	68.2	66.9	54.8	61.9	129.4	127.6	106.6	120.5
Low total cost [M€]	38.0	39.2	35.0	66.3	65.7	66.7	58.2	91.7
2019 total cost [M€]	46.3	47.7	42.3	79.4	80.3	81.4	70.9	110.8
High total cost [M€]	54.9	56.4	49.9	92.7	95.5	96.7	83.9	130.4

Now that the average project costs for the three market scenarios are known, they are compared to the reference case to find out the expense differences. See table 7.4.

Table 7.4: Price differences per project with respect to the reference concept.

	48-WTG Farm			96-WTG Farm		
	1T	4T	8T	1T	4T	8T
Difference low market [M€]	1.2	-3.0	28.3	1.0	-7.5	26.0
Difference 2019 market [M€]	1.4	-4.0	33.1	1.1	-9.4	30.4
Difference high market [M€]	1.6	-5.0	37.8	1.2	-11.6	34.9

The results show that only for the 4T-Frame there are savings to be made. The FlexBase grillage is slightly more expensive due to increased manufacturing costs and only marginal OPEX improvements. The fabrication costs of the 8T-Frame are so high that they completely write off any financial gains obtained with shorter average project times, and even greatly increase costs. For smaller wind farms, the CAPEX of the 8T-Frame are over 50% of the total costs. Surprisingly, the reference concept scores an overall second, closely followed by the FlexBase grillage. But yet again, the 4T-Frame comes out as a winner.

Starting in any arbitrary month, the average savings obtained with the 4T-Frame reduce the total project cost with 8.6% to 10.0% for the 48-WTG farm and with 12.9% to 13.8% for the 96-WTG farm, depending on market conditions.

8

Conclusions and Recommendations

The research question of this thesis is defined as:

What are the critical activities in a feeder system for installation of WTGs with an SSCV and how can they be improved so that HMC can make a competitive entrance to the WTG installation market?

The first part of this question is mainly addressed from chapter 2 onwards and answered in chapter 4. Chapters 5 and onwards address the second part of the research question, to which the answer was found in chapter 7. The subquestions from section 1.5 are discussed throughout the report, of which the conclusions follow in this chapter.

The importance of floating installation of wind turbines has become clear after a market review on the current state of the offshore wind turbine installation industry. The jack-ups of today can only just handle the biggest turbines but difficult soil types, earthquake prone areas, deeper waters and ever growing turbines require new solutions for the next generation of WTGs. HMC Thialf's motion response in wind seas is great, and it can use its two cranes to install WTGs relatively quickly. For the case study, location Halfdan on the Dogger Bank is a suitable location, with as turbine the largest model available on market scale: the Vestas V164.

After investigating logistical options for the supply chain, it is found that the marshalling yard will remain crucial as a storage and assembly hub for the wind turbine components. The blades, nacelles and towers need to be brought from the marshalling yard to the offshore location, where Thialf remains to install turbines. A solution was to be found to fulfill this task in an economically efficient way, to help HMC make a competitive entrance to the offshore wind market. After a qualitative assessment based on findings in the market review and experience in offshore operations, two activities in the supply chain were assessed to be potentially critical and investigated into more detail: turbine tower transport and tower offloading.

8.1 Conclusions on transport

To find the effects of different cargo vessels and component configurations, motion response analyses were done for tower and nacelle transport with a similar sized barge and HTV. It was found that the position on deck of the components do have a large impact on the motions of the supply vessel, because the motions are largely governed by the high inertia of the turbine towers. The HTV performed better than the barge during transit, but both types only reached the maximum allowed roll motion at sea states with a significant wave height equal to or higher than 2.5 meters. Making smart use of supply routes can increase the workability during transport if the sea states are higher than allowed. Because of this result, tower transport was not considered limiting.

However, transport is not the only criterion for vessel selection. A basic study on the influence on natural period of the amount of towers on deck showed that during offloading, the natural period of the supply vessel decreases as more towers are taken off the supply vessel. In the offloading condition, the barge showed a slightly better motion response than the HTV, especially in the scenario where only one tower is left on board of the supply vessel. With the barge being cheaper and scoring better in offloading, but the HTV being faster and scoring better in sailing condition, it is difficult to draw direct conclusions on which solution is the better alternative. The differences in motion response were, though present, rather small. The decision on which kind of supply vessel to use will therefore rely more on project specific parameters, such as low mobilization cost, or the number of require vessels to supply the SSCV within time for a certain distance from shore to OWF. A barge with a ship shaped bow was chosen as the transport asset for the rest of the research, because it is both cheap and more stable in sailing condition than the shoe-box shaped barge with planar bow which was used earlier.

The basic offloading analysis did show that the motions of either vessel were still too high to safely offload a tower. For this reason, the offloading activity was confirmed to be the most limiting of all and needed further research.

8.2 Conclusions on offloading

Earlier testing in HMC's simulation center had shown to result in two problems with tower offloading procedures as designed by HMC. These problems were tipping of the tower once it had been released from its sea fastening and swinging of the tower base after it was lifted from the barge. After a considering some market ready solutions, it was determined that these were not suitable applications to solve the problems.

Three new concepts were introduced, the FlexBase grillage (a modification of the original concept) and two types of frames carrying multiple towers, each optimized for a specific purpose. The FlexBase grillage has a heavier base to reduce risk of tipping and a hinging grillage in guides to mitigate the swinging problem. A frame with eight towers, executed in two fold was designed to maximize the SSCV's crane capacity and towers on board, totaling to a number of 16 towers. For this concept, however, the project sequence needs to be fundamentally changed, also influencing third parties. A last concept, with four towers on one frame, is a heavy lift solution fitting in the current installation procedures.

Each concept was analyzed through a series of software programs as in 6.1 to define the weather down time per activity in the project and the total expected project duration. Per concept, three test cases were defined, based on in-house manuals for single crane offshore lift operations. For each test case, limit motions, forces and accelerations needed to be added based on either engineering guidelines, expert opinion, or crew experience from earlier projects. The outcome of the program sequence is fairly dependent on limit definition and the durations of each activity, hence they were chosen with care.

8.2.1 First simulation run

The first findings resulted in an unexpectedly high weather down time for barge related activities, especially the first one in the sequence. The reason for this was an operational limit, originating from crew transfer to barges and defined in the 1970s for oil and gas projects in North Sea conditions. This limit, a significant wave height of $H_s = 2.0$m, is responsible for most of the weather downtime over the project duration for all cases. Since many barge operations need to be executed, this limit was to be improved. This can be solved by using a supply vessel with a motion compensated gangway, or using a cradle thrown from a secondary tug and using a crew basket to transfer crew for the mooring operation. A last alternative would be to use an HTV for transport as was assessed earlier, as a result of which crew transfer to the supply vessel is eliminated entirely. All of these options are possible in a sea state with $H_s = 3.0$m. A second simulation run was done with this new limit.

8.2.2 Second simulation run

Regarding weather downtime, the multi-tower frames perform significantly better than the single tower concepts. A notable finding was that the 8T-Frame did perform very well WoW wise, but due to the high net project duration, the total project duration with this solution succeeded the reference scenario in the summer months. The longer net project time can be tracked down to the fact that this concept has many time consuming barge movements around Thialf, needed to offload the two large frames from a single barge. In addition there are many more sailing hours, and gangways need to be put out to the foundation twice for every wind turbine due to the double campaign. In addition to this, the fabrication costs are tremendously high, even surpassing the operational costs for smaller projects.

