Feasibility assessment of novel on-site installation methods for offshore Ultra Large Wind Turbines.

Concept generation and feasibility assessment of on-site installation methods for future generations of bottom founded offshore wind turbines using floating vessels.

S.J.Sanders

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by

S.J.Sanders

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Preface

This report is the second report in a series to complete a master's thesis, to acquire a double degree in M.Sc. Offshore and Dredging Engineering at Delft University of Technology and M.Sc. Technology-Wind Energy at the Norwegian University of Science and Technology(NTNU). The first report in the series, the literature review part[43], served as the problem statement on which the research question of this report is based. The thesis was written in cooperation with GustoMSC NOV, who provided the basis on which the research question was defined. I want to express my sincere gratitude to everyone at the company who made me feel immediately at home, and to all who participated in discussions regarding the content of my thesis.

For a proper understanding of this report, knowledge of offshore wind turbine installation methodologies and basic physics is required. The conclusions can be understood without any of those, but especially the generation of concepts and the technical feasibility assessment require some prior knowledge. To acquire an understanding of installation methodologies, it is recommended to read the literature review part of this thesis, as it explains all current and novel methodologies. A summary of this research is presented in the introduction. The report can be obtained by contacting the author of the research; since it is only published internally at NTNU, it is also recommended to read the paper [24], which provides a review of offshore wind turbine installation methods.

The purpose of the report is to identify technically feasible novel installation methods for Ultra Large Wind Turbines (ULWTs) by generating and assessing the feasibility of novel concepts. Readers interested in the framework used for the generation, selection, and comparison of methods are referred to Chapter 2 and Chapter 3. In which the boundary conditions and the use of feasibility assessment methods are discussed. Readers interested in how to generate and screen concepts are referred to Chapter 4, where the entire process of concept generation and selecting the most promising ones is explained and performed. Readers interested in the technical feasibility assessment process are referred to Chapter 5. And readers who are only interested in the technically feasible concepts are referred to Section 6.7.

I would like to express my sincere gratitude to all of my thesis supervisors, who helped me tremendously throughout the entire process. All the discussions and meetings we had really helped me improve the content of my thesis and keep an eye on the process. I want to thank them not only for this, but also for the fun we had along the way! In addition to the members of the committee. I also want to thank, Andries Hofman and Thomas Lerchenmuller, of GustoMSC NOV, who are not officially part of the graduation committee, but were present at many meetings and helped me throughout my thesis. I got to make use of their expertise, and they helped me on many occasions, for which I thank them deeply.

S.J. Sanders
Delft, August 2022

Contents

Glossary

AC Academic Concept. 26, 29, 30

CAPEX Capital expenditures. 13, 14, 87, 88, 168

COB Centre Of Buoyancy. 199, 200

COG Centre Of Gravity. xii, xiii, xvi, 49, 51, 65, 67, 68, 70, 75, 77, 78, 150, 151, 162, 163, 174, 179–184, 190, 199, 201

DAF Dynamic Amplification Factor. 177, 194

GC Generated concepts. 26, 29, 30

HLV Heavy Lift Vessel. 44, 45, 48, 50, 53, 54, 56–59, 66, 79–81, 127

IC Industry Concept. 26, 29, 30

LAT Lower Astronomical Tide. xvii, 39, 55, 62, 64, 75, 148, 176, 177, 208

LCOE Levelized Cost of Energy. 1, 11, 13, 14, 207

OPEX Operational Expenditures. 13

OWT Offshore Wind Turbine. 2, 9, 15, 18, 43, 73

SCF Stress Concentration Factor. 168, 169

TP Transition Piece. 39, 53, 54, 58, 65, 74

ULWT Ultra Large Wind Turbine. iii, xi, xii, xv, xvii, xviii, 1–4, 6–10, 12–16, 18, 21, 23, 26, 28, 35, 38–41, 46, 50, 53, 54, 57–59, 61, 63, 66, 67, 69, 72, 73, 77, 87, 93, 97, 99, 101–103, 105–107, 131, 132, 145–147, 178

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Summary

During the literature review part of this thesis[43], it was determined that new and more robust installation methods are needed to accommodate the increase in size of offshore wind turbines. They are set to increase even beyond all current scopes of installation. The combination between the hub height, weight of components, and induced relative motions during mating, make that the traditional top-down installation cannot be performed anymore. Therefore, the research aims to generate new and more robust installation methods for the installation of Ultra Large Wind Turbines (ULWTs) using floating vessels. ULWTs are turbines even beyond the size of 25MW, during this research a study case wind turbine is used with main particulars of, a hub height of 250 metres above LAT, a blade length of 200 metres, a nacelle mass of 2000 metric tons, and a tower mass of 2000 metric tons. The research question is defined as follows:

"What would be feasible novel on-site installation methods for a bottom founded Ultra Large Wind Turbine using floating vessels?"

The goal of the research is to generate novel installation methods that can be used for the installation of ULWTs and to test them on their technological feasibility. The methodology used to answer this research question is fully visualised and explained in Figure 1.1 and can be summarised as follows. During the research, three main phases were defined, the first being the definition of the framework on which the concept generation, comparison, and feasibility assessment are based. Second, concepts were generated and screened to find the most promising ones. Lastly, the selected concepts were evaluated on their technical feasibility and compared with each other to identify differences in usability and performance.

Definition of the framework:
In Chapter 2 the boundary conditions, requirements and base case are defined that are used as the basis for the generation, selection and feasibility assessment of the concept. They arise from the problem statement defined during the literature review part of the thesis[43]. The boundary conditions and requirements resulted in the base case of: Floating vessels must be used, a jacket-type foundation is already in place at the installation location, concepts must be able to install all components of a wind turbine, and novel concepts must be feasible.

Before the next phase of research can begin, a deeper understanding of feasibility was established in Chapter 3. The TELOS framework[38] is used to identify which parts of overall feasibility will and can be used during the research. Two of the five feasibility categories, technical and economical feasibility, were selected. The first one, as that is the goal of the research, and the latter because technical feasibility only tells if a project/concept can be realised but does not provide sufficient handles which can be used for comparison between concepts. In-depth economic analysis will not be performed during this research, but considerations that affect economic feasibility are identified and selected. These are used in two ways, to identify the most promising concepts after generation and to compare technically feasible methods on their usability and performance. The considerations are related to cost-effectiveness, safety, complexity, flexibility, and influence on wind turbine construction.

Concept generation and screening:
Using the framework as basis, in Chapter 4, 15 concepts will be generated and pooled with previously defined novel installation methods originating from industry and academia. Only high-level and general information on all these concepts will be generated and used during the screening. This is so that it is possible to quickly generate and identify concepts which should be evaluated further. To identify the most promising ones, a screening was performed. All concepts were grouped into branches which are based on the same underlying principles, so that a fair comparison between the concepts can be made. Within each branch, a relative qualitative comparison will be performed based on economic

feasibility considerations to identify the most promising concepts. The six branches are self-climbers, self-erecting, pivot, integrated lift, large man-made floaters, and others.

Technical feasibility assessment and comparative analysis:
The most promising selected concepts are tested for technical feasibility in Chapter 5. First, the information on each of the concepts was enlarged to end up with a full description of the workings, logistics, equipment, and installation process of each of them. Using this information, critical factors related to five groups, size and strength, equipment, logistics, workability, and process, are identified. The first two are evaluated in detail to investigate the technical feasibility of the concept, the other factors are included because of their importance but will not be worked out during this research. The concepts which are deemed technically feasible will in Chapter 6 be compared on their relative differences described by the economic feasibility considerations. This is used to identify differences in performance and usability. Using all the information obtained during the technical feasibility assessment and relative comparison of the technically feasible methods, it is finally possible to answer the research question.

One note should be provided on the state of development of the concepts, all of them still require loads of engineering work to realise, as only relatively high level quasi-static analysis have been performed to determine the technical feasibility and initial size. Thus, further work should be done on the concepts in which detailed design and dynamics are included, to get a full view on workability and the definite feasibility of the concepts. All information on the concepts is summarised in Section 6.7.

Technically feasible concepts:

- Self-climbing mechanisms, the elevator platform. Attaches itself to the tower and builds up the ULWT piece by piece. Can be used with current day vessels, but has a low flexibility w.r.t. turbine size and has a relatively long installation time and waiting on weather. Also, has a large requirement on tower strength;
- Integrated lift concept, the lifting frame. Uses a frame with a large counterbalance at the bottom to stabilise it during the lift. Requires a double crane operation and can be used with vessels like the Sleipnir. Has a low installation time and waiting on weather, but a relatively large day-rate of vessel and equipment. The main bottleneck for this concept is the assembly of the ULWT onshore, as this requires innovation in port.
- A large man-made floater, the installation tower semi-submersible. A large semi-submersible vessel with lattice towers on top, on which a gantry crane is located. Internal lifting can be performed, creating 3D motion compensation possibilities. It is relatively flexible and can be used for a wide range of turbines and for major repair and replacement of all parts. The main downside is that it uses a large and expensive, never before built semi-submersible vessel.

Final conclusion and recommendations:
From all this, the conclusion can be drawn that two main concept groups can be used for the installation of ULWTs. All technically feasible concepts revolve around these two concept groups. Thus, the industry should look at these 2 solution groups of installation methods. Both have exactly opposite pros and cons, so no clear winner can be identified between the two without further research.

- Self-climbers: Especially interesting because they can be used with existing monohull lifting vessels. The main downsides are the relatively low flexibility w.r.t. wind turbine size, usability, and the fact that they have a long installation time. They are promising, as they decouple the size of the installation vessel and size of the turbine entirely;
- Large semi-submersible vessels: Either, using lifting equipment, so that existing vessels can be used. Or, specifically designed vessels that provide large flexibility with respect to the size of the turbine and usability. The main downsides are the size and costs of these vessels. They are promising, as they provide a platform on which the needed height can be reached effectively.

During the research, only technical feasibility was investigated in full, to determine the overall feasibility of the concepts further research into the economic feasibility is needed. Furthermore, environmental impact and a deeper lifetime analysis of the concepts should also be included. The last recommendation is to use the provided framework, of concept generation and assessment, for the case where jack-up vessels can be used for the installation of ULWTs in shallow waters, as this fell outside the scope of the research.

1

Introduction

A combination of current geopolitical events and the continuous battle against global warming resulted in the spiking of interest in green energy sources, even more than it has already in the last few decades. The transition from fossil fuels to greener alternatives is high on the agenda of almost every major economy, and governments and organisations have promised large investments in any and all greener alternatives. In the near future, the combination of photovoltaic, hydro-electrics, thermal, wind-energy and many more green sources will become the main generators of electrical power.

One of these sources, wind energy, has seen a transition from onshore to offshore in recent decades. The lack of space on land and up-scaling of turbine sizes led to the need of exploiting further away and harsher environments, where more space is available and there is arguably less impact on society. This, along with a higher supply of wind resources, has led to the development of large numbers of offshore wind farms, of which many are still to be built. Taking Europe as an example, the current goal is to achieve at least 450[GW] of installed offshore wind power by 2050, of which only 25[GW] has been installed up until 2020[58]. This sketches out the enormous challenge that governments and the public market are facing as we speak.

The market is highly competitive, where small increases in efficiency of one of the many complex steps within the development of offshore wind farms can make or brake companies and projects. The eventual goal of increasing the efficiency of the overall process is to decrease the Levelized Cost of Energy (LCOE) of a wind farm. One of the main approaches to increasing this efficiency has been to up-scale wind turbines, in the last decades, the size and power output of wind turbines have already more than doubled from an average of 3MW of installed power per wind turbine 15 years ago to an average of 8.2MW in 2020[58]. This trend does not seem to stop any time soon, as wind turbines of 12-15MW are in active development. The industry has already expressed interest in turbines of 20-25 MW and even beyond this. Turbines beyond these sizes will be referred to as Ultra Large Wind Turbines (ULWTs). The first step during the research was to identify where problems arise when using traditional means of installation for ULWTs. During the literature review part of the thesis [43] the following research question was answered:

"What are the bottlenecks in current installation techniques when used for offshore Ultra Large Wind Turbines?"

Problem statement

The first step to answering this question was to obtain an understanding of the state of the market, by investigating current trends. The demand for offshore wind energy was found to increase in the coming decades[13][58]. More and more wind farms will be located offshore, reducing available space and pushing future farms further offshore into deeper waters. Currently, water depths of 20-60 metres are exploited, but this will increase to 100 metres and even more in the coming decades. Therefore, the research will focus on water depths of 60-100 metres, since that will be the most probable water depth where newly built ULWTs will be installed[13]. No comments are made about when these turbines will become a reality, as the assumption is made that they can and will be built, but not when. Shallower water depths could also become available once existing wind farms are decommissioned and replaced by new farms. However, as shallower waters can be utilised, fewer problems are set to surface due to the fact that jack-up vessel can be used. Due to this, the more difficult case of installation was chosen in 60-100 metres of water depth. This in combination with the increase in the size of wind turbines leads to the need for research on the robustness of traditional installation techniques.

Before this could be done, the premises of the problem had to be established. First, an estimation of the size of ULWTs was performed. A study case provided by the research's partner, GustoMSC NOV, was compared to two other methods used for the determination of the sizes. The methods used were: nonlinear regressive trend research using academic[28][4][14] and industry-defined turbines, and linear scaling laws derived using basic properties and physics[15]. This resulted in that the provided study case was deemed acceptable and will be used for further research, the study case is further described in Chapter 2. The most important particulars are a hub height of 250 metres, a blade length of 200 metres, a nacelle weight of 2000 metric tons, and a tower weight of 2000 metric tons.

Subsequently, an evaluation of current foundation types for OWTs was performed, and their scalability was assessed using experience gained in the oil and gas industry. This leads to the fact that both bottom-founded and floating foundation types can be used for the posed water depths of 60-100+ meters[47]. Which is preferable depends on the water depth and costs of the foundation types[59]. At which water depth floating foundation will become more economical to use cannot be said, as this boundary has not been found by the industry. The most probable bottom-founded foundation that can be used for this water depth was found to be jacket or tripod foundations. However, due to the lack of recent development on tripod foundations, the choice was made to use a jacket-type foundation for the bottom founded part. Creating the need to look into both on-site and in harbour installation. The installation of foundations was not part of this research and will thus not be discussed further.

With the premises of the question of the literature review part set, the identification of the bottlenecks could start. However, not before a deeper understanding of current installation techniques was obtained. For on-site installation, so-called split installation of wind turbines in 5 or 6 different parts is currently the leading method[2]. This is mainly due to the increase in size and weight of offshore wind turbines in the last decades. Suggesting that this will also be the preferable method for ULWTs. Wind turbines are installed from an installation vessel with a traditional crane, components are lifted in a top-down configuration and assembled from the bottom up[24]. The common procedure followed for on-site installation is as follows:

- Installation of a wind turbine tower in one or two pieces on the foundation, using a top-down crane vessel. *Lack of literature on the installation of the tower suggested that this has not been a major bottleneck in the past*;
- Installation of the heaviest part, the nacelle[27], using a crane vessel;
- Installation of blades using lifting tools[55] and crane vessel;

Three main types of crane vessels can be identified: mono-hulls, jack-ups, and semi-submersibles. Jack-ups are currently one of the most widely used types of vessels, as they provide a stable lifting platform. To reduce installation costs, purpose-built jack-up vessels that can provide storage, a stable lifting platform, and have good open-water behaviour are becoming the new norm. Although, this is currently the case, the use of jack-up vessels will become economically less attractive due to the increase in water depth, as costs of these vessels will explode. This, in combination with the fact that, jack-up and down operations, have a significant effect on the installation time and thus costs of installation. Make that the use of jack-up vessels for this water depth is deemed unfavourable. Due to this, the use of either mono-hull vessels or semi-submersible vessels is preferable, no choice is made between these two and both will be used in further work.

In harbour installation[49][9] has seen use for floating foundations, where the sheltered environment of the harbour was used to reduce environmental-induced motions. The general procedure is to install all wind turbine components on the floating foundation, either next to the quay side using quay side cranes or slightly further away from shore using installation vessels. Followed by a tow out procedure where the turbine and foundation are moved to the intended installation site. However, because floating foundations are still more expensive than bottom-founded foundations, this method is not further investigated. Furthermore, on-site installation is more interesting to investigate, as more problems will arise here with respect to environmental conditions. Thus, the bottom-founded case, where a jacket is used as foundation, will be the case that is used in further research.

Industry and academia have already seen the need for novel installation methods that reduce installation time, costs, and cater to the increase in turbine size. Eleven concepts were listed during the literature review part, to get a feel about what is under development and deemed possible by academia and industry. These concepts have not been developed for use with ULWTs, but can serve as a basis for concept generation and can be evaluated on their applicability for use with ULWTs. Furthermore, the found concepts were evaluated to distil lessons learnt from them. The most important lessons are: cost reduction and size increase have been the main drivers of the developments, making the installation height independent of vessel size is preferable, relative motion reduction is of high interest, and floating installation vessels are of high interest due to increasing water depths and circumventing the need for timely jack-up and down operations. Further confirming the fact that jack-up vessels are not preferred. These concepts will be used again during the second part of the research and will be judged on their usability with ULWTs.

When looking at the traditional installation procedures of the tower, nacelles and blades, it became clear that the main critical factors during installation were the crane capacity, crane height, and the relative motions of components during installation. Relative motions are caused by wave-induced motions on the lifting vessel and foundation, wind-induced motions of the cargo, and flexibility-induced motions of the tower and crane. Using basic kinematics, well-known stress-strain relation, and forget-me-nots, the problems that surface when scaling up current installation techniques were assessed. Using this assessment and the knowledge gained during the literature review, the bottlenecks of the installation of ULWTs could be identified, the bottlenecks found are listed below.

- The needed size of lifting cranes;
  - Increase in height results in greater flexibility of the crane, and the larger the crane, the greater the influence of rigid body motions of the lifting vessel.
- The height of the wind turbine tower;
  - Same as with the crane, the flexibility will most probably increase and influence of rigid body motions of the foundation will be amplified.
- The preference for floating vessels, as deeper water will have to be exploited;
  - The susceptibility to wave-induced motions will be greater relative to that of jack-up vessels.
- The loads on components due to wind during lifting;
  - The loads will increase with size, the influence on motions differs per lifting method and component.

Definition research question
It was concluded that the combination of installation height, flexibility of the whole system, water depth and size of components will lead to relative motion-related problems. This results in the fact that economically scaling up traditional techniques is highly unlikely. Therefore, there is a need for new and more robust installation methods that can be used for the installation of ULWTs, which address the problem of relative motions. The next step in the research is to use the found bottlenecks, the defined base case of the installation, and the provided study case of an ULWT to generate and assess novel installation methods for ULWTs. The research question for this thesis is thus defined as:

"What would be feasible novel on-site installation methods for a bottom founded Ultra Large Wind Turbine using floating vessels?"

The choice was made to look into the problematic case in which jack-up vessels are deemed not economically viable, bottom-founded foundations are the most cost-effective to use still and traditional installation method using top-down cranes cannot be used anymore due to relative motion related bottlenecks, as was determined during the literature review part of the thesis. Reducing relative motions will be one of the main points of interest during the generation of concepts.

The purpose of this report is to generate and present novel concepts that are technically feasible and can be used for the installation of ULWTs using floating vessels. The second purpose is to present promising concept groups that seem promising for use and further development. A study case of the sizes and weights of an ULWT has been provided by the research's partner, GustoMSC NOV. Using this study case, the defined bottlenecks, the found boundary conditions and the fact that traditional installation cannot be used anymore for the installation of ULWTs, novel installation methods will be generated and judged on their feasibility. The entire process is explained in detail in the following paragraphs, and a flow chart depicting the process can be found in Figure 1.1.

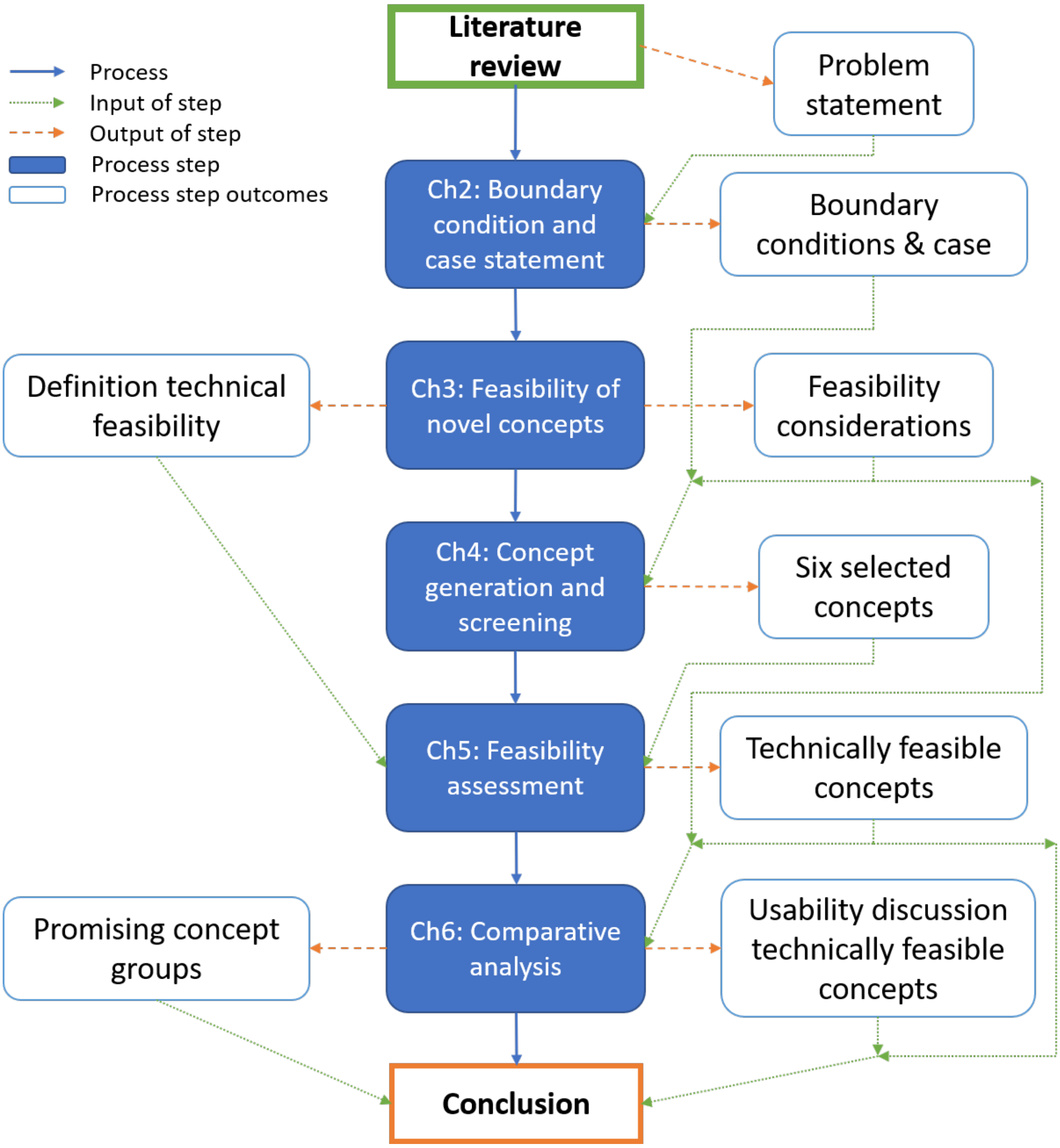


Figure 1.1: Flow chart of the entire process taken for answering the research question.

Definition of framework
The first step in generating and assessing the feasibility of novel concepts is to start building the framework that will be used throughout the report. Starting with a summary and definition of the boundary conditions, requirements, and base case, which will be utilised as a starting point for concept generation. All these are distilled from the results of the literature review part of the thesis, which served as the problem statement. These are all defined to provide a basis for concept generation and define on what the concepts will be tested in later stages of the research.

The next part of the research will further define the framework by defining the use of feasibility during this research and relating it to existing definitions of feasibility assessment. This is done to obtain a deeper understanding of feasibility and how it can be assessed. The TELOS feasibility framework[38] will be used to define feasibility categories that can be used for the feasibility assessment. The main categories which will be investigated are the technical feasibility, so if a concept can be realised, and the economic feasibility, so how does a concept perform. From the latter, feasibility considerations will be defined, which revolve around the economic feasibility. An in-depth economic feasibility assessment will not be performed during this research, as technological feasibility precedes all other categories and must be assessed first. However, considerations must be defined, as the boundary conditions, base case, and requirements describe only what a concept must suffice to at minimum. They do not provide any handles with which concepts can be compared to each other. Thus, the feasibility considerations are needed, as technical feasibility only tells if a concept can be used and not how promising it is. This will be needed during the next phase of the research, the concept generation phase, as a wide range of novel installation concepts will be generated which will have to be compared to one another to select the most promising ones.

Concept generation and screening
The next phase of the research is to start generating concepts using the defined boundary conditions and base case. Concept generation is performed using 3 separate techniques, starting with the core function identification using the found concept as a starting point, followed by the exploration of the design space using Mindmaps, and finally the generation of concepts using a Morphological chart. The goal is to generate general high-level information, so that a high-level comparison can be performed to identify the most promising concepts. Using the chart, concepts will be generated and put into one pool with the found academic and industry concepts. All these concepts will be screened, to identify the most promising concepts. The screening starts with the grouping of all concepts into branches. These branches are based on different installation principles distilled from the Mindmaps, so that all concepts within one branch are based on the same underlying principle and a fair comparison can be performed. The high-level comparison of the concepts is based on the feasibility considerations which were defined before. Not all feasibility considerations can be used here, as only high-level information of all concepts is considered, leading to a judgement based on selected considerations.

Feasibility assessment
The next phase of the research is to assess the concepts which were selected through screening on their technical feasibility. A more in-depth description of the concepts will be generated that includes the necessary vessels, equipment, installation procedure, and logistical approaches. Using these, critical factors of the concepts are identified and grouped. The groups of critical factors which describe the technical feasibility are evaluated first, to gain insight into the technical feasibility of the concepts. Here, only the technical feasibility is assessed, as if a concept is technically infeasible, it cannot be realised, and further evaluation is not necessary. The concepts which are deemed technically feasible will continue to the last part of the research, the comparative analysis based on the feasibility considerations.

Comparative analysis of feasible concepts
The last phase of the research is a comparative analysis of the feasible concepts based on all feasibility considerations. The more in-depth description of the concepts generated during the feasibility assessment makes the judgment of the concepts possible on all feasibility considerations. This time, all of them can be fully evaluated, as all the information about the feasible concepts needed to evaluate them is available. The comparative analysis is performed to further identify shortcomings, and relative differences in performance and usability of the technically feasible concepts. This, in combination

with the information obtained during the feasibility assessment, is used sequentially to fully describe the concepts on their technical feasibility and usability. In the end, all previous knowledge gained is used to provide a holistic discussion on the feasibility of the branches. The latter is of importance, as it identifies promising principles and gives advice on usable concept groups. Finally, answering the research question in two ways, one presenting technically feasible concepts and one identifying promising concept groups and combinations.

Report structure

The structure of the report is as follows. Chapter 2 describes the boundary conditions for novel installation methods for ULWTs and gives an overview of the defined case. Chapter 3 describes the use of feasibility during the research and defines feasibility considerations, which are used throughout the research for comparison between concepts. In Chapter 4, concepts are generated using a combination of concept generation techniques. The generated concepts, together with the concepts found during the literature review part of the thesis[43], are grouped into branches based on the same underlying principle. Within each branch, a screening is performed to identify the most promising concepts. Ending up with one concept of each branch that will be described in full and assessed on its feasibility in Chapter 5. In this chapter, first, a further definition of the wind turbine construction is presented to obtain all information needed for the feasibility assessment of the selected concepts. Followed by a general discussion on logistics, after which all selected concepts are described and assessed on their technical feasibility. The feasible concepts are compared using the feasibility considerations in Chapter 6. Using all the knowledge gained, a final summary of the feasible concepts is presented, and the chapter ends with a discussion on the feasibility of the branches. Finally, everything is concluded in Chapter 7 where recommendations and further work are also defined.

2

Boundary conditions, requirements, and case statement

In previous work, it was determined that new installation methods will be needed for the installation of ULWTs. The combination between the to be conquered physical challenges and economic viability of up-scaling traditional methods, gives rise to the need for newer and more robust methods. Before the assessment of proposed novel methods and the generation of novel installation methods can begin, the research framework must be set up. In this chapter, the boundary conditions on the to be generated concepts which originate from the literature review are summarised and briefly explained. Followed by the explanation of the main requirements which novel methods should suffice to. Finally, the two are combined to form the definition of the base case, which will be used during this research. This is the first part of defining the framework of the research, in which the grounds for the generation of concepts is defined.

In Section 2.1 the boundary conditions for novel installation methods are listed. Followed by Section 2.2, where the main requirements of novel concepts will be discussed. Ending the chapter with Section 2.3, in which the case that will be used to generate concepts is presented.

2.1. Boundary conditions

In this section, the boundary conditions on the to be generated concepts will be summarised and briefly explained. They will be used during concept generation and feasibility assessment, as they describe what a concept should minimally suffice to. The boundary conditions follow from the problem statement, which was researched during the literature review. They follow from a couple of factors, the physical size and weight of an ULWT, water depth, and relative-motion related issues during the mating phase of the components of the wind turbine. The size and weight boundary condition originates from the study case of an ULWT provided by GustoMSC NOV. This case was deemed acceptable during the literature review part[43] and the main particulars of the turbine can be found in Table 2.1. All boundary conditions are defined from the installation methods point of view so, e.g. the conditions and requirements on used installation vessels will not be defined.

Table 2.1: Main particulars of provided study case of an ULWT.

	Study case
Rotor Diameter[m]	400
Blade length[m]	200
Hub height[m]	250
Nacelle dimensions(LxWxH)[m3]	30x15x15
Nacelle mass[ton]	2000
Blade mass[ton]	140
Tower mass[ton]	2000

From the found water depth of 60-100 metres, two boundary conditions are formulated. The first is that a jacket-type foundation is the most likely to be used[59]. Thus, a novel method should be able to install ULWTs on at least a jacket-type foundation, but preferably for all types of bottom-founded foundations. The latter will be reflected upon in Subsection 3.2.2 and worked out in Chapter 6. Deeper waters will most probably require floating foundations to be economical, at which water depth the transition from bottom-founded to floating foundations will take place has not yet been defined in the industry. Floating foundations will be left out of this research, as they are deemed uneconomical at this water depth and on-site installation is more interesting to look into.

The second boundary condition that follows from the water depth is that the use of jack-up installation vessels is considered unfavourable. The market currently moves to floating vessels to further reduce installation times, and thus costs. Although upscaling of jack-up vessels is possible, the increase in water depth causes the size of the legs to explode, decreasing the overall cost-effectiveness of using jack-up vessels. The exact boundary at which water depth jack-up vessels will become uneconomical is yet to be seen, during this research they are deemed to be uneconomical. Thus, the focus will be on floating installation vessels.

One more boundary condition for the generation of novel concepts can be defined from the bottlenecks found during the literature review part of the thesis. The combination of the bottlenecks results in relative motion-related difficulties. These motions should be kept below mating tolerances, the exact tolerances will not be defined during this research, as this situational. However, a general boundary condition can be formulated; the relative displacements of components should be kept within mating tolerances. Thus, the methods should be able to line up components.

The last boundary condition is that the novel methods should be able to install all components of a wind turbine, the tower, nacelle, and blades. This is taken as a starting point so that only all encompassing methods will be evaluated. This results in a wider view on possible solutions, as it might be possible that, from an all-encompassing method, it surfaces that the installation of a specific component can be performed well by a method. Basically, it is casting the net wide and after distilling what is learnt from this. All boundary conditions for the generation of novel installation methods are listed below.

- Must be able to install the defined ULWT;
- Must be able to be used with at least jacket type foundations, usable with all bottom-founded types is preferred;
- Floating installation vessels are preferred;
- Must be able to line up components for mating;
- Must be able to install all components of a wind turbine.

2.2. Requirements

In this section, requirements for novel installation methods will be worked out in more detail. The main requirement that will be looked into during this research is the feasibility of novel concepts. The goal is to in the end present concepts and concept groups that are deemed feasible. The definition of feasibility and the manner in which it is used during this research will be presented in Chapter 3, as here only the requirements will be stated. The feasibility is of importance, as this makes or breaks concepts. It would not be sensible to further develop and assess concepts that are not feasible, and feasibility must be determined before further work on a concept is performed, more information and reasoning about this are presented in Chapter 3.

Some secondary requirements must be mentioned due to their importance, but these will not be widely used during the research. This is because including these requirements requires an in-depth analysis of the workability of a method. These analyses take a large amount of time and add little value to the objective of the research, presenting technically feasible concepts. These analyses are part of the overall feasibility assessment of novel concepts, however, the choice is made to only look into technical feasibility in detail. Thus, the secondary requirements are stated due to their importance but not included into detail during the feasibility assessment.

The following requirements come from the workability of an installation method, the workability refers to the operational safety limits that a method has. Safety limits are described using five factors: significant wave height, peak period, wave direction, associated wind speed, and direction. In general, it can be said that higher workability of a method is always preferred. Current methods used for smaller turbines in the North Sea have operational limits of around $2 - 2,5$ metres significant wave height, as discussed with project supervisors. The workability also depends on the peak period, but no specific number can be provided here, as a full spectrum will need to be analysed to fully capture the effects of the peak period on a certain type of vessel. The workability for smaller turbines suggests that lower limits will cause too much waiting on weather for a method to be economically valid; thus, a limit of 2 metres is assumed as the bare minimum.

Furthermore, the wind velocity should be taken into account, as installation procedures will be affected by this. The exact limits on the wind speed will depend on the shape and size of the cargo and equipment. Wind speeds that must be taken into account can be deducted by investigating the wind speed that is associated with a significant wave height of 2 metres. This was done by looking at scatter diagrams of significant wave height vs. wind speed. For this, the upper bound of the average wind speed bin that is associated with 2 metres H_s is taken to be the bare minimum requirement. A wind speed of 6.5 [m/s][22] was found to be the upper estimate of the mean wind speeds seen at a significant wave height of 2 metres in the North Sea. This data was obtained at a height of 10 metres above the mean water line and is a 1-hour average. The combination of the limits on significant wave height and wind speed would lead to a workability of approximately 24% in the North Sea over a full year. Only year-round scatter diagrams were available, so comments on seasonal workability cannot be made. The wind speed value must be scaled up to hub height and recalculated to a 10-min average, the value for the wind speed will then become 9.75 [m/s][53]. The 2D scatter table of wind speed versus wave height, inputs used to find this value, and further calculations to get the wind speed can be found in Appendix A.

The last requirement comes from the resulting motions due to a certain wind wave climate. The allowable velocities and displacements during the mating phase of OWT components are not to be exceeded. The general requirement is that a component can be mated without damaging itself or the lifting equipment. The exact limits depend on the components and equipment. These limits are expressed in terms of allowable velocities and accelerations, but cannot be defined as such, as the limits are usually in-house knowledge and the equipment for the installation of ULWTs has not been developed yet. Only the general requirement of keeping the velocities and accelerations within acceptable levels can thus be defined. The primary and secondary requirements are listed below.

- **Primary requirement:**
  - Must be feasible.
- **Secondary requirements:**
  - Must be able to function in sea states with a significant wave height of at least 2 meters;
  - Must be able to function safely with a wind speed of at least $9.75 m/s$;
  - Must keep relative velocities and acceleration below safety thresholds.

Up until what level of detail the secondary requirements can be used for the determination of the feasibility of novel concepts has to be seen. The novel methods that have been found during the market review in the literature review part of the thesis[43] all have different levels of technological readiness. This leads to discrepancies in the amount of information that is available on them. Thus, the possibility of testing these novel methods on these requirements will differ. For the concepts that will be generated, this will also lead to difficulties, as an in-depth workability analysis will not be performed during the research. Nevertheless, these requirements should be stated to give an overview of what limits should be taken into account when designing and generating novel methods.

2.3. Case definition

In this section, the case definition used throughout the research is presented. The case is as follows: a foundation is already in place at a non-determined location offshore, on the jacket an ULWT must be installed using a floating vessel and method which suffices to the boundary conditions and primary requirement. The secondary requirements will be of influence, but will not make or brake concepts, as the scope of the thesis is to define methods which make the installation of ULWTs possible. Once that is achieved, more research must be performed to determine the exact workability of the concepts, further development can be done to increase workability, and economic feasibility must be assessed.

As a starting point, only all encompassing methods will be formulated. One concept must be able to install all components of wind turbines, so the tower, nacelle, and blades. This so that the critical factors of each concept can be identified throughout the installation procedure. The critical factors can then be used to define the usability of concepts for particular cases, e.g. a concept cannot install a nacelle but can be used for blade installation. So, start wide to gather as much information as possible and use that information to define narrower usability of concepts, if applicable.

The boundary conditions, requirements, and case describe only the physical limitations and design boundaries that a novel method will have to meet. However, they do not provide measures to compare the methods with each other and no definition of feasibility has been provided yet. Both will be defined in the next chapter to further define on what novel methods will be tested and how they will be compared.

3

Feasibility of novel concepts

The second part of the definition of the framework of this research is defined in this chapter. In the previous chapter, the grounds on which the concepts generation will be based was defined. This does not give any information on how and on what generated concepts will be tested and compared to identify the promising ones. This will be defined in this chapter. A novel method must not only meet the boundary conditions and the case set in Chapter 2, but also adhere to the feasibility requirement on which it will be tested. This chapter sets out to define how different categories of feasibility will be used throughout the research and to provide a basis for understanding overall feasibility.

Feasibility is determined by a wide range of categories that together describe the overall feasibility of novel installation methods. Some of these factors will be selected for use during this research. The goal of this chapter is to define the use of feasibility and provide tools that can be used for the comparison of novel installation methods. The latter must be defined, as sufficing to the boundary conditions and defined case does not provide any handles to compare concepts to one another. This will be needed to select the most promising concepts after concept generation.

In this chapter, first feasibility of novel concepts is defined and related to existing feasibility assessment definitions and methods in Section 3.1. Next, the economic feasibility considerations are defined in Section 3.2. In which, first, a discussion on the cost-effectiveness related to the Levelized Cost of Energy (LCOE) of energy generating plants is presented. Followed by the formulation of four influential factors on the cost-effectiveness that can be determined for novel installation concepts. In Subsection 3.2.2, further considerations of safety, complexity, flexibility, and influence on wind turbine construction are described. In Section 3.3 a summary of all feasibility considerations is provided.

3.1. Definition of use of feasibility

In this section, the definition of how feasibility is used during this research will be presented. Feasibility can be defined in multiple ways, one of which is the TELOS framework[38]. TELOS separates overall feasibility into five categories:

- Technical feasibility, is the concept technically possible?
- Economic feasibility, is the concept economically viable?
- Legal feasibility, will critical people accept the concept?
- Operational feasibility, does it suit the organization?
- Scheduling feasibility, how long will development and construction of the concept take?

All of these categories are interdependent on each other and must be assessed before a novel method can be deemed fully feasible for use and development. The evaluation of all these categories requires a large and multidisciplinary team with expertise in engineering, planning, economics, etc. This makes that not all categories can and will be used during this research. The choice was made to use two of the five categories, the technical and economical feasibility of novel installation concepts.

The technical feasibility is defined as the technical achievability of a concept and will be used to determine if it is possible to design and construct a novel concept. During this research, the technical feasibility will be determined by identifying critical factors which make or brake concepts. The critical factors that will be evaluated in detail are related to the strength, size, and equipment that novel concepts need to achieve installation of ULWTs. They will be evaluated using quasi-static relations and related to existing equipment, vessels, and constructions to provide insight into the achievability of concepts. No overarching critical factors can be formulated, as each concept will revolve around different principles and use different equipment. Thus, they will be concept dependent and will be worked out for selected concepts in Chapter 5. More critical factors related to, for example, logistics or installation process will be mentioned, but will not be evaluated in detail, but are mentioned due to their importance, as they relate to other feasibility categories.

The economic feasibility is defined as; the economic viability of a concept and will be used to define handles with which concepts can be compared to one another. No in-depth cost analysis will be performed, as cost-effectiveness of concepts depends on a wide plethora of factors including but not limited to location, distance to port, needed equipment, downtime due to weather, lifetime of a concept, etc. These will not be defined during the research, as the main goal will be to determine technical feasibility. However, some of these factors will be selected and used to define feasibility considerations related to the economic feasibility of a concept. These considerations will be used to differentiate between concepts which adhere to the set boundary conditions and the defined base case. Therefore, the final say on the economic feasibility of concepts will not be included in the report, but it will be used as a relative comparison to identify the most promising concepts and evaluate them on usability. Factors that influence economic feasibility can be defined as overarching factors, as these are not defined by the workings of a particular concept, these factors will be further defined in Section 3.2.

These two were selected due to the fact that if a concept is technically not feasible, and thus not possible, there is no need to further evaluate the other feasibility categories, as it precedes the other categories. Furthermore, the technical feasibility assessment is the first step to determine the overall feasibility, the goal of the research will be to propose technically feasible concepts or concept groups which will have to be assessed further to determine its final feasibility. However, the technical feasibility does not give handles to compare concepts with each other. It only says if a concept is possible, yes or no, and not if it is promising or viable. The comparison will be made using considerations defined from the economic feasibility part of a feasibility study. To determine the feasibility of projects, three steps have been defined for feasibility studies[32]. Feasibility studies require three different phases to get a view on the overall feasibility of a project. The three phases are defined as:

- Scoping study, is used to define potential concepts and eliminate options that are unlikely to become optimal;
- Prefeasibility study, used to select the preferred concepts from the selected concepts defined by the scoping study and provide a case on whether to commit to the final phase;
- Definite feasibility study, is used to refine and optimise the concepts defined during the prefeasibility study and to determine its full feasibility.

The research will focus mainly on the first two phases of feasibility studies, the scoping study, and the prefeasibility study of concepts. The scoping study will be to generate a wide range of novel installation concepts and sequentially select the most promising concepts based on economic feasibility considerations. The prefeasibility study will mainly focus on the technical feasibility of the selected concepts, as if a concept is technically not achievable further feasibility assessment will not be needed. The selected concepts will be judged on their feasibility to get rid of even more options and continue on with the most promising ones. The final phase, the definite feasibility study, requires assessing all five defined feasibility categories in detail, this will not be performed during this research but can be performed on the concepts that will be proposed at the end of this report. Thus, this report is one part of the total feasibility study of novel concepts that focusses primarily on proving the technical feasibility of concepts. Furthermore, the economic feasibility is used to compare and assess usability of concepts.

3.2. Economic feasibility considerations

In this section, the second part of feasibility which will be included into the assessment of novel methods, the economic feasibility, will be presented. The economic feasibility of novel installation methods is determined by the cost-effectiveness of a concept. The cost-effectiveness of a wind farm determines the eventual cost of the generated energy, which is expressed using the Levelized Cost of Energy (LCOE). The goal of every energy-related project is to decrease this value as much as possible. However, some aspects of novel methods cannot yet be expressed in costs. Not all details of novel methods, which are needed for a full costs analysis, will be worked out within the scope of this research, as the main goal is to prove technical feasibility of methods. However, due to the importance of economic feasibility and to provide handles with which comparisons between concepts can be made, it must be included. Technical feasibility only tells if a concept can be built, not if it should be built, or how promising it is.

Next to the cost-effectiveness, further consideration will be defined which have an influence on the cost of a concept but which cannot be expressed in terms of costs. For example, the flexibility of a concept regarding turbine size determines the range of turbines that can be installed using a certain installation concept. This inherently determines the lifetime of said concept, the larger the flexibility, the higher the cost-effectiveness, as investment costs can be earned back over a longer time frame, reducing usage costs. The exact cost benefit of this cannot be expressed without in-depth economic analysis, which is not part of the scope of this research, but should be taken into account when comparing methods. The further considerations that will be taken into account are the safety of an operation, the complexity of a concept, the flexibility of a concept, and finally the influence on the wind turbine construction due to a concept.