The Flexbase grillage performed only marginally better than the reference case, while being slightly more expensive to fabricate. Particularly, the support force limit in the grillage while the tower is freely standing on the barge deck remains an issue. A solution would be to widen the base of the FlexBase grillage, but this would result in a high amount of steel per unit tower. If a similar workability as the 4T-Frame concept is to be reached, the combined grillage size of four single towers may even approach or surpass that of the 4T-Frame. Making a larger grillage for every tower also quickly increases the investment costs for the FlexBase grillage.

Judging project duration, the design with four towers on a frame is the best solution on all fronts. It has the lowest amount of WoW days, the lowest net project times, and in all cases it performed better than any other concept. The production costs are slightly higher than those of the single tower concepts, but the low project times easily compensate the extra expense. As a result, the savings with respect to the reference case range from 8.6% to 10.0% for a small wind farm, and from 12.9% to 13.8% for a large wind farm. While it is not expected that this will put Heerema directly in a competitive position, it does contribute to significant cost reductions and a more promising entrance to the WTG installation market.

8.3 Practical advantages and disadvantages

In this section, practical advantages and disadvantages of each of the designs are listed. These can be practical aspects or a result of the simulations.

8.3.1 FlexBase grillage

Advantages

- Directly compatible with any amount of wind turbines in a farm. The last transport may be less effective, as the full capacity of 4 towers per barge mmay not be completely used;
- Low investment to test feasibility on full scale;
- Relatively small grillages are more easily accepted by crew and subcontractors and more convenient to handle in a marshalling yard.

Disadvantages

- Larger footprint required to make the concept more feasible, which may rise concerns regarding available deck space on Thialf;
- Preparing the tower with the diverter frame and taking it off again on the Thialf deck require a lot of extra actions;
- Not scalable to a larger turbine model without doing crane upgrades due to the aux hook capacity and height limits;
- Many offshore tower lifts with respect to the other concepts, increasing risk.

8.3.2 Four-tower frame

Advantages

- Lowest weather down time and costs;
- Reduced number of tower lifts results in lower lifting exposure time and reduced risk;
- Can be transported by SPMT in the marshalling yard;
- Concept is scalable to larger turbines. The mass of the system is considerably lower than the capacity limit of Thialf's cranes;
- Height limit of the main hook is not an issue with increasing turbine sizes.

Disadvantages

- In case of an uneven number of turbines in a wind farm, it is inevitable that the frame will once be loaded asymmetrically. A dead weight of the same mass as a turbine tower has to be attached to the frame as counterweight to restore the balance;
- If installation is done with a different SSCV or turbine resulting in an odd number of turbines on deck, the concept will likely not be effective.

8.3.3 Eight-tower frame

Advantages

- Lowest number of tower lifts results in lowest lifting exposure time and reduced risk;
- Largest footprint, providing a stable platform which does not tip over easily;
- Can be transported by SPMT in the marshalling yard.

Disadvantages

- Quickly becomes inefficient with varying OWF sizes, particularly for smaller wind farms. Because 16 towers are transported at once, the concept is most effective when all 16 tower slots are in use. This means that to maximize the potential of the concept, an OWF has to have a number of turbines equal to a multitude of 16. Additionally, the project also needs to be a multitude of the 6 nacelles and blade set transports per cycle. This particular situation rarely happens. The other concepts are less sensitive to this, as they only need a multitude of 4 of all components;
- The design is already maximized to seek the limits of Thialf, meaning that any changes in mass or dimensions of the turbines could mean it would not work anymore;
- Difficult to implement due to fundamental changes in the construction sequence of a wind farm, and the effects thereof on third party contractors.

8.4 Lessons learned

There are two main lessons learned in this thesis. The first lesson is that when entering a new market such as offshore wind, it is of the essence that it is known what conventional operational limits are based on. It should be realized that conservative, perhaps dated limits from the oil and gas industry that never used to be governing can become a pivotal factor in the wind market. The limitations should therefore be not necessarily directly copied from user manuals, but chosen with care and updated where necessary.

The second lesson is that lifting a large frame with all towers on it solves two major problems that were encountered when lifting each tower separately:

1. The change of the barge-tower system's natural frequency with every offloaded tower;
2. The increasing uncertainty of good weather continuity with every offloaded tower.

The fact that a scenario with a single tower on a supply vessel never occurs is very valuable, because during offloading, the system will never have a natural frequency close to dominant wave frequencies in wind waves.

8.5 Recommendations

The results of this research have shown that the 4T-Frame solution for tower offloading is the most attractive solution of the assessed concepts. Nevertheless, the research is highly conceptual and will need further assessment to prove that this is indeed a feasible solution. Granted, this is true in any case as no proven solution for floating offshore transfer of wind turbine components yet exists. This section discusses recommendations for implementation, opportunities for scope expansion to other turbine and vessel models and further research.

8.5.1 Implementation

It is advised to continue the research of using the 4T-Frame, or a multi-tower frame in general, for installation with Thialf. Tweaking of the geometrical parameters of the system will likely not improve the results greatly, as the motions between the barge and the crane tip will likely remain governing. A more valuable addition to this research would be to test the frame as it is in HMC's Simulation Center, which will provide a visual check in the time domain. From the results of the Simulation Center, appropriate adaptations and a more detailed design can be made. Design the frame in a way that it is compatible with different tower types, or that it can be modified with only little changes to support other towers. It should be considered an asset, not a disposable.

With the final design of the frame, make a more in-depth assessment of the transport of the frame with towers on the supply vessel, either in-house or with an external company depending on the intended used supply vessel. If availability of HTV's allow for a reasonable price, it is advised to use it over a barge because of better dynamic behaviour while sailing, less risk of delays due to higher sailing velocity and the absence of crew transfer operations.

8.5.2 Scope expansion

Recent developments within HMC are that there is an intent to do the T&I of WTGs mainly with Heerema's monohull Aegir. The vessel will receive a crane upgrade and should be able to install 12MW wind turbines, such as the Haliade X by General Electric. With these larger turbines and the smaller deck space of Aegir, components for two turbines fit on deck. The same principle of a multi-tower frame should be investigated for this vessel. The frame including two turbine towers would compute to a mass in the range of 2600 to 3400 metric tonnes, which can be lifted even by Aegir's current crane. It should be noted that the installation workability of Aegir is yet unknown. Therefore, it cannot be said with certainty that offloading of the towers is the most critical activity in the T&I sequence.

For wind farms in the US, offloading with a two-tower frame would be a good option as the Jones Act forces European vessels to work with a feeder system with American flagged barges, similar to the system discussed in this research. This could give Heerema a head start in WTG installation developments for the US market. In Taiwan, however, the OWF blocks are located close to the coast. Since Aegir is a fast sailing vessel, shuttling between marshalling yard and OWF site with Aegir and resupplying in a port may be more attractive than offshore offloading. On the North Sea, most blocks are located increasingly further offshore meaning that the offshore offloading is becoming increasingly more beneficial.

8.5.3 Future research

As the FlexBase grillage does not perform better than the reference grillage, it is not worth it to further develop it at this stage. Although it may have some practical advantages which are not captured by the software sequence, the tipping problem remains governing for the delays. A better investigation for the single tower frames would be to increase the dimensions of the base of the grillage until the same operability is reached as with the 4T-Frame. If the CAPEX of the single tower solution is still lower and there is enough room on the installation vessel, a cost comparison should again be performed. Considering the results of this research, expectations are that the combined footprint of four 1T-Frames is similar to that of one 4T-Frame. With limited deck space and the inconvenience regarding taking the diverter frames on and off the towers, the 4T-Frame likely will still win.

The results of this research are based on wave spectra valid for North Sea conditions, which are dominated by wind waves. While it can be expected that in areas where WTGs are placed, much energy will be present in the higher frequency (wind) waves, it would be interesting to research the effects of a swell component in the wave spectrum. Swell waves have a lower frequency than wind waves, Therefore, they may interact negatively with the low frequency system of a multi-tower frame, which was its strength in wind driven seas. This is particularly interesting for exposed waters with long fetch, such as the US East coast.

Appendices

A North Sea Data Maps

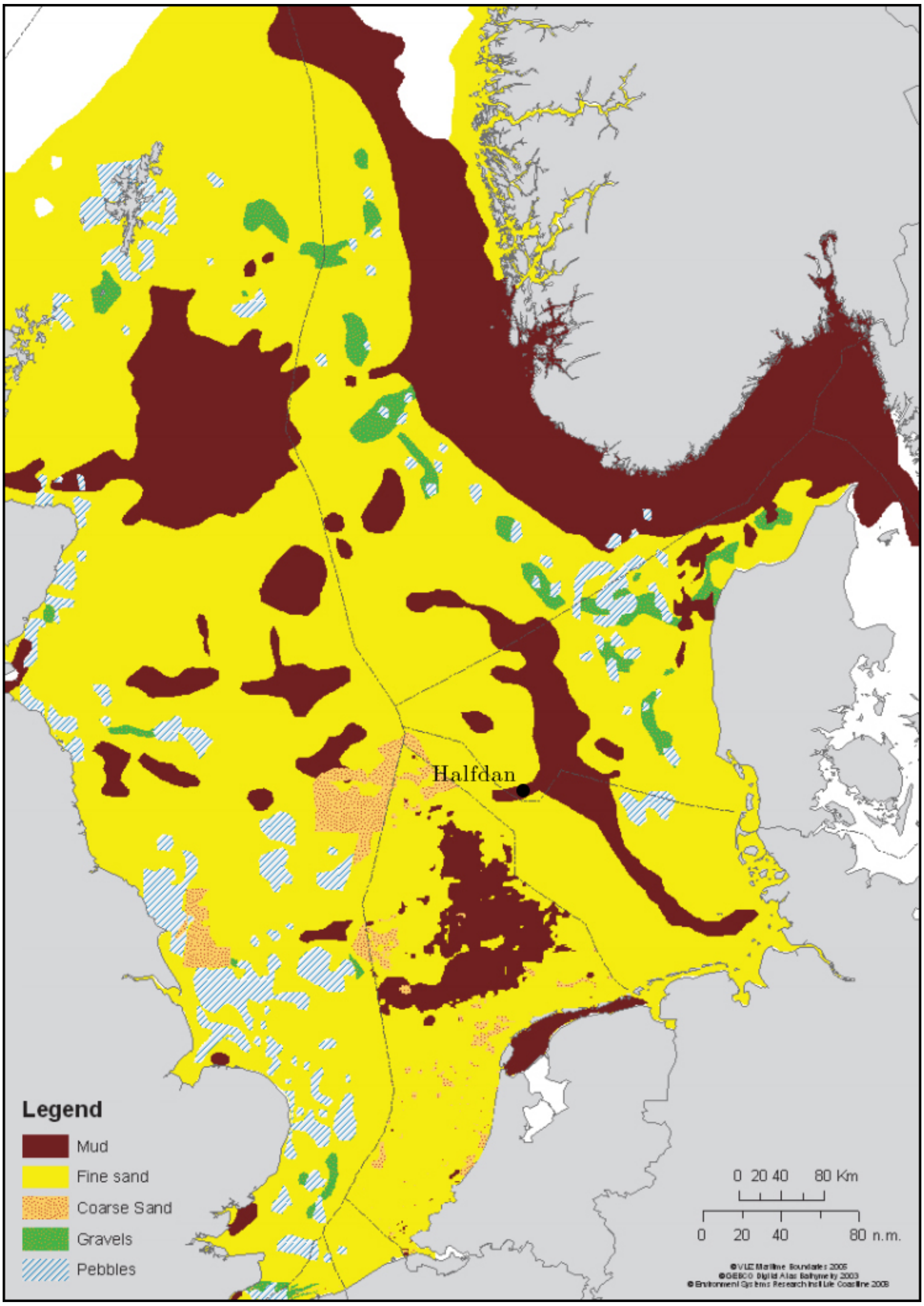

Figure A.1: Sediment map of the North Sea area.

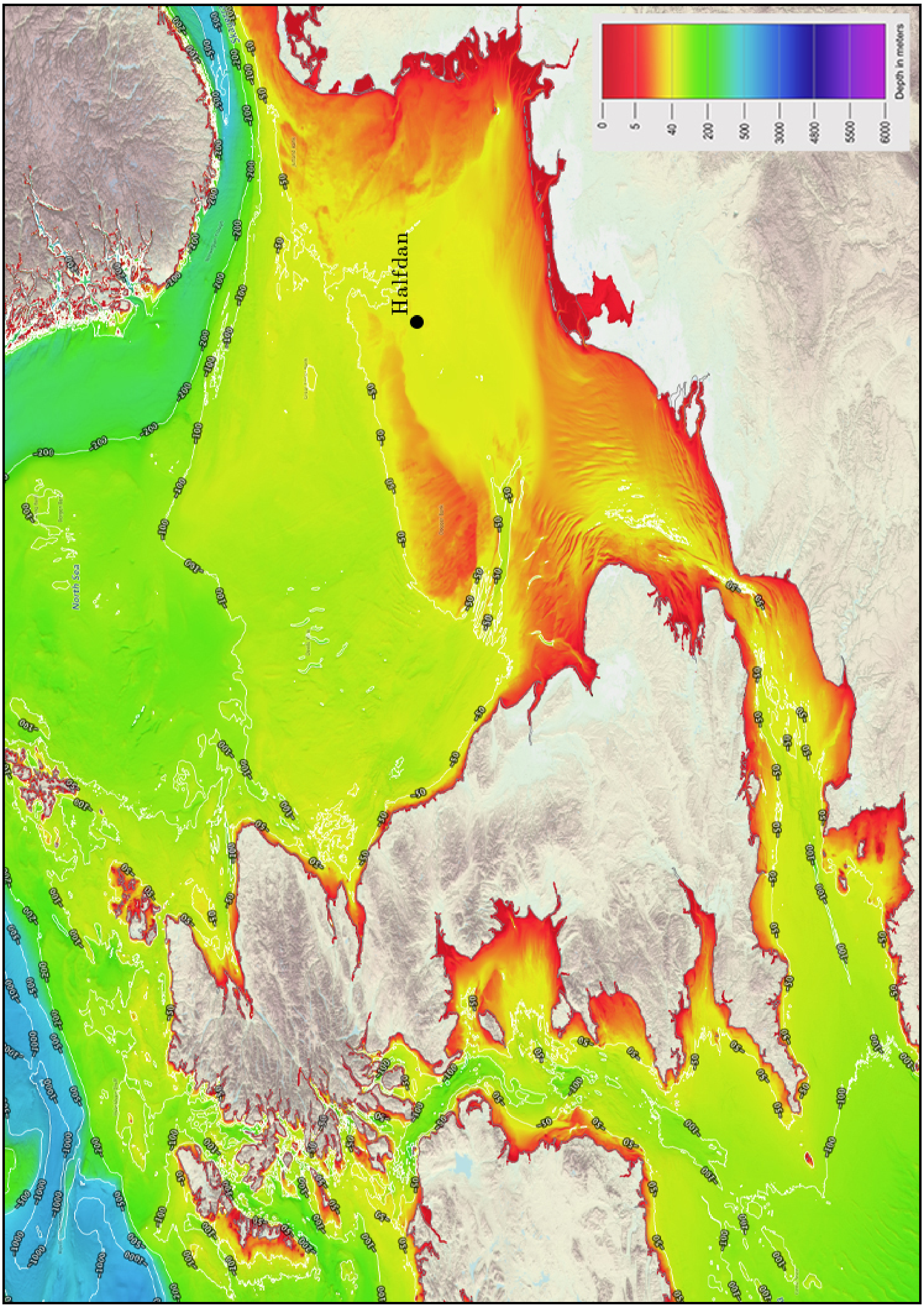

Figure A.2: Bathymetry map of the North Sea area.