3.2.1. Cost-effectiveness

In this subsection, the cost-effectiveness of energy-generating plants is discussed. In the industry, the LCOE is used to describe the cost-effectiveness of wind farms. The LCOE is one of the main indicators that is used to determine the economic-ability of an electricity generating plant. Thus, it can be used to determine the cost-effectiveness of novel methods. The LCOE described the average revenue of energy that is required to finance the investment and operational costs of a generating plant. It is calculated by the ratio of the costs over the produced energy, resulting in cost per unit of energy, see Equation 3.1 for the general formulae[52]. In general, it can be said that the lower the LCOE of a certain project, the more economical it will be. All steps in the development of wind farms influence the LCOE of the project, including the installation. Thus, LCOE can be used to describe the cost-effectiveness of installation methods.

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=-m}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=-m}^{n} \frac{E_t}{(1+r)^t}} \tag{3.1}$$

In which $LCOE$ is the Levelized Cost of Energy in [$\frac{€}{MWh}$], I_t is the total Capital expenditures (CAPEX) expected in a certain year in [€], M_t is the Operational Expenditures (OPEX) expected in a certain year in [€], $E_t$is the electrical energy generated per year in [MWh], r is the discount rate used to estimate the net present value, n is the lifetime of the project in years and m is the time in years before the generating plant goes into operation. The CAPEX, OPEX and the generated energy are the three main components that influence the LCOE. They must be related to the installation of ULWTs by novel methods to be usable for the determination of their cost-effectiveness. Installation costs occur before the wind turbine is operational and are therefore inherently part of the CAPEX. It has nothing to do with either the OPEX or the generated energy. So, when comparing installation methods with regard to LCOE, it's effect on the CAPEX is of main interest. Note that, some novel installation methods will actually influence the OPEX as well, because they can be used for maintenance of the wind turbines. However, since the scope of this research is focused on the installation part, this will be disregarded in the cost-effectiveness considerations. Furthermore, the generated energy is also effected by installation methods. The earlier a wind turbine is installed, the earlier it can start generating energy; the impact of this will also be omitted, as that is outside the scope of the research.

Capital expenditures

The Capital expenditures (CAPEX) refers to the investment cost of fixed assets that a company produces. In terms of wind farms, these are the costs of development, construction, and installation of wind turbines. The development of ULWTs is outside the scope of this research, and the assumption is made that ULWTs can be designed and are cost-effective. The same applies to the cost of the construction of wind turbine components. This leaves only the installation costs as an indicator which can be used for the differentiation between novel methods. Installation costs cannot be directly quantified because of the stage of development of novel concepts; some parameters that influence installation costs can, however, be quantified. The installation costs are mainly driven by two factors, the charter costs of the needed vessel(s) and the rental/construction/purchasing costs of needed equipment. The choice was made to separate these two because the cost of vessel and equipment are independent of each other, e.g. a small and cheap ship that needs super-expensive equipment might still be more expensive than a super-large and expensive ship with cheap equipment.

The eventual charter cost of a vessel is determined by the amount of time it takes to complete the installation of a wind farm. This amount is determined by a couple of factors, including, but not limited to: installation procedure time, downtime due to waiting on weather, transit time, inter-array time, and (un)loading time. From these factors, a choice will have to be made as to which of them can be used for the differentiation between novel concepts. Factors that can be used must be quantifiable and show a clear difference between concepts. All the aforementioned factors have these two characteristics. However, for the purpose of this research, the choice was not to include a study case of a wind farm. This makes the determination of the factors of transit time, inter-array time, and (un)loading time impossible as no details about harbours or the wind farm are defined. Thus, these three factors will be disregarded. On top of that, not much is known about the specifics of novel concepts, both to be generated and already proposed ones. So, no proper estimations can (yet) be made about these three factors. This leaves two influential factors to the installation time which can be used to differentiate between concepts, the installation procedure time, and the downtime due to waiting on weather.

The installation procedure time refers to the time it takes to complete the total installation of an ULWT on a bottom-founded foundation. It is assumed that perfect weather conditions are present so that all procedures that a method entails can be performed in succession without any downtime. This is assumed because it will give a quantifiable factor that can easily be compared, however, it does not show the entire picture. To get a better view of the performance of a novel method, the time waiting on weather should also be considered. A method might be fast under perfect weather conditions but, if the workability is low, will have a lot of time waiting on weather. The time it takes before a workable weather window presents itself can be longer than a method which is slower under perfect conditions, but has a higher workability. Thus, both factors should be taken into account to get a substantiated way of comparing methods on installation time.

The total installation time cannot be used without relating it back to costs of the installation. Otherwise, no comments about the cost-effectiveness of novel installation methods can be made. The reasoning behind this follows from the fact that a method that is fast can, in the end, be more expensive than a slow method when using expensive vessels or equipment. Thus, in addition to installation time, the day-rates of vessels and some way of defining the costs of novel equipment will have to be included into the assessment of novel methods.

In conclusion, the cost-effectiveness of novel installation methods can be determined by looking at how they influence the LCOE. They only influence the CAPEX part of the LCOE as the installation is inherently part of it. Only the installation costs itself will be considered, as other parts of the CAPEX fall outside the scope of this report. Installation costs cannot be directly quantified at this stage of development of novel methods. Therefore, it was decided to use four factors that describe the cost-effectiveness of novel methods. How they are determined is discussed in Chapter 6 and all these and all other considerations are summarised in Table 3.1. The four factors are as follows:

- Installation procedure time;
- Waiting on weather;
- Vessel(s) day rate;
- Equipment costs.

3.2.2. Further feasibility considerations

In this subsection, further considerations are defined that will be used for the differentiation and judgment of novel installation methods. To obtain a view on the economic feasibility of novel methods, further considerations must be defined. These considerations cannot be expressed in costs, but still influence the eventual costs of a method. Four fields are formulated in which considerations will be defined: safety, complexity, flexibility, and influence on the construction of a wind turbine. Three main criteria must be met by the factors describing these considerations, they should be quantifiable, be applicable to all novel methods, and can be used to differentiate between the methods. e.g. "Can this concept climb the tower without damaging it" is an badly defined consideration as it is only applicable to tower climbing mechanisms.

All considerations are interdependent, as they all have an influence on the eventual costs of an installation method and influence each other. As, e.g., in the case that a method requires alterations to the construction of the wind turbine, inherently the flexibility of the method decreases. To make differentiation between novel installation methods possible, the assumption is made that all considerations are independent of each other. Furthermore, it is impossible to quantify the interdependence of factors that cannot be easily quantified by themselves. Thus, the assumption is made that they can be determined independently.

3.2.3. Safety

In this subsection, the first further consideration of safety will be discussed. OWTs are installed far from civilisation and in harsh environments, increasing the risk of all hazards, as medical help is not nearby. During the installation of OWTs, personnel must be present at all lifting and mating operations. During these operations, a number of hazards can occur, including but not limited to: Machinery, getting stuck in-between components, equipment dropping, crushing of body parts, etc. Most of these hazards are hard to quantify, as random human factors come into play. However, when looking at the root cause of the hazards some of them can be quantified using the basic principle of interaction frequency, e.g. two procedures are better than 10, as you only have two occasions where something can go wrong. Safety refers to the safety of personnel, equipment, and construction. The safety of assets and life are both important, but will not be judged separately, since the most dangerous procedures for both are the same.

Now it is important to identify the root causes which are of main influence to the hazards during the installation of ULWTs, are quantifiable and can be used for the comparison of novel methods. Looking at the novel methods of both academia and industry that were presented in the literature review, one main difference comes to light. The number of mating procedures that must be performed. From a single one when utilising integrated installation techniques to six or more when using split installation techniques. This difference makes it possible to include safety as a quantifiable parameter.

One more thing should be taken into account, the nature of the mating procedures. If mating takes place automatically, no personnel has to be present making personnel safety a non-issue, safety of equipment and environment will still be of interest. The actions required after mating should also be included in the nature of the mating procedures. Especially when using a modular tower design, tower pieces will need to be connected by bolting, this is performed by on-site personnel at great heights. Which is inherently more dangerous than low-altitude operations.

Thus, the nature and amount of mating procedures will be used together for the determination of the safety of a method. The amount of lifting procedures could also be used as a safety criterion, however, not all novel installation methods will require traditional lifting to take place. Mating will still have to take place because the components need to be connected. These and all other considerations are summarised in Table 3.1.

3.2.4. Complexity

In this subsection, the further consideration of complexity will be discussed. Complexity refers to the measure of how easy it is to develop, produce, and use the mechanisms a certain method needs to succeed. It is subdivided into two factors, the complexity of the mechanisms entailed by a method, and the complexity of the process that must be carried out to fully install an ULWT. This subdivision is made because non-complex mechanisms might require complex processes for installation, e.g. a double crane operation using 'low tech' lifting equipment. The equipment is relatively non-complex, but the double crane operation is complex due to the need to move and operate two cranes in unison.

Complexity should be taken into account when differentiating between concepts because of two reasons. The first one being that an increase of complexity also increases the costs of a method. The exact increase in costs cannot really be quantified, as not all details of novel methods are known. This report will only give high-level information of concepts, in which not every single small component will be designed, and not every process can be worked out into detail. Resulting in insufficient information to perform an exact cost estimate and relate that back to the complexity of a method. However, complexity should thus be taken into account when comparing methods.

The second reason is that the more complex a method is, the more that can go wrong. One might say, just make all systems with further redundancy, however, this will again further increase the costs of a method, as more systems will need to be in place to uphold its safety. This in itself is not necessarily a problem, as it can be done and super-complex systems that function properly have already been built. Thus, complexity is not something that should be shunned. However, when comparing methods, it can be used, as the preference will always be to perform installation with an as easy and non-complex method as is possible. The general idea behind this is that the functional outcome of novel installation methods will always be the same, the installation of ULWTs. This can be done with numerous methodologies, which consists of different levels of complexity. If a choice between these mechanisms can be made, the least complex will be preferable, as they will always result in methods with lower costs, maintenance, need for personnel, education, etc.

The first of the complexity factors is the complexity of the needed mechanisms. Complexity is hard to quantify, as the question of how complex something is will be answered differently by everyone who is asked this question. There is no clear definition of what complexity is. To work around this, the complexity of the mechanisms will be expressed using two parameters. The first one will be the amount of needed major mechanisms for a method to successfully install an ULWT. This provides insight on how many and what types of mechanisms will need to be designed, integrated, and used. The only thing that has to be defined further is what a major mechanism is. For the purpose of this report, a major mechanism is a mechanism that dictates the workings of a method, e.g. a flip frame when using a pivot method, or a tower attachment system when using self-climbing mechanisms.

This summation does not take into account one important thing, the technological readiness of the major mechanisms. Thus, the second parameter is the technological readiness of the major mechanisms. Concepts based on proven technology are easier to develop and use, as a lot of knowledge is readily available on them. This can drastically reduce the development time and costs, but how much is again not quantifiable. Judgement will need to take place about the technological readiness of all major mechanisms. How this will be performed is discussed in Section 6.3, as in this section, only the reasoning behind the included considerations is given.

The second factor of complexity is the complexity of the process. The process refers to the actions that are undertaken using the mechanisms that a novel method entails to fully install a ULWT. This because non-complex mechanisms might need a complex process to work properly, an example of a complex operation is the inverted pendulum principle further described in Section 5.6. Where crane and vessel movement operations must be performed in unison, all the while effecting each other. Thus, the number of processes that must be performed in unison can be used as a measure to compare novel installation methods. The number of procedures does not take into account how complex they are. Thus, the same reasoning as for complexity of the mechanisms is applied here, and judgement on these processes will have to take place. These and all other considerations are summarized in Table 3.1.

3.2.5. Flexibility

In this subsection, the next further consideration, the flexibility of a novel method, will be discussed. The flexibility here refers to the possibility of using an installation method in different circumstances. Traditional installation methods have been proven to be very flexible. They can be used during all phases of the lifetime of a wind turbine and can be applied to a wide range of wind turbine sizes and foundation types. Obviously, depending on the size of the installation vessel. This shows that the flexibility of a method is an important factor, in the end this can all again be related back to the costs of an installation method. An installation method that can be used for a wide range of turbine sizes and foundation types is always preferable. This will increase the lifetime of a novel installation method, increasing the time-frame in which a method is applicable. Resulting in lower day rates, as there is more time to earn back the development and construction costs of a method. Again, the quantification of this cost benefit cannot be performed. It is impossible to determine the cost benefit of flexibility without in-depth analysis on the entire process of installation, and predictions on the rate of up-scaling of wind turbines. However, it can be said that the more flexible a method is, the more preferable that method becomes.

Flexibility will be subdivided into three factors that will be used to differentiate between novel concepts. The first is the possibility of using a novel method during multiple phases of the lifetime of a wind turbine. It is preferable that a method can be used for installation, major maintenance and repair, and decommissioning, this reduces the number of methods that have to be developed for each of the stated cases. All methods can be used for installation and decommissioning, as decommissioning is, in essence, reverse installation. If it is the most effective way is debatable, and there are probably more efficient ways of decommissioning, but that is outside the scope of this report. Therefore, no differentiation can be made on the basis of decommissioning between novel methods. However, the usability of novel installation methods during the operational phase of the lifetime of a wind turbine can be used.

During this phase, maintenance and repair of components will have to take place. Small maintenance and repair can be performed using helicopters or the (small)crane and elevator which are on-board of each wind turbine. However, if a major failure of large parts occurs, problems arise. They cannot be repaired using traditional means. Therefore, it is advantageous if an installation method can also be used for major repair and replacement. If a method can be used for major repair and replacement of parts, it can easily be determined and is a simple yes/no answer. To further distinguish between methods that can be used for major repair and replacement, the set-up time before maintenance can be performed is used. Furthermore, this factor is included to identify possible outliers, so a method that can theoretically be used for major repair and replacement but takes long to use, resulting in an unpractical solution. This directly translates into downtime due to a defect, which should be as low as possible. The choice is made to only look at the preparation time, as no case will be defined regarding the type of repair or replacement to keep the comparison general. The preparation time here refers to the set-up time of a method before repair or replacement can begin. For example, the entire process of attaching a self-climbing system and the time it takes the system to get into position.

The second factor of flexibility will be the applicability of an installation method to multiple types of foundations. In Chapter 2, it was already stated that the method should at least be usable with jacket-type foundations. However, it is preferable that the methods can be used for multiple types of foundation, as this expands the usability of a method. The scope of the research is on bottom-founded foundation. Thus, the criteria becomes, usability of novel installation methods for different types of bottom-founded foundation, without the need of alterations to the design made for use with jacket-type foundations. This can be quantified by looking at a combination of the need for alterations to major mechanisms, to facilitate the use with multiple types of foundations, together with the nature of the alterations. The latter because a minor alteration to an attachment system is obviously less drastic than a needed redesign of all mechanisms.

The third factor of the flexibility is; the usability of an installation method for differently sized turbines without alterations to the initial design of the method. Ideally, a method is usable for a range of sizes, as has traditionally been the case with the crane vessel top-down approach. Obviously, depending on the size and weight of components and size of the used lifting vessels. This has been the leading method in the past because of its ease of use and flexibility, and thus lower costs. Novel installation methods might make use of turbine-specific frames or lifting mechanisms. Requiring redesign or modular design to use them with differently sized turbine. This will drive up installation costs, as different sized frames and mechanisms will need to be designed and constructed. The exact cost increase of this is hard to quantify at this stage of the research. However, it can be assumed that a larger flexibility of a method is always preferred. Thus, the less impact wind turbine size has on installation methods, the better they are.

The same way of quantifying the flexibility with respect to foundations will be used for the flexibility with regard to size. Thus, determining if a method is effected by turbine size, and if so, to which degree the method is effected. The latter again because the need for alterations does not give any measure on the nature of them. A judgement factor is included to define the nature of alterations. These and all other considerations are summarized in Table 3.1.

3.2.6. Influence on construction of wind turbine

In this subsection, the last further consideration, influence on the construction of wind turbine components due to an installation method, will be discussed. Traditional top-down lifting installation has been the preferred method for the last decades. The lifting equipment used and its necessary attachment points on wind turbine components have not changed significantly in this time frame. Novel methods might require alterations to the traditional design of a wind turbine to be able to perform installation. However, the willingness of turbine manufacturers to alter their designs has not been confirmed. Manufacturers prefer to build their turbines according to a standard, as this makes series production much easier, and they have years of experience using these standards. Thus, in general, it can be said that no alterations to the design of turbines are preferred. However, if a new method emerges that alters the design, but results in lower installation times and costs, a case can be made that in the future the alteration of the construction of OWTs is beneficial. Even though this is the case, as little alterations as possible are preferred, as a lot of experience and knowledge on the design of current wind turbines has already been obtained. Alterations to designs will lead to new challenges which have not yet been thoroughly researched, leading to higher risks for turbine manufacturers.

Raising the discussion if an installation method should follow the design of wind turbines or the other way around. The general answer to this question is that if there is no need to alter the design of wind turbines, this is always preferred. This comes from the fact that if a method does not influence the construction of a wind turbine, it can inherently be used for a wider range of wind turbines, as not all turbines will be adapted for use with a certain installation method. Or a new method must surface which eclipses all other methods in terms of costs, then a new standard can be formulated, and all wind turbines adjusted to cater to this. Furthermore, in the case when there is no other way of installation possible, due to vessel availability, or availability of other installation methods, it might still be beneficial to the overall costs of installation to alter the design of a wind turbine.

Thus, the factor that describes the influence on the construction of the OWT will be: the need for alterations to the construction of wind turbines to facilitate the use of a certain installation method. This says nothing about how drastic these alterations are, so some sort of measure should also be included to judge this. Again, because the need for alterations does not say anything about the nature of these alterations. The strengthening of a part of the construction is obviously less drastic than complete redesign of a tower or nacelle.

The choice is made to not make this consideration a make or brake criteria. The problems that arise when installing ULWTs may only be solvable if the construction of wind turbines is altered. That said, it is still preferable if this is not the case. When performing a comparative analysis using all the defined feasibility considerations, it will become clear if a case can be made for the alteration of the design, if a method requiring this scores well on all considerations except this one. These and all other considerations are summarised in Table 3.1.

3.3. Summary of feasibility considerations

In this section, a summary of all feasibility considerations is provided. Table 3.1 shows the summary of all the feasibility considerations, the factors describing these considerations, the parameters used to define the factors and how the parameters are quantified. It becomes clear that quite a lot of parameters will be quantified using judgement. All of this will be worked out by a relative discussion on the technically feasible concepts, as presented in Chapter 6.

A brief summary will be provided about the reasons as to why all these considerations are included. First and foremost, the considerations are included to provide handles which can be used for the comparison and judgement of the performance of novel concepts. The first consideration is cost-effectiveness, this is included to get a measure that describes how expensive a method will be. The to be judged novel methods will not have been worked out in detail, making an exact cost estimation impossible. Thus, the choice was made to look only at parameters that can be determined

Table 3.1: Summary table of all feasibility considerations, the considered factors, and parameter.

Consideration	Factors	Parameters	Quantification
Cost-effectiveness	Time	Installation procedure time	Hours
		Waiting on weather	Relative judgement
	Cost	Charter costs vessel(s)	Day-rate
		Equipment costs	Day-rate
Safety	Human safety	# of mating procedures	Number
		Nature of mating procedures	Judgment
Complexity	Major mechanisms	# of major mechanisms	Number
		Technological readiness of major mechanisms	Judgement
	Process	# of activities that have to be performed at the same time	Number
		Complexity of actions	Judgement
Flexibility	Usability during lifetime	Usable for major repair and replacement	Yes/No
		Major repair and replacement time	Hours needed for set up
	Foundations	No alterations needed to major mechanisms	Yes/no
		Nature of alterations	Judgement
	WT size	No alterations needed to major mechanisms	Yes/No
		Nature of alterations	Judgement
WT construction	Influence on construction	No alterations needed to WT construction	Yes/No
		Drasticness of alterations	Judgement

without in-depth design. The other four considerations are included, as they have effect on the cost-effectiveness, but cannot be expressed in terms of costs yet. The second consideration is safety, this is included as safety of personnel and assets is always of high importance. The third and fourth considerations are complexity and flexibility, respectively. They are included because of their effect on the cost of a method. Their exact effects on cost cannot be determined because of the need for in-depth analyses, which are outside the scope of this research. However, they should be included, as they will have a significant effect on it. It is preferable that a method is as flexible as possible and as non-complex as possible. The last consideration is the influence on the wind turbine construction, this is included as some methods will need alteration to components, which is not preferred by wind turbine producers.

Eventually, all further considerations have an effect on the cost of a certain method. The problem here is that this effect cannot yet be captured in a quantifiable manner. This is because not enough information is available on the novel concepts to do an in-depth cost analysis. Cost is and always will be the main deciding factor about whichever method is preferable in the highly competitive offshore wind market. This is why all these considerations should be taken into account when comparing novel installation methods. The defined feasibility factors can now be used in the coming chapters in two ways, first to identify the most promising concepts during the screening of the to be generated and concepts found in industry and academia. Secondly, after the technical feasibility assessment of the most promising concepts, the considerations will again be used to compare the concepts, and to identify shortcomings and provide more insight in the usability of them.

4

Concept generation and screening

In the previous chapters, the framework was established for the feasibility assessment of novel installation methods for ULWTs. Using the boundary conditions, base case, feasibility definition, and the economic feasibility considerations, all to be generated concepts can be designed, judged, and compared. The next step in the process is to start generating concepts. In this chapter, concepts are generated for the installation of ULWTs, using a combination of concept generation techniques that are used throughout different engineering disciplines. In addition to this, more novel concepts were presented in the literature review part of this research[43]. They will be judged on their applicability to the defined case, of bottom founded on site installation of ULWTs. Together with the generated concepts, they will make the concept pool out of which the most promising concepts will be selected to continue on to the next phase, the technical feasibility assessment. Selection will take place by a screening process based on a high-level relative economic feasibility comparison between concepts that are placed in so-called branches. Each branch will contain concepts based on the same underlying principle, to make a fair comparison of the concepts possible. The end goal of this chapter is to select the most promising concepts which will be passed on to the next phase of the research, the technical feasibility assessment of the screened concepts.

In Section 4.1 the approach taken for the generation and screening of concepts is discussed in detail. In Section 4.2 the concept generation is described in full. Starting with a high-level function analysis in Subsection 4.2.1. Followed by the exploration of the design space laid out by the basic-level functions in Subsection 4.2.2. Ending with the generation of concepts using a morphological chart, as shown in Subsection 4.2.3. In the next section, Section 4.3, all generated and found novel installation concepts will be screened to select the most promising concepts. Subsection 4.3.1 shows the determination of the applicability of novel concepts found in academia and industry to the stated case. In Subsection 4.3.2 all concepts are grouped into branches based on the same principle, and Subsection 4.3.3 shows the screening of the concepts within each branch. The chapter ends with a summary of the branches and selected concepts in Section 4.4.

4.1. Concept generation and screening approach

In this section, the approach used to generate concepts and screen them will be discussed. For the generation of novel concepts, multiple concept generation methodologies[23] will be used. This will properly document the process and give tools for others to explore the design space and try to come up with solutions of their own. Just starting out of the blue will not result in substantiated concepts. A starting point must be formulated and will be based on novel concepts that were presented in the literature review part of the research. The first step is to use them in a high-level function analysis[56], to define the core functionalities of installation methods which together describe the workings and components a method needs to succeed, which can be found in Subsection 4.2.1. With this, an understanding of the needed functionalities of possible novel concepts is established, and a start can be made with the exploration of the design space.

The second step of generating concepts is the design space exploration by use of Mindmaps. Each

Mindmap is centralised around one core functionality, and options to meet this core functionality will be formulated in Subsection 4.2.2. This results in a structured way of exploring and documenting the concept generating process. While creating these Mindmaps all regards to the boundary conditions, technical- and economical feasibility are dismissed, to have an as open mind as possible. For example, jack-ups will be present in them, even though they cannot be used, these options will at a later stage be disregarded. This way of creating Mindmaps helps to get ideas that are stuck in your mind out of it, and helps to continue to find more solutions. Furthermore, it makes sure that the generation phase and the screening phase do not overlap, as judging methods while creating them can result in biased concepts.

The last step, during the generation phase, is the generation of concepts using a Morphological chart [23]. This chart is populated by the options that fulfil the basic level functions found using the Mindmaps. Using the chart, a wide range of concepts will be generated in Subsection 4.2.3. Only high-level and general information on the workings of the concepts will be generated during this phase of the research. This so that it is possible to quickly and efficiently generate and identify concepts that should be further evaluated.

The next step in the process is grouping all concepts into branches, both the found and generated concepts. First, the branches will be defined using main principles on which concepts are based. The principles will be defined by the use of the core functions and by analysing all the novel concepts. Each generated, and existing concept will be placed into one of the branches. Thus, within each branch, multiple concepts which use the same installation or mechanical principles are placed. The principles used will be defined in Subsection 4.3.2. An effort will be made to create branches with significant differences. These differences will (hopefully) make it clearer whichever method/branch of methods will be the most promising, and result in a wide exploration of the design space. Many concepts will be defined and sorted into the branches. However, not every generated concept will be equally promising.

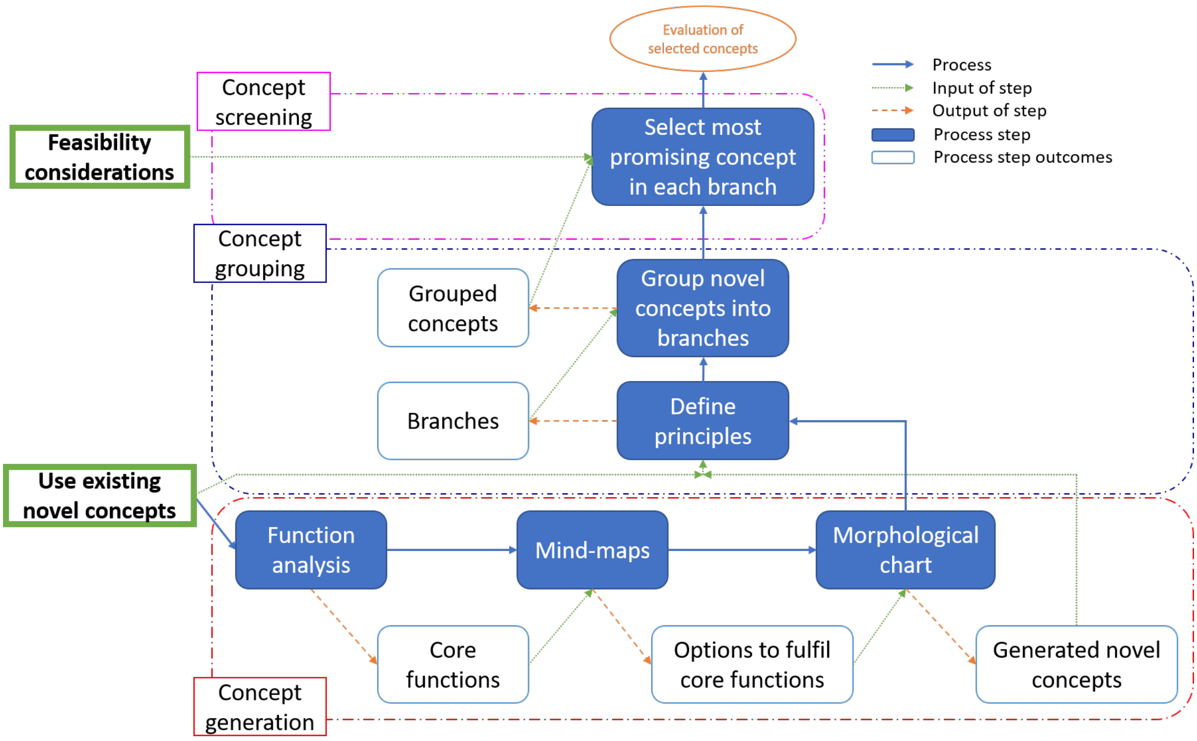


Figure 4.1: Concept generation process flow chart.

Thus, the last step will be to screen the concepts within each branch. The goal is to reduce the number of concepts that will continue to the next phase of the research by selecting the most promising ones. The most promising concept of each branch will be chosen, using a qualitative relative comparison within each branch. The comparison is based on some feasibility considerations presented in Section 3.2, not all of them can be used as this requires deeper-level information on the generated concepts. This level of information is not yet available, as that requires an in-depth description of the concepts. That is not part of this phase of the research due to the need for efficient and fast generation and screening of concepts. The criteria that will be used to select the most promising concepts are defined in further detail in Section 4.3 and, as mentioned, are based on the feasibility considerations presented and summarised in Section 3.3. During this comparison, only the concepts within one branch are compared. The comparison of the branches/selected concepts will be performed after the concepts have been assessed on their technical feasibility. The entire process of concept generation and grouping is summarised and depicted in Figure 4.1.

4.2. Concept generation

In this section, the concept generation phase will be fully explained. Starting with the function analysis, to determine the basic-level functions of novel installation methods. Followed by the exploration of the design space using Mindmaps. These Mindmaps are sequentially used to populate a morphological chart, which is used to generate novel installation concepts.

During the setting up of the Mindmaps, no regards are given to the boundary conditions, case, feasibility, and logistics of a method, to keep an as open mind as possible. The latter will be of high importance to the overall feasibility of a method, as a concept can have an effect on the entire process from production to installation of wind turbines. After the screening, the logistics will be included and discussed for the selected concepts.

4.2.1. High level function analysis

The first step in generating concepts is to properly understand what makes up an installation method, so to understand the core functionalities it must have. The core functions and main components that novel installation concepts need, will be defined using a functionality analysis[56]. All concepts, even though they are based upon different principles, have in the end the same functional outcome, the installation of an ULWT on a bottom-founded foundation. How this outcome is reached differs from method to method, but the core functionalities and needed working facilities remain the same.

The functional outcome is used as a starting point for the evaluation. To reach this outcome, multiple functions must be met, Figure 4.2 shows the main functions a novel method should have. Normally, the basic-level functions already describe an action which can be performed to reach the goal of the higher-level function. In this case, the choice was made to keep the basic level functions as broad as possible, so that they can be used in the next step of concept generation. Furthermore, the basic level functions that will be defined must be applicable to all novel concepts, so “To keep the platform attached to the tower” is not included when using a self-climbing mechanism. These more specific functions will be worked out after the selection of the concepts in each branch has been performed.

Basic-level functions are described in more detail in Table 4.1. These five functions together can describe each novel method, both already proposed as the to be generated ones. More basic level functions could be formulated as: to provide moving capabilities to the working platform, this is, however, not needed for all novel concepts and will thus not be specified in the function analysis.

A debate can be had about the placement of the basic-level functions in the function tree. For example, to reach the needed height could also be a lower level function of to install subcomponents. The idea behind this is that all the basic-level functions are independent of each other. To reach the needed height and installation methodology might seem dependent, as, for example, integrated installation inherently means that the needed height is that of the transition piece. However, there are multiple ways to lift the entire assembly, from the bottom of the tower or hanging under a crane. This results in different needed heights for each option. Another example is that the used installation methodology has no effect on the manner in which mating takes place.

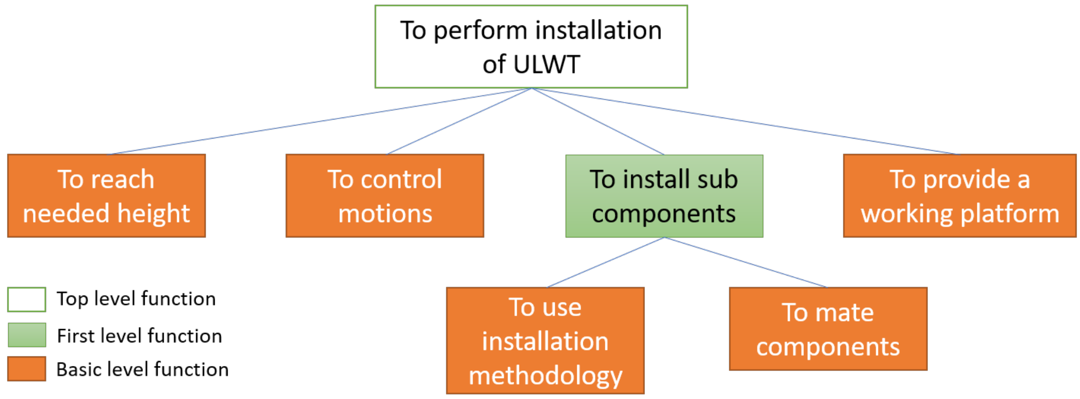


Figure 4.2: High level function tree installation ULWT

Table 4.1: Basic-level function with further description

Basic level function	Description
To reach the needed height	An installation method should be able to install wind turbine components at the needed height. This height depends on the method and used equipment.
To control motions	Motions of components and working platforms need to be controlled to safely and without damage, install WT components. To avoid contacts that will lead to unacceptable damages and to allow different components to be connected. levels.
To use an installation methodology	A method can install components in multiple arrangements, e.g. integrated lift or 6 piece installation.
To mate components	A method needs to be able to perform a mating procedure. A mating procedure refers to the action of lining up, reducing relative motions, and connection of 2 components.
To provide a working platform	A method needs to provide a working platform from which personnel and equipment can perform operations. This can consist out of multiple vessels, as sometimes feeder or logistics vessels will be needed.

4.2.2. Basic-level function design space exploration

Using the basic level functions defined in Subsection 4.2.1 the design space can be explored. Mindmaps [23] are used to generate and document options that fulfil basic-level functions. Within the Mindmaps sub-solutions to the options can be found, these will be used in the generation of concepts when choosing one of the options for the basic level functions, and serve as a basis for the generation of concepts. However, there could be more sub-solutions for each option that are not listed in the Mindmaps. If they come up during the generation of concepts, they will not retroactively be inserted into the Mindmaps, as they only serve as a basis to explore the design space and give a starting point for compilation of a morphological chart.

During the creation of these Mindmaps no regards are given to the set boundary conditions and defined feasibility considerations, to keep an as open mind as possible. Furthermore, one wants to separate the generation and judgement of concepts, otherwise 2 phases of the research will merge together, and both the generation and judgment will be biased. The boundary conditions and feasibility considerations are introduced again during the screening of concepts, and will be used as tools for judging and distinguishing between concepts.

In Figure 4.3 the Mindmap of the basic level function of reaching the needed height for installation can be found. The Mindmaps of the other basic-level functions can be found in Appendix B. These Mindmaps will be used to synthesise a morphological chart using the 'options to fulfil basic functions' as solutions to the basic level functions.

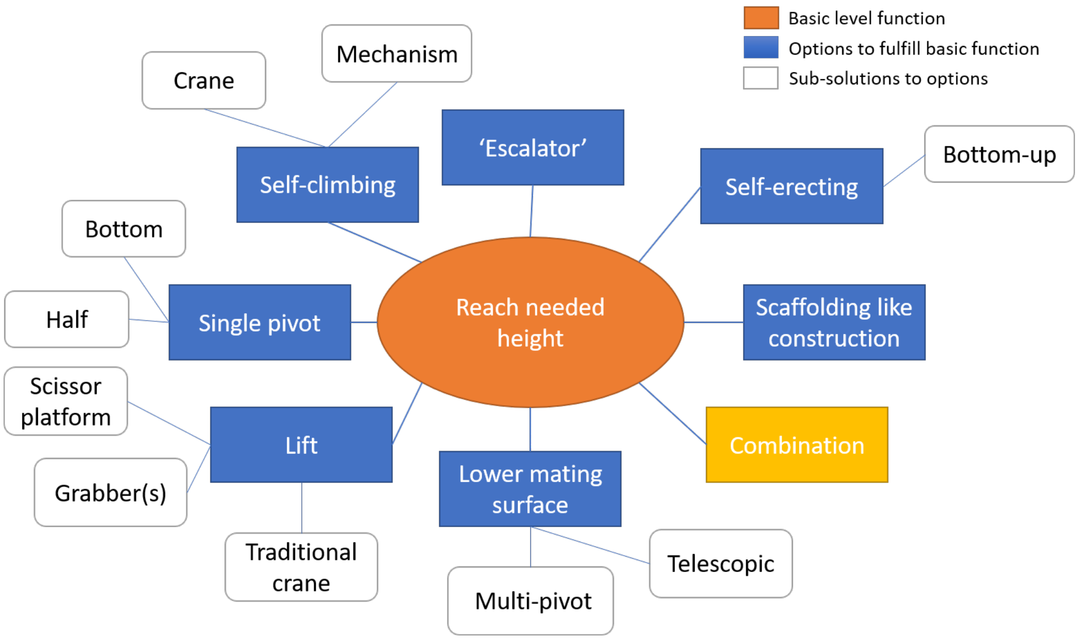


Figure 4.3: Mindmap of basic level functionality of reaching the needed height.

4.2.3. Concept generation using morphological chart

Using the Mindmaps and the options to fulfil the basic level functions defined within them, the morphological chart[23] was compiled. In this chart, the basic level functions are placed on the left most vertical and the options that can fulfil these functions are placed on the horizontals. Concepts can now be generated by choosing one option on each horizontal. The generated concepts are presented in Appendix C and the morphological chart can be found in Figure 4.4.

Core functions / Options	1	2	3	4	5	6	7
Reach needed height	Lift	Single Pivot	Self-climbing	Escalator	Self-erecting	Scaffolding	Lower mating surface
Relative motion control	Fix	Active dampening	Passive dampening	None			
Installation methodology	Traditional split	Modular Split	Integrated				
Mating	Automatic	Manual	No mating needed				
Working platform	Ship type	Barge	Attached to WT	Lage floating man made structures			

Figure 4.4: Morphological chart used for concept generation

In theory, numerous concepts can be generated using the morphological chart, as each option for each core function can be combined with one another. Not all combinations will result in feasible solutions, however, the feasibility of concepts cannot yet fully be determined at this stage in the research. Thus, only highly unlikely concepts will be avoided. Think of the integrated installation of ULWTs using a mono-hull vessel and traditional cranes without any novel lifting equipment. Next to this, the choice is made to try to think of solutions that describe the entire design space, (hopefully) leading to clear differences when further evaluating and comparing them. 15 concepts will be generated, as more is deemed not possible to evaluate in the given time frame, and the width of the exploration of the design space is deemed to be acceptable. All generated concepts, with their general descriptions and explanatory figures, can be found in Appendix C. These generated concepts, together with the already proposed concepts from the industry and the academia in the literature review part of this research, will have to be screened. The goal is to filter out the relatively non-promising concepts and identify the concepts which will continue on to the next phase of the research, the feasibility assessment.

4.3. Grouping and Screening of novel concepts

In this section, the next step in the process of generating and screening novel concepts, the grouping and screening of all novel concepts, will be described. This is carried out to identify the most promising concepts that will be evaluated in later phases of the research. The concepts that were presented in the literature review will be called Academic Concept (AC) if they were found in academia, and Industry Concept (IC) if they were found in the industry. The concepts that were generated and presented in Appendix C will be called Generated concepts (GC). This is done to distinguish between them and provide tags with which concepts can be easily recognised.

Several steps will be taken to fulfil the screening process, first the ACs & ICs will be judged on their applicability to ULWTs and the stated case. The remaining concepts, together with the GCs, will be used to define the principles on which they are based. All concepts will be grouped under these principles, one group of principles will be called a branch. Each of these branches is thus based upon one certain installation principle. The goal is to define 4-6 branches and to select one concept within each branch that will be further evaluated. The grouping is performed to try to find solution groups that are fundamentally different from each other. This leads to a more interesting exploration of the design space, as evaluating concepts which are quite similar will not provide new insights.

4.3.1. Presented novel concepts applicability to ULWTs

Before the ACs and ICs can be used in further evaluations, they have to be judged on their applicability to installation of ULWT and the defined base case. These concepts were originally included as inspiration, and to perform a market study which explores the work that has already been done on novel installation techniques. This served as both a basis for understanding of what a novel concept needs, and what is deemed feasible by the industry and academia for the installation of offshore wind turbines. However, the market study did not include the complete judgment of applicability to ULWTs, some short comments have been made on this during the literature review. The comments and final judgement on the applicability of the ACs and ICs are summarised in Table 4.2. The description of all concepts and their concept tags can be found in Table 4.3. Only a high-level judgement of usability with the defined case and size of ULWTs will be performed on the found novel concepts. After the most promising concepts have been chosen in each branch, a more in-depth evaluation will be performed if they pass through.

Table 4.2: Found novel concepts and their applicability to the defined base case.

Concept Tag	Applicable for ULWTs	Explanation
AC-1	Yes	Theoretically everything could be scaled up to the size of ULWTs.
AC-2	No	Can only be applied using a crane vessel that has a crane that reaches above the hub height of a turbine. However, the blade lifting frame could be used as a guiding mechanism.
AC-3	Yes	Even though a jack-up is used as the working platform, this method is deemed applicable as other platforms can be used while keeping the other workings of the method the same.
AC-4	No	Is designed for use with floating spar type foundations, and cannot be scaled up to the size of ULWT as needed water depth would be too large.
AC-5	Yes	Was proposed for use with spar type foundations, but can easily be adapted for use with other foundations without altering the main workings of the method.
IC-1	Yes	No information is given on foundation types, but it suggests that it can be used for multiple foundations.
IC-2	Yes	The vessel can be up-scaled and be used for multiple types of foundations.
IC-3	Yes	Could be up-scaled and used for ULWTs and multiple types of foundations.
IC-4	No	Can only be used with spar type foundations and is inapplicable for bottom-founded foundations.
IC-5	Yes	Under development for onshore use but offshore applications are next, and the mechanism can be upscaled for use with ULWTs.
IC-6	Yes	Has been only been used onshore but offshore is deemed applicable, and mechanisms can be upscaled for use with ULWTs.

Table 4.3: Description of each academic and industry concept in order of appearance.

Concept tag	Description of concept
AC-1	Integrated installation method using inverted pendulum principle[1]
AC-2	Novel blade installation method from K. De Groot[17]
AC-3	Blade installation and replacement concept using tower climbing apparatus[18]
AC-4	Floating dock principle for installation of spar type turbines[25]
AC-5	Integrated lift installation using catamaran vessel[26]
IC-1	Integrated lift installation vessel, Windlifter from Ulstein[54]
IC-2	Integrated lift catamaran installation vessel, Wind turbine shuttle from Huisman Equipment[20]
IC-3	Integrated lift Installation add-on support tower from Offshoretronic[41]
IC-4	Integrated installation method for spar type turbines, from WindFlip[39]
IC-5	Modular tower integrated installation method using self climbing system, from SMCC and Mammoet[33]
IC-6	Self-climbing crane for onshore installation of wind turbines, from Lagerwey[30]

4.3.2. Formulation of principles and grouping of concepts into branches

The pool of concepts that must be grouped and screened are now known, the grouping will be based on common principles of the concepts. Each group is called a branch, within one all concepts must be based on the same principle. The definition of branches must suffice to a few criteria:

- They must be based on clear indicators of principles which differentiate between concepts, so it will be easy to place all concepts into the branches.
- 4-6 branches must be defined to end up with an amount of concepts that can be fully evaluated, and have enough concepts left over after screening to fully explore the design space.
- The concepts within each branch must be similar, as otherwise the comparison between them is not substantiated when only using high-level judgement. What similar is cannot be quantified and will be based upon the judgment of the author.
- An even division of the concepts over branches is preferred. Thus, no branch consists of only one or a large number of concepts. This would result in either a concept immediately passing the screening, when only one is present. Or result in concepts within one branch that are not similar enough to be relatively compared without deeper level information on the concepts.

The choice was made to use the defined basic-level functions and their respective options for the definition of the principles. This will result in clear differences between branches. Multiple combinations of the option to fulfil the basic level functions have been explored to find a combination that meets the criteria for branches the best. It arose that a combination of core functions of 'working platform' and 'how to reach the needed height' will result in the best subdivision of the concepts. Only using one basic-level function as a way of subdividing the concepts resulted in not all concepts being grouped properly. Significantly different concepts would end up in the same branch, or branches with only one concept in them would emerge. For example, when using the core function of the "installation methodology", the pivot concepts and integrated lift concepts would fall under the same branch of integrated installation. Although, the underlying principle of installation is significantly different.

After trying multiple combinations, the choice was made to use a combination of 'how to reach the needed height', which can be found in Figure B.1 and 'Working platform', which can be found in Figure B.5, to define 6 branches:

- Self-Climbing concepts;
- Self-Erecting concepts;
- Pivot like concepts (Also include the double pivot);
- Integrated lift concepts;
- Super large man-made floating structures;
- Others.

These six branches have been chosen because they provide a clear way to subdivide the concepts, and the concepts can be evenly divided over the branches. Not all options within the basic level functions could be used; this is because some options would result in branches where only one concept could be placed. This is not preferable, as these concepts would automatically pass the screening. To counter this, the branch of "Others" was introduced for concepts which could not be placed in any other branch. This branch can be considered arbitrary, however, not including the concepts in it would also be arbitrary. It is basically choosing the best option out of two non-perfect ones. Some concepts will always be left over when using other definitions of the branches. Thus, the choice was made to accept the branch of others in the evaluation. All concepts can now be put into one of the branches. The concepts with description, tag, branch and further explanation of the choice within each branch can be found in Appendix D. The summarising figure; see **??**, shows all concepts, branches, and concept tags.

Further notes should be given on two of the branches, Pivot and Integrated lift. Both require wind turbines to be assembled on-shore at the quay side, or on a vessel, before they can be put into either pivot or integrated lift mechanisms. If this is possible, remains a question, as only a few of the largest on-shore cranes that are in use today might be able to reach the needed heights and weight to assemble an ULWT. Let alone place them in the mechanisms, as that would require thousands of metric tons lifting capacity with a height of more than 250 metres. A more in-depth discussion will be provided during the feasibility assessment of the selected concepts. For the purpose of this research, it will be assumed that these challenges can be overcome, as otherwise these 2 branches would automatically be infeasible.

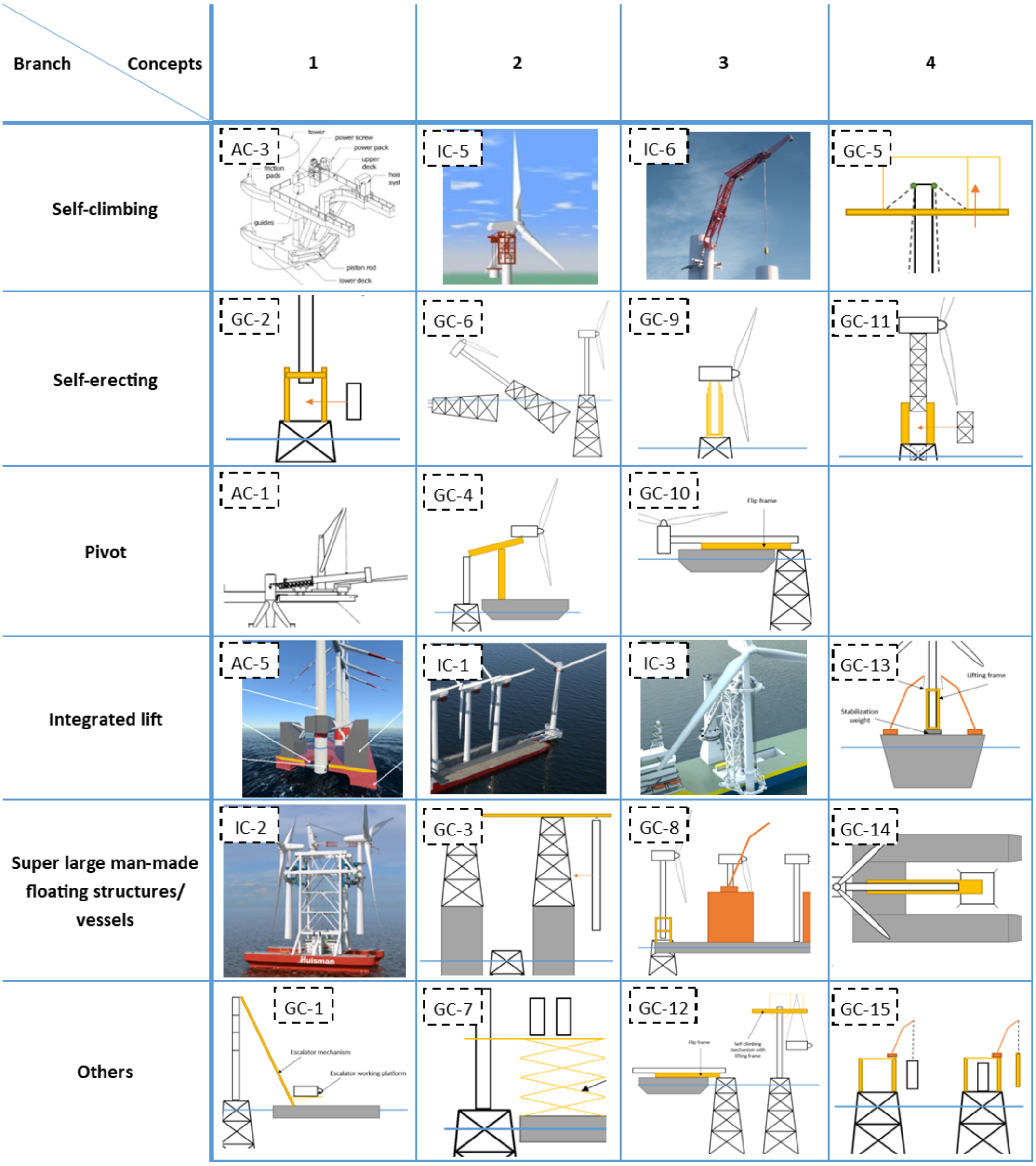


Figure 4.5: Matrix showing all concepts, their tags, branches.

4.3.3. Screening of concepts within each branch

The screening of the concepts within each branch will be carried out using a relative qualitative assessment of the economic feasibility considerations defined in Section 3.2. It is thus based on the comparison of the economic feasibility considerations between the concepts, and technical feasibility will not be assessed during this part of the research. This will only be performed for the concepts that pass through the screening. The goal is to find the most promising concept within each branch, which can then be worked out further to gain enough information to perform a technological feasibility assessment of the concepts.

Only high-level information on the GCs is available, and some deeper level information is available on the ACs and ICs. However, without further description of the concepts, which will not be done here, the technical feasibility cannot yet be assessed for all concepts. So, technical feasibility cannot be used for screening, as this requires deeper level information and assessment of critical factors. The selection of the concepts will thus be based on the economic feasibility considerations, as some of them can be evaluated without deeper-level information. From Table 3.1 the parameters that can be used will be selected, as some factors require deeper level information on the concepts.

The factors of cost-effectiveness cannot yet be determined due to the lack of information on the concepts. This leaves the factors of safety, complexity, flexibility, and influence on wind turbine construction that can be used during screening. Note that the amount of information that is available on novel concepts differs, as the ICs and ACs have been worked out more than the GCs. This difference in information can lead to an unfair comparison between the concepts within one branch. Only the high-level information of each concept will be taken into account when preforming the screening, to make it as fair as possible.

The four considerations that will be used all consist of judgment parameters that are used to describe them. This judgment cannot be fully made yet because the level of information on all concepts is insufficient to make a proper judgement. Thus, the number of parameters that can be taken into account is further reduced. The selected parameters and the quantification used during the screening process can be found in Table 4.4.

Table 4.4: Table showing selected parameters that will be used during the screening of concept.

Consideration	Factors	Parameters	Quantification
Cost-effectiveness	Time	Installation procedure time	Hours
		Waiting on weather	Relative judgement
	Cost	Charter costs vessel(s)	Day-rate
		Equipment costs	Day-rate
Safety	Human safety	**# of mating procedures**	**0-6 or >6**
		Nature of mating procedures	Judgment
Complexity	Major mechanisms	# of major mechanisms	Number
		Technological readiness of major mechanisms	**Relative comparison**
	Process	# of activities that have to be performed at the same time	Number
		Complexity of actions	**Relative comparison**
Flexibility	Usability during lifetime	**Usable for major repair and replacement**	**Yes/No**
		Major repair and replacement time	Hours needed for set up
	Foundations	**No alterations needed to major mechanisms**	**Yes/no**
		Nature of alterations	Judgement
	WT size	**No alterations needed to major mechanisms**	**Yes/No**
		Nature of alterations	Judgement
WT construction	Influence on construction	**No alterations needed to WT construction**	**Yes/No**
		Drasticness of alterations	Judgement

All chosen parameters speak for themselves, except those under complexity. The judgement parameters are still needed to differentiate between the concepts, as the exact amount of mechanisms and processes of concepts are not yet known. However, an initial idea about the technological readiness and complexity of the process can be formulated. Thus, the choice is made to include the judgement factors, even though not all information about the novel methods is known.

The parameters of complexity of major mechanisms and process will be included by ranking the concepts within one branch from most to least complex. The factor of human safety is deemed sufficiently described when only considering the amount of mating procedures. The nature of them will not differ significantly within one branch, as concepts are based on similar principles. This is true except for the branches of 'self-erecting' and 'super large man-made floating structures'. Differences in mating occur only for a few concepts within these branches. Thus, it is deemed acceptable to only look at the number of mating procedures. Furthermore, the general idea that less mating procedures are safer still holds.

The best concept within each branch is selected by assessing the concepts on the selected economic feasibility consideration parameters. A scoring table/matrix will be set up for each branch, giving an overview of the screening process. The table is built up by determining the performance of a method with regard to all parameters within one consideration. For example, when determining the performance of a concept on the consideration of flexibility, the following three parameters are assessed.

- Usable for major repair and replacement;
- Alterations to major mechanisms needed due to foundation type;
- Alterations to major mechanisms needed due to turbine size.

All three parameters contribute to the final score of a concept for the consideration of flexibility. The best performing concept will receive the highest relative score and the worst the lowest, where a higher score is positive. The relative scores are normalised, resulting in a maximum score of 1 for the best-performing concept on one particular consideration. Each consideration will be worked out similarly, resulting in relative normalised scores on the performance of each concept within one branch on all considerations.

The normalised scores for the considerations are added up, and the best concept within one branch can be selected sequentially. No weights are applied to the scores on each consideration, as this is just a high-level analysis. This approach can be considered arbitrary and not in depth enough, however, it does provide an initial idea on the relative economic feasibility of the concepts. Furthermore, a choice had to be made in an as substantiated way as possible. If in the end the selected concept is deemed infeasible on any grounds, still an idea about the feasibility of the principle on which they are based can be formulated. Either that the principle is infeasible or that only that concept is infeasible. Resulting in valuable information either way.

All branches, their screening, and most promising concepts can be found in Appendix D. A fully worked out example of the screening of concepts within the branch of self-erecting is provided in the next section to further explain the process.

Example screening of branch Self-erecting

An example of a screening table can be found in Table 4.5, where the selection of the best concept within the branch of self-erecting is shown. The step-by-step screening procedure is as follows:

- First, the consideration of safety is assessed by taking the following steps:
  - Determine the number of mating procedures required to fully erect the wind turbine. A scale of 1-6 or >6 is used where less is better. The latter will be the case with modular towers;
  - Determine the relative score of all concepts. Example using the branch of self-erecting: *the best concept is GC-6, so this will get a relative score of 4, the next best concept GC-9 will get a relative score of 3. The third-best options will both get a relative score of 2, as they perform the same on this consideration. The relative scoring is always done from the total number of concepts within one branch, here 4, and then counted down to the worst performing concepts within one branch. This makes sure that the normalisation of all relative scores will be determined similarly. When two or more concepts score the same on one consideration, they will receive the same relative score;*
  - Normalize the relative scores to obtain the final score on the consideration of safety. The best-performing concept will always end up with a final score of 1.
- Secondly, the consideration of complexity is assessed by taking the following steps:
  - Rank the technological readiness of the mechanisms needed from the least to the most, using a qualitative discussion. Example using the branch of self-erecting: *GC-9 is deemed to be least based on proven technology. Telescopic towers have never been used before, and the entire internal structure of the turbine tower must also be made telescopic and will thus receive a score of 1. GC-2 is deemed the second worst, as the mechanisms for erecting the tower are not based on proven technology, and thus receives a score of 2. Then GC-6 is the second best, as the mechanisms needed for a float out are known and can be built. However, some mechanisms will be needed to lower the entire structure, which is deemed*

less favourable than GC-11 which is based upon proven technologies, as jack-up systems have been in use for decades already. They receive relative scores of 3 and 4 respectively;
   - Rank the complexity of the process from the least to the most, using a qualitative discussion. No examples will be given here, as it is performed in the same manner as the previous parameter. The full description can be found in Appendix D.
   - Determine relative scores by summing the ranking of both parameters: the concept with the highest sum is the best performing concept. In this example, GC-11, and thus will receive a relative score of 4 for this consideration. The other concepts are sequentially scored from 3-1.
   - Normalise the relative scores.
- Third, the consideration of flexibility is assessed using the following steps:
   - Answer the question: can the concept be used for major repair or replacement?
   - Answer the question of, can the concept be used for different types of foundations without the need for alterations to the initial design?
   - Answer the question of, can the concept be used with different sizes of turbines without the need of alteration to the initial design? All three questions are answered with yes or no. Where yes is positive and no is negative;
   - Determine relative score of concepts by summing the number of yes answers. The concept or concepts with the most yes answers receive the highest score. Similar performing concepts will be scored the same;
   - Normalize relative scores.
- Finally, the consideration of influence on wind turbine construction is assessed using the following steps:
   - Determine influence on wind turbine construction; if yes, the final score is 1 if there is no influence, the final score is 0.
- Sum all relative scores and determine the winner.

Table 4.5: Choosing concept within branch, Self-erecting.

Tag	GC-2	GC-6	GC-9	GC-11
# of mating procedures	>6	1	4	>6
Relative score	2	4	3	2
Normalized score	0,50	1	0,75	0,5
Major mechanisms ranking	2	3	1	4
Process ranking	4	2	3	4
Relative score	3	2	1	4
Normalized score	0,75	0,50	0,25	1
Repair and replacement	no	no	yes	no
Foundation	no	no	yes	yes
Size of WT	yes	yes	no	yes
Relative score	3	3	4	4
Normalized score	0,75	0,75	1	1
Influence on WT construction	0	0	0	0
Sum	2,00	2,25	2,00	**2,50**

4.4. Summary of grouping and screening of concepts

In this section, a summary of all the concept branches and the screening is provided. After the screening was performed, the most promising concept within each branch was determined. The most promising concepts can be found in **??**, where they are highlighted in green. These concepts continue on to the next phase of the research, where they will be worked out further and their technical feasibility will be assessed.

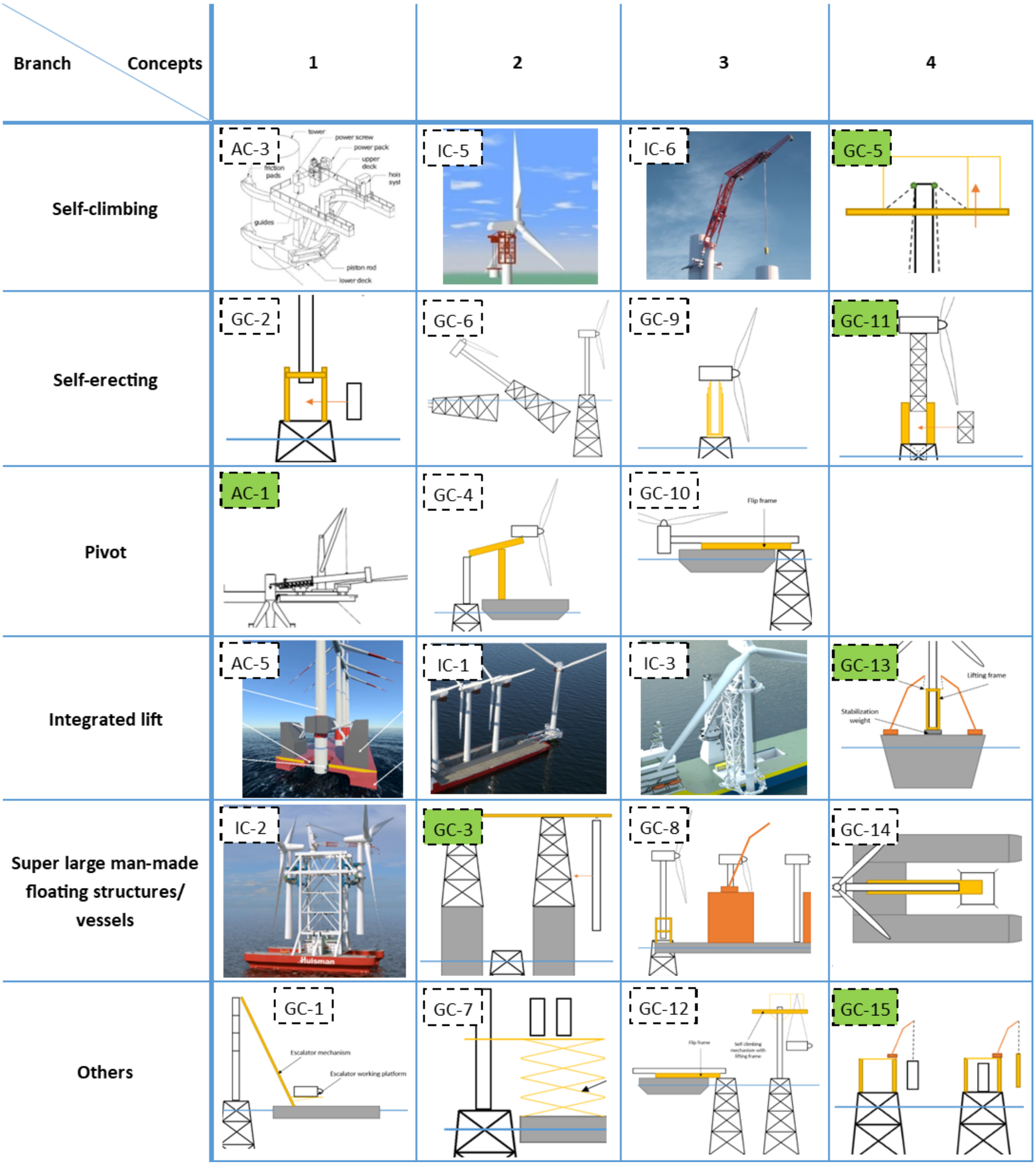


Figure 4.6: Matrix showing all concepts, their tags, branches and final choice in green.

5
Technical feasibility assessment of screened concepts

It has been determined which concepts will continue into the next phase of the research, the feasibility assessment. The goal of the research is to present one or more technically feasible concepts for the installation of ULWTs. In Chapter 3 feasibility was further defined, the choice was made to primarily look into the technical feasibility of concepts, as this precedes the other feasibility categories.

The goal of this phase of the research is to identify the technical feasibility of concepts that have passed through the screening. Up to this point in the research, only high-level and general information about the concepts was generated. This chapter will enlarge the amount of information on the screened concepts to obtain a deeper-level view of what each concept entails. Generation of deeper-level information makes the technical feasibility assessment possible. Each of the screened concepts will be described in full by providing a general description of the concept, listing all components and mechanisms, discussing the logistics of a concept, and describing the vessels used. The critical factors are then identified and listed, and finally a feasibility discussion is presented on each of the concepts based on the evaluation of the critical factors. So, during this chapter, there will be zoomed in on each of the selected concepts to generate information on their technical feasibility and present an inventory on what each concept entails.

The case used during this research has been defined in Section 2.1, and is recapitulatory repeated here. A jacket-type foundation is already in place at the installation site. No specification will be defined as to where this installation site is located. Water depths of 60-100 metres are assumed, so floating installation vessels are deemed most economical. Traditional top-down installation using a singular crane is deemed infeasible due to relative motion-related issues.

In this chapter, first, the approach taken for the feasibility assessment of concepts will be discussed in Section 5.1. To determine technical feasibility, the particulars of the wind turbine will need to be further defined, as done in Section 5.2. In Section 5.3 presents a general discussion of logistics leading up to the installation of wind turbines, to provide a holistic view of the effect of up-scaling of wind turbines on the entire logistical chain. The six screened concepts will be worked out and presented in Section 5.4 up until Section 5.9, in order of appearance in the overview in Figure 4.6. In each section, a general description of the workings, a discussion on possible logistical approaches, the installation process, needed mechanisms, critical factors, initial sizing, feasibility discussion, and final notes on the concept will be presented. In Section 5.10 A summary of the technical feasibility of the selected concepts is provided.

5.1. Approach technical feasibility assessment

In this section, the approach taken to determine the technical feasibility of the concepts selected through screening is discussed. The goal of this chapter is to provide a feasibility discussion of the screened concepts, centred primarily on technical feasibility. This can only be performed once a proper understanding of the concepts has been established. Up to this point, only high-level information on all concepts had been defined and can be found in Appendix C. Here, a general description and visualisation of each generated concept is presented. These descriptions and visualisations will be used as a starting point for further defining the concepts. The process of working out each concept contains three main steps: first, the description of the concepts, second, the initial sizing of the concept, and finally the technical feasibility evaluation. The last two steps are not to be taken as fixed, but rather as fluid, because they are intertwined into each other. A critical factor might surface during the initial sizing, or a critical factor must be evaluated before sizing can take place, the entire process is visualised in Figure 5.1.

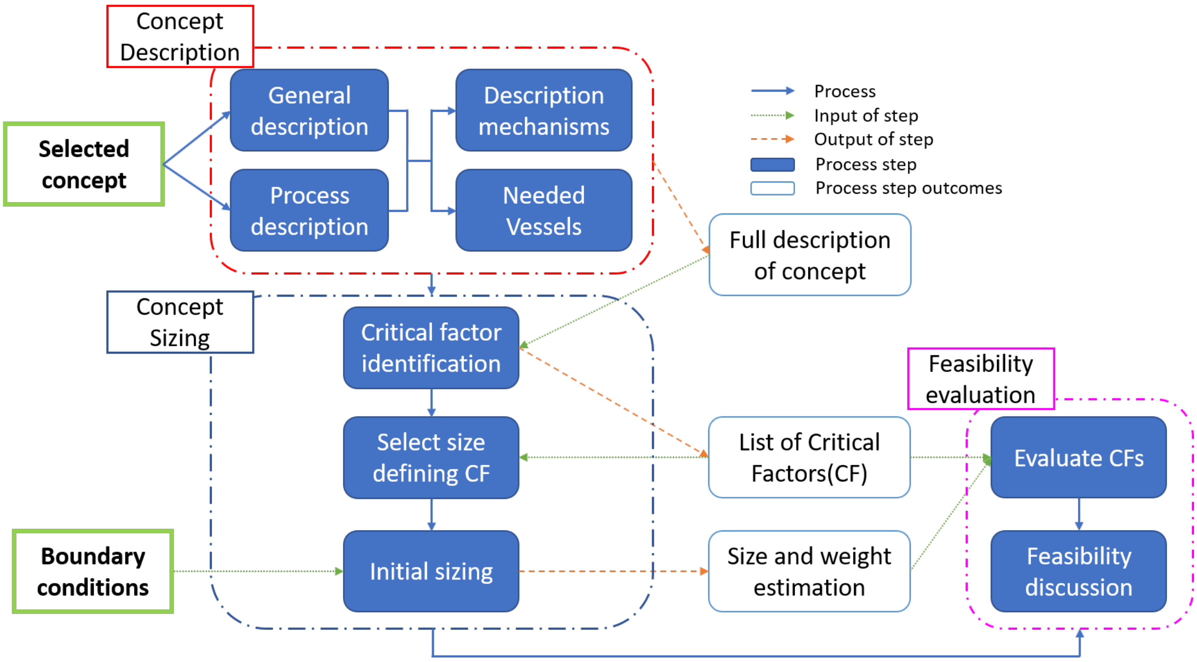


Figure 5.1: Approach to working out of concepts as applied to each concept

The first step, the concept description, is needed to define more details about the functionality of each concept. It contains a general description in which a high-level overview of the concept is given so that readers can easily understand the workings of a concept without having to delve into it further. A list of key selling points is formulated, to define the main advantages a certain concept has. Next, a step-by-step process description of installation is compiled, in which all mechanisms and vessels are listed. During the compiling of the process list, the concept design has started, as writing out of the process helps with understanding which mechanisms are needed to fulfil the functional goal. After the process list is compiled, the needed mechanisms and vessels are known. Each of them will be listed and described to end up with a full descriptive definition of a concept. Parallel to this, a description of the logistics will be provided; the goal is to also identify problems in the logistic chain which may arise when utilising a certain concept. The latter will not be used during the technical feasibility assessment, but must be stated to identify possible showstoppers that lie outside the technical feasibility assessment.

The second step, the initial concept sizing, can take place after a full description of a concept has been set up. Enough information will have been generated to start identifying critical factors, figures, and equipment. The goal is to provide a list containing all factors, figures, and equipment that must be assessed and worked out, in order to say something about the technical feasibility of a concept. The critical factors will be subdivided into 5 groups:

- Size and Strength;
- Equipment;
- Logistics;
- Workability;
- Process.

These five groups emerged after compiling the lists of critical factors. All of these critical factors must be met in order for a concept to be feasible. However, only the critical factors related to size and strength, and equipment will be used for the technical feasibility assessment of concepts. The other critical factors are related to other feasibility categories and will therefore not be fully evaluated during this research. However, they should be stated due to their importance and to provide starting points for further work.

The size and strength defining critical factors, in combination with the set boundary conditions, will be used as a starting point for the sizing of a concept. For example, the first thing that comes to mind when looking at the installation tower semi-submersible is the stability of the vessel, as large lattice towers have to be placed on top of the vessel. During this part of the technical feasibility assessment, a few general assumptions are used while sizing and evaluating the critical factors of the concepts. More assumptions will be made during the sizing which are only of interest for one particular concept, these will be stated while performing the initial sizing. The general assumptions are as follows:

- Calm seas, first a concept must be designed for use in calm seas after which this can be expanded upon during detailed design including rougher seas and a full workability analysis, which will not be performed during this research;
- Only quasi-static analysis will be performed, time and detailed analysis are not part of the research, as only initial technical feasibility is of interest;
- Port side bottlenecks are not of influence to the technical feasibility. They will be mentioned, but are assumed to be solvable.
- All concepts are designed conservatively, all weight and size estimations will be made conservative, as only initial sizing and concept design are performed.

The inclusion of the first two assumptions might seem counterintuitive, as rough seas and dynamics are the main causes of the found bottleneck of relative motions during installation using traditional means. However, this has to be taken as a starting point on which further development can be based, as including these two require a lot of engineering work and detailed design which is timely and costly. It is better to eliminate the options that are already infeasible under these assumptions, before further work on them is performed. Furthermore, it should be mentioned that after the initial sizing under these assumptions, only an initial concept design has been defined. Thus, the state of development of the concepts can only be seen as concept design. To further realise these concepts, more engineering work must be performed, including full dynamic analysis and detailed design of parts and equipment. The goal of the research is to deliver technically feasible concepts and not to fully engineer them, thus this is deemed acceptable. So, after the technical feasibility evaluation of the concepts has been performed, the feasibility of the concepts has been determined, as described in Section 3.1. To determine the definite feasibility, the other feasibility categories must be assessed, and the assumptions must be expanded upon.

However, initial sizing will not be performed for all concepts, as a concept can be deemed infeasible on grounds of any critical factor. Some critical factors will not be related to the initial size and/or weight of a concept, and thus technical feasibility, but need to be evaluated before the size and weight estimate is preformed. If a concept is deemed infeasible on these grounds, then no further work will be done on it. Recommendations and improvements will be formulated that can push concepts into the feasible domain. Thus, at any time during the process of critical factor identification and evaluation, a concept can be deemed infeasible, but the general approach to working the concepts out still holds.

The final step will be to evaluate the technical feasibility of a concept. Now, enough information about a concept is available to assess the critical factors and determine whether the key selling points still hold. The goal is to identify technical feasibility, thus assessing the critical factors related to size and strength, and equipment. If possible, other critical factors will also be included. This will be primarily the case if extreme outliers occur in the other critical factor groups.

Not all critical factors will be worked out in detail; the process, logistical, and workability related critical factors will be stated but not evaluated in detail. They relate to operations that must be worked out for a particular case. This can only be done once the exact vessel, location of wind farm, environmental conditions, sizes, and weights of a concept are known. This is part of detailed design, which is outside the scope of this research. However, these critical factors must be mentioned, as they will influence the overall feasibility of a concept.

Thus, the approach sketched here will result in a feasibility assessment of all concepts, where technical feasibility is the main feasibility category that is evaluated in detail. The evaluation of the size and strength, and equipment related critical factors are thus the main body of the work. During the writing of the feasibility discussion, four levels of feasibility surfaced ranging from fully technically feasible to infeasible and are listed below.

- Fully technically feasible: a concept is deemed fully technically feasible, and no showstoppers have been found;
- Conditionally technically feasible: some conditions apply to the feasibility, so a concept is feasible but is infeasible if certain conditions are not met;
- Conditionally technically infeasible: some conditions apply to the infeasibility, so a concept is infeasible but can become feasible if some conditions are met;
- Fully (technically) infeasible: the concept will not be feasible in any case, this can relate to all feasibility categories and can thus also include outliers found during the critical factor identification and evaluation.

These four levels of feasibility will be used to describe the technical feasibility of all concepts that passed the screening. During the last step of working out the concepts, they are fully defined, and its shortcomings will have been identified. The shortcomings and improvements of each concept will not be worked out in detail. They will be listed, and recommendations will be given on how to improve the concepts to further increase feasibility of and/or improve on aspects of the concepts. These improvements will not be worked out, as only one design iteration will be performed during this research. They do not have to be worked out, as this assessment already identifies the technically feasible concepts that can be used in further research.

In summary, the concepts are described, worked out, and assessed on their technical feasibility as follows. First, a general description will be provided, together with a step-by-step procedure that will be followed to fully erect an ULWT. The Key selling points of the concept will be mentioned and reflected upon after the initial sizing and be part of the feasibility discussion. After this, the concept will be fully defined, and the mechanisms needed to perform the installation are listed. Using the full description and worked out mechanisms, the critical factors of the concept are identified and grouped. From these, the technical feasibility defining critical factors will be assessed to finally end up with enough information to present a discussion on the feasibility of the concepts. Followed by final notes and recommendations of a concept to fully describe what has to be looked into. Note that, during the critical factor identification, outliers could also cause a concept to become infeasible. If this is the case, no technical feasibility assessment will be performed.

5.2. Wind turbine particulars

In this section, the study case regarding turbine size, provided by the research's partner GustoMSC NOV which can be found in Table 2.1, is worked out in more detail. The technical feasibility assessment of the concepts requires a complete definition of the turbine. The definition will be based on assumptions and a reference turbine, as there are no publicly available turbines of this size. The definition will start with hub and blade diameter, followed by tower design, and finally the jacket design.

5.2.1. Blade diameter and hub size

Only the blade length has been provided. To fully define the wind turbine, the hub size must also be known. The hub is assumed to be 10 metres in diameter, as the hubs are usually smaller than the nacelle, which is 15×15 metres. With a blade length of 200 metres, this results in a total blade diameter of 410 metres. However, blades are not attached at the outermost diameter of the hub, and no detailed design will be performed here. So, for simplicity, the blade diameters will be assumed to be 400 metres, including the hub.

Using a rule of thumb that describes the output of wind turbines with respect to blade diameter, the power output of the wind turbine can be estimated. The rule of thumb, provided by GustoMSC NOV, says that wind turbines provide about 300-400 watts of electrical power per square metre of rotor. The number depends on the optimisation of a turbine. 300 is usually reached by the first turbine in a product line, and 400 by the optimised versions of that turbine. Using this, the power output of the proposed wind turbine would be 37 to 50 MW. This is shown to provide the reader with insight on the scale of this turbine.

5.2.2. Tower length

To fully describe the tower, the first step is to define the tower length. Only the hub height was provided, so the tower length has to be deduced using Equation 5.1.

$$L_{tower} = H_{hub} - H_{jacket} - L_{TP} - \frac{H_{nac}}{2} \tag{5.1}$$

In which L_{tower} is the tower length in metres, H_{hub} is the hub height above Lower Astronomical Tide (LAT) in metres, H_{jacket} is the height of the jacket above LAT in metres, H_{nac} is the height of the nacelle in metres and L_{TP} is the length of the Transition Piece (TP) in metres. The tower length is determined by estimating the height of the jacket above LAT and the length of the TP. The height of the jacket depends on the clearance of the water to the topside of the foundation. This is location dependent, as local wave heights and tidal variations have to be taken into account. However, as no site has been assumed during this study, no exact definition of this can be formulated. To have proper clearance, a foundation height above LAT of 15 metres is assumed. This has to be reevaluated for each potential location, and does not have a major effect on the technological feasibility of the concepts, as this only lowers the mating surface of the first tower piece which is installed.

The next part of the construction, the TP height, must be estimated as well. The TP is present on the foundations to completely level the attachment surface of the tower and provide a construction that transfers the loads from the turbine tower into the foundation. The assumption is made that the TP will have a height of 15 metres, which is in accordance with the academic turbine IEA-15MW [14].

This leads to a tower length of 212.5 metres, which will be used as a starting point. The focus of the thesis is not on the design of the turbine and foundation; thus, these estimations are deemed acceptable. The effect on the feasibility of the methods is minimal, as a change in either of these dimensions only causes the tower bottom to reach closer to the water line. This is not the problematic part of the entire installation procedure. The only effect that can influence the technical feasibility, is the tower length when vertical on-shore assembly is required. The longer the tower, the higher cranes need to be to perform pre-assembly of components. This is further discussed during the working out of concepts which require on-shore assembly.

5.2.3. Tower diameter and wall thickness

The next step in further defining the wind turbine tower is to determine the diameters and wall thicknesses of the tower. These are needed to determine the strength of the wind turbine tower. First the tower diameter will be determined, this is done by looking at the main failure criterion of towers, fatigue. To keep tower fatigue below acceptable levels while scaling up, two criteria should be taken into account.

- Keep the number of stress cycles within an acceptable range. This is done by placing the natural frequency of the wind turbine tower outside the excitation frequency ranges of the wind, waves, and blade passing frequencies.
- Keep stress levels constant when scaling up. An increase in stress levels means fewer stress cycles until failure.

Both affect the fatigue life of towers significantly and should be balanced accordingly. To take both criterion into account, an in-depth tower design would be needed. The main focus of this research is on installation concepts and not tower design, so no in-depth design will be performed. Only the constant stress assumption will be used while scaling up a known tower design. This will possibly cause problems, as the tower's natural frequency is set to decrease with length as determined during the literature review. It might end up in the range of wave or blade excitation frequencies, but this will be accepted as a first estimation.

The IEA-15MW [14] is taken as a starting point and is scaled-up to the size of ULWTs. In Appendix E the calculations and more information on the expansion of the tower can be found. First, the diameter is determined with the constant stress assumption. After that, the assumption is made that the ratios of tower diameter to thickness(D/t) will stay the same for the ULWT and the IEA-15. This is done because these D/t ratios will provide enough buckling strength to the tower, both locally and globally. Furthermore, if different D/t ratios are used, the constant stress assumption does not hold anymore. The next assumption that is used is that the cone angle of the tower is the same for both turbines, so the ratio of the tower base diameter and tower top diameter is kept constant during scaling.

When using these assumptions, the base diameter of the tower becomes 16.5 metres and the top diameter 10.5 metres. It was found that the provided tower weight of 2000 metric tons was too low, as the weight of the scaled up tower is around, 3600 metric tons. After deliberations with project supervisors at GustoMSC NOV, this estimation was found to be more acceptable. Therefore, from now on these tower dimensions and weight will be used for further calculations. The final dimensions of the tower are summarised in Table 5.1. A linear slope is assumed from the base to the top of the tower for both the diameter and the D/t ratio. The entire process and approach used for the up-scaling of the tower is worked out in Appendix E.

Table 5.1: Wind turbine tower particulars used for further analysis.

Parameter	IEA-15	ULWT
Tower length [m]	135	220
Base Diameter[m]	10	16.5
Top Diameter[m]	6.5	10.5
D/t at base[-]	250	250
D/t at top[-]	310	310

Some notes should be given on the feasibility of this tower design, as it is based on only one of the fatigue criteria. Only constant stress is taken into account for this first estimation. This can lead to problems, as no consideration is given to the number of stress cycles the tower experiences. A long discussion can be had about the design of ULWT towers, as the soft-stiff design range most probably cannot be utilised anymore due to the 1P and 3P frequency ranges getting closer with decreasing rotational speed. Enlarging blades of turbines always leads to lower rotational speeds. The tip speed is limited to around $95[m/s]$ due to inertial forces in the tips of blades, as has been the limit on all turbines up to now. Using Equation 5.2 the rotational maximal speed of ULWT blades can be determined and the 1P and 3P ranges can be estimated. The 1P and 3P ranges of both the IEA-15 and ULWT can be found in Figure 5.2, overlaid on the wave excitation frequencies of the North Sea described by different spectral formulations. Other locations will result in different frequency ranges of the waves and should thus be investigated differently.

$$V_{tip} = R_b \cdot \omega_b \tag{5.2}$$

In which V_{tip} is the rotational speed of the blade tip in [m/s], R_b is the radius of the blade in metres and ω_b is the rotational speed of the blade in [rad/s]. Using the radius of 200 metres and the maximum tip velocity of 95 [m/s], a maximum rotational speed of 0.47 [rad/s] is found.

Using the found rotational speed, the 1P and 3P upper limits are known, and can be plotted in a wave spectrum to see the possible design ranges of an ULWT. The width of the 1P and 3P ranges is not known, as the cut-in rotational speed of the turbine has not been provided and cannot easily be determined. Using the IEA-15 as a reference point, the ratio of cut-in and rated rotational speeds can be used to determine the ranges of the blade passing frequencies. Using this ratio, the cut-in rotational speed of an ULWT should be around 0.2 [rad/s].

The depiction of the 1P and 3P ranges of both the ULWT and the IEA-15 academic wind turbine can be found in Figure 5.2. In this figure, it becomes clear that the so-called soft-stiff range in between the 1P and 3P ranges of the wind turbines converges and lowers with lower rotational speed. The wave frequencies are exactly in-between the 1P and 3P ranges of the ULWT, resulting in the soft-stiff range being hard to utilise. Perhaps a tower with a first natural frequency of around 0.52 [rad/s] can be achieved without decreasing the fatigue life too much. However, whether that is possible can be debated. Other options are to use the soft-soft or stiff-stiff design ranges for the tower, to keep the first natural frequency away from the excitation frequencies. It cannot be said which of these choices will be made by the industry.

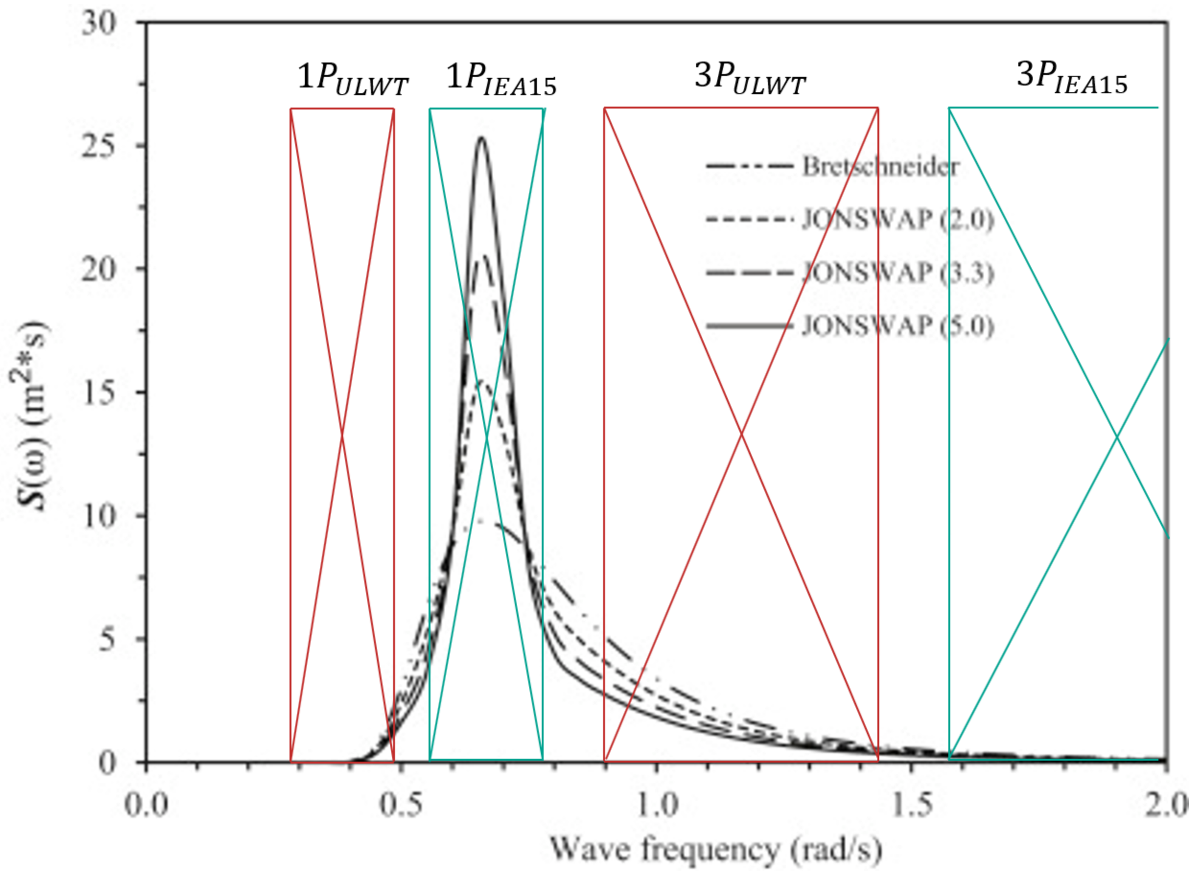


Figure 5.2: 1P and 3P frequency ranges of an ULWT(red) and IEA-15(green) overlaid on wave spectra, obtained from [3] and edited by author.

Using the first natural frequency of the IEA-15, of 1[rad/s], as a point of reference, comments can be made about the natural frequency of an ULWT. The length of the tower increases more than the stiffness of the system, lowering the natural frequencies of the tower. This has been seen with up-scaling turbines in the past, as determined during the literature review part. Thus, the natural frequency of the ULWT will be lower than the IEA-15. Note that the assumption is made that the same foundation type is used. The jacket-type foundation will introduce relatively more stiffness into the system as opposed to a monopile, increasing the natural frequency. Even though this is the case, the ULWT tower natural frequency will be in the wave or 3P excitation ranges, which would make the proposed design infeasible due to fatigue considerations. However, since there are no openly available tower designs of soft-soft or stiff-stiff towers, and the tower design is not the main goal of this research, the proposed design is accepted as a first estimate.

A soft-soft design would mean that the tower and foundation are made more flexible decreasing the first natural frequency; this is done by lowering the D/t ratios and the diameter of the tower, and/or decreasing the stiffness of the jacket by decreasing the base area. A stiff-stiff design would mean the opposite, where more material is added and diameters are increased, to increase the stiffness of the system. The concepts will be judged using the proposed tower design and the effects on the feasibility of either design choice will be discussed, if applicable to the concept.

The concepts that will be affected by the choice in tower design are the concepts which will introduce large moments into the tower, such as the self-climbing and pivot mechanisms. This may lead to local and global buckling problems, which will have to be checked. Especially when soft-soft design is utilised, as then the strength of towers will decrease relative to the tower design proposed in this section. The reduction in wall thickness and diameter reduced the strength of the tower, making buckling a more prevalent failure mode. If stiff-stiff tower design becomes the norm, these problems will be less important, as relatively higher wall thicknesses and further stiffening of towers will increase the strength of the tower. Which one of these design approaches will become the norm cannot be answered here, as that is determined by a plethora of other factors, of which eventual costs are the main driver, but this will not be delved into during this research.

5.2.4. Jacket definition

Jacket foundations of wind turbines follow the same design approach as jackets for oil and gas platforms. The focus of the research is not on the jacket definition, and this will thus not be worked out in detail. The details that are of interest are:

- The size of the jacket at the water line, as this determines the minimal horizontal distance of vessels to the mating surfaces;
- The height of the jacket above the water line, as this affects the length of the tower. Assumed to be 15 metres, to provide enough clearance to the waterline.

The size of the jacket at the water line is determined using three assumptions. The assumptions are listed below. When using them, a surface area of the topside of the jacket of at least 19×19 metres is defined. Using the batter angle, the water piecing area of the jacket can be determined, which will be 21×21 metres.