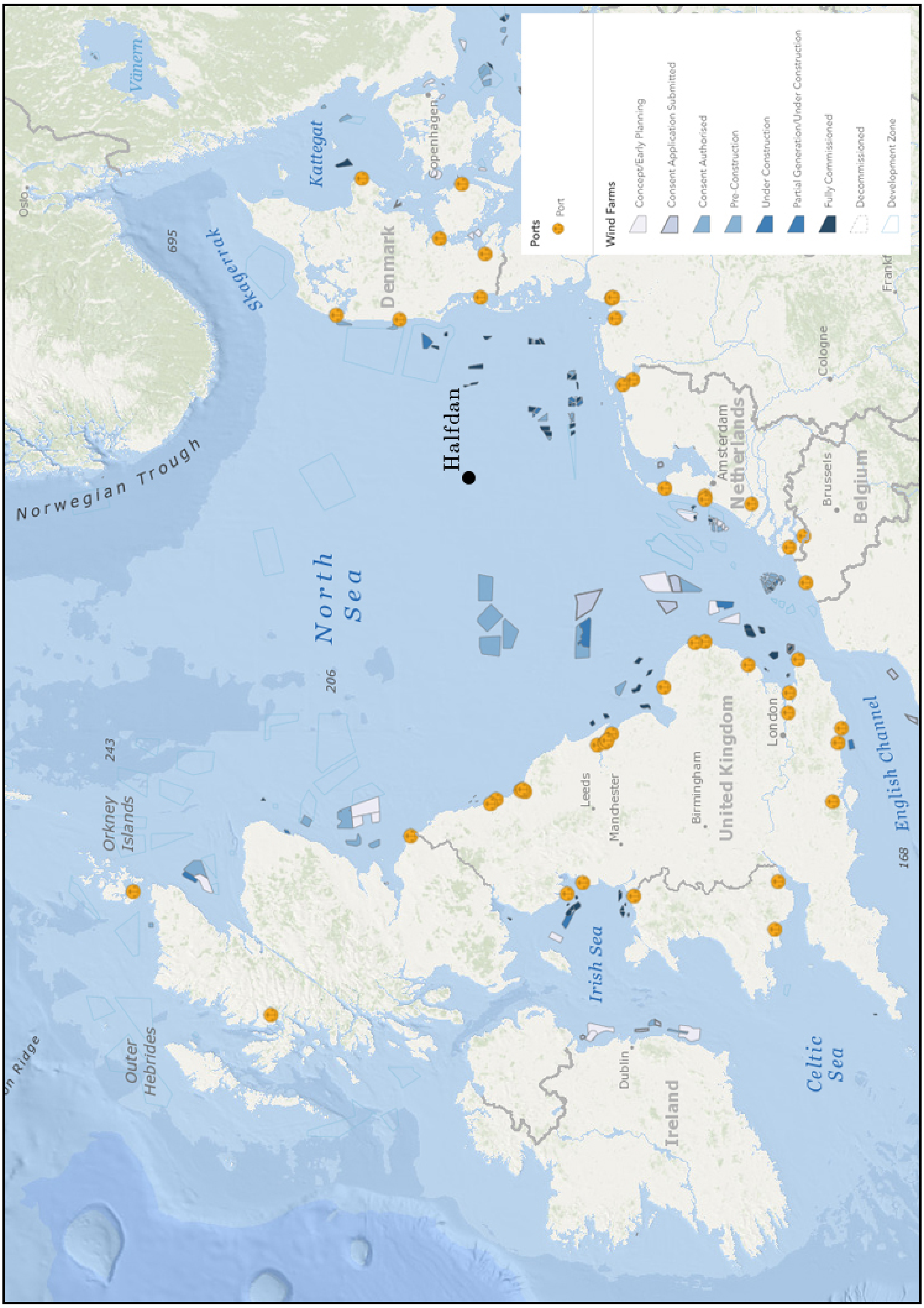

Figure A.3: Locations of wind farms in the North Sea area.

B Thialf Preliminary Deck Layout

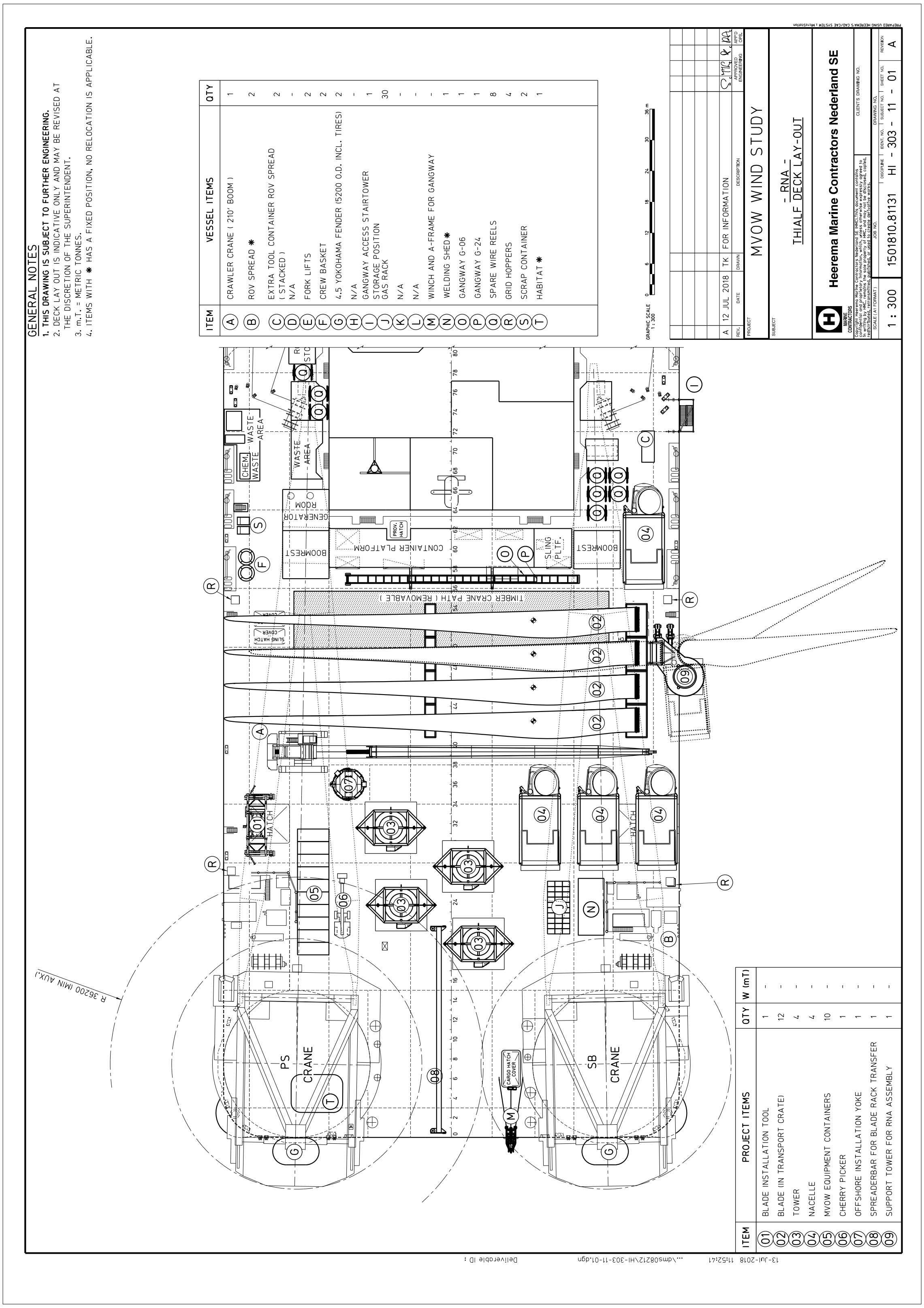

Figure B.1: Thialf's deck layout for WTG installation per October 2018.