- The jacket must provide a working space next to the tower and transition piece, and allow for the placement of an auxiliary crane;
- The jacket will have a batter angle of 1:15;
- The jacket is square and fully symmetric.

5.3. General notes on logistics leading up to on-site installation

In this section, a general description and discussion on the logistics leading up to the on-site installation of wind turbines is presented. The sizes of the components increase by a factor of 2 relative to what is currently common; this will lead to new challenges and further complexify old ones. The comments that will be made here should be mentioned, but will not be solved during this research.

The entire logistic chain, from the production of components to the construction of the wind turbine, will face new challenges. Two types of general logistic processes can be defined, one when utilising split installation techniques, and one when pre-assembly of components is required. The process leading up to the installation of a wind turbine using split installation is as follows:

- Production of components in production facilities;
- Transport of components to marshalling yard;
- Storage of components in marshalling yard;
- Loading of components onto vessel from quay side;
- Transport of components to installation site by vessel.

Each of these phases will be affected by the increase in the size of the components. Traditionally, production facilities could be placed anywhere where transportation to a harbour was possible, as components could be transported by train or road. With the increase in size of the components, it is already becoming increasingly harder to do this. The current sizes of wind turbines, with, for example, tower diameters of 10 metres, already cause the transportation by road and rail to be virtually impossible. The components simply do not fit on roads or trains, a typical road lane is about 3.5 metres wide, which means that for the transport of tower pieces, roads of at least 4 lanes wide would be needed. Here, no further logistical difficulties are considered such as bridge height, road carrying capacity, or the need to close certain roads during transport. Cargo this large and heavy cannot be transported using common trucks, but will need specialised heavy cargo transport, such as Self-Propelled Modular Multi-wheel Transporters[34]. This leads to the need of placing production facilities near waterways, then it is possible to transport the needed materials to, and the massive components from the production facility by ship. If production facilities are located along an inland river, the maximum width of locks and height of the bridges should also be taken into account.

The next step in the process is the storage of the components in the marshalling yard. Components will need to be stored in the yard to make continuous feeding of components onto vessels achievable.

The goal is to install a wind farm in the smallest time frame possible to reduce costs, this means that downtime should be avoided. Thus, the storage of components will be necessary so that it is possible to load the components onto vessels when needed. During this phase, components are already in the state in which they will be installed, fully constructed nacelles, blades, and tower pieces must be stored near the quay side. Here, the already existing problem of quayside ground baring capacity will be amplified, as weights and sizes are set to increase even further. Maximum capacity of quaysides are not openly available, so more comments cannot be made about this, but it should be taken into account when choosing a suitable marshalling yard. Another problem with storage is the size of components, as a nacelle is defined to be around 15 by 15 by 30 metres, which can be compared to a small residential flat of 3-4 storeys high. With blades of about 200 metres in length and tower diameters of 16.5 metres, the sheer amount of space needed to even store the components might become problematic in smaller harbours, depending on the amount of components that need to be stored.

The next step is the loading of the components onto the installation or transportation vessels. Problems may arise regarding harbour crane capacity, as especially transportation vessels might not have cranes with sufficient capacity to lift a nacelle or tower piece from the quayside to the vessel. Quayside cranes with minimum lifting capacities of the weight of the heaviest to be installed component are needed. This in itself is not a problem, as those cranes exist and are used. However, this requires large quay sides with sufficient ground baring capacity to support such cranes. Another note should be given on this, only a few of the currently world's largest quayside cranes can perform the lifting of these components at sufficient radius. Examples of these cranes are, the SK6000 from Mammoet[35] or the Skyhook from Huisman Equipments[21]. Before a quayside crane can lift the components, they have to be transported from storage to the load-out location on the quay. This can be done by multi-wheels or skidding mechanisms and is achievable.

The last phase is the transport of components from the marshalling yard to the installation site. With increasing size and weight of the components, the size of the vessels is also set to increase. Smaller harbours might experience problems with docking these ships, as drafts can exceed the allowable harbour draft, or quay sides are too small. Especially when semi-submersibles the size of the Sleipnir are used, which can only moor off at the world's biggest harbours.

The second type of logistical process leading up to the on-site installation of OWTs requires in harbour pre-assembly. The general process is the same as the first one, except that before components can be stored in the marshalling yard, they have to be assembled, either at the same yard or at a different location. A more in-depth discussion about this case will be presented under the concepts which utilise integrated installation techniques.

In conclusion, the increase in size leads to new challenges in the entire logistical chain, and possibly new harbour infrastructure must be constructed to tackle these challenges. Solving these problems is outside the scope of the research, but they should be mentioned nevertheless to give an overview of the entire process that will have to be taken into account when installing up-scaled wind turbines.

5.4. Concept 1: Wind turbine elevator(GC-5)

In this section, the selected concept of the branch of self-climbing mechanisms, the elevator platform, will be further worked out. In Figure 5.3 an overview of the elevator platform concept can be found. It is depicted installing the nacelle to get an initial idea of the shape and workings of the concept. This depiction was created after the initial sizing was performed.

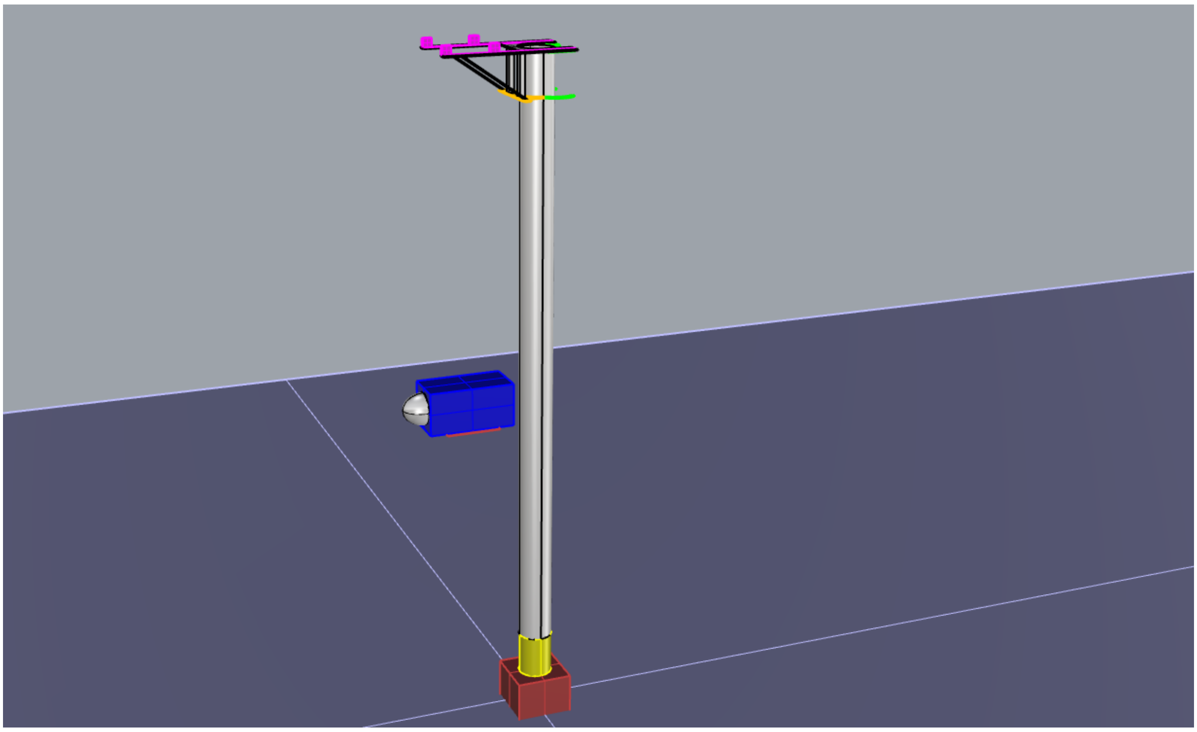


Figure 5.3: Artist impression of wind turbine elevator platform concept, while lifting nacelle.

5.4.1. Concept 1: Description

General description

This concept deals with the relative motion related issues by fixing itself to the tower and is a different take on self-climbing mechanisms. The tower will be installed to reachable height by traditional means of installation. A tower-encircling mechanism is placed around the tower at the largest height attainable. This mechanism is attached to lifting wires which run from the tower top where pulleys are present to the tower bottom where lifting winches are present. It can be lifted by automatic winches placed on the transition piece of the foundation, and this choice is made to lower the weight of the platform as much as possible. The platform can be lowered or lifted, creating a mobile working platform.

The installation procedure is as follows. The platform is raised to the tower top, and the modular tower is built piece by piece, lifting each piece to the needed height and skidding it over the mating surface. Lifting takes place using a lifting mechanism, so that the platform can remain in place and does not have to fully go up and down the tower each time a component has to be lifted. Decoupling the lifting mechanisms of the platform and of the components, reducing the requirements on the lifting mechanism of the platform. During the installation of components, the platform fixes itself to the tower, so that the lifting mechanism does not have to carry any loads while lifting components. Once a tower piece is installed, the pulleys/attachment point of the platform lifting wires must be moved upwards to the new tower top surface. To do this, an auxiliary crane is present on the platform to assist personnel. This will be repeated until all components are installed. A feeder vessel will deliver the components. The only influence on the wind turbine construction due to this concept is the modularity of the tower.

General description and discussion on logistics

A Heavy Lift Vessel (HLV) picks up the elevator platform and the initial piece of the tower in the harbour. It sails to the intended location of the wind farm, where a jacket foundation is already pre-installed. The

HLV installs the initial tower piece at maximum attainable height. The next step is to attach the elevator platform to the initial tower piece. If multiple elevator platforms are available, the HLV can sail to the next foundation and install the initial tower piece and platform on it. Resulting in the possibility of parallel installation of wind turbines. Components for installation will afterwards be fed to the platform by barges. After the full installation of a wind turbine is completed, the HLV is needed again to detach the elevator platform. If more turbines are required to be installed, the HLV can be used again to pick up the platform after the installation of the first turbine has been completed and repeat the process for the next turbine.

The general idea behind this is to only use one HLV that can perform both the installation of the initial tower piece, and the attachment/detachment of the platform. Low-cost barges are used to feed in the components. The barge that is used for the feeding of the blades needs to be equipped with tugger lines to keep motions of blades within acceptable levels, and to angle the blade appropriately when attaching to the hub.

Key selling points

- Lowering the size of needed HLV;
- Lowering time needed for HLV to be present at one wind turbine;
- Possibility to erect multiple turbines at once using only one HLV vessel, provided that there are multiple platforms available;
- No need for tall cranes, less motion related issues;
- Fixed to tower, so next to none relative motions during the mating phase.

Needed vessels

Two types of vessels are needed to carry out the installation using concept 1, the elevator platform. One heavy lift vessel for handling of the platform, and feeder vessels for components, so:

- Heavy Lift Vessel: For the preparation phase and detachment of the elevator platform. The vessel can preferably install and carry multiple platforms in one run, so that multiple turbines can be erected at once using only one vessel;
- Feeder barges/cargo vessels: On which the nacelle, tower pieces, and blades are placed to feed components to the platform. The option is to have them self-propelled and using DP, or to use tug boats for tow out and manoeuvring of the barges. Multiple barges are needed to continuously feed components to the platform.

Step-by-step process description

The installation process is described below by a step-by-step procedure description. A story board of the nacelle and blade installation process can be found in Appendix F. Figures and descriptions of all mechanisms can be found in Subsection 5.4.2.

Preparation phase:

1) Install tower to max attainable height using traditional means and HLV;
2) Lift elevator platform to the tower using HLV;
3) Attach elevator platform to the tower using locking mechanism and connection mechanism;
4) Connect lifting wires and perform rigging operation of the platform and automatic winches;
5) Tension wires using the automatic winches;
6) Adjust tower guiding mechanism to tower diameter;
7) Lift platform to needed height;
a. If needed, adjust guiding mechanism to tower diameter again;
8) Lock platform in place with locking mechanism;

Tower installation:

9) Lift tower piece from barge to the top of the tower using the lifting frame and mechanism;
10) Move tower piece to mating surface using the skidding system of the lifting mechanism;
11) Mate tower piece using guiding frame;
12) Make connection of tower piece and tower, and connect internal components;
13) Detach lifting wires and pulleys from the previous tower piece and attach to pulleys on the new tower piece using the auxiliary crane on lifting platform;
14) Repeat step 5 to 13 until tower is fully installed;

Nacelle installation:
15) Lift Nacelle to hub height using component lifting frame and mechanism;
16) Move nacelle to mating surface using the skidding system of the lifting mechanism;
17) Mate nacelle using guiding frame;
18) Connect nacelle to tower top;
Blade installation:
19) Lower platform to blade installation height;
20) Vertically lift blade using component lifting mechanisms and tugger lines on feeder barge to keep motions of blade within acceptable levels;
21) Mate and connect the blade to the hub using the tugger lines to angle the blade;
22) Lower platform to acceptable height;
23) Rotate blade to face upward;
24) Perform platform elevation procedure to blade installation height (steps 6-7-8);
25) Repeat steps 20-24 up until all blades are installed;
26) Lower platform and detach using HLV.

Using the step-by-step description, the mechanisms that are needed for the concept to work have been identified. The next step is to define these mechanisms to further describe the concept.

5.4.2. Concept 1: Mechanisms and components

The mechanisms needed to install an ULWT using the elevator platform are listed below. A depiction of the needed mechanisms can be found in Figure 5.4 and in Figure 5.5.

Platform tower guiding mechanism: The platform needs a mechanism to keep it centred around the tower and guide it while being lifted.
Function: To guide the platform along the tower and stabilise the platform.
Description: Dampened-spring rollers around the tower, which are part of tower rings.

Platform locking mechanisms: During the lifting and mating of wind turbine components (especially the nacelle), the platform needs to be fixed to the tower to sustain the extra load on the platform, and to reduce motions during lifting and mating. The full load of the platform must be sustained by this mechanism, as it is load bearing when the platform lifting cables are moved upward, and during lifting of components.
Function: To fix platform and reduce motions.
Description: Hydraulically released friction pads that are part of the tower rings.

Platform lifting mechanism: To lift and lower the platform, automatic winches are used, just as wire winch jack-up vessels[37], they are placed (can be permanently or modularly depending on what is more cost-efficient) on the transition piece. Wires run from the top of the tower to the automatic winch along the outside of the tower, and are guided through the platform with wire guide that are placed in tower rings.
Function: To lift and lower the platform.
Description: Automatic hydraulic winches placed on the foundation.

Platform connection mechanism (tower ring): The tower guiding and locking mechanisms must be able to open up so that the platform can be placed around the tower.
Function: To connect the platform to the tower and provide enough strength to bear loads during lifting of components.
Description: Hydraulically closable tower ring, in which locking- and guiding mechanisms are present.

Component lifting & mating mechanism: Components must be lifted to the height at which they have to be installed, after which the component must be displaced from the lifting position next to the tower, to the installation position on top of the tower. Needs to be able to lift the nacelle, as that is the heaviest component.
Function: To lift components to the needed height, skid the components to the desired place and mate components.
Description: Strand jacking system, such as the HLS-Series of ENERPAC[10], to lift components to needed height. On top of a skidding system, such as the Mammoet Heavy Skidding system[36], to

displace the component to the mating surface. Mating takes place by using these 2 systems in unison, a component is skidded over the platform till the flanges and bolts are aligned, after which the lifting mechanisms lowers/lifts the component onto the flange.

The platform must be as light and small as possible, and thus also the mechanisms on it. The choice of lifting systems falls on strand jacks, as they provide high lifting capacities relative to their size and weight. The downside of using strand jacks in contrast to automatic winches is that the lifting speed is lower, as strand jacks can only reach 30-50 metres per hour[8] and winches can archive a multitude of this depending on the load[48]. Further discussion can be had on which lifting mechanism to implement on the platform, but only initial design of the concept is performed, so for now the choice falls on strand jacks due to their size and weight. If this concept is worked out in more detail, this is open to change, but a choice has to be made here to enable the estimation of the weight of the concept. Furthermore, the strands(wires) of a strand jack are usually used for a single or a few lifts due to the way the strands are used during the lift and must be replaced after a few lifts. How many is not openly available. This should be further investigated, as replacement of the strands is expensive and time-consuming. Further discussion on this is presented at the end of this section.

Lifting and Mating frames: Lifting and mating frames are needed to accommodate the lifting mechanism and to place components on during lifting.
Function: To provide a lifting platform, and make mating of components possible.
Description: Lifting frame designed specifically for each component, consisting of anchor points at each corner for attachment of the lifting wires, and guiding frame to easily mate the component to the wind turbine when skidding over the elevator platform.

For an artistic impression of the mechanisms and concept, see Figure 5.4. For an impression of the tower ring with the locking mechanisms, tower guiding mechanism and the elevator platform lifting wire guides, see Figure 5.5. The same principle for the tower ring is used for the lower platform. Further information on the size and shape of the platform can be found in Subsection 5.4.4.

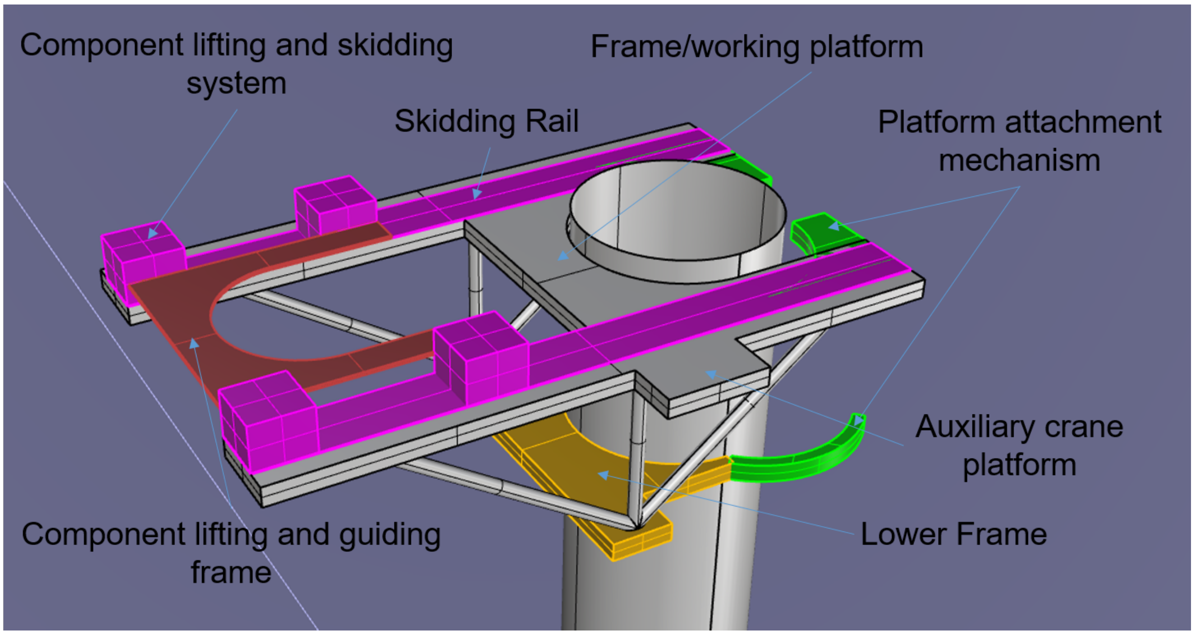


Figure 5.4: Artist impression of the mechanisms and elevator platform while attached to tower.

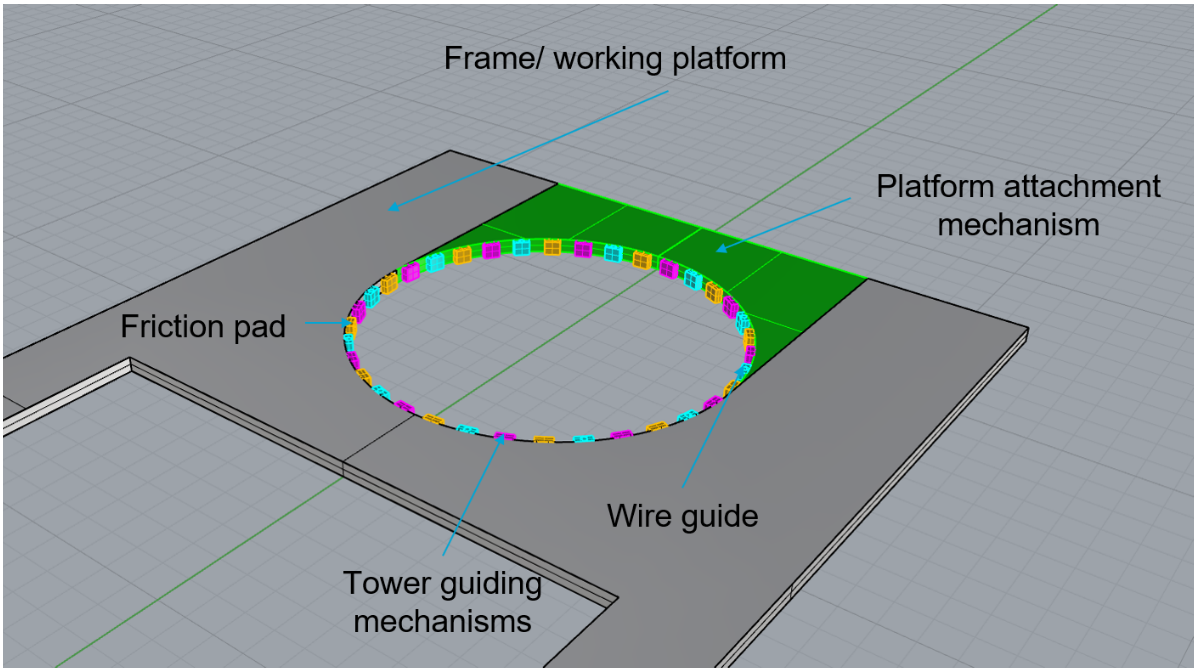


Figure 5.5: Artist impression of tower ring upper platform including locking, tower guiding and wire guides.

5.4.3. Concept 1: Critical factors

The last step, before initial sizing and shaping of the elevator platform, is to define the critical factors of this concept. All critical factors are listed and described below.

Size and strength:

- Lifting of nacelle: The nacelle is the largest and heaviest component that has to be lifted. The platform must be able to carry its own weight, the weight of the nacelle, and the weight of equipment. The weight and size of the nacelle are guiding for each of these;
- Clearance of blades: Lifting platform and equipment on top of it should not interfere with the blades when rotating outward after the blade installation. Evaluation of this critical factor resulted in that it is not possible to place large structures on top of the platform;
- Load on tower: The clamping and lifting moment that will be introduced into the tower while lifting can cause structural problems. A check must be performed on the buckling and ultimate strength of the tower;
- Location of feeder barge: To reduce the eccentricity of the load and thus the moment on the tower, the platform cannot protrude too far from the tower. This results in the need for small distances between the foundation and the feeder vessels. The risk of collision of feeder vessel and the foundation should be checked. Guidelines state that the minimum distance from any fixed platform to a floating vessel during lift should be at least 5 metres if no fenders are used [16].

Equipment:

- Rewiring of platform: After the pulleys have moved upward, the wires must be reconnected. If this is possible and/or practical, must be assessed, as this is a difficult operation;
- Lifting of platform: Automatic winches must be strong enough to lift and lower the platform. The size of them will dictate the amount of space that is needed on the foundation;
- Lifting equipment: Present on platform, must be as light and small as possible but also be as fast as possible. The size and weight are determined by the heaviest load that must be carried.

Logistics:

- Downtime of HLV: If installation takes too long, the HLV will have downtime, which increases costs unnecessarily. The use of multiple platforms can circumvent this, as the HLV can then parallel install turbines;

Workability:

- Downtime due to weather: The operation takes a long time, as all parts of the wind turbine have to be installed one by one. During the entire operation, the platform must be attached to the tower, so only large weather windows can be used to perform the entire procedure safely. The exact limits should be determined by more in-depth analysis if this method is deemed feasible.
- Attachment of platform to tower: A floating lifting vessel must be used for the attachment of the platform. Motions of the vessel must be kept within mating tolerances to safely perform the attachment of the platform. The workability of this procedure must be investigated to determine the economic feasibility of this method. It can definitely be performed but in which time frame is the question;
- Motions of components during lifting: Components cannot hit the tower or other structural elements, as the risk of collapse is always present, personnel will be present on/near the platform when lifting and mating components;
- Motion of feeder barge: During the unloading of the components from feeder barges, the barges will move due to wave- and current-induced loads. This might result in misalignment of the cargo with the lifting mechanism, at which wave climate these motions will become problematic and must be assessed to determine the workability.

Process:

- Lifting clearances: During the entire process, lifting clearances stated in guidelines must be respected. It is of particular importance to this concept, as all lifts take place relatively close to the wind turbine.

5.4.4. Concept 1: Initial sizing and weight estimate

In this subsection, the approach taken and the results of the initial sizing and weight estimate are presented. The initial sizing of the elevator platform is based on the largest and heaviest component, the nacelle. The design choices made and working out of selected critical factors can be found in Appendix F. The procedure followed to work out this concept is as follows:

- Initial sizing of concept around size of nacelle & blade clearance;
- Selection of equipment on platform using maximum load;
- Weight estimate of platform using initial size, equipment, and maximum load case;
- Determine load on tower due to the lifting of the nacelle, and assess the buckling and ultimate strength of the tower;

The size of the upper platform, weight of the concept and eccentricity of the COG of the nacelle from the centre of the tower can be found in Table 5.2. A visualisation of the concept design can be found in Figure 5.6. All further particulars of the concept and the reasoning behind them are presented in Appendix F. After evaluating the loads on the tower, it was found that the lifting of the nacelle and load of the platform combined will not cause the tower to buckle.

Table 5.2: Main particulars elevator platform.

Parameter	Value	Parameter	Value
Length overall[m]	51	Width overall[m]	30
Height overall[m]	18	Weight platform[ton]	1500
Distance COG nacelle to tower[m]	30		

5.4.5. Concept 1: Technical feasibility discussion

In this section, the technical feasibility of the elevator platform will be discussed. The concept is deemed conditionally technically feasible because:

- The existence of wire winch jack-up vessels, even though not many are in use, suggests that similar techniques can be used to lift and lower the platform;
- The total weight of the platform is estimated to be around 1500 metric tons; this can easily be carried by a few automatic wire winches, as capacities of 300 metric tons already exist[48]. When using a pulley system, the needed capacity can be brought down depending on the amount of pulleys used;

- All key selling points still hold after the initial sizing and weight estimation of the concept;
- The largest and heaviest component is the nacelle; the existence of heavy lifting strand jacks and super heavy skidding systems suggests that: the lifting and skidding of the nacelle over the platform is possible. The integration of the 2 systems into one lifting apparatus has to be further looked into.
- The evaluation of the critical factors that define size and strength showed that the yield and buckling checks are passed. Note that only global loads have been checked; local loads should be investigated further to check for local plate buckling of attachment points. Furthermore, the strength checks are passed for the proposed tower design in Section 5.2, other tower designs will affect technical feasibility. If soft-soft towers are used, local and global buckling will make lifting the nacelle impossible at the proposed radius.
- The clearance of the blades has been checked; no interference with blades and platform occurs during rotating of blades.
- The vessels that are needed to use the elevator platform already exist. The heaviest part that has to be lifted from a vessel is the elevator platform itself, with a weight of 1500 metric tons. Specialised lifting equipment will be needed to attach and detach the platform from the tower.

To determine the economic feasibility, further steps will have to be taken. The workability critical factors must be assessed to determine whether the environmental conditions in which the concept can operate safely and leave large enough weather windows to perform the installation in a competitive time frame. The logistical critical factors must be assessed to determine a logistical strategy, which results in the lowest downtime of the large HLV. In addition to these critical factors, more conditions can be defined that influence the feasibility of the design.

In the case that further work on the concept, the critical factor of re-rigging and moving up of the lifting points must be assessed first. If this is possible and/or practical, makes or breaks the entire concept. If infeasible, another system has to be developed for the lifting and lowering of the platform, all other systems can stay the same.

In conclusion, the concept is deemed conditionally technically feasible. In essence, self-climbing mechanisms can be used, like the proposed elevator platform. However, the tower design must supply enough strength to perform the lifting of the nacelle. The economic feasibility of the concept needs to be assessed, but since the goal of the research is to make the installation of ULWT possible and assess the technical feasibility. An artistic impression of the concept can be found in Figure 5.6.

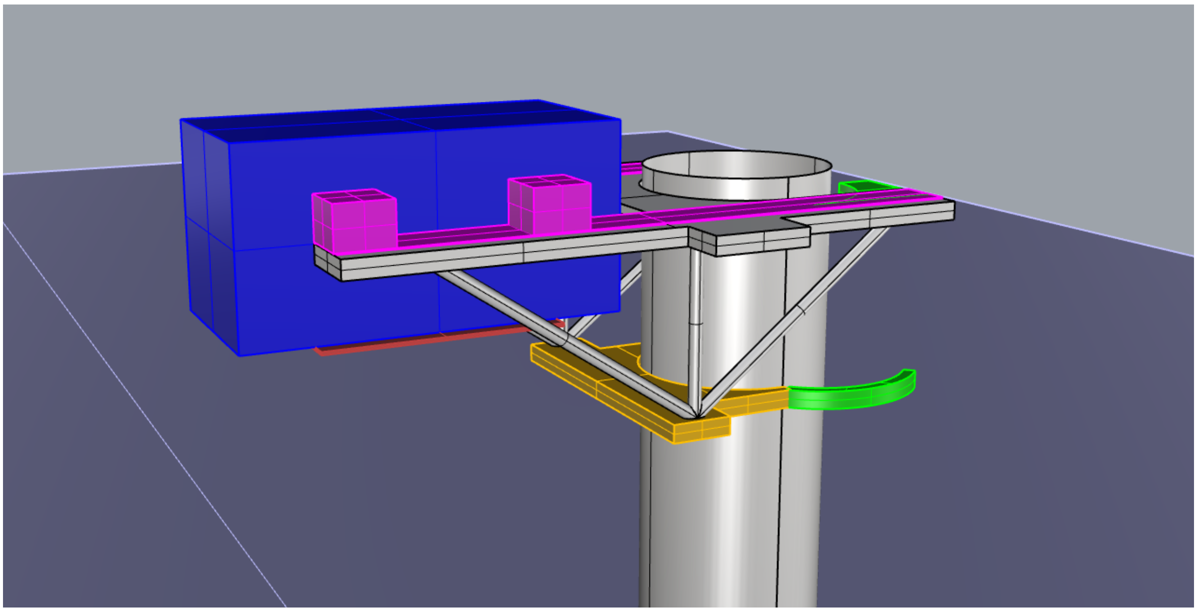


Figure 5.6: Perspective view elevator platform at tower top while lifting nacelle, concept design.

5.4.6. Concept 1: final notes and recommendations

In this subsection, notes on and recommendations for further development of the elevator platform concept are presented. First, the influence of the turbine design on the feasibility of the concept.

The first note that should be given is related to blade length. If the proposed design of the wind turbine is used, the concept is feasible. However, if the blade length increases, the clearance of the blades will become insufficient, causing interference between the platform and blades. This is a major problem, as the author thinks that the proposed blade length is smaller than what is possible for the provided hub height. Whether it is technically possible to increase the blade length is left open for debate. The clearance of the blades to the water line is about 50 metres; this can be reduced to 30 metres or fewer.

The second note relates to the feasibility of the concept with a change in tower design. The proposed tower design can withstand the stresses due to the global loads that are placed on it. However, this design is a soft-stiff tower, just as the reference tower used for up-scaling. If the tower design moves towards the soft-soft range, the tower wall thickness and diameter will decrease, lowering the stiffness of the system, this will result in lower yield and buckling capacities. Especially, local buckling will become problematic as the diameter-to-thickness ratios of the tower will decrease. The loads on the tower should be checked, but a soft-soft tower is unlikely to withstand the loads. If the choice falls on a stiff-stiff designed tower, no problems will arise, as buckling and yield capacities will increase even further.

The third note relates to the effect of different types of foundations on the feasibility of the design. The use of another type of foundation will affect the feasibility of the design, as the load-out of the wind turbine components is done from a barge next to the foundation. Foundations with larger base areas, such as a gravity-based foundation, opposed to the proposed jacket, will require the nacelle to have a larger eccentricity to the tower, increasing the load on the tower. Smaller base areas, like a monopile, result in lower eccentricities and thus have no effect on the feasibility of the design.

The fourth note is related to the (un)boarding of personnel on the platform. The installation procedure will take considerable time. Personnel cannot remain on the platform for the entire installation procedure, as it will probably take multiple days. Thus, personnel should be able to (un)board the platform at all times. In the event that the on-board elevator and/or stairs in the tower cannot be used, an auxiliary personnel boarding mechanism is needed.

The fifth note relates to the lifting mechanism. The proposed stand-jacks are commonly used for singular lifts. Information on the achievable number of consecutive lifts without replacing the strands cannot be found publicly, but should be investigated. If a strand of the strand jacks cannot be used for all consecutive lifts needed to install one turbine, they have to be replaced. This would be a time-consuming task and could make the use of wire winches more attractive. Furthermore, the lifting speed of the strand-jacks has a large effect on the installation time. Faster lifting leads to lower installation times, but requires wire winches. These are heavier and larger than strand jacks, creating a snowball effect on the weight and costs of the concept. If further work is done on the concept, an analysis of wire winch versus strand jack is advisable, to find the most cost-effective solution.

The second to last note is on the effect on the wind turbine construction due to the concept. After installation has been completed, the pulleys and wires, used to lift the platform, will remain attached outside the tower. The effect of this must be investigated, possibly the wires must be tensioned to prevent them from hitting the tower and scraping off the corrosive resistant paint.

The final note relates to the use of the concept with differently sized turbines. Different sizes of turbines will require significant redesign of the platform. The tower rings are designed for one particular tower, and can only be used on a small range of tower designs. Larger tower diameters require a full redesign of the platform. However, smaller diameters could be possible, if tower rings can be made modular and interchangeable.

The first and final recommendation is based on the orientation and size of the nacelle. The concept has been designed around the proposed size of the nacelle, including a small tolerance. If a different type of nacelle is used, the U-shaped cavity in the platform can become too small, especially when direct drive nacelles are used. They are wider than high-speed drives of the same power output. A redefinition of the lifting and skidding mechanisms can circumvent this, and is advisable to increase the applicability of the concept to different nacelle sizes. Another option to increase the feasibility range of the concept is to rotate the nacelle 90 degrees, so that the COG of the nacelle is located closer to the tower. However, this makes that a secondary lifting system is needed for the installation of the blades, as the platform cannot rotate around the tower to re-align itself with the hub.

5.5. Concept 2: Jack-up tower principle(GC-11)

In this section, the winning concept of the branch self-erecting concepts, the Jack-up tower principle, will be discussed in more detail. In Figure 5.7 a visualisation of the jack-up tower concept can be found. Depicted during the skidding of a tower piece underneath the already installed tower nacelle and blades.

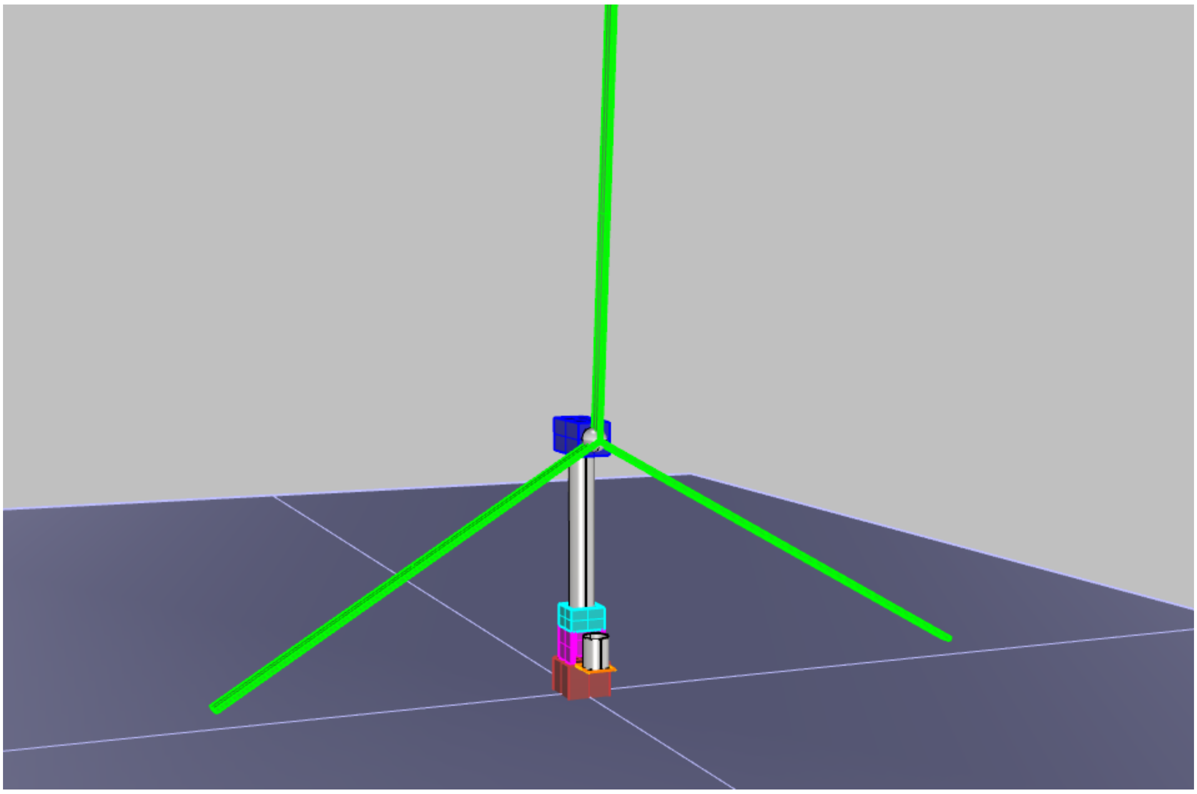


Figure 5.7: Artist impression overview of jack-up tower principle after blade installation and during skidding of tower piece.

5.5.1. Concept 2: Description

General description

The general idea behind this concept is to lower the height at which the nacelle and blades must be installed. Lowering the requirements on vessels and cranes, and possibly reducing the relative motion-related bottlenecks to an achievable point. This might make the installation of an ULWT possible using relatively small HLVs. On the foundation/TP of the wind turbine, a preinstalled (and preferably disassemble) jack-up mechanism is placed, with a feeder mechanism underneath it. A piece of the tower is installed with the initial height needed for the tower to accommodate the installation of the nacelle and blades using traditional means of installation. After the nacelle and blades have been installed, a tower piece is inserted into the feeder mechanism and skidded underneath the tower inside the jacking mechanisms. The piece is connected, followed by a jacking operation to make way for the next tower piece. This is repeated until the nacelle is at the needed height. The effect on the design of the wind turbine is that the tower must be modular.

General description and discussion on logistics

The logistics of this concept are quite similar to the elevator concept described in Section 5.4. One HLV will be used for the installation of the jack-up system, feeder system, initial tower piece, nacelle, and blades. After which a feeder vessel will feed in the tower pieces needed for the jacking up of the tower. So, a minimum of 2 vessels are needed for the full installation of the wind turbine. If the jack-up system can be made detachable, the HLV is needed to detach it after full erection of the tower. The system can sequentially be used again for another turbine. If multiple jack-up systems are available, parallel installation can take place.

Key selling points

- Lower the height at which the installation of the nacelle and the blade must be performed, reducing relative motion-related difficulties;
- Usage of proven technology for the erecting of the turbine;
- No need for tall cranes, less motion related issues;
- Usage of relatively small HLVs.

Needed vessels

Two types of vessels are needed to perform the installation using the jack-up leg concept. One heavy lift vessel for installation of the jack-up system, nacelle and blades, and a smaller vessel to feed in tower pieces:

- Heavy Lift Vessel: For the installation of the jacking mechanism, the initial tower piece, nacelle, and blades;
- Smaller Heavy Lift Vessel: For placement of tower pieces on the skidding frame.

Step-by-step process description

The step-by-step process description of the Jack-up tower concept can be found in the list below. Further information on the mechanisms can be found in Subsection 5.5.2, and a story board further explaining the installation procedure can be found in Appendix G.

Preparation phase:

1) Place tower piece inside jacket using traditional lifting equipment and HLV;
2) Place jack-up mechanisms on foundation using HLV;
3) Install tower piece in jack-up mechanism using traditional means with height of 'initial tower height';
4) Install nacelle using traditional means;
5) Horizontally Install blade using traditional means;
6) Rotate blade upward;
7) Horizontally install next blade using traditional means;
8) Rotate blades upward;
9) Install last blade using inclined blade mounting tool, like LT975 – Blade dragon[31];

Tower erecting phase:

10) Lift tower piece onto feeder mechanism using HLV and skid underneath tower using skidding mechanism;
11) Attach tower piece to tower and install/connect internal components;
12) Jack up tower to new height using jacking mechanism;
13) Repeat steps 10 to 12 until needed height is reached;
14) Attach tower to tower piece stored inside jacket;
15) Jack up tower to final height using jacking mechanism;

Tower fastening phase:

16) Make rigid connection between tower and foundation/TP;
17) Detach Jack-Up mechanisms using HLV (provided that the system is detachable).

If other types of foundations are used, no part of the tower can be stored inside the foundation. Thus, steps 1, 14 and 15 will become invalid, and steps 10 to 12 must be repeated more often to reach the final height of the tower.

5.5.2. Concept 2: Mechanisms and components

In this subsection, the mechanisms needed to realise the installation of ULWTs using the jack-up tower concept are listed. A visual representation of the systems can be found in Figure 5.8.

Jack-Up Mechanism: A jack-Up mechanisms needs to be placed on the foundation/TP. It is used to jack up the tower, after this is completed, the mechanism becomes redundant, so detachability is preferred. Different jacking techniques can be used to erect the tower, preference goes to jacking systems, which can possibly be designed to be detachable.
Function: To jack-up the tower.
Description: Adapted pin-hole jacking mechanism using protruding flanges, for a discussion on why this type of jack-up mechanism is chosen see Appendix G.

Tower piece Feeder Mechanism: A mechanism on which a tower piece of to be determined dimensions can be placed by a heavy lift vessel. The piece will sequentially be skidded underneath the tower, which is already in the jack-up mechanism held up by the support frame.
Function: To feed in tower pieces underneath the jack-up mechanism.
Description: Skidding mechanism on which a tower piece can be placed.

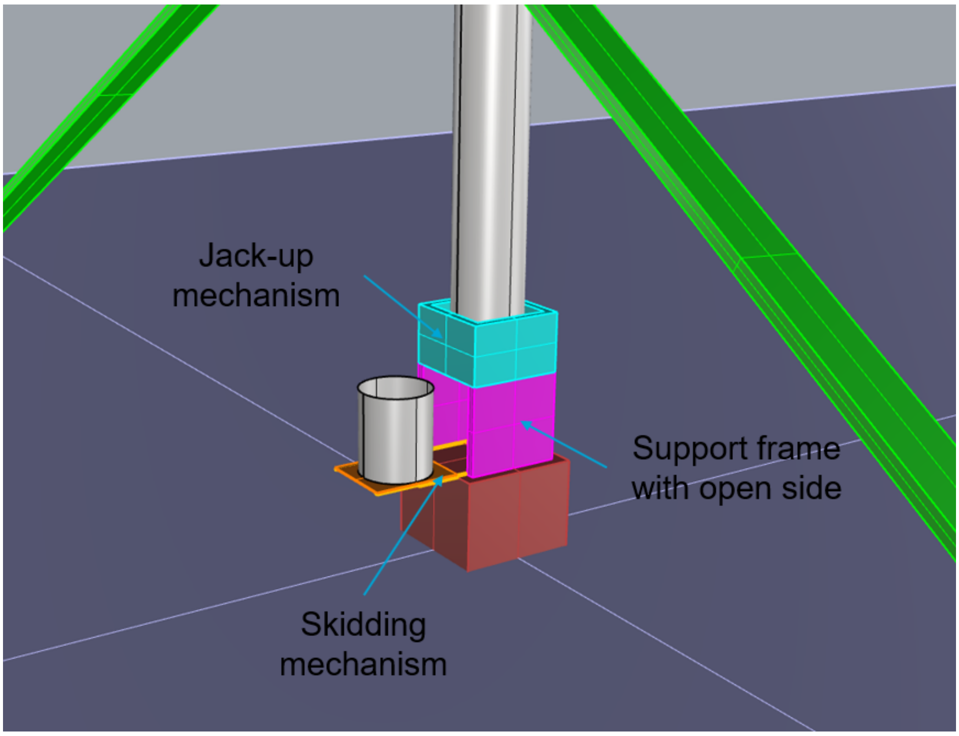


Figure 5.8: Artist impression of mechanisms of Jack-up tower concept.