C Software Wave Direction Conventions

The software packages have different conventions for coordinate systems and incoming wave angle. There are two notable differences. In Sinai, the coordinate system's origin is located at the bow of the vessel. For Workability Chunks, the wave headings are mirrored about the x-z plane. This can be confusing when switching from program to program.

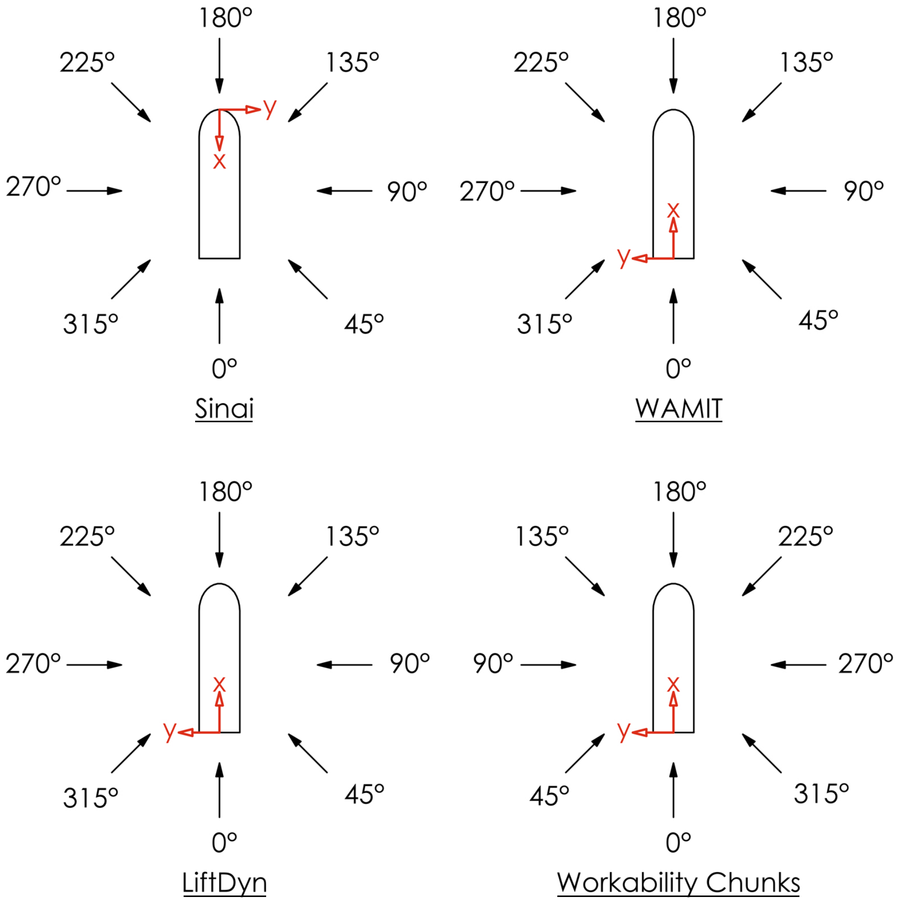

Figure C.1: Coordinate system and incoming wave angle conventions for used software.

D Iterative Frame Design Approach

The optimal design for a multi-tower frame is not evident from the start. There are many limitations to be considered, some of which may affect each other. An iterative design approach is used to optimize for a maximum amount of towers on a frame.

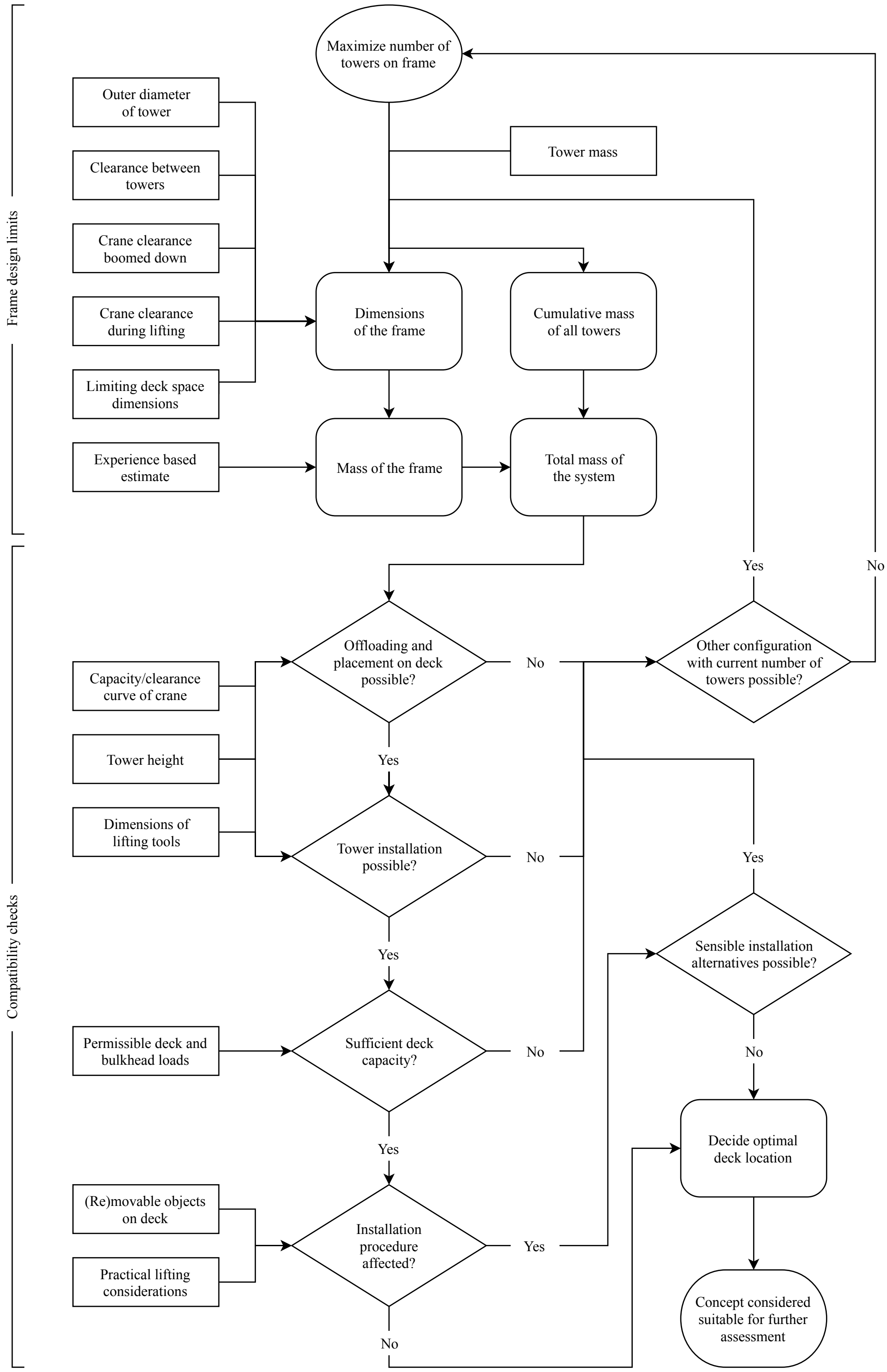

Figure D.1: The iterative process of the frame design.