5.5.3. Concept 2: Critical factors

The critical factors of the second concept, the jack-up tower, are listed below. The evaluation of the selected critical factors that influence the technical feasibility and the decision-making about the type of jack-up mechanism to use can be found in Appendix G.

Size and strength:

- Initial tower height: Before the blades and nacelle can be installed, sufficient elevation of the hub is needed to install the blades. The minimum height required can be determined by Equation 5.3.

$$H_{tower} = L_{blade} \cos 60 + H_{clear} + H_s + H_{tidal} + H_{flex} \tag{5.3}$$

  In which, H_{tower} is the initial tower height above LAT in [m], L_{blade} is the length of the blades in metres, defined to be 200[m]. H_{clear} is the clearance of the blades to the water line in metres, assumed to be 5 metres. H_s is the significant wave height in metres, taken to be 2 metres as defined in Chapter 2. H_{tidal} is the height of the tidal variation in metres; this is location dependent and is assumed to be 3 metres. H_{flex} is the added height due to the static flex of the blades in metres, no designs of blades of this size are publicly available yet. So, an educated guess will have to be made, 5 metres is assumed to be sufficient when also taking the height reduction due to blade cone angle into account. Therefore, an initial tower height of 115 metres above LAT is needed;
- Tower piece height: This has to be as tall as possible to reduce the number of jacking procedures that must be performed to reach the hub height, which is taken to be 15 metres. The design consideration that must be taken into account is the cost of the size of the support frame versus the benefit of having fewer feeding procedures; this needs to be further optimised.

Equipment:

- Minimum jacking capacity: Is determined by weight of nacelle tower and blades combined, this is around 6000 tons. The existence of jack-up vessels suggests that this is achievable, as jack-up systems of single legs can reach this capacity, as discussed with project supervisors at GustoMSC NOV;
- Moments in jacking mechanism due to wind on tower nacelle and blades: The jacking mechanism must also carry the moment loads;
- Redundancy of jacking mechanism after installation: Preferable to make jacking mechanism detachable, as otherwise a large system will be present on the foundation that is only used once or twice during the lifetime of the turbine. If this is possible, should be investigated;
- Skidding system for tower pieces: The pieces must be skidded underneath the jacking mechanism. Skidding systems of more than 300 tons already exist, as described in Subsection 5.4.2 so this is deemed achievable;
- Cone shape of tower: Jacking mechanisms are usually used with constant-diameter legs. If it is possible to jack up a conical tower remains to be seen, a solution might be to include a jacking frame into which the tower is placed. However, this is not included in this concept design, as technical feasibility must first be assessed. Newer towers become less and less conical, so this might not even be a critical factor in the future.

Logistics:

- Downtime of large HLV vessel: The vessel is only needed for the installation of the initial tower piece, jack-up system, nacelle, and blades. An option is to use one vessel which also feeds in tower pieces, the other option is to install multiple turbines in parallel so that the HLV only needs to install the initial components and smaller vessels can feed in the tower pieces.

Workability:

- Floating installation of nacelle and blades at initial tower height: The nacelle and blades must be installed at around 115 metres above LAT. Motions must be evaluated to determine the feasibility of this procedure;
- Feeding of tower pieces using floating vessel: Tower pieces of approximately 300 tones, assume 20 tons per metre, must be lifted onto the feeder mechanism using a floating vessel. The vessel must be close to the foundation and already installed tower pieces and blades. Collision risks must always be taken into account and evaluated.

5.5.4. Concept 2: Initial sizing and weight estimate

This concept does not have an initial sizing and weight estimate. The evaluation of the critical factor of, “Floating installation of nacelle and blades at initial tower height” resulted in the concept being technically infeasible. The floating installation at the initial tower height cannot be performed, as was evaluated in Appendix G. This is on grounds of a combination between technical and economic feasibility, as discussed in the next section.

This means that the concept is deemed infeasible for the determined case where floating installation vessels must be used. In the next subsection, more information on this is provided.

5.5.5. Concept 2: Technical feasibility discussion

The concept is deemed conditionally technically infeasible due to the need for a floating installation of nacelle and blades at a height of 115 metres. The main problem is that monohull vessels cannot install nacelles and blades in a competitive time frame due to motion-related difficulties, as described in Appendix G. In theory, mating at the initial tower height is possible if and only if there are no wind and waves. This makes that it is theoretically technically feasible in this case, however, almost no weather windows will present if self which make it possible. This results in that the concept will have an unacceptable high waiting on weather time, resulting in economic infeasibility. Thus, it is economically infeasible to use this concept due to the fact that it is technically infeasible to perform installation under normal weather conditions. Installation at these altitudes is currently only performed using jack-up vessels. They provide a stable working platform enabling the installation by reducing the relative motions.

A workaround could be to further lower the initial tower height, to reduce the motion-related problems further. However, the blades must then be installed using a different installation method, as the clearance with the water line will become insufficient. This is further discussed in Section 6.8.

Another option would be to use semi-submersible vessels to perform the installation of nacelle and blades, but the operation has never been performed on a commercial scale and probably needs additional guiding frames or stabilisers. Furthermore, the key selling point of using a relatively small vessel for the installation of the wind turbine cannot be met anymore in this case, as only the largest semi-submersible vessels in the world would be able to perform installation using this concept. Resulting in the fact that this option is non-preferable.

New lifting apparatuses or frames can potentially make the concept technically feasible. If and only if they can reduce relative motions of especially the blades during installation with a floating vessel. The design of these apparatuses is a research topic in itself and will not be performed during this research, as here only the general procedure of installation using a certain concept is assessed on technical feasibility.

In conclusion, this method is deemed conditionally technically infeasible, as relative motion-related issues make floating installation of wind turbine components at the initial tower height not possible, with relatively small HLVs in a competitive time frame. However, if new lifting devices are designed to circumvent relative motions or the initial tower height can be further reduced, the concept can become feasible.

5.5.6. Concept 2: Final notes and recommendations

Some notes can be given on the concept. For the defined case, it is not technically feasible, due to the need for floating installation vessels. However, if shallower waters can be exploited, the use of jack-up vessels becomes economic again. Existing jack-up vessels can already install blades and nacelles at a height of 115 metres above the water line. This case would result in a feasible concept, as the motion-related problems are circumvented by the stability provided by a jack-up vessel. Then all key selling points still hold, as a relatively small vessel can be used to install an ULWT.

The general idea behind the concept of lowering the mating altitude of the nacelle and blades is still promising. The lower the mating surface, the easier the installation, in general. This concept requires that all three blades be attached before the jacking of the tower can start. However, if only 2 blades are installed prior to the erecting of the turbine, the blades can be faced upwards. Significantly reducing the initial tower height. The motions of the crane tip are linearly dependent on the height of the crane, and thus decease with needed crane height, this might allow for the installation to be performed in a cost-effective way. The final blade must then be installed using a bottom-up vertical installation method or another method. Thus, if a blade installation method for the third blade can be defined, this method can be used and be mechanically feasible, more information on this is provided in Section 6.8. If the usage of two different mechanisms for the installation of one turbine is economically feasible, will have to be investigated, but falls outside the scope of this research.

5.6. Concept 3: Inverted pendulum principle(AC-1)

In this section, the winning concept of the branch pivot concepts, the inverted pendulum principle, will be worked out in more detail. This concept follows directly from a concept proposed in academia[1]. An overview of the method can be found in Figure 5.9.

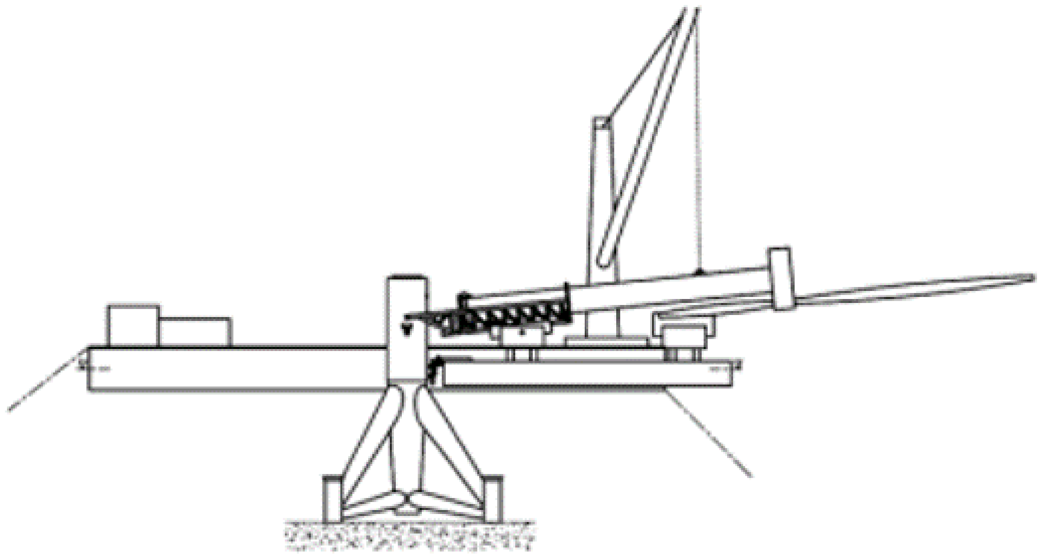


Figure 5.9: Overview of inverted pendulum principle, taken from paper[1]

5.6.1. Concept 3: Description

General description

This concept follows directly from a paper[1] in which this method is fully described. It works around the relative motion-related difficulties, as only a small crane is needed and only one mating procedure at relatively low height has to be performed. The general description is as follows. The turbine is assembled on shore at the quay side and loaded into a horizontally placed flip-frame placed on a barge. The barge consists of multiple support points for the frame and tower of the wind turbine. The turbine is loaded into the frame with downward-facing blades, to lower the CG of the system as much as possible, and to avoid interference of crane and blades in the final stages of the upending. One other vessel is needed, a medium-sized Heavy Lift Vessel (HLV), this vessel is used to upend the turbine using the crane, and crawler motion of mooring systems in unison. The turbine is upended by mooring the barge next to the foundation, starting to lift the turbine in the flip frame, and mate the frame to the pivot point on the foundation. After mating, the turbine is lifted further by the crane on the vessel and by moving the vessel forward in unison, until the turbine is vertical. The frame locks in place, and uses internal hydraulics to lower the turbine onto the flanges present on the foundation/TP. Now the frame can be detached and stored on the barge again. A small alteration to the foundation is needed to accommodate the flip-frame, two supports must be present on the foundation in which the frame can be rested during the up-ending.

General description and discussion on logistics

Before the installation operation using this concept can start, the wind turbine must be pre-assembled on-shore, and placed into the flip frame on the barge. There are two options for the preassembly of the wind turbine, horizontal assembly and vertical assembly. The latter is bottlenecked by the size and capacity of harbour cranes, as vertical assembly of ULWTs cannot be pulled off even by the largest on-shore cranes in existence, such as the SGC-250[44]. This crane has a maximum jib height of just under 250 metres, with a maximum capacity of 850 tonnes at this height. The combination of the maximum attainable height and capacity make even this crane is unable to meet the requirements of vertical assembly of ULWT onshore. Therefore, novel on-shore cranes must be designed and build to circumvent this bottleneck. If vertical assembly is possible, the placement of the turbine into the frame will be the next bottleneck. The turbine will must be lifted from the top, or toppled over to be manoeuvred into a horizontal position. Both actions cannot be performed yet as the requirements on the combination between crane height and capacity cannot be reached. A topple over operation, like is done with jackets, might be possible, but would require further research and development of equipment. Thus, new on-shore lifting equipment will have to be developed before this concept can be used.

The second option is the horizontal assembly of wind turbines; this circumvents the need for tall cranes, and manoeuvring from vertical to horizontal orientation. However, horizontal assembly has never been performed before to the author's knowledge. This will require new and specialised lifting equipment and tools, both to manoeuvre and assemble components. Wind turbine towers are not designed to be horizontally orientated and might need extra strengthening to not excessively ovalize[7] under its own weight. Apart from these challenges, the sheer amount of space needed on the quay side to perform horizontal assembly of ULWTs is huge. A fully assembled turbine is around 450 metres in length and 400 metres in width. Setting a huge requirement on the quay side available space. If all these challenges can be overcome, the last step is to place the turbine into the flip-frame. Movable or revolving cranes that can lift the entire assembly are required and can definitely be used, as handling of jackets with larger weights than an ULWT has been performed in the past.

The third option is to assemble the turbine horizontally in the flip frame. The same problems arise as with the previous options, but loading of the frame after assembly of the wind turbine is no longer required. However, this results in a longer downtime on the barge and flip frame, as the assembly of a wind turbine will inherently take longer than a single loading procedure due to the fact that more lifts and mating procedures have to be performed. Whichever method will be preferable must surface from further evaluation of the approaches and their effect on the cost-effectiveness of the concept.

After the wind turbine has been placed on the barge, it is transported towards the intended installation site, by use of tugboats (or self-propelled). The barge is connected to the foundation and the installation operation starts. After the installation has been completed, the barge with empty flip frame is transported back to harbour, and loaded with the next turbine. To efficiently install an entire wind farm, multiple barges and flip frames will be needed so that the crane vessel can work continuously.

Key selling points

- Reduction in vessel size, as needed crane height is lower than hub height;
- Ease of transportation;
- No need for installation vessel to go to port to reload;
- Vessel size does not follow from turbine size but from lifting capacity;
- Reduction of number of offshore actions;
- Only mating procedure that has to be performed is at low height and can be performed without cranes, reducing relative motion-related problem.

Needed vessels

Three types of vessels are needed, one for the transportation of the wind turbine and flip frame, one for the up-righting of the frame, and tug boats to support the transportation barge:

- Heavy Lift Vessel with crawler mooring system: Needed for the upending of the wind turbine using the flip-frame. Size to be determined after the evaluation of critical factors.
- Feeder barges: Used for float out, horizontal storage, and pivoting of wind turbine. Multiple of these will be needed to continuously install turbines.
- Tug boats: For the positioning, float out and return to port of the transportation barges. Depending on the size and weight of the barge, the number of tugs must be determined.

Step-by-step process description

The step-by-step process description can be found listed below. A visual representation and story board of the installation procedure can be found in Appendix H.

1) Align and fix barge to foundation;
2) Make rigging connections;
3) Lift-off of tower from cargo barge while pivoting around barge stern;
4) Mating of up-ending frame and supports on the foundation;
5) Load transfer from barge to supports on foundation;
6) Move barge away from foundation;
7) Upending of frame using crane and vessel movement;
8) Once vertical, lower wind turbine assembly onto foundation/TP using hydraulic lowering mechanism;
9) Connect wind turbine to tower;
10) Detach upending frame and store on vessel/barge;

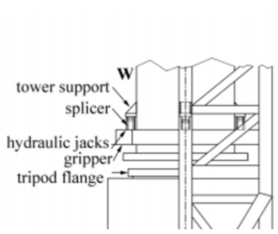
5.6.2. Concept 3: Mechanisms and components

Three separate major mechanisms or components are required. No detailed description of, e.g. the components in the frame used for opening it up, will be described, as that is part of detailed design. The concept consists of, the flip frame, in which a hydraulically lowering system is in place and a pedestal that can pivot around the stern of the barge. The mechanisms are depicted in Figure 5.10.

Upending frame: Frame in which the turbine lays horizontal. Pivots around barge stern and supports on the foundation.
Function: To support the turbine during transit and up-righting of the turbine.
Description: Frame that can open up after installation, consisting of a lattice frame and protruding supports at the bottom of the tower.

Hydraulic lowering mechanism: After the entire assembly is vertical, a system is needed to lower the turbine onto the foundation.
Function: To lower the wind turbine onto the foundation in a controlled manner.
Description: Clamping system placed inside the frame that can support and lower the entire weight of the turbine.

Pivot pedestal at stern of barge: Support that must be able to pivot so that the frame can be mated to the supports.
Function: To make the load-out of the frame and turbine possible using a relatively small crane.
Description: Support on which the frame and turbine can rest, which can pivot to align the frame with the supports on the foundation.



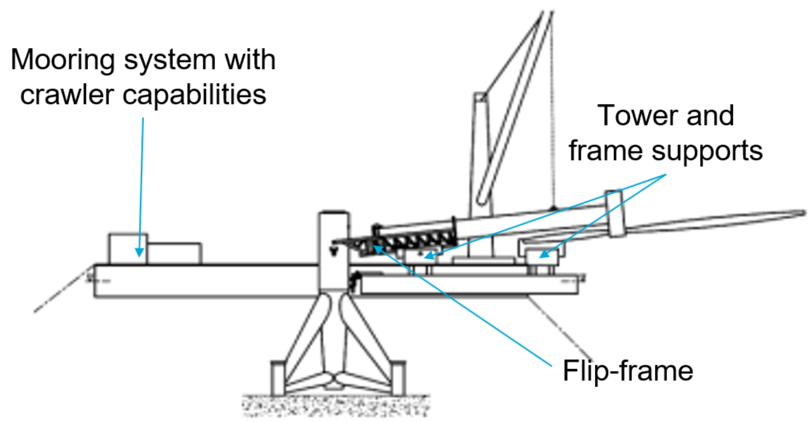


Figure 5.10: Mechanisms needed for the inverted pendulum principle. Left: lowering mechanism, Right: upending frame and barge. Depicted for use with a tripod. Taken from paper [1] and edited by author.

5.6.3. Concept 3: Critical factors

In this subsection, the critical factors of concept number 3 are discussed. Per critical factor, a small discussion is presented in which the significance is described.

Size and strength related:

- Lifting capacity of vessel: The turbine weight plus the frame weight must be carried by the crane. After initial lift-off, the turbine is almost horizontal and forces on the crane are largest. This is induced by the eccentricity of the frame and turbine mass. The needed crane capacity should be determined;
- Moment in the tower during upending: Moment in the tower will be dictated by the weight of the nacelle, and location of the attachment point of the lifting wire. A check should be performed in which the strength of the tower is assessed, to see if the tower can withstand the induced internal moments;
- Strength of supports on foundation: The frame will pivot on 2 supports on the foundation, these supports must be able to withstand the weight of the turbine and frame combined. This may require additional strengthening of members or slight redesign of the jacket, as members are not designed to withstand perpendicular loads.

Equipment related:

- Width of foundation at pivot height: jacket-type foundations are wider compared to monopiles or tripods at the water line. Resulting in, the width of the pivot frame being relatively larger than proposed in the paper[1] to accommodate this.

Logistics related:

- Assembly of wind turbine on shore: Only the largest cranes and ports can handle onshore assembly of ULWTs. In this case, horizontal pre-assembly of the wind turbine is needed, new lifting apparatuses, frames, supports, etc. will need to be designed to accommodate this, as it has never been performed to the author's knowledge;
- Loading of frame-wind turbine assemblies onto barge: Due to immense weight and size, a feeder system or mechanism must be designed. Movable quay side cranes can also be used if suitable capacities are available;
- Quay side requirements: Horizontal load out of an ULWT will take enormous amounts of space on the quay side of the marshalling yard. The total height of the turbine is about 450 metres, with a rotor diameter of 400 metres. Storing one single turbine horizontally requires about half a square kilometre. Compared to vertical storage of wind turbine assemblies or separate components, this is an enormous amount of space.

Workability related:

- Transit of turbine: Environmental conditions must allow transport, as the blades cannot hit the water due to barge motions. Furthermore, flex of the blades can become an issue that has to be investigated;
- Location of barge w.r.t. foundation: The barge is moored next to the foundation, to make mating of frame and supports possible. This results in risk of collision and exceeding of maximum loads in the foundation's structure.

Process related:

- Upending of turbine: Two difficult and sensitive operations must be performed at the same time. The hoisting and movement of the crane, and crawler motion of the vessel using the mooring system;
- Horizontal transport of nacelle/tower: Extra reinforcement of components such as the gearbox and generator will be needed to withstand loads due to horizontal transport. Furthermore, wind turbine producers do not like this because components need to be redesigned.

5.6.4. Concept 3: Initial sizing and weight estimate

In this subsection, the initial sizing and evaluation of selected critical factors of the concept will be discussed. Before sizing of this concept can take place, the critical factors defining the size and weight must be assessed. The critical factors that will be checked first are, "the moment in the tower during upending" and the "needed lifting capacity". Only if the tower can withstand the loads due to lifting, the concept is feasible. During the evaluation of these critical factors, it surfaced that the combination between the stresses in the tower and the needed lifting capacity causes the concept to be technically infeasible. Thus, no initial sizing was performed for this concept. In Subsection 5.6.5 the discussion and more information on the feasibility is provided.

5.6.5. Concept 3: Technical feasibility discussion

In this subsection, a discussion on the feasibility of the pivot concept will be provided. The concept is deemed technically infeasible, as the needed capacity and crane height exceed all current envelopes. The calculations behind the assessment of the critical factors of, "moment in the tower" and "needed crane capacity" can be found in Appendix H. The following reasons for infeasibility are formulated.

The tower must be supported at least 185 metres from the base to not surpass maximum yield stresses in the tower. Otherwise, the stresses in the tower due to gravity on the nacelle, the blades, and own weight of the tower exceed yield stresses. A buckling check has not been performed, as this already shows the limits of the concept. Two options arise catering to this; either the lifting point must be this high up on the tower, or the frame must support the tower along almost the entire length.

The first option requires that the lifting point must be at 185 metres from the tower base. Requiring a crane height around 215 metres above LAT, when taking into account the height of the jacket and transition piece. Even the current largest crane vessels in the world cannot reach this, thus the minimal height of the lifting point must be lowered. This can be achieved by strengthening the tower, 2 cases have been investigated:

- Constant tower diameter from bottom to top, resulting in a minimum supported height of 150 metres. Barely reachable by the largest offshore cranes. Additionally, the tower will be about 1,5 times as heavy.
- Constant diameter and wall thickness from tower bottom to top, resulting in a minimum supported height of 125 metres. Still only reachable by the largest few offshore cranes, but definitely possible. Furthermore, the tower would be about twice as heavy.

Although, the crane height problem is solved by this, the increase in tower weight will be significant. The increase in weight will significantly increase the tower cost. Resulting in infeasible tower designs, as costs are the main driver behind the overall feasibility of offshore wind projects. Note that, a stiff-stiff designed tower could possibly reduce the minimum support height to achievable heights. However, the tower would need to be about two times as heavy to reach achievable crane heights. This will never be acceptable, as the increase in tower weight will have a snowball effect on the costs of a wind farm. In addition to this, it will also increase the needed crane capacity by a lot, which will be discussed further in the following paragraphs.

The second option, of a frame that supports almost the entire tower, is also technically infeasible. The weight of the entire system is so large that only a handful of the strongest offshore cranes can perform the up-righting of the turbine. This directly contradicts the main selling point of, "being able to install the turbine using a relatively small vessel".

The needed lifting capacity depends on the height of the crane, as the taller the crane, the lower the needed capacity. The moment due to gravity on the wind turbine and frame have to be overcome by the crane. So, the combination of crane height and capacity determines the feasibility of the lift. Using the Sleipnir as an example, the height of the main hoist above the water line is about 115 meters, at a radius of 45 meters[19]. With this crane height, a capacity of more than 9500 tons is needed, when only the weight of the turbine itself is taken into account.

No weight estimation on the frame has been performed, as the lifting capacity needed due to the wind turbine alone already shows the technical infeasibility of the concept. If the weight of the frame is included, it will only increase the needed capacity further. Surpassing the capacity of the strongest offshore cranes in operation today of the Sleipnir, with a capacity of, 10000 metric tons.

Furthermore, the load case of this concept will probably not allow cranes to operate at maximum capacity. During the erecting of the turbine, the crane will be loaded vertically and horizontally. Cranes are designed for a predominantly horizontal load case, so more research is needed on the crane capacity of cranes when performing this type of lift. The needed capacity is already close to the maximum capacity of the Sleipnir, thus the up-righting of the turbine is deemed unreachable.

Thus, the option of a relatively small frame with the lifting point above the frame, as proposed for this concept, is technically infeasible. The required crane height cannot be reached. The option of a large frame to support the tower so that it does not fail under its own weight, could circumvent this. However, due to the needed crane capacity, this is unattainable even with the largest current lifting vessels, and is thus also deemed infeasible. Significant alterations to the concept will be needed to possibly achieve technical feasibility. These possible alterations and other notes can be found in the next section, but will not be worked out during this research.

Another factor that comes into play when judging the feasibility of this concept, is the horizontal assembly and storage of the wind turbine on the quay side. Due to the size and weight of components, vertical assembly and loading of the flip frame cannot be performed with current on shore cranes. Resulting in the need for horizontal assembly and storage of the wind turbines. In this case, the needed space on the quay side becomes immensely large, as an ULWT would be about 450 metres long and 400 metres wide. Thus, roughly the same surface area as 40 football fields is needed to store one turbine. Let alone if multiple turbines must be stored in a marshalling yard to continuously feed in the turbines onto the transportation barges.

Furthermore, turbine producers do not like to store the nacelle and tower horizontally. Normally, components are designed to only be transported and stored upright. All electrical and mechanical equipment included in the wind turbine must be redesigned for horizontal orientation. If this is possible, and if the producers are willing to accommodate this, is highly debatable. Especially if other methods can still be used for installation, further confirming that this concept is technically infeasible.

In conclusion, this concept is deemed fully technically infeasible due to the combination of the stated critical factors of, ”the needed lifting capacity” and ”the moment in the tower due to the own weight of the wind turbine”. Furthermore, the needed horizontal assembly of the wind turbine on-shore, and the horizontal orientation of nacelle and tower also further confirm that this concept is infeasible. Large alterations to the concept could make it feasible, but then it can also be considered another concept. These alterations and further discussion can be found in the next subsection.

5.6.6. Concept 3: Final notes and recommendations

In this subsection, final notes and recommendations on the inverted pendulum concept are provided. The concept is deemed technically infeasible, as the vessel assisted pendulum requires either tall cranes or high-capacity cranes. Both are not available currently or deemed practical.

The first note relates to the horizontal transport and storage of wind turbines. It has already been briefly discussed in Subsection 5.6.5, but should be stressed again. First and foremost, the internal components of both the nacelle and the tower must be adapted to withstand the loads on due to the horizontal orientation. This requires a full redesign of all internal components. Furthermore, the ovalization of the tower under its own weight should be investigated; possibly stabilisation of tower pieces is needed to prevent this. The author cannot claim to know enough of this phenomenon to make hard statements on the ovalization, but before further work is done on pivot mechanisms this should also be investigated.

The final note on this concept relates to the use of the concept for tower erection. Pivot installation methods can be used for the installation of the tower. Most of the stresses in the tower originate from the weight of the nacelle and blades. In combination with self-climbing mechanisms, the other components could be installed. Another advantage is that only one installation operation is needed to fully install the tower, contrary to using only a self-climber. They require the towers to be installed in relatively small pieces. This could significantly reduce the installation time of self-climbers, especially if one vessel can be used to upend the tower and attach a self-climbing system. More discussion on this is presented in

Section 6.8.

The recommendations follow from the two options which were investigated. The first option, with a small frame and a lifting point high up on the tower, will not be practical. Tall cranes more than 200 metres above LAT are needed, which are not currently in use. The second option of a frame that fully supports the tower cannot be pulled off due to the requirements of crane capacity. However, the second option could prove feasible with appropriate modifications to the concept.

The first recommendation relates to the improvement of the second option. The needed crane capacity can be reduced if assistance is added, possibly pushing the concept into the feasible domain. Some options arise that can provide the assistance:

- A movable ramp that can be hydraulically displaced towards the aft of the transportation barge.
- The supports furthest away from the pivot point can be jacked-up to increase the lift-off angle of the tower, reducing the needed crane capacity.

These adaptations would require a full redesign of the concept, and includes many more mechanisms. Due to this, the concept itself is still deemed fully technically infeasible, but the general approach of pivot can still be classified as conditionally technically feasible. The reasoning behind this is that the principle of pivot should not be disregarded due to this concept not working out. In hindsight, the third option in the branch of super-large floaters, as depicted in Figure 4.6 could also be a promising concept, as here no cranes are used for the upending of the pivot frame.

5.7. Concept 4: Wind turbine lifting frame(GC-13)

In this section, the wind turbine lifting frame concept, the winner of the branch of integrated lift, will be worked out and described further. In Figure 5.11 an artist impression of the concept can be found, depicted with a stylised semi-submersible crane vessel.

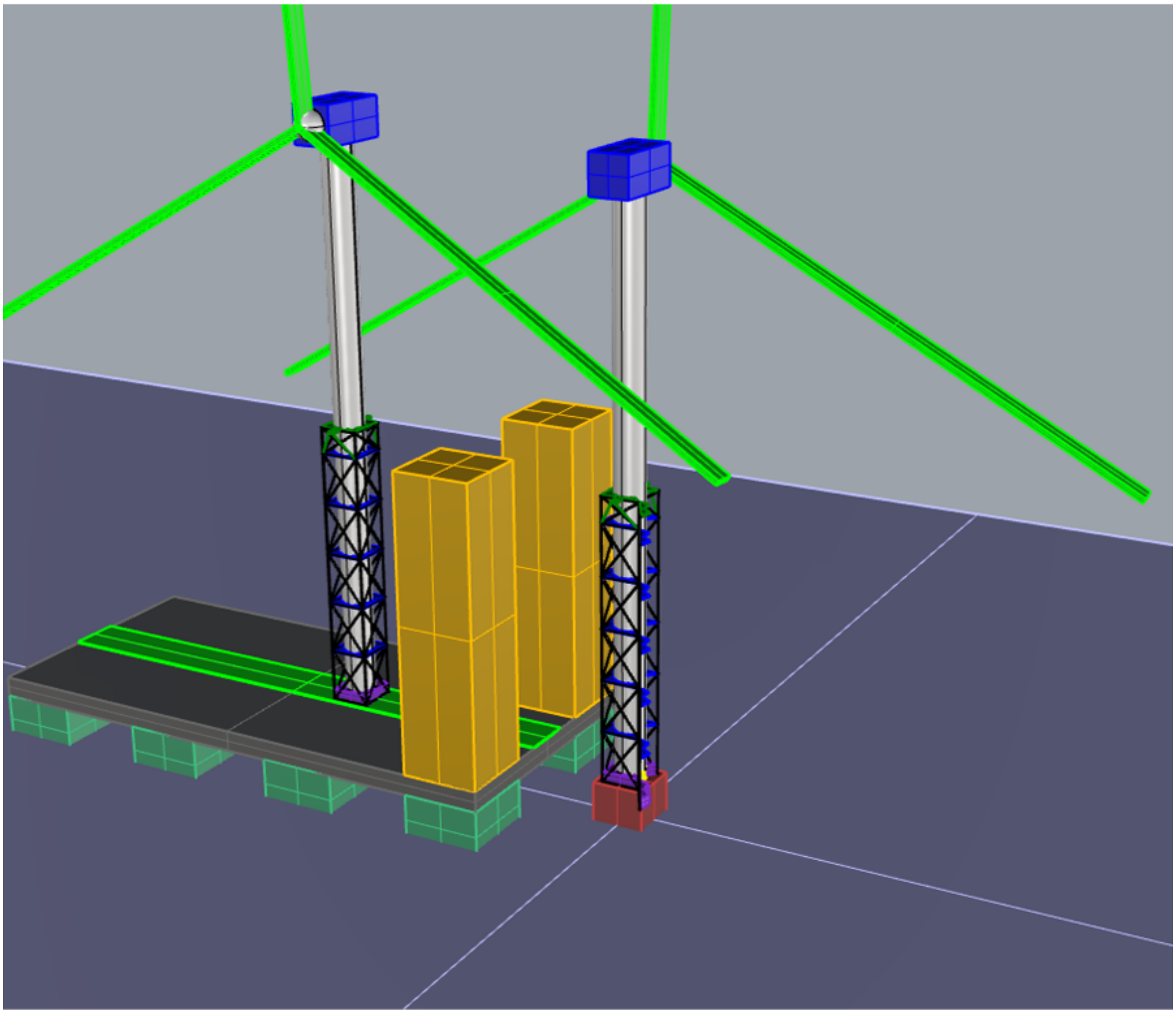


Figure 5.11: Artist impression of opened up lifting frame with turbine and stylized semi-submersible vessel after mating.

5.7.1. Concept 4: Description

General description

This concept addresses relative motion-related problems by lowering both the needed crane height and the altitude at which mating will take place. A frame is constructed that can be opened on one side, so that insertion of a wind turbine and disconnection of the frame are possible. This frame is placed on the deck of a large lifting vessel with double cranes. The frame has a counterweight at the bottom to lower the Centre Of Gravity (COG) of the frame and wind turbine assembly below the lifting points and ensure stability during the lift. The frame is lifted by two cranes in a tandem operation, lifted over the stern of the vessel, using the Sleipnir for example, and mated to the foundation/TP. Within the counterbalance, a guiding frame is present, making mating easier.

General description and discussion on logistics

This concept requires the wind turbine to be pre-assembled on shore. Due to its immense size, discussion can be had about the technical feasibility of this, as not even the tallest on-shore cranes can reach the needed height. After assembly, the wind turbine must be placed in the lifting frame, after which the entire assembly has to be lifted onto the ship.

Multiple problems arise, as there are no cranes available yet that can perform the vertical on-shore assembly of ULWTs. Even the largest on-shore cranes available, the Sarens SGC-250[44], cannot reach the combination between the needed height and capacity to assemble the ULWT. Thus, new cranes will need to be developed to nullify this bottleneck. Even if an ULWT can be pre-assembled on-shore, it is impossible using current cranes to load the turbine into the frame using traditional top-down lifting. Furthermore, the up-scaling of on-shore cranes can become impractical due to the immense requirements on the combination of size and capacity when lifting an ULWT. Thus, the turbine is preferably assembled in the frame to reduce the requirement on the used cranes.

The next step in the process is to load the wind turbine frame assemblies onto the installation vessel. The turbine can now be lifted using the lifting points on the frame, lowering the required crane height. The weight of the frame has not been determined yet, but will be large, creating a problem regarding crane capacity. In the case that the vessel's own cranes can be used, this will not be a problem, but if feeder vessels are used on-shore crane capacity will be limiting.

The next step in the process is the installation of the wind turbine using the frame. After installation, the frame must be detached and stored on the installation vessel. The weight of the counterbalance and size of the frame could cause difficulties with respect to the handling and storage of the frame. Probably, only the main cranes of the vessel have enough capacity to lift the frames. Another option is to store them on a barge, which is floated back to harbour and reloaded with another turbine.

Apart from these bottlenecks, the vessels that can be used for the installation with a lifting frame will be large and have large drafts. The latter can cause difficulties when entering harbours. The requirements on harbour facilities, depth, and quay size make that this concept cannot always be used efficiently. Only some of the largest harbours in the world can accommodate vessels like the Sleipnir, and the assembly of the turbine.

If the installation vessel cannot be serviced in a nearby port, a second logistic approach, the use of feeder vessels, can be utilised. They pick up a wind turbine frame assembly in harbour and float-out to the installation location. The installation vessel lifts the turbine and performs the installation. This can only occur if there is enough space on the quay side to build the turbine, and lifting of ULWTs is possible.

Possibly special harbours, marshalling yards, and quay sides will need to be constructed to cater to the need of preassembly of ULWTs on-shore. Specialized equipment must be present to allow for the pre-assembly and loading of ULWTs. This, in combination with the requirement on the draft of the harbour, results in only a handful of harbours in the world that can cater to this type of installation. Resulting in a situational approach where only wind farms near these harbours can be installed cost-effectively using integrated installation techniques.

Another factor that must be taken into account is the maximum carrying capacity of quay sides, as a wind turbine is a localised load, strengthening the quay sides might be needed to supply the needed capacity. This will not be discussed in more detail, as that is outside the scope of this research, but must be mentioned to show the complete picture.

Key selling points

- Make installation possible with already existing (super large) vessels like Sleipnir;
- No complex mechanisms;
- Reduce the number of offshore actions;
- Crane height independent of turbine size, instead of size-, concept becomes capacity-driven;
- Lowering of crane height and mating surface to reduce relative motions.

Needed vessels

One type of vessel is always needed, a large semi-submersible with double cranes. If using the second logistical approach, a secondary feeder vessel is needed.

- Large semi-submersible Heavy Lift Vessel (HLV): The vessel must have a double crane set up or single crane vessel with the capacity to lift an entire ULWT plus frame. Vessels such as the Sleipnir or Saipem7000 can be used for this concept.
- Optional feeder vessels: If no port is available to service the super large semi-submersible, feeder vessels are needed to transport wind turbine and frame assemblies to the installation site.

Step-by-step process description

The process description of the lifting frame concept can be found in the list below. Further information on the mechanisms can be found in Subsection 5.7.2 and a story board further explaining the installation procedure can be found in Appendix I.

1) Station keep near foundation;
2) Attach tugger lines to frame;
3) Attach lifting frame to cranes;
4) Lift frame from deck;
5) Move frame overboard by pivoting the cranes outward;
6) Line up frame with foundation;
7) Lower WT on foundation using guiding frame;
8) Connect tower to foundation;
9) Open up lifting frame and store on vessel;
10) Move next turbine to lifting location on the vessel using displacement mechanism present on deck;
11) Move vessel to next installation site and repeat all steps until no turbines are present on the vessel anymore.

5.7.2. Concept 4: Mechanisms and components

The installation using the lifting frame only needs three main components: the lifting frame itself, a guiding frame used for mating of the tower to the foundation, and skidding mechanisms so that multiple turbines can be stored on a vessel. In Figure 5.12 a depiction of the frame and guiding mechanism can be found. The frame is depicted as a lattice frame structure, the horizontals, and braces have not been optimised and are open to change in orientation and amount. The suggested placement of multiple turbines on a lifting vessel and the displacement mechanism are depicted in Figure 5.13

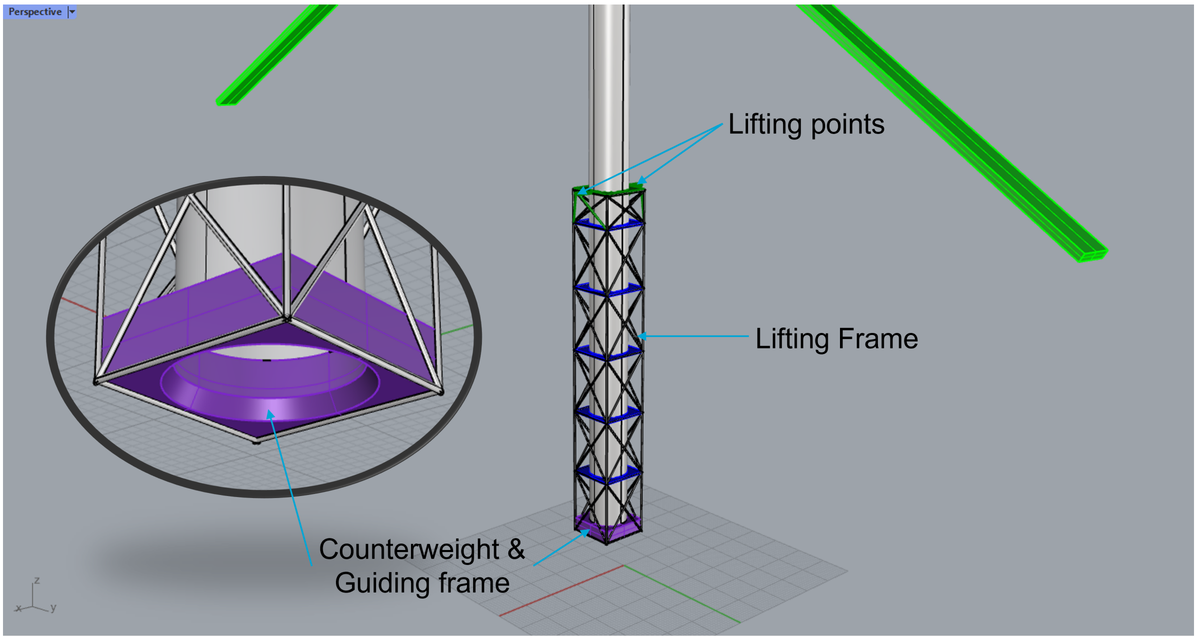


Figure 5.12: Artist impression of mechanisms and components of the lifting frame concept.

Lifting frame: A frame designed to hold a fully assembled ULWT. The main 2 goals of the frame are to lower the COG below the crane tips and to provide lifting points for the cranes. Consists of horizontals and lattice structure for structural integrity. The horizontals have friction pads to clamp the tower.
Function: To support the wind turbine assembly and counterbalance the turbine during the lift.
Description: Frame that is as tall as possible depending on the used ship, with a counterbalance mass at the bottom to get the COG of the assembly below the lifting points. The frame should also be able to open up using hydraulics or other means.

Lowering guiding frame: A guiding frame must be present to guide the lifting frame when lowering the wind turbine onto the Transition piece.
Function: To guide the frame onto the foundation/TP during the mating.
Description: Conical flange at the bottom of the lifting frame.

Displacement mechanism: Due to the size and weight of frame and wind turbine assemblies, only the main cranes can be used to move the load over the deck, or a system must be in place to displace the frame and turbine assemblies.
Function: To move frame and turbine assemblies from storage location on deck, which is outside the reach of the main cranes, to lifting location.
Description: Heavy skidding system or strand jack load-out system.

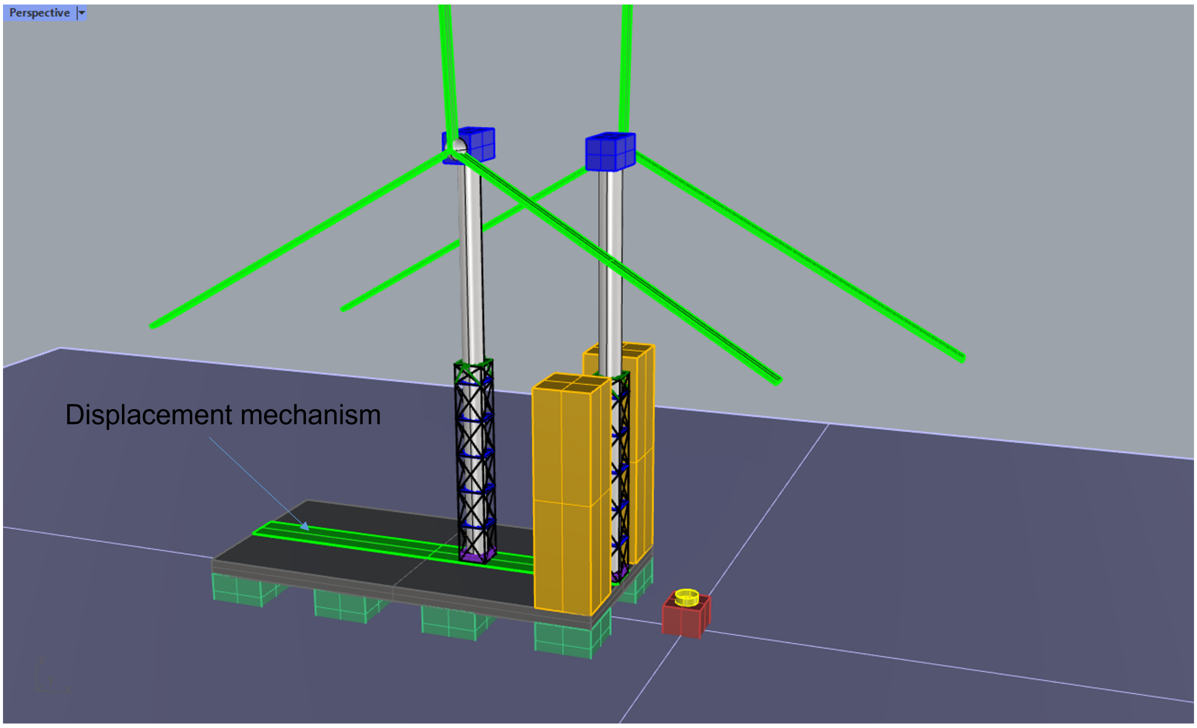


Figure 5.13: Artist impression of lifting frame concept on stylized Sleipnir, with suggestion on how to place multiple turbines on vessel and showing displacement mechanism.

5.7.3. Concept 4: Critical factors

The critical factors of the fourth concept can be found listed below. Each critical factor includes a small discussion on it.

Size and strength related:

- Stability of wind turbine in frame: The lifting points are below the COG of the wind turbine assembly. Stability of the frame and wind turbine while lifting must be reached. The COG of the assembly must be within the lifting points and/or below the lifting points to achieve stability. The initial sizing will assume that the COG must be below the lifting points. This will result in a conservative estimate of the weight of the frame and counterbalance, but only serves as a starting point for further evaluation;
- Height of cranes above deck: The maximum size of the frame is dictated by the maximum attainable height of the cranes above the lifting vessel's deck. Or, is determined by the vertical distance from the deck of a feeder vessel to the crane tip. Depending on the choice of logistic process;
- Strength of frame: Frame must support the immense weight of counterweight and the wind turbine combined during the lifting.

Equipment related:

- Immense weight of counterbalance and frame: Due to its immense weight and size, storage and handling of the frame must be taken into consideration. After installation, the frame must be stored on the deck of the vessel, resulting in the need for a large storage space. Another option is to use barges or feeder vessels, on which the frame is placed after installation. The vessel can then sail back, and another turbine can be loaded into the frame, lowering the amount of frames that are needed to continuously install wind turbines using this concept;
- Handling of frame-wind turbine assemblies on deck: Ideally, multiple turbines can be stored on deck. Due to the size and weight of the assemblies, only the main cranes of the vessels can handle it. Therefore, the assemblies must be placed within range of the main cranes, or a displacement mechanism must be available.

Logistics related:

- Assembly of wind turbine on shore: Only the largest cranes and ports can possibly handle onshore assembly of ULWTs. As discussed in Subsection 5.7.1, port side innovation is needed on crane capacity and height to make assembly possible;
- Loading of frame-WT assemblies onto vessels: Due to immense weight, a feeder system or mechanism will need to be designed, as no single crane exists yet that can carry these loads. A solution to this is assembly of the turbine in the frame, to hereafter use the frame to lift and load the turbine onto vessels. This can be achieved easily when the cranes aboard the installation vessel, such as the Sleipnir, can be used to load the vessel itself. However, if feeder vessels are used, the cranes that perform the lift must be present on the quay side. Not even the largest current on-shore cranes can perform these lifts, so innovation at the port side is needed;
- Water depth of harbours: Vessels that have the required lifting capacity require deep harbours, as drafts of 10-15 metres are common for these vessels (Sleipnir, Saipem7000). If feeder vessels are used, this is less of a problem.
- Quay side requirements: Size of vessels means that not all quay sides can accommodate them. Furthermore, the carrying capacity of the quay should be taken into account, as localised loads on the quay can become large. If feeder vessels are used, the size requirement of quays will be of less interest, as smaller vessels can be used.

Workability related:

- Tugger line operation: Needed to keep lifting frame balanced during the lift and reduce motions to acceptable levels. Tugger lines are currently used for lighter loads of e.g. blades. Further research is needed on the up-scaling of tugger line operations and to investigate if the operation can possibly be performed without tugger lines;
- Motions of the turbine while in transit: The workability of this procedure has to be assessed, as turbine flexibility and size will cause the assembly to move. These motions must be kept within acceptable levels for the transit to be able to take place;
- Location of vessel: The vessel must be close to the foundation during the lifting and mating of the wind turbine. Lifting curves of cranes will dictate the maximum radii at which the lift can be performed. Possibly leading to collision risks between vessel and foundation;
- Motions of vessel during lift: To make mating possible, the motions of the vessel, and thus cargo during the lift have to be assessed. Angular motion will be the most critical, so alignment of vessel with wave direction might be needed to reduce motions;
- Motions of the cargo due to wind loads: During the lifting of the frame, wind will act on the wind turbine assembly, this will cause motions. If this, or the motions of the vessel during the lift is guiding for the workability, must be assessed.

Process related:

- Double crane lifting operation: Two cranes must move in unison to lift the frame. The coordination of such operations requires thorough planning and communication to safely perform;
- Interference of crane tips with wind turbine: As this is a tandem lift, both crane booms must be taken into account when planning the operation. They must not hit each other or the turbine during the installation procedure.

5.7.4. Concept 4: Initial sizing and weight estimate

To determine the initial size and weight of the concept, first the weight and strength defining critical factors were worked out. The procedure taken is listed below, and the calculations can be found in Appendix I.

- Choose vessel;
- Determine frame size due to maximum crane height above deck using load curves;
- Simplify frame and calculate frame weight and strength excluding counterbalance weight;
- Set target COG height of assembly;
- Determine weight counterbalance to reach target COG height;
- Recalculate strength and weight of frame to include counterbalance weight.

The frame will be sized for use with the Sleipnir and the turbine size defined in Chapter 2. Heerema claims that the tandem capacity of the two main cranes is, 20000 metric tons, which should be more than enough. When looking at the load curves of the Sleipnir[19] it becomes clear that only the main hoist can be used, as the auxiliary hoist is not strong enough. The main hoist reaches 110 metres above deck, so that will be the maximum height of the frame in this case.

No detailed design of the horizontals and the lattice construction has been performed, as optimisation of this is part of detailed design. Only an artist impression of how the frame can possibly look is given, with estimates of the mass and needed counterbalance to show technical feasibility. More information on how the mass estimation of the frame and counterbalance mass was performed can be found in Appendix I. The approach is to first calculate the needed steel thickness to carry the weight of the turbine. Then use the weight of the frame and turbine to calculate the counterbalance mass needed to get the COG of the entire system below the lifting points. The assumption is made that the COG is sufficient at 105 metres above deck, with crane height of 110 metres. The final step was to recalculate the needed strength of the frame, also including the counterbalance mass. The results of the calculations can be found in Table 5.3.

Table 5.3: Main particulars lifting frame.

Parameter	Value
Height frame [m]	110
Width frame [m]	17.5
Mass frame [ton]	385
Mass ballast [ton]	2000
Mass assembly [ton]	8405
COG assembly [m]	104.4

5.7.5. Concept 4: Technical feasibility discussion

In this subsection, the technical feasibility of the fourth concept, the lifting frame, will be discussed. Only conclusions regarding the technical feasibility of the concept will be provided. The concept is deemed technically feasible for the following reasons:

- The total approximate mass of the assembly is about 8400 metric tons. A ship like the Sleipnir can easily reach the needed capacity, as the maximum tandem load is, 20000 metric tons. Thus, the lift is possible from a capacity point of view;
- The mechanisms that have to be present on the ship and frame are already available, super heavy skidding systems exist, and a frame that can be opened up using hydraulics, or other means, can definitely be designed. All mechanisms are relatively low-tech and based on proven technology.
- Wave-induced vessel motions of semi-submersible vessels are significantly lower than mono-hull vessels, as shown in Section I.2. Thus, lift is deemed reachable. The exact limits on workability still have to be determined, as that is outside the scope of this research.
- The key selling points stated in Subsection 5.7.1 all still hold:
  - Existing vessels can be used, albeit only some of the largest vessels in use nowadays like Sleipnir or Seipem7000;
  - Only a few offshore actions are required to perform the installation, including, but not limited to, mooring of vessel, lifting and mating of frame and detachment and storage of the frame;

- The problem is indeed capacity driven, as size of cranes only influences the height of the frame and weight of the counterbalance.

Although the concept is feasible, it is situational. The lift can only be carried out by the largest vessels in existence. Furthermore, the requirements for pre-assembly in harbour make that only the largest harbours available can be used. Using feeder vessels, the number of ports that can accommodate the concept can be expanded, due to shallower draft requirements. However, the pre-assembly of wind turbines on-shore will still be a bottleneck. Thus, the concept is deemed technically feasible from an installation point of view, but the bottlenecks in port will have to be solved before the concept can be used. If these bottlenecks cause the concept to be infeasible will not be assessed during this research as that is outside the scope. Not enough information has been acquired on harbour facilities and the possibility to upscale on-shore cranes, but should be investigated in further research. In the past, the increase in size of wind turbines also led to innovation in port, and up until now no problems have arisen regarding the stated bottlenecks.

5.7.6. Concept 4: Final notes and recommendations

In this subsection, some notes and recommendations on the fourth concept, the lifting frame, are provided. The first note relates to the motions of semi-submersible vessels. They are relatively stable in waters with short wave lengths. However, if they are used in waters with longer swell waves, with periods of 15-25 seconds, motions can still become problematic. The natural frequencies of semi-submersible vessels are in this region, as shown in Appendix I. This leads to a situational approach where semi-submersibles can be used in water with only short wave periods, as e.g. the North Sea, where there are almost no low period swell waves. However, it cannot be used in waters where longer period waves exist, e.g. off the coast of Africa, where these waves are a lot more common. This is not a critical factor, as the concepts are not designed for a particular region in the world, but it should be noted nonetheless. In general, it is important to know the common limits of vessels and how they relate to the operational regions and workability of said vessels.

The second note relates to the effects of the size of wind turbines on the design of the lifting frame. Smaller and lighter turbines can be installed using the frame. Only the attachment points of the frame to the tower must be adjusted to accommodate a smaller diameter tower. However, when using the frame for larger turbines problems will arise, two main influential factors are identified.

- The first is the mass of the counterbalance. If a turbine is heavier than the initial turbine, more mass is needed to balance the turbine, especially when the nacelle is heavier. To increase the flexibility of the frame, the counterbalance mass should be made modular. The mass can then be adjusted for use with different turbines. Another solution would be to have a certain amount of mass always in place, and use water tanks located at the bottom of the frame to adjust the mass to the needed level. The tanks can also be emptied after installation to make frame handling easier. A major downside is that water is significantly less dense than steel, thus a large volume of water is needed to have a significant effect on the stability of the frame;
- The second influential turbine design factor is the diameter of the tower. If this becomes too large, the frame will need to be redesigned and rebuilt, as the width of the frame is fixed. A workaround would be to over dimension the frame so that it can cater to a range of turbines, then one frame can be used over a longer time period, enlarging the lifetime of the concept and lowering the usage costs.

The first recommendation is to make the frame modular in height and counterbalance mass. This so that the frame can be used with differently sized vessels and turbines, as one critical factor is the crane height above deck. By creating a modular frame, sections can be added or removed, catering to different crane heights above deck of installation vessels or feeder barges. If the added costs of this addition to the construction of the frame outweigh the benefits, cannot be determined at this stage, but can be investigated.

The second recommendation is to investigate the lifting of the frame with single crane operations. This would increase the amount of vessel that can use this concept. The main problem will still be the necessary crane capacity, as only a handful of vessels are capable of performing the lift. However, a single crane of the Sleipnir could theoretically pull off this lift and only using one crane is always easier than two, as the operation becomes less complex.

5.8. Concept 5: Installation tower Semi-submersible(GC-3)

In this section, the winner of the super-large man-made floater branch, the semi-submersible installation tower concept, is discussed in more detail. In Figure 5.14 an artist impression of the semi-submersible vessel can be found.

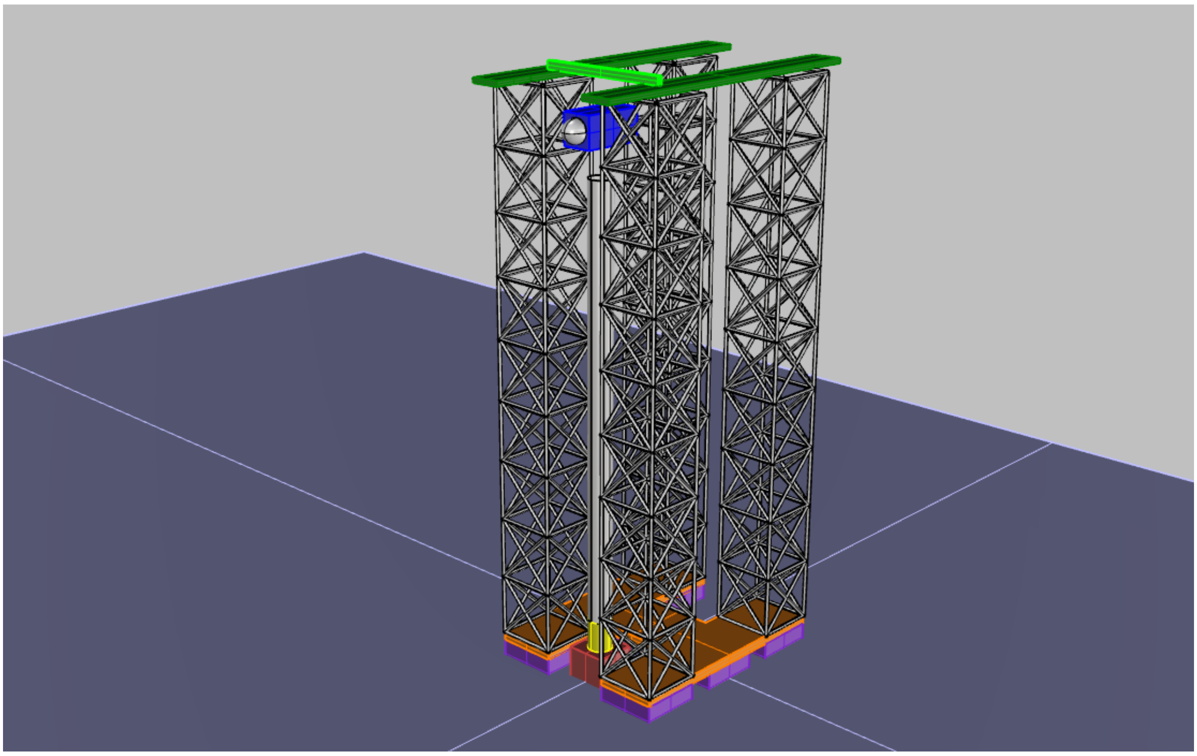


Figure 5.14: Overview of installation tower semi-submersible concept during nacelle installation.

5.8.1. Concept 5: Description

General description

The concept is a purpose-built large semi-submersible vessel, like the Sleipnir or Thialf, with lattice towers on top of the deck that tower above the needed altitude of the nacelle. On these towers a gantry crane is located to preform lifts, the lifts are internal, and thus 3D motion compensation is possible. Due to the internal lifting and the possibility of 3D motion compensation, the relative motion related problems can be lowered or even nullified. The general idea is to make the traditional top-down installation of wind turbine components possible for ULWTs. Components can be stored on deck or delivered by feeder barges/ships. Using the gantry crane, the wind turbine can be installed using a traditional top-down approach, which leads to minimal effects on the design of the wind turbine.

General description and discussion on logistics

Two main logistical approaches can be applied to the semi-submersible tower installation vessel.

The first approach is that the vessel sails to the intended location, moors next to the foundation, and installs the wind turbine. The components of the wind turbine are fed to the vessel on a barge, which can moor off at the opposing end of the vessel. Next, components are lifted from the barge and installed on the foundation. The vessel is basically only a floating crane platform and does not provide a large deck area to store components. Due to the size and draft of the vessel, problems can arise when entering harbours. These problems have already been described in Subsection 5.7.1.

This approach requires the feeding of components using a transport barge that can deliver all components to the intended location. The semi-submersible can remain at the wind farm and perform installation without the need to return to harbour. This option would lower the requirements on the installation vessel, as it does not have to be able to store wind turbine components, but can stay at the wind farm during the installation phase of all wind turbines in the farm.

The second approach is that the vessel can also store components of a couple of wind turbines. The main difference is that some components can be stored on the vessel, so that as many components as possible can be transported from the port to the installation site without the use of secondary barges. Before the vessel can sail to the installation site, the components must be loaded onto the vessel. For this, the on-board crane can be used, however, this requires specific loading/unloading platforms as it cannot reach far over the sides of the vessel. A protruding quayside which can fit into the moon-pool-like centre of the deck can accommodate this. On this quay, the components can be placed and then skidded underneath the crane on the ship.

After the initial batch of wind turbines has been installed, new components must be loaded onto the vessel before installation of more turbines can take place. Here 3 options for continuation arise:

- The vessel will go back to port and reload the components, this can only be done if the quay side can handle the size of the vessel and loading platforms are present;
- The second option is to have an intermediate step of unloading components from barges, storing them on the vessel, and continue installation after multiple turbines have been stored on the vessel;
- The third option is to continue like the first logistical approach. Unloading components from a barge and installing them immediately afterwards.

Which of these options is preferable depends on the workability of the unloading and installation of components. If unloading from a barge has a higher workability than the installation, downtime can be averted by unloading and storing components on the installation vessel. Whichever logistical approach will be the best, must surface from in-depth economic analysis and further workability analysis, which will not be performed during this research.

Key selling points

The key selling points of the fifth concept, the semi-submersible installation tower, are presented and are listed below.

- Make traditional split installation possible for ULWTs;
- No need for alteration to traditional design of OWTs;
- Provide a solution for both installation and maintenance & repair;
- Internal lifts, more options for motion control of components;
- Possibility for use with lifting of other offshore project, e.g. monopile installation, if crane capacity allows.
- Traditional cranes are not needed.

Needed vessels

The needed vessels for the installation with the fifth concept are provided. Depending on the choice of logistical process, either only the Semi-Submersible is needed or both the installation vessel and feeder barges. The needed vessels are listed below:

- Specifically designed semi-submersible vessel: Size is probably comparable to that of Sleipnir and Thialf. The exact size is determined during the initial sizing of the concept. This vessel can be used for installation, repair, and replacement of wind turbine components. It can also be designed to perform other lifts, if they are within the size and capacity of the vessel, think of installation of monopiles or other foundations.
- Feeder vessels: To feed in the components into the vessel, so that the main installation vessel does not need to return to port.

Step-by-step process description
The step-by-step process description of installation using the concept of the semi-submersible installation tower can be found below.

1) Station keep vessel around foundation;
2) Lift tower pieces from barge or deck using gantry crane;
3) Mate and connect tower pieces to TP;
4) Lift nacelle from barge or deck using gantry crane;
5) Mate and connect nacelle with tower;
6) Move vessel to blade installation position;
7) Horizontally lift blade from barge or storage using gantry crane;
8) Mate and connect blade to tower;
9) Rotate blade and make next blade attachment point horizontal;
10) Horizontally lift second blade using gantry crane;
11) Mate and connect second blade;
12) Rotate blades and make final blade attachment point horizontal;
13) Horizontally lift and connect final blade using gantry crane;

The size of the tower pieces is determined by the capacity of the gantry crane. The vessel will initially be designed around the lifting of the nacelle of 2000 tons. Using the tower of 3600 tons, the tower will have to be split into 2 pieces to stay below the weight of the nacelle.

5.8.2. Concept 5: Mechanisms and components

This method only needs two specifically designed mechanisms and one major component. The mechanisms are for the lifting and motion reduction of wind turbine components. The major component is the purpose-built semi-submersible vessel. All mechanisms and components are listed below. In Figure 5.15 all components are visualized.

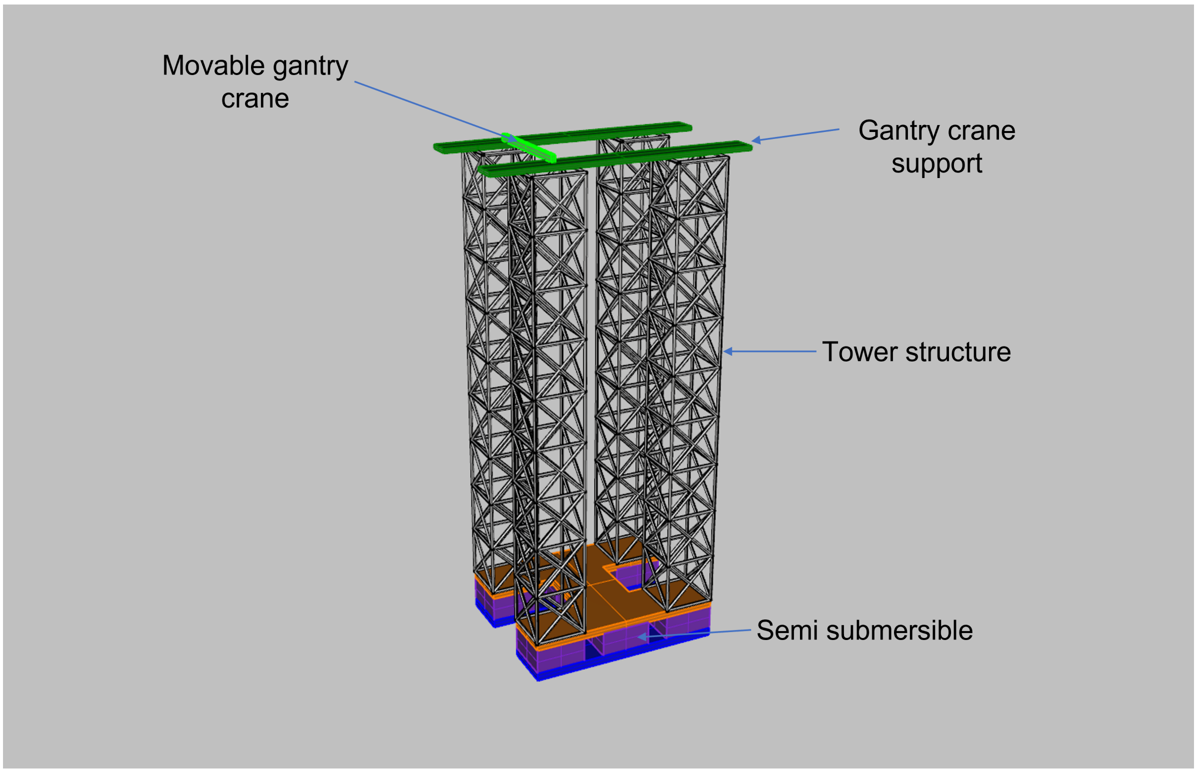


Figure 5.15: Depiction of mechanisms needed for installation tower semi-submersible concept.

Semi-submersible vessel: This concept requires a purpose build semi-submersible vessel.
Function: To provide a platform for the lifting mechanisms and towering structure.
Description: Purpose-build vessel of semi-submersible type with lattice towers on top that reach above the needed hub height.

Gantry crane platform: Movable gantry crane on a platform on top of the towers. It can be compared to movable top-down gantry cranes in ship construction halls[29].
Function: To lift and move wind turbine components from transportation barges, or storage, to the foundation.
Description: Gantry crane like construction on top of stationary lattice towers, where the crane can be moved over the length of the ship.

Motion reduction mechanisms: The lifting of the components is carried out by a gantry crane. These lifts can be classified as internal lifts, tugger lines can be placed on the deck of the ship and/or the towers, creating 3D motion compensation possibilities. These mechanisms will not be worked out further in this research, but the option should be mentioned nonetheless.
Function: To provide extra motion compensation possibilities during the mating phases of components.
Description: Tugger line winches placed on top of the deck or in the towers.

5.8.3. Concept 5: Critical factors

The critical factors of the fifth concept are presented below. Again they are subdivided into the categories of, size and strength, logistics, workability, equipment, and operations related. Of which, size and strength, and equipment related critical factors are of main interest to this research.

Size and strength related:

- Stability of vessel: The stability dictates the size of the vessel. Due to the extreme height of the towers, the stability of the vessel will be one of the main points of interest. The Centre Of Gravity (COG) will be pushed upward by the towers, gantry crane, and altitude of the cargo. The choice can be made to over dimension the vessel to take into account future growth of turbines. This will not be done during this research, as only the technical feasibility of such a vessel will be assessed;
- Height of installation tower: The height affects the stability of the vessels and must be large enough for installation of components at hub height. The tower should at least reach 260 metres above LAT. If the size of turbines increases even further, the vessel will become unusable, or the towers will need to be enlarged;
- Lifting capacity: Dictates the needed strength of the towers and gantry, the minimum lifting capacity is the weight of the nacelle. The gantry crane can also be designed for a higher capacity, if other lifts are required. The tower can theoretically be lifted in one piece. It might be the case that, the installation costs can be brought down significantly if the tower can be installed in one lift. The crane could also be over designed even more, increasing the crane capacity. The vessel can then be used for e.g. monopile installation. The starting point for the initial sizing will be turbine installation. If the concept is deemed technically feasible, further research can be done on expanding its functions, as the more functions such a vessel has, the easier it is to continuously use it and increase its economic feasibility;
- Blade clearance: Blades are the longest component and must not collide with the vessel's towers while rotating outwards. Depending on the achieved clearance between the blades and the towers, the vessel has to be re-positioned to avoid interference during the rotation of the blades. Preferably, this is not necessary, as repositioning of the vessel is another procedure that increases the time and cost of installation.

Equipment related:

- Gantry crane on top of towers: Gantry cranes are commonly used in harbours or construction facilities of e.g. ships. However, no case of offshore use has been recorded to the author's knowledge. Therefore, more research needs to be done on the design of such a crane platform. The needed strength of the gantry crane is guided by the maximum load on it.

Logistics related:

- Water depth of harbours: The to be designed semi-submersible will probably have drafts of 10-15 metres, as are common for similar vessels, such as Sleipnir or the Saipem7000. This means that not all harbours can accommodate vessels of this size. However, when using feeder barges, this can be circumvented;

- Quay side requirements: Size of vessels means that not all quays can accommodate the semi-submersible vessel. Furthermore, if the second logistical approach is utilised, the loading of components from quay to vessel will be required. To accommodate this, specialised loading platforms must be present at the quay side. This can be circumvented using feeder barges or ships, like the first logistical approach.

Workability related:
- Motions of vessel: As no automated mating tools or frames are used, the motions of the vessel will dictate the workability. The combination of the height of the towers on the vessel and vessel motion can cause relative motion-related problems. Thus, motions will have to be checked, and the options, and need for motion compensation should be assessed;
- Location of vessel w.r.t. foundation: The vessel is large and enfolding on the foundation, so the risk of collision is always present and must be evaluated. Especially because the size and weight of the vessel will cause significant damage to the foundation or components in case of collision.

Operation related:
- Internal lifting: In the event of catastrophic crane failure, heavy components can drop onto the critical structure of the vessel. This risk must be considered when designing the vessel and performing the lifts;
- Blade installation position: Blades must not interfere with the towers. The vessel must be rotated so that pure horizontal installation of the blade can take place. Otherwise, the blades cannot be rotated outward without interface. Due to this, the vessel has to relocate slightly, see Appendix J for the story board and more information.

5.8.4. Concept 5: Initial sizing and weight estimate

In this subsection, the initial sizing of the semi-submersible installation tower is presented. The initial sizing of the concept revolves around the stability of the vessel, lifting of the nacelle, and proposed hub height of the wind turbine. The vessel will be designed to reach positive small angle intact stability in all directions, thus positive GMs in all directions[50]. A top-down approach is taken for the initial concept design of the vessel. First, the topside is designed, followed by the vessel, since the topside will influence the stability and, thus, size of the vessel. For the initial sizing of the vessel, the choice is made to use the first logistical approach, only feeding of components, as this results in the lowest requirements. Thus, no regard is given to storage space on deck. The approach is listed below and is explained in detail in Appendix J.

- Choose initial layout of semi submersible vessel;
- Parameterize semi submersible vessel dimensions;
- Set initial dimensions;
- Determine size topside;
- Design crane platform for size topside and lifting capacity of 2000 metric tons;
- Set size tower lattice structure;
- Determine size and weight of lattice structure using rules of thumb for jackets and initial dimensions;
- Check tower leg stability;
- Determine stability of the vessel during lifting of nacelle;
- If not reached, redefine dimensions to reach positive GMs in all direction;
- Check all dimensions of all parts if still plausible;
- If yes, no problem. Else redefine dimension and check stability again.

Using the posed approach listed above, a semi-submersible vessel was designed. The main particulars of the vessel can be found in Table 5.4.

Table 5.4: Main particulars of semi-submersible installation tower.

Parameter	Value	Parameter	Value
Length overall[m]	120	Displacement[m3]	50000
Width overall[m]	100		
Draft[m]	10.5	GM_{xx}[m]	6.7
Free board[m]	14.0	GM_{yy}[m]	13.9
Height towers above deck[m]	270	Capacity gantry crane [ton]	2000

5.8.5. Concept 5: Technical feasibility discussion

In this subsection, the technical feasibility of the fifth concept, the semi-submersible tower installation vessel, is discussed. During the working out of the concept, a theoretically stable vessel was designed, and all initial stability checks were passed, of both the vessel and tower legs. This suggests that the creation of such a vessel is possible, a lot more engineering work must obviously be performed to further work out the concept, and end up with a finalised design. However, as a first estimate, the design can be accepted, as the goal was to see what the approximate size and weight of such a vessel would be. The weight of the parts of the vessel directly relates to its size, especially the weight of the gantry crane, its supports, and the towers, as those have a large effect on the height of the COG of the ship. In general, it can be said that the higher up this is, the larger the vessel has to be to have positive stability. Therefore, even if the components end up being heavier than estimated, the concept is still feasible. Albeit, it will end up larger than proposed here. However, the mass of the deck has a different influence, as this will always lower the COG of the vessel and thus increase its stability. Thus, the vessel itself is deemed technically feasible due to the following two reasons:

- The vessel itself will be around half the size of the Sleipnir, suggesting that it can be built, but will be expensive;
- Gantry cranes with spans of over 100 metres and capacities of 2000 tons exist[29]. These cranes are in use in shipyards around the world and are used to lift entire sections of ships. This suggests that the creation of the gantry crane, which spans around 70 metres and can lift 2000 metric tons, is technically feasibly;

As mentioned above, the vessel will become expensive to build, and thus use for the installation of ULWTs. Thus, the economic feasibility of creating such a vessel must be investigated further. However, due to the limited effect on the construction of wind turbine components, and the possibility to perform split installation that reduces the requirements on ports and quay sides, the concept is definitely promising, more information on this can be found in Chapter 6. The latter results in lower overall costs of the method, as opposed to integrated installation, if this outweighs the large costs of building and/or chartering the vessel is to be seen, and will not be investigated during this research.

Due to the size of the vessel, the effect of using differently sized turbines or types of foundations is limited. However, if turbines are scaled up beyond the posed 250-metre hub height, the proposed height of the tower must be enlarged. The vessel is currently designed with the defined hub height and turbine size in mind, only to get a feeling of how large such a vessel would be. Whether the added costs of over dimensioning the vessel will outweigh the increase in lifetime of the concept, will not be answered, but is definitely important to investigate.

In conclusion, the concept of the semi-submersible installation tower is deemed fully technically feasible. Vessel stability can be reached even with tall lattice towers on deck, and gantry cranes of this size and capacity are already in use on shore. The big if for this concept is the economic feasibility, as it consists of a large semi-submersible that is expensive to build and maintain. More research will be needed into this to determine the overall feasibility of the concept. In the next section, notes on the feasibility and recommendations for improving the concept are provided.

5.8.6. Concept 5: Final notes and recommendations

In this subsection, notes and recommendations on the fifth concept, the semi-submersible installation tower, are presented. The same notes and problems due to the size and draft of the vessel hold as has been discussed in Subsection 5.7.6 and will not be repeated here.

The first note on the feasibility of the concept relates to the flexibility of towers and gantry crane. If they end up too flexible, the motions due to the rigid body vessel motions and flexibility of the crane system could exceed the installation tolerances. If stiffness has to be increased, the mass of the top side of the vessel will also increase, thus increasing the size of the vessel.

The second note relates to the effect of the wind on the tower structure. The towers add surface area above the water line; the larger the surface area, the higher the loads due to wind will be. It can be compared to a sailboat with a high mast and sail. Wind could have significant effects on the motions of the vessel, if the force exerted by wind is large enough. Due to this, an overturning moment will be enacted on the vessel, leading to low-frequency semi-static heel and pitch angles, and higher-frequency motions. The motions will have effect on the installation of wind turbine components if they become too large. It should also be checked if under high winds the vessel can withstand the overturning moments due to wind loads.

The third note relates to the design of the vessel. First, the weight and size determination of the towers and gantry crane should be considered when designing the vessel. The top side mass and altitude of the COGs are the main factors determining the overall stability of the vessel. A slight reduction in mass of any component on top of the deck will significantly affect the needed size of the design, and should thus always have a high priority.

The fourth note relates to the mooring of barges inside the moon-pool-like centre of the hull. A motion analysis should be performed to see if this is possible without large collision risks. The shielding of the semi-submersible will be significant if placed appropriately in the wave direction. The author thinks that this will be possible, especially because the opening is about 40 metres wide, which is more than enough to leave more than five metres of clearance on all sides between a transportation barge and the vessel.

The final note relates to the choice of utilizing the first logistical approach. The vessel is currently designed without taking into account the cargo space on deck. It might be that the concept is more cost-efficient if a couple of turbines can be stored on deck. This requires a larger vessel, especially in length, so that blades can be stored on deck. Specialised storage and handling equipment must be designed, and/or auxiliary cranes would be needed for the handling of wind turbine components. If this option results in a more cost-effective concept, should be investigated.

The first recommendation relates to the clearance of the blades while rotating during installation. The design of one of the towers could be altered so that there is no need to reposition the vessel for blade installation. This eliminates the repositioning step during installation, resulting in a shorter installation time and thus lower costs.

The second recommendation is an alteration to the crane design. It might be beneficial to have 2 gantry cranes on the ship. One used for installation, which has to be high up on the vessel, and one that can unload components from a feeder barge. This decouples the unloading and the installation operational requirements. However, it does add another step into the process, as unloading and installation of a component will be 2 separate steps. If vessel motions allow, these steps could be performed simultaneously, which could lead to a decrease in installation time. However, it would add to the cost of the vessel, as a second crane must be constructed. If this is in the end beneficial to the overall costs of the method can be investigated.

5.9. Concept 6: Scaffolding build-up principle(GC-15)

In this section, the winner of the branch others, concept 6 the scaffolding build-up concept, is discussed. This concept has no detailed drawings or initial sizing, as it was deemed fully infeasible when evaluating the critical factors; see Subsection 5.9.5. In Figure 5.16 a rough initial concept drawing of the concept is shown, as generated during the concept generation phase, and can be found in Appendix C.

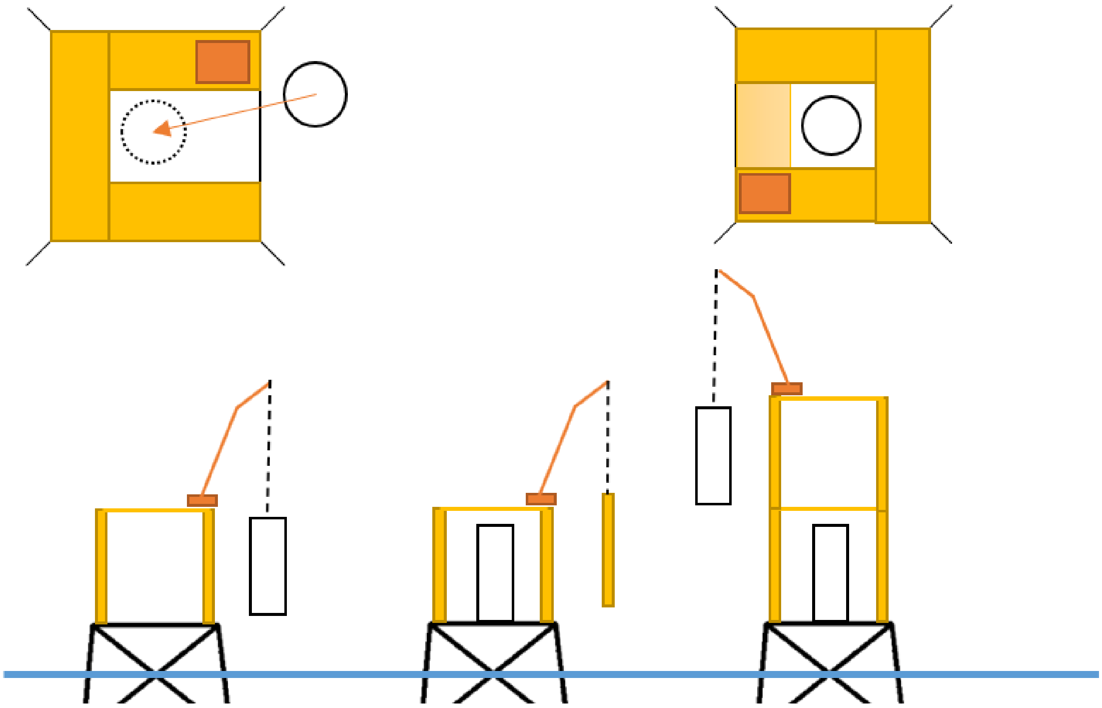


Figure 5.16: Concept drawing scaffolding build-up principle.

5.9.1. Concept 6: Description

General description

This concept uses a scaffolding build-up principle. To make this possible, an enlarged foundation is needed, this can be achieved by enlarging the foundation or making detachable platforms on which scaffolding, and cranes can be placed. The first level of scaffolding is built up by a Heavy Lift Vessel (HLV), after which cranes are placed on top. These cranes are used to lift, mate, and connect a tower piece to the foundation. Next, crane 1 will build up the scaffolding further, disassemble crane 2 and place the crane on the next level of scaffolding. Crane 2 does the same with crane 1 and a following tower piece is installed. This is repeated until the tower is fully installed, and the other components can be installed. Once the turbine is fully erected, the scaffolding is disassembled with the reverse assembly procedure. This concept deals with the found bottlenecks that result in relative motions by attaching the scaffolding directly to the tower, reducing relative motions. The only effect on the wind turbine construction this concept has, is that the tower must be made modular, as it cannot be installed in one or two pieces.

General description and discussion on logistics

A HLV is needed to install the first level of scaffolding and place the cranes on top of it. After this, only feeder barges/vessels are needed to supply components and scaffolding to the cranes. If enough cranes and scaffolding are available, multiple turbines can be built up simultaneously using only one HLV and a multitude of feeder vessels. Loads of feeder vessels will be needed to supply and transport both the components and the scaffolding.

Key selling points

- No need for large HLVs;
- Installation of multiple turbines can be performed simultaneously, depending on available cranes and scaffolding;
- Turbine size independent;
- No need for multiple large installation vessels;
- Scaffolding is attached to the tower, reducing relative motions during installation.

Needed vessels

Only two types of vessels are needed for use with the scaffolding build-up concept.

- Heavy Lift Vessel: To place cranes on first level of scaffolding during preparation phase and detach cranes after installation;
- Feeder vessels: To supply wind turbine components and scaffolding to cranes during installation.

Step-by-step process description

The step-by-step procedure is described and listed below. No storyboard is available for this concept, as it was deemed infeasible before drawings were made.

Preparation

1) Place first part of scaffolding on enlarged TP/foundation;
2) Lift cranes onto scaffolding;

Tower assembly

3) Lift tower piece from cargo vessel/barge using cranes;
4) Mate and install tower piece;
5) Build up scaffolding to new elevation and fasten to tower;
6) Use crane 1 to disassemble crane 2 and move to next level of scaffolding;
7) Build up scaffolding for placement crane 1;
8) Use crane 2 to disassemble and move crane 1 to next level;
9) Repeat steps 3 up until 8, until entire tower is installed;

Nacelle assembly

10) Lift nacelle from cargo vessel/barge using cranes;
11) Mate and install the nacelle;

Blade assembly

12) Lift blade 1 from cargo vessel/barge;
13) Mate and install blade 1 using cranes;
14) Rotate hub to get blade attachment point of next blade into position;
15) Repeat step 12 to 14 until all blades are installed;
16) Disassemble cranes and scaffolding step by step until nothing remains on the foundation.

5.9.2. Concept 6: Mechanisms

In this subsection, the mechanisms of the sixth concept, the scaffolding build-up concept, are described. Only two major mechanisms are needed, the cranes, which are used for the building up of the scaffolding and the wind turbine and the scaffolding itself.

Cranes which can be disassembled: two cranes are needed, which can disassemble each other and reassemble at another location.
Function: Cranes used for installation of components and build-up of scaffolding.
Description: Two rotatable cranes, each capable of lifting about 1000 metric tons, so the tandem capacity is enough to lift the nacelle.

Slip joint scaffolding: Scaffolding that can be easily be disassembled and assembled by the 2 cranes that are placed on the scaffolding.
Function: Easy build up and disassembly of scaffolding.
Description: Three platforms on which scaffolding can be built, which can be attached to the foundation of the wind turbine.

5.9.3. Concept 6: Critical factors

Only three critical factors have been defined for this concept, as they must be evaluated before further work on the concept can take place. These critical factors were found to cause significant problems with respect to the overall feasibility of the concept. Based on these critical factors, the concept was deemed infeasible, thus only these three were defined.

Size and strength related:

- Size requirements on foundation: Cranes and scaffolding will take up a lot of space on the foundation. Platforms next to the foundation will be needed to support scaffolding and cranes. They have to be attached to the foundation;
- Size and weight of Nacelle: The widest and heaviest component to install, is thus guiding the dimensions of the cranes and scaffolding.

Logistics related:

- The amount of lifting and mating procedures: A large amount of mating and lifting procedures will have to take place, the turbine, scaffolding, and cranes will have to be built up, and the scaffolding and cranes will have to be disassembled.

5.9.4. Concept 6: Initial sizing and weight estimate

No initial sizing of the concept has been performed, as the concept was deemed fully economically infeasible. No technical feasibility evaluation has been performed, as this concept is an outlier relative to the other methods with regard to its economic feasibility.

The critical factors that have been evaluated are guided by the size of the cranes that are needed for this concept to function. If the assumption is made that two cranes can work in tandem, two cranes with a safe lifting load of at least 1000 metric tons must be utilised. This results in a needed surface area of one of the cranes of about 20×20 metres, when using on-shore cranes, which can easily be disassembled[45]. The defined jacket provides a working platform of about 20 by 20 metres minus the size of the transition piece. It becomes immediately clear that the cranes need more space than is available on the foundation itself. This can be circumvented by artificially creating platforms that are attached to the foundation. The weight and size of these platforms will be significant; the towers designed for the installation tower semi-submersible are in the range of the needed size. These towers are around 2000 tons and have a base area of 30 by 30 metres. Three of these towers would be needed for use with this concept, adding 6000 tons of mass to the sides of the foundation. To support the towers and the attachment platforms on which they are build, the jacket will need significant strengthening and redesign.

5.9.5. Concept 6: Feasibility discussion

Cranes would simply become too large to put on scaffolding that is on the foundation. It is only possible if the area available on the foundation is increased, as the base areas of cranes that can lift these kinds of weights are easily 20 by 20 metres. If tub cranes can be used, if and only if they can be disassembled, the areas can be reduced, but will still be large. This would mean that a redesign of the foundation is needed to support the cranes and the scaffolding, which is highly undesirable, as this will drive up costs a lot.

Furthermore, the disassembly and assembly of cranes cannot be performed in a competitive time frame, as only those actions take just as long as an integrated installation. The disassembly and assembly of one crane could take a couple of hours, if not more. Compared to other concepts, the same vessels are needed, one HLV and feeder vessels, but the time frame in which an installation can be performed can be said to be significantly higher, even without doing further analysis on this. No real comparative analysis has been performed yet, so it seems unfair to disregard this concept on this basis; however, the amount of needed mating procedures are set to be a multitude compared to other methods. Creating such an outlier, with regard to the economic feasibility of the concept, that it is deemed infeasible on grounds of needed installation time.

If and only if all other concepts are deemed infeasible, it will be worth it to work out this concept further. No further figures and notes on this concept will be provided, as it is deemed unfeasible due to these arguments, and small improvements cannot work around the stated problems.

5.10. Summary of feasibility of all selected concepts

In this section, a summary of the feasibility of all concepts that passed the screening will be provided. Concepts 1, 4, and 5 are deemed technically feasible, and concepts 2, 3 and 6 are deemed infeasible. The classification of the feasibility and summary of main augments as to why, can be found in Figure 5.17.