E Derivation of Reaction Forces in Matrix Spring Supports

In 6.3, the limits of the reaction forces in the frame supports have to be found. To do this, the following procedure can be followed, to which figure E.1 is used for reference.

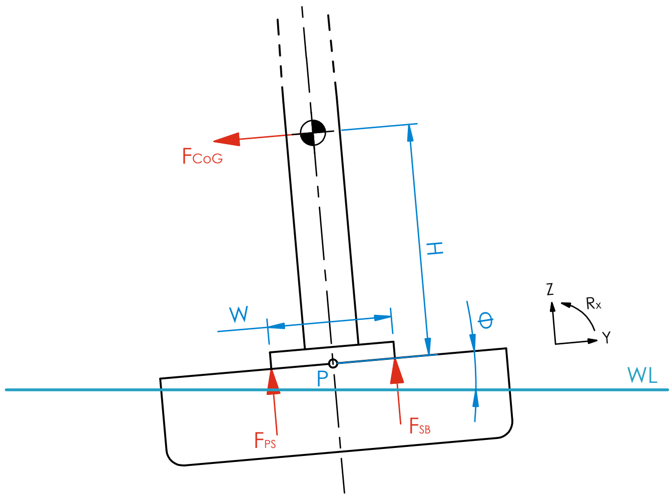

Figure E.1: The tipping problem with parameters for support reaction force derivation.

The force in the CoG is defined by equation E.1, in which F_g, F_a, and F_w stand for gravitional, accelerational and wind forces and ϕ the roll angle of te vessel.

$$F_{CoG} = F_g sin(\phi) + F_a cos(\phi) + F_w cos(\phi) \tag{E.1}$$

$F_w cos(\phi)$ is approximated to F_w, so that the wind force is constant and defined by equation E.2 with ρ_a the density of air, v_w the wind velocity, C_d a shape factor, and $A_\perp$ the cross sectional area.

$$F_w = \frac{1}{2}\rho_a v_w^2 C_d A_\perp \tag{E.2}$$

This is a conservative approximation, because $A_\perp$ is at its maximum for $\phi = 0°$, resulting in the highest wind force. F_{PS} and F_{SB} are support forces, each consisting of a static component F_s of the unloaded equilibrium and a dynamic component F_{dyn} which is measured in LiftDyn. The static part equates to:

$$F_s = \frac{1}{4} * (m_{tower} + m_{grillage}) * g \tag{E.3}$$

F_{dyn} is only dependent on the dynamic and gravitational accelerations in the CoG and therefore relates geometrically through equation E.4. It should not be forgotten that in the 4T and 8T scenarios, the parameter W is different in transversal and longitudinal direction.

$$F_{dyn}\frac{W}{H} = F_g sin(\phi) + F_a cos(\phi) \tag{E.4}$$

Equation E.1 can now be rewritten as:

$$F_{CoG} = F_{dyn}\frac{W}{H} + F_w \tag{E.5}$$

The sum of moments about point P of figure E.1 can be derived and the structure will not tip if inequality E.6 holds.

$$\sum M_P = F_s W - F_{CoG} H \geq 0 \tag{E.6}$$

Substituting E.5 in E.6 the inequality then becomes:

$$F_s W - F_{dyn} W - F_w H \geq 0 \tag{E.7}$$

The limits of reaction forces in the spring have to be written as function of F_{dyn} if they are to be compatible with LiftDyn. Rewriting E.7, the inequality results to:

$$F_{dyn} \leq F_s - F_w \frac{H}{W} \tag{E.8}$$

Environmental load factor E and permanent load factor G of the most critical ultimate limit state (ULS) apply according to DNV [26], resulting in $E = 1.3$ and $G = 1.0$. Implementing these load factors in E.8 results in:

$$F_{dyn} E \leq F_s G - F_w \frac{H}{W} E \tag{E.9}$$

Or, rewritten, values for E and G substituted:

$$F_{dyn} \leq \frac{F_s}{1.3} - \frac{F_w H}{W} \tag{E.10}$$

When inequality E.10 holds for the springs on all sides of the frame or grillage, it can be confirmed that the structure will not tip over.

F Limiting Activities

The average WoW in hours for each activity is shown, based on an OWF with 48 turbines. The months dictate the starting month of a project. Example: If installation starts in January, a crew needs to wait 23 hours on average to connect the first tower.

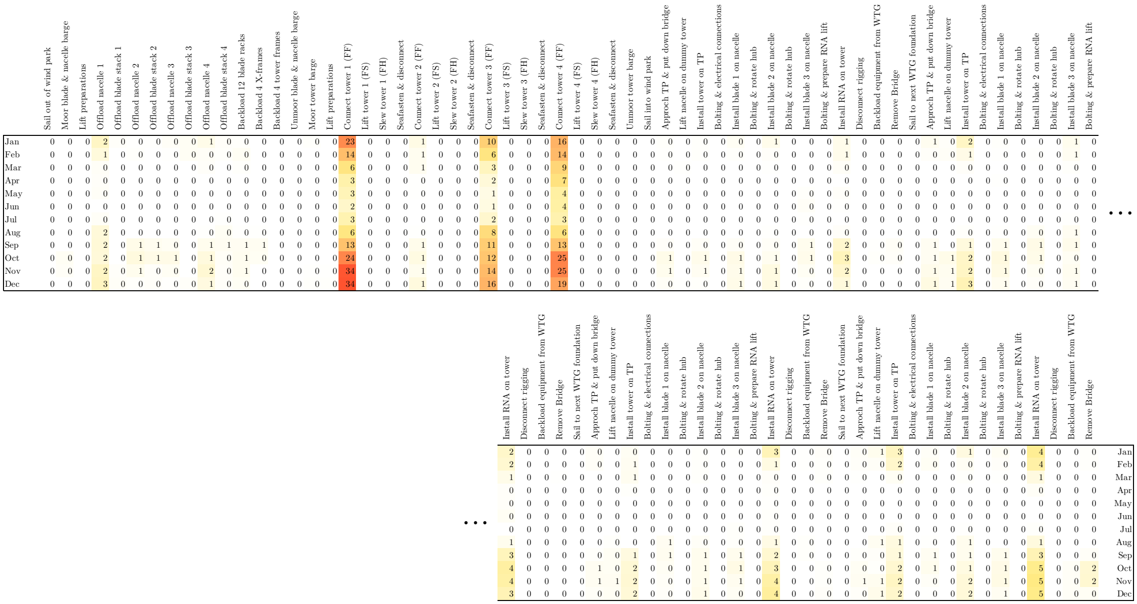

Figure F.1: Number of hours of WoW per activity for the reference case.