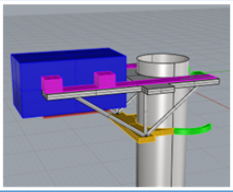
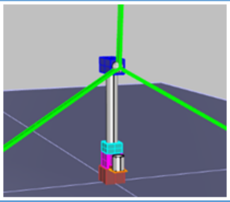
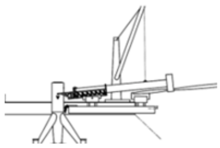
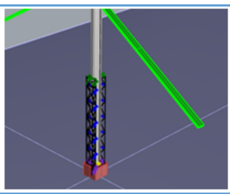
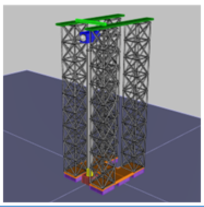
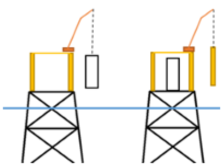
Branch	Concept	Feasibility classification	Main reasoning
Self-climbing		Conditionally technically feasible	• Mechanisms are based on existing equipment. • Tower design effects feasibility, if soft-soft design is used concept becomes infeasible. • Parallel installation of wind turbines is possible.
Self-erecting		Conditionally technically infeasible	• Jack-up mechanisms can be designed. • Installation at initial tower height not yet possible in competitive time frame, if this is can be made possible the concept becomes feasible.
Pivot		Fully technically infeasible	• Tower strength is insufficient to perform lifting at needed height. • Needed lifting capacity is too large. • Key selling point of small HLV cannot be reached
Integrated lift		Fully technically feasible	• Vessels already exist which can pull of the lift. • Frame can be designed and made, as it is based on existing technology. Note: On-shore assembly requires innovation in port.
Super large man-made floating structures/ vessels		Fully technically feasible	• Vessel stability can be reached. • Gantry crane is based on proven technology which is used on land, has to be mde sea fast. Note: Economic feasibility has to be checked due to size of and purpose build vessel.
Others		Fully economical infeasible	• Size requirements on foundation to large • Number of needed mating procedures make concept non-competitive.

Figure 5.17: Matrix table showing the 6 concepts which passed through the screening, their branches, feasibility, and main reasoning behind the feasibility assessment.

Note that, all designs presented in this chapter are concept designs based on high-level evaluations of the critical factors. All designs are open to change, and realising them will require much more engineering work. This work will not be performed during this research, as the goal is to identify promising and technically feasible concepts, not to present a detailed design. Furthermore, they have been designed and sized using quasi-statics and the assumption of calm seas. This might seem counterintuitive, as rough seas and dynamics are the main causes of the found bottleneck of relative motions during installation using traditional means. However, this has to be taken as a starting point on which further development can be based, as including these two require a lot of engineering work and detailed design, which is timely and costly. It is better to weed out the options which are already infeasible with these assumptions before further work on them is performed. In the next section, the technically feasible +concepts will be compared on their relative economic feasibility to try to identify differences and provide a better view on their usability.

6

Comparative analysis of technically feasible concepts

This chapter is the final phase of the research, the comparative analysis of the technically feasible concepts. The framework has been established in the first few chapters, using the framework concepts were generated, screened, and evaluated on their technical feasibility, resulting in 3 technically feasible concepts. During an overall feasibility analysis, the other feasibility groups must also be assessed. However, during this research, the choice fell on proving technical feasibility; this only shows if a concept can be used or not from a technical point of view, and does give little information on when it can be used and if it should be used. The latter question requires an in-depth economic analysis of the concepts which will not be performed during this research, but to provide more information on the concepts, the economic feasibility considerations defined in Chapter 3 and summarised in Table 3.1 will be used. The methods will be compared on their relative economic feasibility to identify shortcomings, and differences in usability of the concepts. Using all knowledge gained on both the technical and relative economic feasibility of the technically feasible concepts, it will be possible to present a full comparison of the three concepts and formulate the pros and cons of each of them. Furthermore, it is also important to take a step back and use all that is learnt to evaluate the feasibility of all the branches that have been defined in Section 4.3 in a holistic manner. The goal will be to identify and describe the usability of the principles within each branch, to end up with a discussion and conclusion on which principles and concepts are most promising.

First, the cost-effectiveness of the technically feasible concepts is evaluated in Section 6.1. Next, the relative safety of the concepts is discussed in Section 6.2. In Section 6.3 the complexity of the three technically feasible concepts is evaluated. Section 6.4 describes the flexibility of all technically feasible concepts. In Section 6.5 The influence on wind turbine construction due to concepts is discussed. In the next section of this chapter, Section 6.6 provides a summary of the comparative analysis and provides a discussion on the usability of the technically feasible concepts. Followed by, a summary of all technically feasible concepts distilled from all knowledge gained during the research in Section 6.7. Lastly, in Section 6.8 a holistic discussion on the feasibility of the branches is presented.

6.1. Cost-effectiveness

In this section, the cost-effectiveness of technically feasible concepts is evaluated at a high level. To get a full idea on the cost-effectiveness of a method, a location, a complete logistical plan, and a workability analysis would be needed, among many other factors. However, the choice was made to not include any of these in the research, as the goal was to assess the technical feasibility, and that does not require any of these. Furthermore, a concept should be able to operate in all conditions within the boundary conditions, as an as wide as possible usability is always preferred. The downside of this is that it is impossible to provide an all-encompassing discussion on the cost-effectiveness. Furthermore, the cost-effectiveness of installation methods is highly situational, and depends on the following factors, but not limited to; distance to port, inter-array distance, water depth, available vessels, needed harbour infrastructure, and many more. It is a complex system of variables that, in the end, will determine the cost-effectiveness of a certain concept in a certain situation. To be able to say something about the cost-effectiveness without looking into the stated factors in detail, four sub-factors have been defined which can be assessed. The four factors defined in Subsection 3.2.1 will be used to assess the concepts. In Figure 6.1 a summary of the factors is provided, in the following paragraphs it is explained how they are determined.

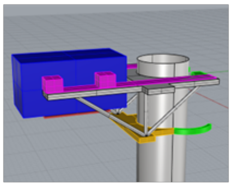
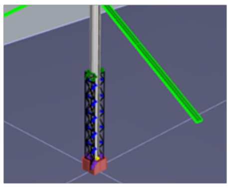
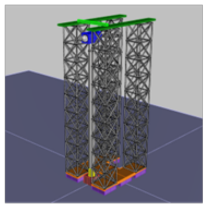
Cost-effectiveness \ Concept	Concept 1: Elevator Platform (GC-5) 	Concept 4: Lifting Frame(GC-13) 	Concept 5: Semi-submersible installation tower(GC-3) 
Installation time [hours]	99	13	30
Waiting on weather [relative]	GC-5>>GC-3>GC-13		
Vessel costs [k€/day]	Supporting vessel: 150-300 (not needed for entire procedure) Barges: 6-10	600-1000	Semi-submersible: 250-375 Barges: 6-10
Equipment costs [k€/day]	30-45	60-90	Vessel includes equipment

Figure 6.1: Summary matrix of the cost-effectiveness of the feasible methods.

The first factor is an estimation of the installation time, the installation time will be estimated by assuming perfect weather conditions and logistics. Each action within the procedures can be performed in perfect succession without waiting on weather or waiting on vessels, equipment, or components to arrive at the installation site. The waiting on weather part will be discussed in the next factor that is evaluated. This to create a benchmark for each concept that is based on the same underlying principles. It will be estimated by listing the actions that have to be performed to complete the installation. Followed by an estimate of the duration of each action by investigating comparable installation methods, and approximated lifting speeds of equipment. By no means this can be considered an accurate estimate, however, the same estimated for certain actions will be used for all concepts to base the estimation on the same benchmark. Leading to a comparative time estimate rather than an actual time estimate. The goal is to investigate the relative differences in installation time, and to document which steps during installation are the most time-consuming. The entire estimation can be found in Appendix K, and a summary is provided in Figure 6.1. From the analysis, it surfaced that the elevator platform will have the longest installation time of around 100 hours, followed by the semi-submersible installation tower concept, which has an installation time of around 30 hours, and the lifting frame will have the shortest installation time of around 12 hours.

To put this into perspective, a smaller turbine can be installed with an average installation time of 40-60 hours[51] depending on location and used foundation type. This is the total installation time, including waiting on weather, so a one-on-one comparison cannot be made with the installation times presented here. However, it shows that installation using the elevator platform takes significantly longer than what is currently average. The installation tower concept can, in theory, reach this average installation time if not too much waiting on weather occurs. The lifting frame concept can install a wind turbine in significantly less time than averaged, however, no integrated installation techniques were analysed in the article describing installation times[51].

One final note should be given on the elevator platform concept. The tower installation will take about half of the total installation time. If the assumed tower piece height has to be reduced due to lifting stability considerations, or the assumed lifting speed of strand jacks cannot be reached, the installation time will blow up further. Both cases might justify the use of a secondary installation method that can install a wind turbine tower in one piece, such as the proposed pivot method in Section 5.6. The reduction in installation time could prove beneficial to the overall costs of installation, even if a secondary system is used. If this is the case, cannot be said without further evaluation of the costs of the installation procedures.

The second factor is the waiting on weather. This cannot be fully determined, as no in-depth workability analysis was performed during the research. However, a relative qualitative discussion can be had about how much the weather influences the concepts. Installation time is leading during this discussion, as a longer installation time inherently has a larger time waiting on weather. The longer a method takes to install a wind turbine, the greater the chance that during this time the weather will become too harsh to function safely. Another way of formulating this is that a larger weather window is needed before a method with a long installation time can be safely deployed. So, the longer the installation time a method has, the larger the needed weather window, the larger the impact of weather on a method, and thus more time waiting on weather.

This, in conjunction with the common workability characteristics of vessels, is used to determine the relative workability of the methods. For this, the assumption is made that barges have the lowest workability, followed by non jack-up mono-hull vessels and semi-submersibles having the highest workability. This is not true for any and all locations on earth, as workability is determined by the response of vessels to excitation with a certain period, amplitude, and direction. The periods, amplitudes, and common wave directions of some locations, might make it that a semi-submersible vessel is exited more than a mono-hull vessel. However, in general, this statement is true. The discussion on the workability is listed below.

- The elevator platform concept (GC-5) uses feeder barges and a mono-hull lifting vessel. The mono-hull vessel is only needed for attachment and detachment of the platform, and barges are needed throughout the installation of the ULWT to feed in components. The barges have the lowest workability of the 3 types of vessel which are considered, and are used throughout the entire installation procedure. The procedure is also the longest of all feasible concepts. This makes that the downtime due to weather of this concept is deemed the largest of all three concepts.
- The other 2 concepts both use a semi-submersible vessel as main installation vessel, and depending on the choice of logistical process both require feeder barges, so on this basis no distinction can be made. However, split installation inherently takes longer than integrated installation, as was also determined during the installation time estimate.

Thus, the integrated lifting frame concept using a large semi-submersible(GC-13) will be the least affected by weather, and the semi-submersible installation tower(GC-3) will be moderately affected by weather. This makes that the waiting on weather is worst for the elevator platform, followed by the semi-submersible installation tower concept and the least downtime will be for the integrated installation concept, as can be found in Figure 6.1.

The third factor that determines the cost-effectiveness is the cost of the vessels that are used during the installation procedure. It will be expressed in terms of day rate and is determined by looking at comparable vessel day rates and, if those could not be found publicly, the rule of thumb that the day rate can be estimated by the construction costs of the vessel divided by 1000, which was provided by the research's partner GustoMSC NOV. This is basically the CAPEX of a vessel averaged over 1000 active days. The full determination of the day rates can be found in Appendix K, and the final day-rates can be found in Figure 6.1. The needed vessels can be found in the list above.

The last factor is the equipment cost of a method. This will also be expressed in day-rates and is determined by use of two rules of thumb. The first being that the equipment is between 15-20 euros per kg of steel, where 15 is used for equipment with low complexity, and 20 is used for complex equipment which includes loads of hydraulics and other systems. The masses of the concepts have been determined and can thus be used to estimate the costs. Sequentially, the same rule of thumb that is used for the day-rate determination of the vessels is used to determine the day-rate. Both rules of thumb have been provided and are used by the research's partner GustoMSC NOV. The lifting frame is considered to be of low complexity and will thus have a cost of 15 euros per kg, and the elevator platform is considered to be of high complexity and will thus have a cost of 20 euros per kg. The semi-submersible tower concept does not use separate equipment and therefore will not have equipment costs, as can be seen in Figure 6.1. More information on the determination of the equipment costs can be found in Appendix K.

Note that the rule of thumb for the day-rate assumes that a vessel or equipment can be used for more than 1000 active days to reimburse the CAPEX of a concept, not taking into account costs for usage and maintenance. For vessels, this is a good estimate, as the lifetime of an average vessel is around 30 years, which leaves more than enough room to start making profit with the vessel. It can be debated whether that is desirable for equipment, as this directly relates to the assumed lifetime of the equipment. If the maximal predicted lifetime of the equipment is lower than 1000 active days, the day-rate must be increased to end up with an economically feasible piece of equipment. However, for now, it is taken as applicable, as no goal on or estimations of the lifetime of equipment has been made. However, the day-rate should be related to the minimal lifetime of a piece of equipment if further work is done on the concepts. Furthermore, using the same basis for the cost-estimation for all concepts results in a more clear and fair comparison.

6.2. Safety

In this section, the relative differences in safety of the 3 feasible concepts will be discussed. Safety is hard to quantify, so the choice was made to look at the number of mating procedures that must be performed to fully erect a wind turbine. This is due to the fact that mating procedures are the most dangerous, as personnel has to be present to guide and connect components to each other. Some proposed concepts make use of guiding frames and/or automatic mating, resulting in less dangerous mating procedures, but personnel will still have to perform the bolting of mated components. The full description and reasoning behind the inclusion of this consideration can be found in Subsection 3.2.3. The summary of all factors in the consideration of safety can be found in Figure 6.2, in the following paragraphs it is explained how they are determined.

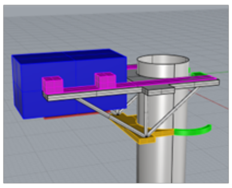
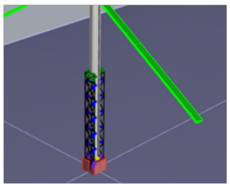
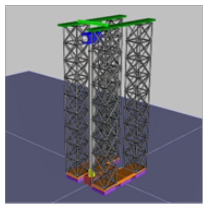
Safety \ Concept	Concept 1: Elevator Platform (GC-5) 	Concept 4: Lifting Frame(GC-13) 	Concept 5: Semi-submersible installation tower(GC-3) 
Number of mating procedures	11	1	6
Nature of mating procedures	GC-3<GC-5<GC-13		

Figure 6.2: Summary matrix of the safety of the feasible methods.

The number of mating procedures is determined by summing up all the procedures where something has to be mated, including the attachment of equipment to a wind turbine like the elevator platform. The elevator platform must use a modular tower, which will inherently require more mating procedures than the other concepts. For the determination of the amount of procedures, the same assumptions were used as during the determination of installation time, that the modular tower is installed in six pieces. The initial largest piece of 50 metres by a mono-hull vessel, followed by five pieces of around 34 metres to reach the needed hub height. After that, the nacelle and blades are installed separately.

The lifting frame concept is an integrated lift concept and thus only has one mating procedure, if the detachment and placement on deck/transportation barge of the frame is not seen as a mating procedure. The semi-submersible installation tower concept uses split installation with two tower pieces, to reduce the needed crane capacity. This leads to six mating procedures in total.

The nature of the mating procedure is the secondary factor that is used to judge the concepts on safety. The nature refers to how dangerous the procedure is, this is not easy to quantify and will thus be considered using a qualitative discussion. The discussion on each of the methods is listed below:

- The first concept, the elevator platform, has mating frames that guide the tower pieces and nacelle into place without the help of personnel. However, the mating procedures will still require personnel to bolt components together. The blades will need help of personnel to mate and check the alignment of blots to the flanges on the hub. All procedures have to be performed at high altitude.
- The lifting frame concept only has one mating procedure, which is also guided by a guiding frame and can be performed at relatively low altitude. Due to the frame hanging of two cranes, the frame can rotate slightly, and thus personnel will be needed to check the alignment of bolts and flange.
- The semi-submersible installation tower has six mating procedures, all of which will require personnel to be present, as they are performed in a traditional fashion. The procedures are also at high altitude.

This makes that the mating procedure of the lifting frame concept is deemed the least dangerous, followed by the elevator platform, and the semi submersible installation tower is deemed the most dangerous, albeit it is quite similar to the elevator platform. The difference is that guiding frames are used for mating of tower pieces and the nacelle. The summary of the comparative analysis regarding safety can be found in Figure 6.2.

Some notes on safety must be given on 2 of the concepts; the elevator concept requires personnel to be present on the platform at all times, unless remote operation of lifting and skidding systems is possible. In the event of failure of the platform, all personnel on it will be in danger of serious harm due to the altitude at which the platform operates. Fail-safe systems must be in place and personnel must be able to safely exit the platform at all times during the installation.

The second note is on the internal lifting performed by the semi-submersible installation tower. This has both advantages and disadvantages; one advantage is the options for 3D motion compensation by tugger lines or other compensation devices. The main downside of this is that the entire lift takes place above the vessel's deck, in the event of catastrophic failure of the lifting devices, the cargo will drop on top of the deck. Tower pieces can be especially dangerous, as they can easily cut through the upper deck.

6.3. Complexity

In this section, the complexity of the feasible concepts will be assessed. Complexity is subdivided into two main categories, the complexity of the mechanisms a concept needs to perform the installation procedure, and the complexity of the process. The first is judged by listing the amount and type of mechanisms needed for a concept to function and sequentially determining if they are based on proven technology or not. The second category is judged by listing which actions have to be performed simultaneously and discussing which processes are most to least complex. The full reasoning and description of all factors used to determine the complexity of the methods can be found in Subsection 3.2.4 and the summary of the judgment can be found in Figure 6.3. In the following paragraphs, it is explained how they are determined.

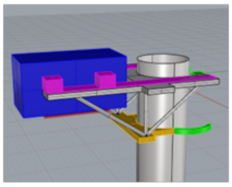
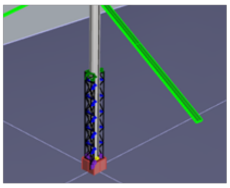
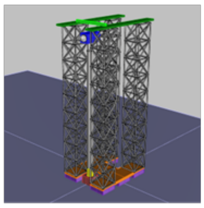
Complexity \ Concept	Concept 1: Elevator Platform (GC-5)	Concept 4: Lifting Frame(GC-13)	Concept 5: Semi-submersible installation tower(GC-3)
			
Number of major mechanisms and components	6	3	3
Technological readiness of mechanisms	Separately all used before, combined never.	All mechanisms and components based on proven technology.	Gantry crane used before on shore never on this scale on floaters.
Maximum number of activities at the same time	1) Mooring feeder barges; 2) Lifting/lowering of lifting mechanism; 3) Moving up of lifting point.	1) Double crane operation; 2) Opening up of frame.	1) Lifting of component; 2) Motion compensation.
Complexity of actions	GC5>>GC-13>GC-3		

Figure 6.3: Summary matrix of complexity of the feasible methods.

The first category of complexity of major mechanisms is judged by summing up all the main mechanisms that make up the concept. All the mechanisms needed for each concept are listed below.

- The elevator concept has six main components, as described in Subsection 5.7.2;
- The lifting frame has three main mechanisms and components, the frame, skidding mechanism and the guiding frame as described in Subsection 5.7.2;
- The semi submersible installation tower has three main components, the gantry crane, the motion compensation system, and the entire vessel as described in Subsection 5.8.2.

It can be seen as unfair to compare the semi-submersible concept with the other two, as the last concept requires the construction of an entire vessel, opposed to a relatively small frame or platform. However, during the assessment of complexity, no notion is given to the investment costs or size of the needed components and mechanisms, only to the amount and technological readiness of said components and mechanism. A discussion on the technological readiness of each concept is listed below and is summarised in Figure 6.3.

- The elevator platform concept mechanisms are all based on proven technology, as each individual mechanism has been used before on a commercial scale. However, the combination of these mechanisms and components has not been used before. Separately, all components are known to work and have high technological readiness, only the integration of them will require further work. This is not entirely true for strand-jacks, which will be used for the lifting of the components, as they have traditionally been in use for singular lifts, if and how many times a single strand can be reused during lifting must be further investigated;
- The lifting frame concept is fully based on proven technology, the frame is a low tech construction where only some sort of opening mechanisms is needed. The frame itself has never been used before, but as it consists of relatively low tech components, it can be said that it is indeed based on proven technology;
- The semi-submersible installation tower concept is semi-based on proven technology. The vessel itself can definitely be built, as comparable lifting semi-submersibles have been in commercial use for the last few decades. The only thing that has not been used on a large scale before, is the

gantry crane on top of the vessel at such a large altitude. Gantry cranes of these dimensions exist and are in commercial use in, e.g., the ship building industry, but have not seen use in the offshore environment. More work will need to be performed on the design of the crane to make it sea-fast.

The second part of the complexity is the complexity of the process, to judge this, the installation time action list that can be found in Appendix K is used. This list was also used for the estimation of the installation time. When looking at the maximum number of operations that must be performed at the same time, an initial idea about the complexity of the process could be established. No regard is given to the station keeping of vessels, as all concepts need this to function. In the list below, the discussion for each concept can be found, and is summarised in Figure 6.3.

- The elevator platform concept has to perform a maximum of three actions simultaneously. It occurs right after the installation of a tower piece, when the auxiliary crane must be used to move up the lifting points of the platform, the lifting frame has to be lowered to sea level, and a barge must be moored next to the foundation to feed in the next tower piece. The latter two have a great effect on each other, as the drop-off point must be aligned with the feeder barge. The first one does not have a direct effect on the latter two actions, but it still has to be performed at the same time, requiring more personnel and coordination;
- The lifting frame concept has two operations that have to be performed simultaneously. They occur immediately after the installation of the wind turbine. The lifting frame must be opened, while the double cranes keep the frame balanced and detach it. A double crane operation is inherently complex, as the two cranes both have an operator. These operators must be in contact with each other and a coordinator to safely perform lifts.
- The semi-submersible installation tower concept also has a maximum of 2 operations, which have to be performed simultaneously. The lifting of a component and the motion compensation of it(if needed). The concept only uses a single crane, making the lift easier compared to the lifting frame, also less weight is attached to the crane. The lift is also internal, so motion compensation will be easier to pull off.

Due to the number of actions that must be performed at the same time, the elevator platform is deemed to have the most complex process. Followed by the lifting frame, as a double crane operation is needed. The semi-submersible installation tower is deemed the least complex in terms of process, as only a single crane is used during mating. The summary of all the factors that describe complexity can be found in Figure 6.3.

6.4. Flexibility

In this section, the flexibility of the feasible methods will be assessed. This will provide a better view on the usability of the concepts. Three main aspects are described, first, whether the method can be used for major repair and replacement, second, what the effects on the concept are when different types of bottom-founded foundations are used, and finally, the effect of different sizes of wind turbines on the concepts. The full description and reasoning behind the inclusion of these factors can be found in Subsection 3.2.5, and the summary of the discussion can be found in Figure 6.4.

The first aspect is the use of concepts for the repair and replacement of components. Hub heights will be out of reach of conventional cranes and vessels. In the event that a major failure occurs, components will have to be replaced, these failures will occur one way or another and must be dealt with. This aspect is split up into two parts, the first one simply looking at if a concept is usable for major repair and replacement, and the second part describing how long it takes for a method to prepare for major repair and replacement. The latter to be able to possibly identify outliers, which could mean that a concept can be used for major repair and replacement, but it is not practical.

Thus, if a concept can also be used for major repair and replacement, the bottleneck is also solved. The time leading up to a repair or replacement action is calculated using the installation time estimation action list presented in Appendix K and is summarised in Figure 6.4. The judgement on this for each concept is listed below.

- The first concept, the elevator platform, can be used for blade repair and replacement. The platform can be re-attached to the tower and the reverse procedure of installation followed by installation of a new blade can be performed. If heavy components inside the nacelle have to be replaced, it becomes more difficult. The auxiliary crane must have enough capacity to lift heavy components, it is assumed to have a maximum capacity of 20 tonnes, which is too low for replacement of, e.g., a gearbox. Two options arise to circumvent this, The size and capacity of the auxiliary crane can be increased, if it is deemed cost-effective. The second option is to design a crane that can be lifted by the lifting mechanisms with the appropriate capacity and boom length. It must then be placed on a specifically designed lifting device, and can be used for major repair and replacement of components within the nacelle. If this is cost-effective must be investigated, but technically speaking it would be possible;

- The lifting frame concept cannot be used for major repair or replacement of components. It can only carry a fully assembled wind turbine and does not provide a platform for cranes or lifting devices that can reach up to the needed height;
- The semi-submersible installation tower can easily be used for major repair and replacement, due to the characteristics of the gantry crane. It reaches above the hub height and can lift an entire nacelle, thus, smaller components within a nacelle can also be lifted. Blade replacement using this concept is the same as installation, which it is designed to perform.

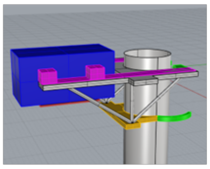
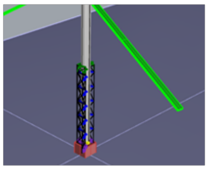
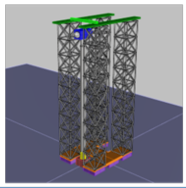
Flexibility \ Concept	Concept 1: Elevator Platform (GC-5) 	Concept 4: Lifting Frame(GC-13) 	Concept 5: Semi-submersible installation tower(GC-3) 
Usable for major repair and replacement	Yes Note: Does need large auxiliary cranes if nacelle components have to be replaced	No	Yes
Set up time for repair and replacement	Mooring, attachment and elevation of platform needed. +-8 hours	n/a	Only mooring and feeding of components needed. +- 5 hours
Change in (bottom founded) foundation effect on concept	No effect	No effect	No effect
Alterations needed due to change in foundation	n/a	n/a	n/a
Change in turbine size effect on concept	Concept can only be used on small range of turbine sizes.	Depending on the modularity of the frame the concept can be used on a medium range of turbine sizes.	Only affected by hub height and nacelle weight and can thus be used for a wide range of turbine sizes.
Alterations needed due to change in turbine size	Full redesign needed for larger or smaller turbines.	- Frame width; - Counterbalance mass.	- Height of towers on deck; - Gantry crane construction.

Figure 6.4: Summary matrix of flexibility of the feasible methods.

The second aspect is the influence of foundation type on the concepts. All concepts are not affected by the change in foundation type, as long as the foundation is bottom-founded. The only type of foundation that would affect the concepts is a gravity-based foundation, as these have larger surface area at and below the water line. This would make the mooring of feeder barges within the range of the elevator platform impossible, and might not fit into the moon pool like centre of the installation tower concept. However, this type of foundation cannot be used effectively in water depths of 60 meters[59] and will therefore not be considered. A summary of this aspect can be found in Figure 6.4.

The final aspect is the influence of changes in the size of the wind turbine on the concepts. Changes here refer to the increase or decease in size of the wind turbine relative to the ULWT. A concept can preferably be used for a wide range of turbines, so that it can also install smaller turbines, and can be used if turbines are up-scaled beyond the size of ULWTs. Being able to use a concept for a wide range of turbines drastically increases the lifetime of a concept, increasing the cost-effectiveness. The influence of wind turbine size on all concepts is listed below and summarised in Figure 6.4.

- The elevator platform is designed around one particular turbine. This inherently means that it can only be used for a small range of turbines. The diameter of the tower highly influences the size of the platform. The size and weight of the nacelle are guiding for the size and weight of the platform and lifting devices. Probably some form of modularity can be achieved for the platform, but even then it can still only be used on a small range of turbines, slightly larger and heavier, or smaller. For the use with larger or heavier wind turbines, the platform will need a full redesign of all parts to accommodate to this;
- The lifting frame concept can be used for a medium range of turbines. Smaller is always possible, as those turbines are also lighter, and will thus be stable when using the frame. In this case, the attachment points of the frame to the tower will need to be reduced in diameter, so modality is preferred. The needed counterbalance mass will also be lower, if this can also be made modular, the total mass of the frame can be reduced. Resulting in a frame that is easier to handle. Larger turbines will tend to be heavier, causing stability problems and problems with the width of the frame if the tower diameter exceeds this. If the frame can be made modular in height and counterbalance mass, it can cater to a wider range of wind turbines more efficiently;
- The semi-submersible installation tower can be used for a wide range of wind turbines. Smaller is always possible, and larger to a certain degree. The limiting factors for larger turbines are the height of the towers on the semi-submersible vessel above the deck, and the capacity of the gantry crane. If a turbine exceeds the height of the towers or the maximum capacity of the gantry crane, it cannot be installed. It might be beneficial to over-dimension the concept so that its lifetime can be increased, and larger turbines can also be installed.

6.5. Influence on wind turbine construction

In this section, the influence of a concept on the construction of a wind turbine will be discussed. This is an important factor, as wind turbine designers and producers tend to dislike changes to the design of the turbines. The full reasoning behind the inclusion of this factor and an in-depth discussion can be found in Subsection 3.2.6, the summary of this feasibility consideration can be found in Figure 6.5.

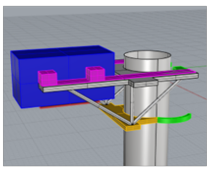
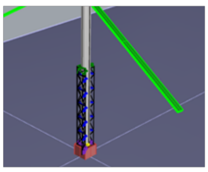
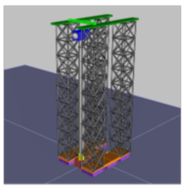
Influence on construction / Concept	Concept 1: Elevator Platform (GC-5) 	Concept 4: Lifting Frame(GC-13) 	Concept 5: Semi-submersible installation tower(GC-3) 
Influence on wind turbine construction	Yes, modular tower and inclusion of lifting pulleys at tower top	no	no
Drasticness of alterations	Splitting up towers is common practice already, however, not in this many pieces. Lifting wires and pulleys remain on tower after installation.	n/a	n/a

Figure 6.5: Summary matrix of influence of wind turbine of the feasible methods.

Only one of the concepts has influence on the construction of the wind turbine, the elevator platform. Two main changes must be made, both affecting the tower design. The first is the splitting up of the tower into many pieces. For the calculation of the installation time, it was assumed that the tower must be split into 6 pieces. The main effect of this is that more flanges are needed in the tower to connect the pieces relative to a one- or two-piece tower. Requiring the tower design to take the installation method into account, raising the discussion if an installation method should follow the design of wind turbines or the other way around. The general answer to this question is that if there is no need to alter the design of wind turbines, this is always preferred. However, in the case where no other way of installation is possible, due to vessel availability or the availability of other installation methods, it might still be beneficial to the overall costs of installation.

The second effect on the design of the tower is the inclusion of the platform lifting mechanisms, as described in Subsection 5.4.2. Pulleys have to be present on the tower to make it possible to raise and lower the platform. These pulleys will be moved upward during tower installation up until the hub height is reached. They will remain between the tower and the nacelle so that the platform can be reattached if major repair or replacement of components is needed. This also means that the lifting wires must remain attached to the pulleys at all times. The downside of this is that there will be wires and pulleys exposed to the environment, as they are located on the outside of the tower. The wires have to be tensioned at all times, to make sure they do not hit the tower, as this can damage the paint and construction over time. Paint is there to keep oxidisers of the steel construction away from the steel, damage to this can cause corrosion and become problematic when not treated. The other 2 concepts do not have any effect on the design of the wind turbine, the discussion of influence is summarised in Figure 6.5.

6.6. Summary of comparative analysis and usability discussion

In this section, a summary of the comparative analysis, and usability discussion of the three technically feasible concepts are provided. First, a discussion of all relative comparisons of the feasibility considerations is presented. Within this discussion, the concepts will be roughly ranked from worst to best on each of the feasibility factors. However, no valued judgment will be provided, as the assessment is based on relative differences and serves to identify and describe the shortcomings and usability of the concepts. The latter will be discussed in the final subsection.

6.6.1. Summary and discussion on relative comparison

The economic feasibility considerations will be discussed in the same order as they were presented in the previous sections, starting with the cost-effectiveness. The discussion will include qualitative scoring where this is possible, and to further describe the relative differences, no comments will be made on how large the differences are, as no way of quantifying and weighing all factors has been defined. Even without this, the differences between the methods will become clear.

The first feasibility consideration is the cost-effectiveness. The eventual costs of a method depend on two main factors, the day-rate of all vessels and equipment combined, and the installation time. The effect of waiting on weather could not be fully assessed, thus, no real conclusion can be drawn yet about the overall costs. However, a discussion can be had on the effects of the combination of day-rate and installation time. The end goal is to have as low as possible installation costs, so either installation time or day-rates must be low. Three degrees of combinations of day-rate and installation time emerged:

- The elevator concept can function with relatively small vessels and cheap equipment, but it has a longer installation time;
- The lifting frame concept has a relatively large and expensive vessel, but a low installation time;
- The semi-submersible tower concept has relatively medium-sized vessel and installation time.

All three approaches could be valid from a cost-effectiveness point of view, depending on the actual waiting on weather time. No conclusion can be drawn on the relative costs effectiveness, as one concept takes long but has a low day-rate, one concept is fast but has a high day-rate, and one concept is in the middle of both. The result is that no best concept based on cost-effectiveness can be defined.

During this comparison, only the installation time of one turbine is included, as no case has been defined regarding a wind farm. Due to this, possible parallel installation has not been included into the analysis. This is of interest for the elevator platform concept, as if multiple platforms are available, parallel installation of wind turbines is possible. This will decrease the overall installation time for an entire wind farm compared to non-parallel installation. Further research will have to be done into optimised logistical processes, and the waiting on weather of the concepts to get a more in-depth view on the costs of installation.

The second feasibility consideration is safety; the discussion of safety is listed below from the most dangerous to the least dangerous.

- The installation tower and elevator platform score about the same and are deemed more dangerous than the lifting frame concept. Most of the mating procedures performed by the elevator platform are automated, but more of them must be performed. When using the installation tower semi submersible, the mating procedures are more difficult, as no guiding frames are used, but fewer procedures have to be performed.
- The lifting frame concept is the least dangerous. Only one procedure must be performed, which is also guided.

The third factor is complexity. Below, the concepts are ranked from most to least complex.

- The elevator platform scores worst, as the equipment has never been used in an integrated manner, and the processes required for installation require a high degree of coordination and preparation to perform safely.
- The lifting frame concept is medium complex compared to the other methods. The equipment used is based on proven technology, and the installation process is straightforward, apart from the double crane operation.
- The installation tower semi-submersible is deemed the least complex. The equipment used is based on proven on-shore technology, albeit it still has to be made usable offshore. The process is entirely based on the traditional wind turbine installation procedure.

The fourth factor is flexibility; below the concepts are listed from least to most flexible and a short explanation is provided.

- The lifting frame scores the worst overall, as it can only be used for installation and is affected to some degree by the turbine size;
- The elevator platform is deemed medium flexible, as it can be used for repair and replacement, but is highly affected by the turbine size. If the latter makes the elevator platform can be deemed less flexible, then the lifting frame is open for debate;
- The semi submersible installation tower is the most flexible of all concepts. It can be used for a wide range of wind turbines, and for major repair and replacement of all components of a wind turbine. Only the height of the towers and weight of the entire nacelle influence the flexibility.

The last factor is the influence on the construction of wind turbines. Only the elevator platform has an effect on the construction of the wind turbine, as the tower must be modularised in this case. The splitting up of the tower inherently leads to longer installation times, and a tower redesign will be needed. The other methods do not have an effect on the construction of the wind turbine. A summary table of all considerations can be found in Figure 6.6.

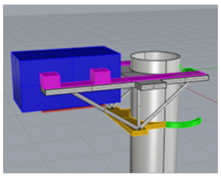
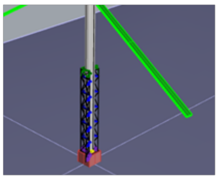
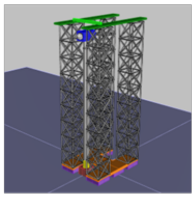
Considerations \ Concept	Concept 1: Elevator Platform (GC-5) 	Concept 4: Lifting Frame(GC-13) 	Concept 5: Semi-submersible installation tower(GC-3) 
Cost-effectiveness	Time: +-100 hours Waiting on weather: Most Day-rate: Lowest	Time: +-12 hours Waiting on weather: Least Day-rate: Largest	Time: +- 30 hours Waiting on weather: Middle Day-rate: Middle
Safety	Mating procedures: 11	Mating procedures: 1	Mating procedures: 6
Complexity	- Individual components high technological readiness, integration still needed. - Complicated procedure, requiring high degree of coordination.	- Low-tech frame based on proven technology. - Double crane operation, requires high degree of coordination.	- All components based on proven technology, gantry crane must be made usable in offshore environment. - Easy process based on traditional installation practices.
Flexibility	- Usable for major repair and replacement of blades. - No effect of different foundation type. - Highly effected by turbine size and design.	- Unusable for major repair and replacement. - No effect of different foundation type - Moderately effected by turbine size and design.	- Usable for major repair and replacement of all components. - No effect of different foundation type. - Slightly effected by turbine size and design.
Influence on WT construction	Modular tower	None	None

Figure 6.6: Summary matrix of all feasibility considerations for the technical feasible concepts.

6.6.2. Usability discussion of technically feasible concepts

In this subsection, the usability of each of the technically feasible concepts will be discussed. The usability is defined using all knowledge gained up to this point, of both the discussion in the sections above and during the technical feasibility assessment summarised in Section 5.10. All three concepts were deemed technically feasible and have been judged on the relative differences regarding the economic feasibility considerations. No valued judgment has been made on the relative differences, as each of the concepts will be usable.

The elevator platform concept scores relatively bad on all feasibility considerations. This might seem as though this concept can be deemed unusable on grounds of the comparison. However, it is the only concept of technically feasible concepts that can be used with relatively small mono-hull vessels. The other concepts require semi-submersible vessels, one even a purpose-built one. The main downside of this concept is the large effect of turbine design on the usability of the concept. Only a relatively small range of turbines can be serviced and installed by one particular platform, as an entirely new platform needs to be built to install larger or smaller turbines.

The lifting frame concept can only be used by a handful of vessels due to the requirements on lifting capacity and the need for double cranes. Currently, only the Sleipnir, Saipem7000, and Thialf have enough capacity to use the lifting frame. Raising one big issue regarding the availability of the vessels for the installation of ULWTs using the lifting frame concept. Furthermore, the concept can only be used for installation purposes and the frame can only be used for a relatively small range of turbine sizes. Especially for larger and heavier turbines, they require the construction and design of a new frame. Thus, the usability of this concept is quite limited; it can only be used for installation for a relatively small range of turbines. Due to the needed mass of the counterbalance, the frame will also be quite expensive relative to its limited usability. Furthermore, to meet the global demand for installation of ULWTs, much more than three of these vessels will be needed. Therefore, more of these vessels must be constructed or combinations of methods must be used to meet the demand.

The main downside of this method is that on-shore assembly of the wind turbine is required, this requires innovation of harbour facilities. Not every harbour in the world can cater to this innovation, as requirements of quay side capacities, marshalling yard sizes, or harbour water depths cannot be reached everywhere. Thus, this concept needs the availability of large harbours near the installation site to be cost-effective, as otherwise transit times will have a snowball effect on the costs of the method.

The installation tower semi-submersible concept requires the construction of a new purpose-built vessel. This requires a large investment from a company that dares to create such a vessel. Again, a single vessel will not be enough to cater to the global demand of installation of ULWTs, but rather a whole fleet of vessels will be needed. One big plus for this concept is that it can easily be used for installation, and major repair and replacement of wind turbine components of all sizes below the maximum size of the vessel. Resulting in a larger usability range than the other methods. Possibly warranting the construction of a large fleet of such vessels, as repair and replacement is needed for all sizes of wind turbines. In the case that the capacity of the vessel is large enough, it might also be usable for the integrated decommissioning of wind turbines, further expanding the usability of this concept. On-shore assembly of ULWTs is not needed, so the requirements on the harbour are significantly lower, opposed to the lifting frame concept. However, due to the size and draft of the vessel, not all harbours can accommodate these vessels.

Therefore, from a singular installation procedure point of view, the concepts of the lifting frame and installation tower are definitely viable, but considering the entire market and future demand for installation, it is also promising to utilise different installation techniques that can be used by smaller vessels. Furthermore, more and more installation vessels are being built which can install smaller wind turbines. Within the lifetime of these vessels, wind turbines are set to outgrow either the size or lifting capacity of these vessels. Rendering them unusable for traditional means of installation of larger turbines. However, if concepts such as the elevator platform are realised, these vessels can still be used. They will not end up without work in the offshore wind industry, or need a large refit of e.g. the crane. These vessels can also be serviced in more ports than the other 2 concepts, increasing the locations where the elevator platform concept can be economically more attractive than the other concepts.

In conclusion, all three concepts can be used for the installation of ULWTs, but seem promising under different circumstances. The lifting frame concept needs availability of large harbours near the installation site where the ULWT can be assembled on-shore, and the semi-submersible can be moored. The installation tower semi-submersible concept can be used in more circumstances, as it does not require on-shore assembly of wind turbines. The main downside of both concepts is that they require vessels that are not widely available(yet). Therefore, in the case that these vessels cannot be used cost-effectively due to requirements of the harbour or vessel availability, the elevator platform concept can be used. If and only if the tower design allows for the stresses introduced due to the lifting of the nacelle. A more in-depth assessment of the economic feasibility is needed to investigate the cost-effectiveness of each concept. This helps to further define the cost-effective scenarios in which they can be used. This will not be performed during this research, but is recommended.

6.7. Summary of technically feasible concepts

In this section, a summary of all three feasible concepts will be provided, all information obtained and generated up to this point will be summarised to show all selling points, pros, and cons of the concepts. The concepts are all deemed technically feasible and attractive under different circumstances, as described in the previous section. First, a description of all three concepts is provided, in which the most important findings are described. It is followed by a summary table that shows the technical feasibility classification, all pros, cons, and notes on the three feasible concepts.

Self climbing mechanism, the elevator platform

- Description: A platform which is attached to the wind turbine tower and can elevate and lower by use of automatic winches placed on the foundation. A secondary component lifting mechanism consisting of strand jacks is placed on the platform, to decouple the lifting mechanisms of the platform and the components. A component is lifted at a sufficiently large radius parallel to the tower. Once on top of the platform, skidded over the flange of an already installed component, after which it is mated and bolted. Components are fed into the system by barges. The main particulars are summarised in Table 6.1, a more in-depth view on the design is presented in Section 5.4 and Appendix F.
- Highlighted pros:
  - Can be used with current lifting vessels, as capacities of around 1500 metric tons are needed;
  - Relative motions are a non-issue during mating, as the platform is fixed to the tower;
  - Relatively low day-rate, due to small size and relatively low weight of the concept, the construction costs are relatively low.
- Highlighted cons:
  - Highly effected by turbine design and size, the platform can only be used on a small range of turbines. Raising issues with the lifetime of one particular platform;
  - Long installation time, inherently takes long due to splitting up of the wind turbine tower.
  - Relatively large waiting on weather time, due to use of feeder barges and long installation time, suitable weather windows will be far and few between.

One note has to be further explained, related to the installation time of the elevator platform. Almost half of the installation time is spent on the tower installation. One option to reduce this is to use hydraulic lifting winches instead of strand-jacks, as the bulk of the tower installation time is due to the lifting speed of strand-jacks. The downside of lifting winches is that they are several times larger and heavier than strand-jacks. This will have a snowball effect on the entire weight of the platform, as it still has to be able to carry the equipment. Another option is to use a different tower installation technique, such as the concepts from the pivot branch, as discussed in Section 5.6. This can radically reduce installation times, and comes with an added benefit of options to place the lifting equipment for the elevation of the platform inside the tower structure.