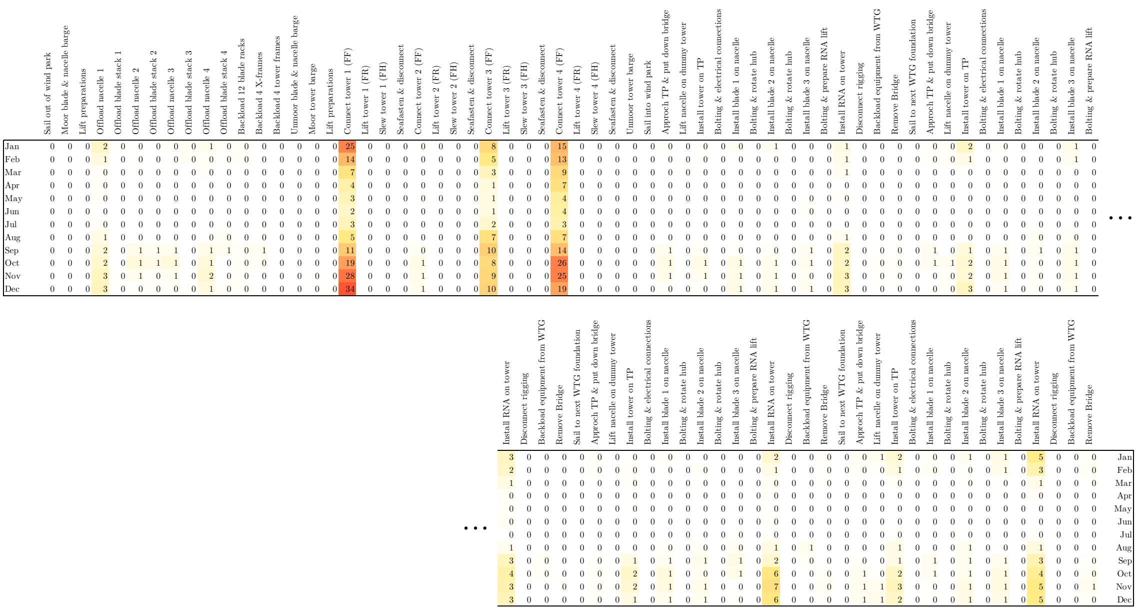

Figure F.2: Number of hours of WoW per activity for the FlexBase grillage concept.

Month	Sail out of wind park	Moor blade barge	Lift preparations	Offload blade stack 1	Offload blade stack 2	Offload blade stack 3	Offload blade stack 4	Backload 12 blade racks	Backload 4 X-frames	Backload tower frame	UnMoor blade barge	Moor nacelle & tower barge	Lift preparations	Offload nacelle 1	Offload nacelle 2	Offload nacelle 3	Offload nacelle 4	Lift preparations	Attach tower frame (FF)	Pretension tower frame (PT)	Lift tower frame and slew (FH)	Seafasten & disconnect	Unmoor nacelle & tower barge	Sail into wind park	Approch TP & put down bridge	Lift nacelle on dummy tower	Install tower on TP	Bolting & electrical connections	Install blade 1 on nacelle	Bolting & rotate hub
Jan	0	1	0	0	0	0	0	1	0	1	0	1	0	1	1	1	1	0	5	0	0	0	0	0	0	0	3	0	1	0
Feb	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	2	0	0	0	0	0	0	0	2	0	0	0
Mar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Sep	0	1	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	3	0	0	0	0	0	0	0	1	0	1	0
Oct	0	1	1	0	0	0	0	1	0	0	0	1	1	1	1	1	1	0	4	0	0	0	0	0	1	0	1	0	1	0
Nov	0	2	1	0	1	0	0	1	0	0	0	1	0	2	1	2	1	0	5	0	0	0	0	0	1	0	3	0	1	0
Dec	0	2	1	1	0	1	1	1	0	0	0	1	0	1	1	2	1	0	5	0	0	0	0	0	1	0	3	0	1	0

Month	Install blade 2 on nacelle	Bolting & rotate hub	Install blade 3 on nacelle	Bolting & prepare RNA lift	Install RNA on tower	Disconnect rigging	Backload equipment from WTG	Remove Bridge	Sail to next WTG foundation	Approch TP & put down bridge	Lift nacelle on dummy tower	Install tower on TP	Bolting & electrical connections	Install blade 1 on nacelle	Bolting & rotate hub	Install blade 2 on nacelle	Bolting & rotate hub	Install blade 3 on nacelle	Bolting & prepare RNA lift	Install RNA on tower	Disconnect rigging	Backload equipment from WTG	Remove Bridge	Sail to next WTG foundation	Approch TP & put down bridge	Lift nacelle on dummy tower	Install tower on TP	Bolting & electrical connections	Install blade 1 on nacelle	Bolting & rotate hub
Jan	0	0	1	0	4	0	0	0	0	0	0	1	0	1	0	0	0	1	0	5	0	0	0	0	0	0	2	0	0	0
Feb	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3	0	0	0	0	0	0	1	0	0	0
Mar	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Sep	0	0	1	0	3	0	0	0	0	0	0	1	0	1	0	1	0	1	0	3	0	0	0	0	0	0	1	0	1	0
Oct	1	0	1	0	5	0	0	0	0	0	0	2	0	1	0	1	0	1	0	4	0	0	0	0	0	0	2	0	1	0
Nov	1	0	1	0	5	0	0	0	0	1	1	4	0	1	0	1	0	1	0	5	0	0	1	0	0	0	3	0	1	0
Dec	0	0	1	0	6	0	0	0	0	1	0	3	0	1	0	1	0	1	0	6	0	0	1	0	0	0	3	0	1	0

…

Month	Install blade 2 on nacelle	Bolting & rotate hub	Install blade 3 on nacelle	Bolting & prepare RNA lift	Install RNA on tower	Disconnect rigging	Backload equipment from WTG	Remove Bridge	Sail to next WTG foundation	Approch TP & put down bridge	Lift nacelle on dummy tower	Install tower on TP	Bolting & electrical connections	Install blade 1 on nacelle	Bolting & rotate hub	Install blade 2 on nacelle	Bolting & rotate hub	Install blade 3 on nacelle	Bolting & prepare RNA lift	Install RNA on tower	Disconnect rigging	Backload equipment from WTG	Remove Bridge
Jan	1	0	1	0	4	0	0	0	0	0	0	2	0	0	0	1	0	1	0	5	0	0	0
Feb	0	0	1	0	2	0	0	0	0	0	0	1	0	0	0	1	0	1	0	4	0	0	0
Mar	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Sep	0	0	1	0	2	0	0	0	0	0	0	2	0	0	0	0	0	1	0	2	0	0	0
Oct	1	0	1	0	4	0	0	0	0	0	1	3	0	1	0	1	0	1	0	4	0	0	0
Nov	1	0	1	0	5	0	0	1	0	0	1	3	0	0	0	1	0	1	0	6	0	0	0
Dec	1	0	1	0	6	0	0	0	0	0	0	2	0	0	0	1	0	1	0	6	0	0	1

Figure F.3: Number of hours of WoW per activity for the 4-tower frame case.

Month	Sail out of wind park	Lift PS frame on empty SB frame	Moor tower barge	Lift preparations	Attach tower frame 1 (FF)	Pretension tower frame 1 (PT)	Lift tower frame 1 and slew (FH)	Unmoor tower barge	Seafasten & disconnect frame 1	Move barge to SB side	Moor tower barge	Lift preparations	Backload 2 empty frames	Seafasten & disconnect	Unmoor tower barge	Rotate barge	Moor tower barge	Lift preparations	Attach tower frame 2 (FF)	Pretension tower frame 2 (PT)	Lift tower frame 2 and slew FH)	Seafasten & disconnect frame 2	Unmoor tower barge	Sail into wind park	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation
Jan	0	0	3	0	4	0	0	0	0	0	3	0	1	0	1	0	2	1	4	0	0	0	1	0	1	3	0	1	1	0
Feb	0	0	2	1	3	0	0	0	0	0	2	1	1	0	0	0	2	1	3	0	0	0	1	0	1	3	0	0	0	0
Mar	0	0	2	0	2	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	1	0	0	1	0	1	0	0
Apr	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sep	0	0	1	1	1	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0
Oct	0	0	2	1	4	0	0	0	0	0	2	0	1	0	1	0	1	1	2	0	0	0	1	0	1	2	0	1	0	0
Nov	0	0	3	1	4	0	0	0	0	0	3	1	2	0	1	0	1	0	3	0	0	0	1	0	1	2	0	0	0	0
Dec	0	0	3	0	4	0	0	0	0	0	3	0	2	0	1	0	1	1	3	0	0	0	0	0	1	3	0	0	0	0

Month	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation
Jan	1	2	0	1	0	0	1	2	0	1	0	0	1	3	0	0	0	0	2	2	0	1	0	0	1	3	0	1	0	0
Feb	0	1	0	1	0	0	1	2	0	1	0	0	0	2	0	1	0	0	0	1	0	1	0	0	1	2	0	1	0	0
Mar	0	2	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sep	1	1	0	0	0	0	1	0	0	1	0	0	1	1	0	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0
Oct	1	1	0	1	0	0	0	1	0	1	0	0	0	1	0	1	0	0	1	1	0	1	0	0	0	1	0	1	0	0
Nov	1	2	0	0	0	0	0	2	0	1	0	0	0	2	0	1	0	0	1	1	0	1	0	0	1	2	0	1	0	0
Dec	1	3	0	1	0	0	0	2	0	1	0	0	0	3	0	1	0	0	1	2	0	1	0	0	0	3	0	1	0	0

…

Month	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation
Jan	0	4	0	2	0	0	0	2	0	1	0	0	1	2	0	1	0	0	1	3	0	1	0	0	0	2	0	1	0	0
Feb	1	2	0	0	0	0	1	1	0	1	0	0	1	2	0	1	0	0	1	3	0	2	0	0	1	3	0	1	0	0
Mar	0	1	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
Apr	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sep	1	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0
Oct	0	1	0	1	0	0	1	2	0	1	0	0	1	2	0	1	0	0	1	1	0	1	0	0	1	3	0	1	0	0
Nov	1	2	0	1	0	0	1	2	0	1	0	0	1	2	0	1	0	0	1	3	0	1	0	0	1	2	0	1	0	0
Dec	1	4	0	1	0	0	1	2	0	1	0	0	1	3	0	1	0	0	0	3	0	1	0	0	1	3	0	2	0	0

Month	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge	Sail to next WTG foundation	Approach TP & put down bridge	Install tower on TP	Bolting & electrical connections	Backload equipment from WTG	Remove bridge
Jan	1	2	0	1	0	0	0	3	0	2	0	0	0	2	0	1	0	0	0	2	0	1	0	0	1	2	0	1	0
Feb	0	2	0	1	0	0	1	2	0	1	0	0	0	2	0	1	0	0	0	1	0	1	0	0	0	2	0	1	0
Mar	0	1	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sep	0	1	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0
Oct	1	2	0	1	0	0	1	2	0	1	0	0	1	1	0	1	0	0	0	2	0	1	0	0	0	1	0	1	0
Nov	0	2	0	1	0	0	1	3	0	1	0	0	1	1	0	1	0	0	1	2	0	1	1	0	1	3	0	1	0
Dec	0	2	0	1	0	0	1	5	0	1	0	0	0	2	0	1	0	0	0	2	0	1	0	0	0	3	0	1	0

Figure F.4: Number of hours of WoW per activity for the 8-tower frame case.

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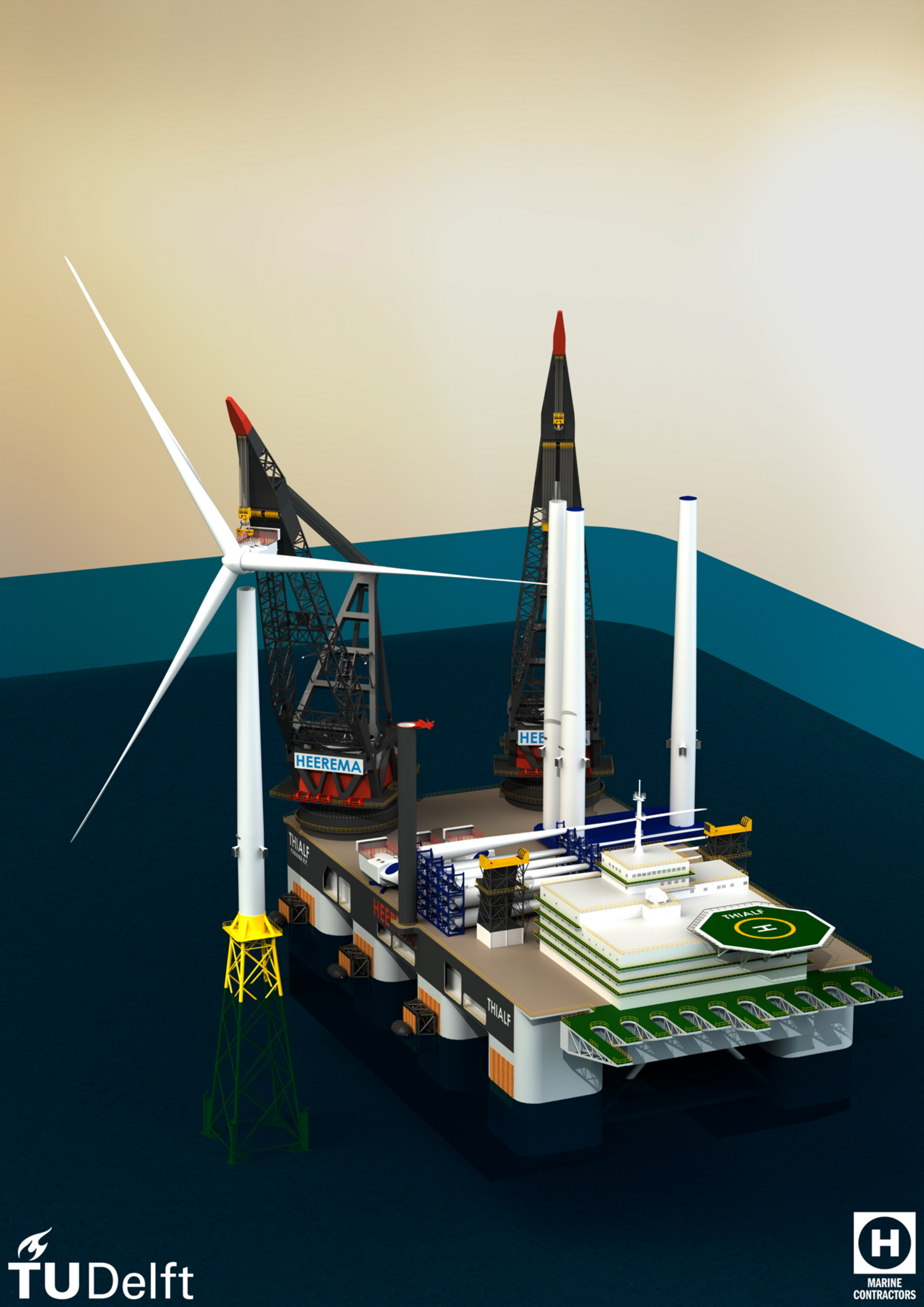

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