Table 6.1: Main particulars elevator platform

Parameter	Value	Parameter	Value
Length overall[m]	51	Width overall[m]	30
Height overall[m]	18	Weight platform[ton]	1500
Distance COG nacelle to tower[m]	30		

Integrated installation method, the lifting frame:

- Description: A frame with a counterbalance at the bottom. A pre-assembled turbine is placed within the frame and can be lifted using a double crane set up on a semi-submersible vessel like the Sleipnir. The presented main particulars in Table 6.2 are for use with this vessel, other vessel require slight adaptations to frame height and counterbalance mass. More information on the concept can be found in Section 5.7 and Appendix I.
- Highlighted pros:
  - Usable with current semi-submersible lifting vessels, albeit only the three largest ones in the world, Sleipnir, Thialf, and Saipem7000;
  - Relatively non-complex equipment, it is basically only a frame with a counterbalance on the bottom;
  - Reduces the height at which mating has to take place and of cranes. Reducing relative motions.
- Highlighted cons:

  – Heavy frame and counterbalance, large weight means difficulties with handling and storage, and relatively high day-rate of equipment due to sheer amount of steel needed;
  – Needed vessels are expensive to charter or build;
  – Onshore pre-assembly is needed, requirements on the quay side and onshore cranes make that innovation in port will be needed. Even the largest on-shore cranes in existence cannot reach the required capacity and height combination needed for the installation of ULWTs.

Table 6.2: Main particulars lifting frame.

Parameter	Value
Height frame [m]	110
Width frame [m]	17.5
Mass frame [ton]	385
Mass ballast [ton]	2000
Mass assembly [ton]	8405
Height COG assembly [m]	104.4

Large man made floater, semi-submersible installation tower:

- Description: The concept consists of a semi-submersible vessel with large lattice towers on deck. On top of these lattice towers, a gantry crane is placed, with the capacity to lift nacelles. Making internal lifting of wind turbine components possible. There are U-shaped holes at the stern and aft of the vessel in the deck. This so that the vessel can moor off with the foundation in the centre of one hole on one side of the vessel, and components can be fed in using barges on the other side. More information on the concept can be found in Section 5.8. The initial sizing and reasoning behind the sizing can be found in Appendix J. The main particulars can be found in Table 6.3
- Highlighted pros:
  – Internal lifting, makes 3D motion compensation possible, expanding the workability of the concept. How much must be investigated in further research;
  – No effect on turbine design, traditional split installation is possible;
  – Relatively flexible, usable for major repair and replacement of all parts of a wind turbine, and can be used for a wide range of turbine sizes.
- Highlighted cons:
  – Expensive never before built semi-submersible vessel, vessels like this require huge investments and take a long time to build;
  – Size of vessel, makes that not all ports can service it, and it can only operate in moderately deep waters;
  – Many vessels needed to cater to global demand of installation, a fleet of likewise vessels would be needed to cater to the demand, requiring huge investments.

Table 6.3: Main particulars of semi-submersible installation tower.

Parameter	Value	Parameter	Value
Length overall[m]	120	Displacement[m3]	50000
Width overall[m]	100		
Height towers above deck[m]	270	Capacity gantry crane [ton]	200
Draft[m]	10.5	GM_{xx}[m]	6.7
Free board[m]	14.0	GM_{yy}[m]	13.9

All information and knowledge gained on the technically feasible concepts is summarised in Figure 6.7. The information presented in the matrix follows from the technical feasibility discussion of the three concepts presented in Chapter 5 and the feasibility consideration evaluation presented during this chapter. Together, they provide a holistic view on the usability and technical feasibility of the concepts.

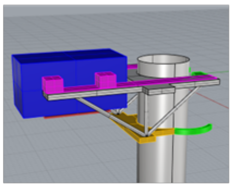
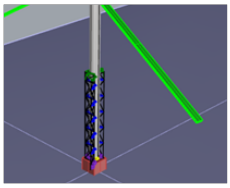
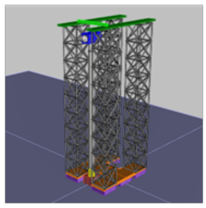
Concepts	**Concept 1: Elevator Platform(GC-5)** 	**Concept 4: Lifting Frame(GC-13)** 	**Concept 5: Semi-submersible installation tower(GC-3)** 
Technical feasibility classification	Conditionally technically feasible: - Tower design must supply enough strength; - Equipment is based on proven technology, however, never been used before in integrated manner.	Fully technically feasible: - Vessels with enough lifting capacity already exist; - Low-tech frame which is based on proven technology.	Fully technically feasible: -Vessel stability can be reached with relatively moderate size semi-submersible; - Equipment is based on proven technology, gantry must be made usable offshore.
Pros	- Relatively low day rate - Usable with current mono- hull vessels; - Parallel installation possible, given that there are multiple platforms available; - Platform is fixed to tower, reducing relative motions; - Split installation lowers requirements on harbour.	- Usable with current large semi-submersible lifting vessels; - Low crane and mating height; - Low installation time; - Only one mating procedure; - Relatively non complex equipment; - Crane capacity driven instead of height & capacity;	- Internal lifting, 3D motion compensation possible; - No effect on turbine design; - Traditional split installation procedure is possible; - Usable for relatively wide range of turbine size and designs; - Can be used for major repair and replacement of all parts; - Split installation lowers requirements on harbour.
Cons	- Highly effected by wind turbine size and design; - Large installation time; - Relatively large waiting on weather time; - Relatively unsafe; - Relatively high complexity of both operation and use of equipment; - Can only be used for major repair and replacement of blades; - Tower must be made modular.	- Relatively high day-rate; - Only 3 current day vessels can use the lifting frame; - Complex double crane operation; - Only usable for installation; - Moderately effected by turbine design and size; - On-shore pre-assembly needed, requires innovation in port; - Handling of frame and turbine assembly is difficult due to weight. *Furthermore, same cons as last three cons GC-3,*	- Expensive not yet existing purpose build vessel; - Currently only designed as crane platform, it could prove beneficial to also include storage space. - Not all ports can service vessel; - Relatively large draft requirements; - Many vessels needed to cater to global demand of installation.
Notes & Recommendations	- Half of total installation time is spent on tower; - Blade length will cause problems if increased; - Proposed lifting mechanism must be investigated further and redefinition is needed to make it independent of nacelle size.	- Modularity of counterbalance weight and frame height is preferred to increase usability w.r.t wind turbine size; - Width of frame is highly influential to lifetime of concept - Single crane usage of frame could expand usable vessels.	- Flexibility of tower must be investigated; - Effect of wind on the vessel must be investigated; - Redesign of lattice towers is needed eliminate interference with blades; - Slight over dimensioning can increase lifetime of concept drastically.

Figure 6.7: Summary matrix of, feasibility classification, pros, cons, and notes on all technically feasible concepts.

From Figure 6.7 it can be concluded that no clear winner can be selected based on the defined considerations. Two solution groups emerge from this evaluation as the main solution spaces for the installation of ULWTs using floating vessels. The groups are; self-climbers and large man-made floaters/semi-submersible vessels. The latter, as 2 of the technically feasible concepts, make use of semi-submersible vessels. The groups and their respective technical feasibility will be discussed in the next section.

6.8. Holistic discussion feasibility of branches

In this section, a holistic discussion about the feasibility of the branches will be presented. It is also important to take a step back and apply what has been learnt to the principles, rather than the individual concepts. Within this discussion, the main bottlenecks of approaches are presented, and recommendations are provided on the further development of infrastructure and/or combinations of mechanisms.

Self-climbing installation methods are definitely a viable option, as they would make it possible to install ULWTs with relatively small vessels. The main advantages of this concept group are that self-climbers fully decouple the size of the installation/support vessel from the size of the turbine, and that they are fixed to the tower, nullifying the relative motion-related issues. The main disadvantages of this solution-group/branch are that; the design of self-climbing mechanisms is inherently effected by the design of the wind turbine, and that installation times are inherently large due to the need for splitting up the tower into many pieces.

Furthermore, the design of the tower will dictate the maximum allowable moment due to the lifting of the nacelle and weight of a self-climber. It also influences the design of tower ring structures, or clamps, used for fastening the platform to the tower, as self-climbing mechanisms must fit around the tower. Resulting in a low flexibility of self-climbers, w.r.t. turbine size and design.

The design of the nacelle, especially the mass, has a large influence on the design of self-climbers, as this will always be the heaviest and widest component that will be lifted. Unless the diameters of the towers become larger than the width of the nacelle. Ideally, the self-climber can lift nacelles of any shape, so that only the lifting capacity will be limiting. If a self-climber is designed around the lifting of the nacelle, the lifting and installation of tower pieces and the blades is inherently non-critical.

Another downside of using self-climbers is that the installation of the tower becomes a time-consuming process, as it will have to be built up piece by piece. During this research, the goal was to develop an all-encompassing installation method that can be used for the installation of all parts of the wind turbine. If this boundary condition is let go, a secondary design space surfaces, the installation of blades using self-climbing mechanisms. The requirement on these self-climbers would be significantly lower, as they can be designed around the lower weight of a blade opposed to the nacelle. This was done with concept AC-3[18], so this concept is definitely promising. The lifting moments on the tower will be significantly lower in this case, making the use of self-climbers on soft-soft towers more probable. In this case, the tower and nacelle must be installed using a different method, which could be either a self-erecting method or another method that can pull this off.

Self-erecting methods, which lower the height at which the nacelle and blade have to be installed, are still promising. However, installation at the needed initial tower height cannot be pulled off yet in a competitive time frame. These methods would definitely be of interest in shallower waters where jack-up vessels can be used. Jack-up vessels are already used to install blades and nacelles around these heights, which is thus deemed technically feasible. However, if the initial tower height can be reduced, the method will also become technically feasible in deeper waters using floating vessels. In this case, another method would be needed for the installation of the blades, as they cannot be installed because of interference with the water at these lower altitudes. Two options arise, the first being, connecting the first 2 blades to the hub and placing them in a so-called 'bunny ear' orientation, where both blades are faced upward and away from the water line. Then the final blade must be installed using another method like a self-climber or another to be developed bottom-up method. The second option is to install only the nacelle on an initial tower piece, erect the tower to final height, and after install all 3 blades using another method like a self-climber. This is preferable if the loads on the hub due to the asymmetry of the blades cause problems, or when the installation time of blades using the second method is shorter than the bunny-ear procedure. The secondary blade installation method would need to be utilised for both options, so why not use it for all blades, as preparation time of the secondary method would be spent in both cases. Which case will be best cannot be determined without further research.

Concepts based on a pivot principle cannot be used in their current form. Mainly due to moments in the tower during the upending, combined with the needed lifting capacity. One option to get around this is to use hydraulic assisted lifting, or a fully hydraulic upending system. Another option is to use large lifting semi-submersibles, however, they can barely reach the needed lifting capacity. When using such a vessel, other integrated lifting techniques are preferable, as no horizontal transport and assembly is needed in this case. This is a general problem for pivot methods which cannot be easily solved. To cater to horizontal transport, the construction of the wind turbine must be altered. Furthermore, harbour and marshalling yards must be adapted to cater to the horizontal assembly, loading of the frame, and storage of wind turbines. Due to these facts, it is highly unlikely that pivot methods will be used for the integrated installation of ULWTs.

Although the method seems unusable when listing the problems, they can be used in one particular situation. Namely, the erecting of wind turbine towers, the nacelle, and the blades are the main contributor to the moments in the tower during horizontal upending and the needed lifting capacity. The approach sketched in Appendix H is used to determine the height required along the tower at which it must be supported. When only upending the tower without nacelle or blades, this results in a supported length of 35 metres with a needed lifting capacity of around 3500 tonnes, if a crane of 100 metres above the pivot point is used. This is reachable by current vessels, both mono-hull and semi-submersible.

Thus, pivot methods in their current form are feasible for the installation of wind turbine towers. After tower installation, the nacelle and blades must be installed by other means of installation. The most promising combination between methods will be to utilise a pivot method followed by a self-climbing method, to fully install an ULWT. This means that in hindsight the concept GC-12, described in Section C.12, is a promising method. During the screening phase, it was disregarded, as two entirely different branches/methods needed to be used, but no technical feasibility assessment of either had been performed. Apart from that, it is a lot more interesting to look at entirely different types of concepts, to get a better overview of the feasible design space.

The next branch of integrated lift concepts is and always will be a promising branch, as installation times can be significantly reduced by integrated installation. The main problem is that with increasing turbine sizes, it is no longer possible to perform a top-down lift, as has been utilised in the past. This leads to the need of lifting frames or purpose-built clamping mechanisms which lift at the bottom of the tower. During this research, only the lifting frame option has been thoroughly investigated and can be said to be technically feasible. Bottom lifters will, depending on the chosen mechanism, have less control in some degrees of freedom of the system, as they are fully fixed to installation vessels. They would need to have compensation and damping systems in the lifter, theoretically this is possible, as there are full 3D motion compensation systems[5]. However, these systems are only used for relatively light applications compared to an ULWT. They require huge innovations and up-scaling before they can be used for the size and weight of ULWTs. This does not mean that those mechanisms should not be looked into further in the future. Before concepts using a bottom gripper are developed further, at least heave, and most probably also roll compensation or dampening will be needed when using mono-hull vessels.

All integrated installation methods will have the same bottleneck with respect to the on-shore assembly, handling, and storage of ULWTs. Innovation in port is needed, as the combination of size and weight cannot be reached by the largest on-shore cranes available. After assembly, the main problem occurs, the handling of the turbine. No current on-shore cranes with the capacity and height combination required to perform top-down lifts of ULWTs are available. Super heavy skidding systems can be used for the displacement of the turbine on the quay side, however, they still need to be loaded onto a vessel. If the installation vessel's own cranes can be used, this is not a big problem. However, if a feeder vessel is used, or the installation vessel does not use cranes, on-shore cranes must be used for the loading operation. In this case, the up-scaling of on-shore quay side cranes is definitely needed, or specialised loading mechanisms must be developed alongside the installation method, adding to the costs of a method. Furthermore, the vessels that can perform the integrated installation of ULWTs will be super large, leading to difficulties regarding harbour entry and servicing of the vessels, due to their size and draught.

When evaluating all feasible concepts and the branch of large man-made floaters, it becomes clear that the use of large semi-submersibles will be one of the main design spaces that can be used for the floating installation of ULWTs. This because the argument can be made that the winner in the branch of integrated lift is also a large man-made floater. However, due to the difference in installation methodology of split vs. integrated, it was interesting to see the feasibility of the difference in approach. Large floaters are preferable because:

- They provide the most stable platform for installation at this height;
- They supply enough lifting capacity for use with different installation methodologies;
- The installation methods which can be used with them, have the least effect on the construction of wind turbines;
- The concepts are less susceptible to changes of the design of wind turbines, this also works vice versa, due to the method being less susceptible to changes in the construction of the wind turbine, it also has less effect on the construction of the wind turbine. Leading to more robust methods which can be used for a wider range of wind turbines;
- The use of large floaters makes the split installation of ULWTs possible in a competitive time frame. This is beneficial to the methods in an overall sense, as the requirements on harbours and quay sides are lower, compared to integrated installation methods. Like this, wind turbines can be split into smaller and easier-to-handle parts.

The main downsides of this branch are the costs of the vessels, and the requirements on harbours. These vessels are large and drafts of 10-15 metres are common. This results in only a small number of harbours around the world where they can moor off and enter. Lowering the cost-effectiveness of such vessels in some regions, as they have a long transfer time between port and installation site in that case. This can be circumvented by using feeder barges that can enter “shallow” harbours and using the large floaters only as an installation platform and not a cargo transport platform. In addition, these types of vessels cannot be used for the installation of wind turbines in shallow waters where the draft exceeds the water depth, however, in these cases jack-up vessels can be used. Furthermore, if a method is designed for use with barges, it can also be used in national waters of the US, as vessels are not allowed to moor off in US harbours under the Jones act, expanding the usability of these methods.

The last branch of others cannot be used as an umbrella term, as the concepts within this branch all use different installation methodologies and mechanisms. Therefore, no overarching conclusions can be drawn here.

7

Conclusion & Recommendations

The goal of this research was to deliver technically feasible novel installation methods and propose promising installation principles, for the installation of Ultra Large Wind Turbines (ULWTs), which circumvent the identified bottlenecks defined during the literature review part of the thesis[43]. The main bottlenecks defined are the capacity and height of the crane, and primarily the relative motions of components during installation, caused by the flexibility of the entire system and weather conditions. The combination between the weight of components and set target hub height of 250 metres makes that novel and more robust installation methods are needed. Thus, the research question that was answered during this research is:

"What would be feasible novel on-site installation methods for a bottom founded Ultra Large Wind Turbine using floating vessels?"

Definition of the framework:
The research question was answered by first defining the boundary conditions, base case, and requirements that followed from the literature review. These are the basis on which concept generation took place. The boundary conditions and requirements resulted in the base case of: Floating vessels have to be used, a jacket type foundation is already in place at the installation location, concepts must be able to install all components of a wind turbine, and novel concepts must be feasible.

Next, a deeper understanding of feasibility needed to be generated. The TELOS framework[38] was used to identify which parts of overall feasibility could be used during this research. The choice was made to use a combination of two of the five feasibility categories defined in the framework, the technical- and the economic feasibility. The primary objective was to prove the technical feasibility of the concepts. However, this did not provide handles with which concepts could be compared to one another, as it only tells if a concept can be realised yes or no. For comparison, economic feasibility considerations were set up, not to determine the full economic feasibility, but only to provide the handles. The considerations relate to: the cost-effectiveness, safety, complexity, flexibility, and influence on wind turbine construction of a concept.

Concept generation and screening:
The framework was now defined and could be used for the concept generation and screening. A total of 15 concepts were generated. The main goal of the generation of concepts was to explore the design space as wide as possible to later be able to provide insights on the entire design space. During this phase, only high-level and general information of each concept was generated. This so that it is possible to quickly generate and identify promising concepts which would be evaluated further. Together with concepts found during the literature review part, they made up the entire pool of concepts. This pool was grouped and sorted into six branches, in which concepts based on the same principle were placed. Using selected economic feasibility considerations, it was possible to identify the most promising concepts within each branch. The six branches are: self-climbers, self-erecting, pivot, integrated lift, large man-made floaters and others.

Technical feasibility assessment and comparative analysis:
The technical feasibility assessment took place by first generating deeper level information on each of the selected concepts. Resulting in a full description of the concepts. This description was used to identify critical factors related to size and strength, equipment, logistics, process, and workability. The first two groups were evaluated to determine the technical feasibility of the selected concepts. The other groups are included due to their importance, but were not worked out in detail. From the evaluation of the critical factors, three technically feasible concepts emerged. These concepts were sequentially assessed on their relative differences using the economic feasibility considerations. This to identify the relative differences in performance and usability, and to identify shortcomings of the concepts.

One note should be provided on the state of development of the concepts, all of them still require loads of engineering work to realise, as only relatively high level quasi-static analysis have been performed during the feasibility assessment. Thus, further work should be done on the concepts in which detailed design and dynamics are included, to get a full view on workability and definite feasibility of the concepts.

The approach sketched out can be used for further work w.r.t. the generation of novel installation methods for offshore wind turbines. If different boundary conditions arise, the entire process can be used to generate, define, screen, and assess the feasibility of novel installation methods which suffice to the reformulated boundary conditions.

Technically feasible concepts:

- Self-climbing mechanisms, the elevator platform. Attaches itself to the tower and builds up the ULWT piece by piece. It can be used with current day vessels and has a relatively low day-rate. However, it has a low flexibility w.r.t turbine size, and has a relatively long installation and waiting on weather time. Also, it has a large requirement on tower strength;
- Integrated lift concept, the lifting frame. Uses a frame with a large counterbalance at the bottom to stabilise it during the lift. Requires a double crane operation and can be used with vessels like the Sleipnir. Has a low installation time and waiting on weather, but relatively high day-rate of vessel and equipment. The main bottleneck for this concept is the onshore assembly of the ULWT, as this requires innovation in port.
- A large man-made floater, the installation tower semi-submersible. A large semi-submersible vessel with lattice towers on top, on which a gantry crane is located. Internal lifting can be performed, creating 3D motion compensation possibilities. It is relatively flexible, can be used for a wide range of turbines, and for major repair and replacement of all parts. The main downside is that it uses a large and expensive never before build semi-submersible vessel.

Final conclusion and recommendations:
From all this, the conclusion can be drawn that two main principles of installation are promising for the installation of ULWTs. All technically feasible concepts revolve around these two principles, and during evaluation of the technical feasibility of the branches, they are central to all promising branches and concept combinations. Thus, the industry should further look into these two solution groups of installation methods. Both have exactly contrary pros and cons on the included considerations, so no clear winner can be identified between the two without further research.

- Self-climbers, either on their own or in combination with other methods. Especially interesting because they can be used with existing mono-hull lifting vessels. Main downsides are the low flexibility w.r.t. wind turbine size, usability, and long installation time. They are promising, as they decouple the size of the installation vessel and size of the turbine entirely;
- Large semi-submersible vessels, either using lifting equipment, so that existing vessels can be used. Or specifically designed vessels that provide large flexibility w.r.t. size and usability. The main downside is the size and costs of these vessels. They are promising, as they provide a platform on which the needed height can be reached effectively.

To further identify the overall feasibility of these two solution groups and the technically feasible concepts, an in-depth economic analysis and the assessment of the other three feasibility categories must be performed. They relate to the legal, operational, and scheduling feasibility of the concepts. Furthermore, analysis on the lifetime and environmental impact of each concept can further provide insights on the overall feasibility, these two mainly relate to economic and legal feasibility. The last recommendation is to also investigate installation of ULWTs in shallower waters where jack-up vessels can be used, as that fell outside the defined base case during this research.

Future work:
Some suggestions for further work have already been mentioned in the sections above and will be recapitulatory repeated and expanded upon in the following list.

- Economic feasibility assessment of the concepts groups: The research only tested concepts on their technical feasibility, and used considerations related to economic feasibility for comparison between concepts. Thus, an economic feasibility assessment is needed to identify the economically most attractive concepts.
- Full dynamic assessment of critical factors in combination with rough seas: Quasi-static analysis and the assumption of calm seas were used for the initial concept design, to determine the definite feasibility and final design, dynamics, and rough seas should be included.
- Assessment of legal, operational and scheduling feasibility: During the research, the technical feasibility was central, before a concept or concept group can be realised all feasibility categories must be assessed.
- Detailed design of concepts: Only initial design was performed, as that already shows technical feasibility. To realise these concepts, a detailed design must be made.

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A

Appendix A: Wind speed calculations

In this appendix, the information for the wind speed calculations that were done for the requirements are further explained and shown. The used scatter diagram can be found in Figure A.1.

Using this scatter diagram, the average wind speed for a significant wave height of 2 meters was found. The wind speed bin in which the probability of occurrence was above half of the total probability of occurrence of the wave height bin of 1,5 to 2 meters was used. This is then $6.5[m/s]$ at 10 meters altitude and measured as 1-hour average. This wind speed has to be converted to a 10 min-average at hub height of 250 meters. First, the time conversion is done by applying Equation A.1

$$U_{T_2,H_1} = U_{T_1,H_1} \cdot Z_p \tag{A.1}$$

In which U_{T_2,H_1} is the average wind speed over T_2 minutes and at an altitude of H_1 meters in [m/s], U_{T_1,H_1} is the average wind speed over T_1 minutes and at an altitude of H_1 meters in [m/s] and Z_p is the power law exponent depending on the roughness length, where $T_1 > T_2$. Z_p is taken to be 0.155[53]. The conversion to the popper height was done by applying the well known log law for wind speeds, see Equation A.2.

$$U_{T_2,H_2} = U_{T_2,H_1} \cdot \frac{ln(\frac{H_2}{z})}{ln(\frac{H_1}{z})} \tag{A.2}$$

In which U_{T_2,H_2} is the average wind speed at the needed height and needed time in [m/s], H_2 is the desired height in meters, H_1 is the reference height in meters and z is the roughness length here taken to be the commonly used $2E^{-4}$ [m] for sea roughness. When these formulae are applied to the found 1-hour average wind speed of 6.5 [m/s] at 10 meters altitude, and are converted to the wind speed of 10-minute average at 250 meters altitude, the average wind speeds becomes 9.75 [m/s]. This wind speed can now be used as a requirement.

	lower	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
lower	upper	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	total
0.0	0.5	0.0	0.1	0.1	0.1	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	0	0	0	0	0	0.4
0.5	1.0	0.2	0.4	0.5	0.6	0.7	0.6	0.3	0.1	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	3.5
1.0	1.5	0.2	0.7	0.9	1.2	1.7	1.9	1.5	1.0	0.6	0.2	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	10.0
1.5	2.0	0.1	0.5	0.7	1.0	1.5	2.0	2.2	2.1	1.8	1.0	0.5	0.2	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	13.6
2.0	2.5	0.1	0.2	0.4	0.6	0.9	1.4	1.7	1.9	2.1	1.7	1.2	0.6	0.3	0.2	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	13.5
2.5	3.0	0.0	0.1	0.2	0.3	0.5	0.8	1.1	1.5	1.8	1.8	1.6	1.1	0.7	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	12.2
3.0	3.5	0.0	0.1	0.1	0.1	0.3	0.5	0.8	1.0	1.4	1.5	1.5	1.3	0.9	0.7	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	10.9
3.5	4.0	0.0	0.0	0.0	0.1	0.1	0.3	0.4	0.6	0.9	1.0	1.1	1.1	1.0	0.8	0.6	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0	8.5
4.0	4.5	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6	0.7	0.8	0.9	0.8	0.8	0.7	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	6.9
4.5	5.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.6	0.6	0.6	0.7	0.7	0.5	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0	0	0	0	5.5
5.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.4	0.4	0.5	0.5	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0	0	0	0	4.1
5.5	6.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.3	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0	0	0	0	2.8
6.0	6.5	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0	0	0	0	2.2
6.5	7.0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0	0	0	1.7
7.0	7.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0	0.0	0	1.3
7.5	8.0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.9
8.0	8.5	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.6
8.5	9.0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0	0	0	0	0.4
9.0	9.5	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.3
9.5	10.0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.2
10.0	10.5	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0.1
10.5	11.0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0.1
11.0	11.5	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.1
11.5	12.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0.0
12.0	12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0.0
12.5	13.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0.0
13.0	13.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0.0
13.5	14.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.0
14.0	14.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.0
14.5	15.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.0
15.0	15.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0.0
15.5	16.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0	0.0
16.0	16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0	0.0
16.5	17.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0	0.0	0.0	0	0	0	0	0.0
17.0	17.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0	0	0	0	0	0.0
17.5	18.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0	0	0	0	0	0	0.0
18.0	18.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0	0	0	0	0	0	0.0
18.5	19.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
total		0.6	2.1	3.0	4.0	5.8	7.7	8.6	9.2	9.9	9.0	8.3	7.0	5.6	5.1	4.3	3.1	2.6	1.8	1.2	0.6	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	100.0

Figure A.1: 2D-Scatter diagram of significant wave height(y-axis) vs. wind speed(x-axis) in the North Sea, obtained from [22]

B

Appendix B: Mind maps of basic level functionalities of installation methods

In this appendix the Mindmaps made on the basis of the basic level functionalities, Figure 4.2, defined using a functional analysis are shown.

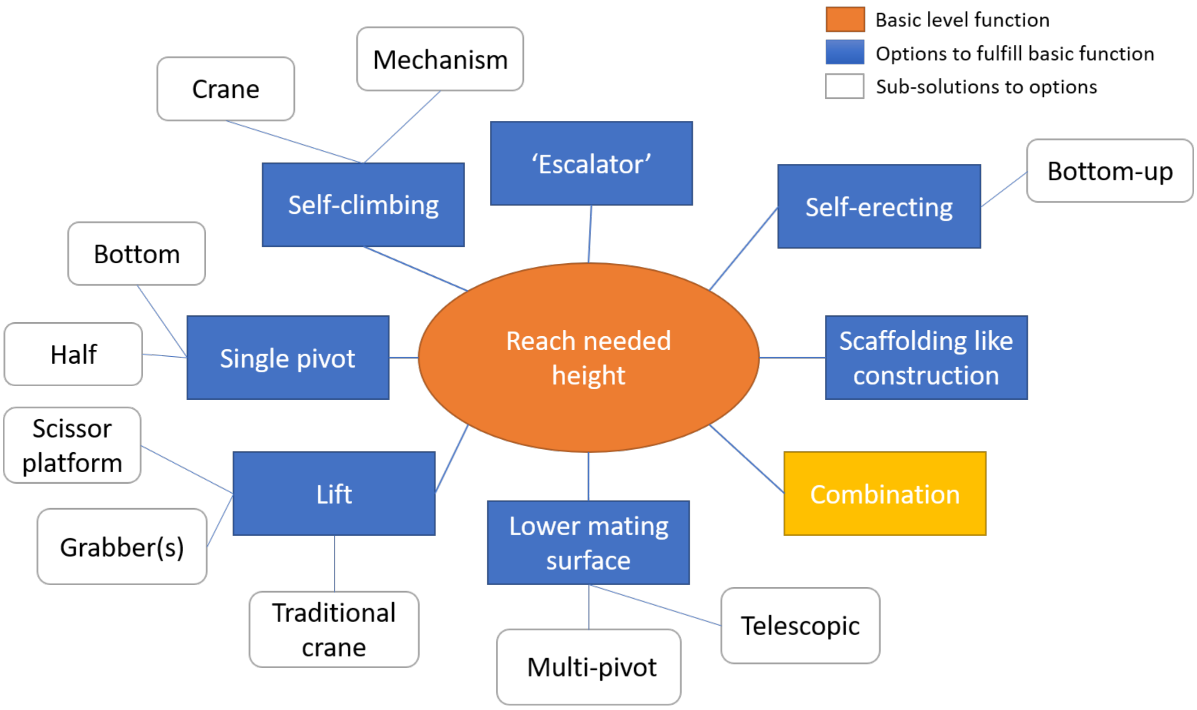

Figure B.1: Mindmap of basic level functionality of reaching the needed height.

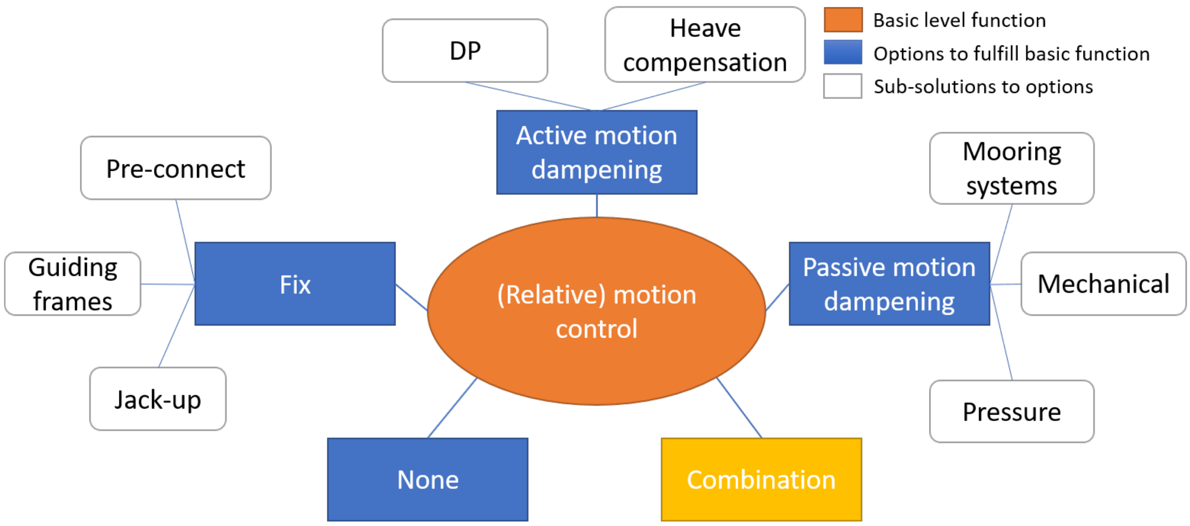

Figure B.2: Mindmap of basic level functionality of motion control.

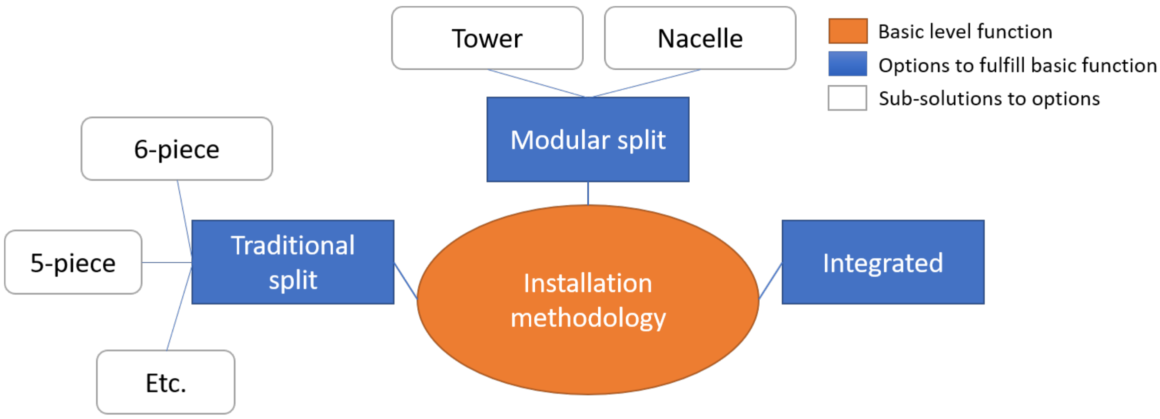

Figure B.3: Mindmap of basic level functionality of the used installation methodology.

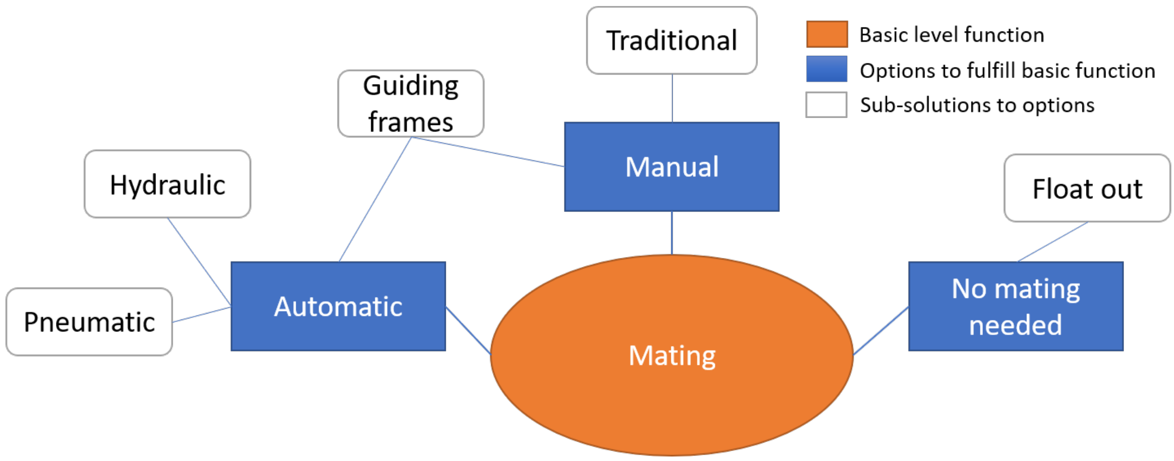

Figure B.4: Mindmap of basic level functionality of mating of components.

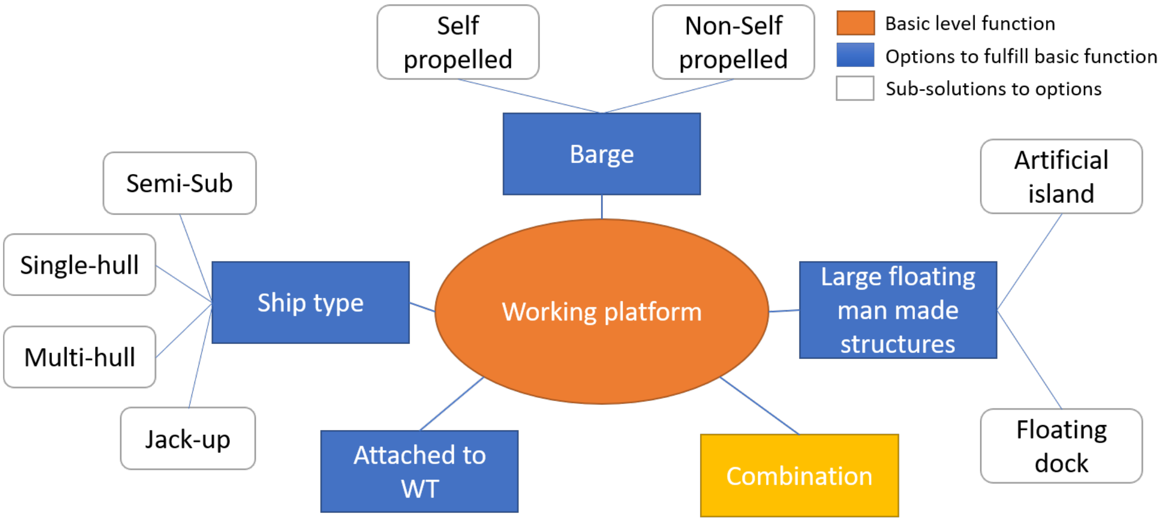

Figure B.5: Mindmap of basic level functionality of providing a working platform.

C

Appendix C: Generated concepts

In this appendix, 15 generated concepts are shown. They were generated by use of the morphological chart in Figure 4.4. Each concept has a general description and rough drawing of its workings.

C.1. Concept 1: Wind turbine escalator (tag: GC-1)

Table C.1: Morphological choices concept 1.

Reach needed height	Motion control	Methodology	Mating	Working platform
Escalator	Fix for mechanism/ active for floating platform	Modular split	Automatic	Barge with supporting feeder vessel

General description: An as large as possible tower piece is pre-installed (ideally) using the same vessel as for the installation of the foundation. Next, the modular tower will be built up piece by piece using an escalator like construction that is attached to the tower. The escalator floats on a barge like vessel. The Barge is large enough to store multiple components and can operate the escalator without the use of further support vessels. Once a tower component is installed, the 'escalator' will be moved up to the new tower top. After the tower is fully installed, the nacelle will be escalated to the hub height and mated, followed by the blades. The escalator might need to be decoupled from the motions of the barge by active or passive motion control.

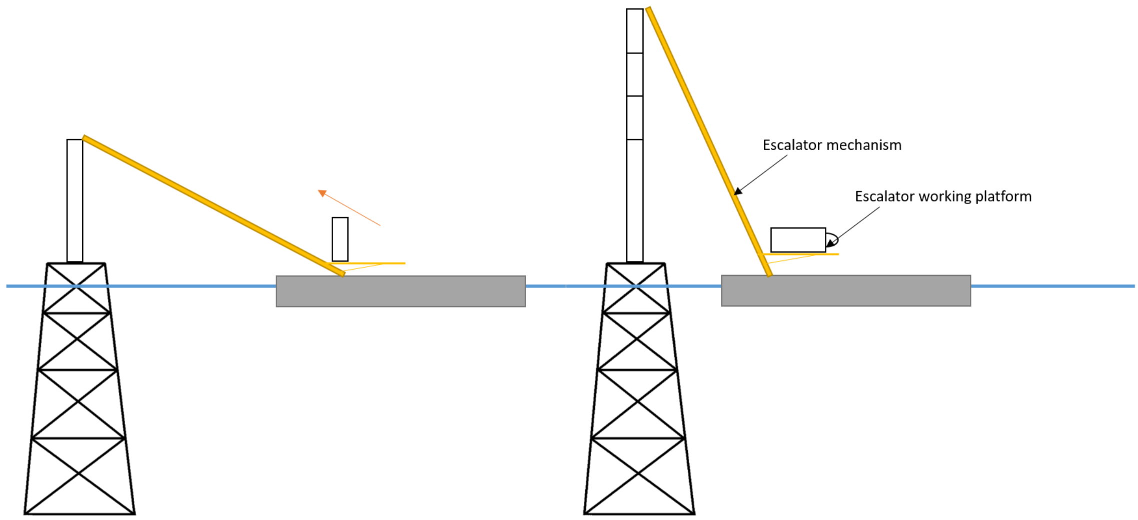

Figure C.1: Sketch of workings generated concept 1, escalator.

C.2. Concept 2: Self erecting modular tower (tag: GC-2)

Table C.2: Morphological choices concept 2.

Reach needed height	Motion control	Methodology	Mating	Working platform
Self-erecting	Fix	Modular split	Manual for Nacelle and blades/ automatic for tower	Attached to WT with feeder vessels

General description: Instead of top-down build up, this concept has a bottom-up principle. A mechanism is placed on the foundation, after which a tower piece with maximum attainable height is installed in the mechanism. This is entirely done in traditional fashion with an installation vessel. Next, nacelle and blades are installed likewise. The tower will now be grabbed by the mechanism and pushed upward. A tower piece of to be determined dimensions is placed under the tower and bolted to the already installed piece. The mechanism pushes the entire structure up again and the next tower piece is installed. This is repeated until the needed hub height is reached. The mating of the tower pieces will be automatic by use of a guiding frame that is present in the lifting mechanism.

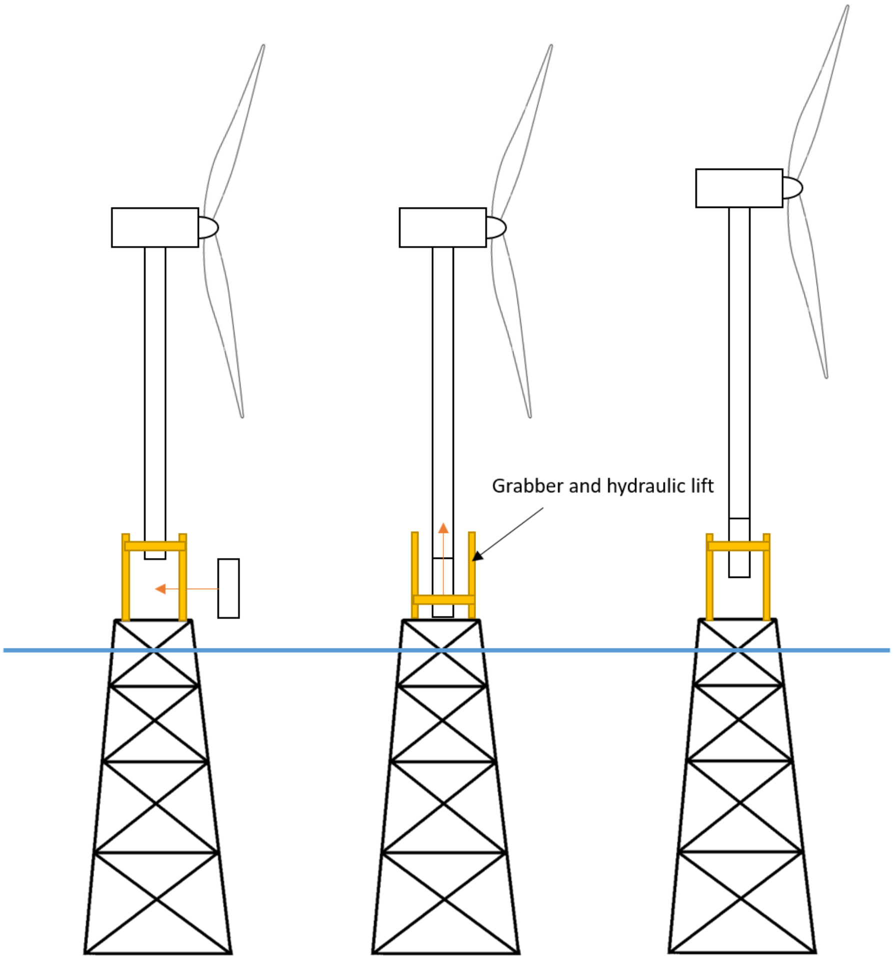

Figure C.2: Sketch of workings generated concept 2, self erecting modular tower.

C.3. Concept 3: Installation tower (tag: GC-3)

Table C.3: Morphological choices concept 3.

Reach needed height	Motion control	Methodology	Mating	Working platform
Scaffolding & Lift	Fix / active	Traditional split	Manual	Large man made floating structure

General description: Huge man-made floating structure which reaches above hub height. A lattice like tower structure is placed on deck, on which a gantry crane is attached so that lifts can be performed internally. Depending on crane capacity, the number of lifts can be determined. Most probably traditional split with 1 or 2 tower pieces, followed by nacelle and blades installation can be applied. The structure can be fixed to the foundation if loads allow, otherwise active motion compensation will be needed to counter heave and roll motions. Due to the size of the structure, motion control might not be needed, as large semi-submersibles are minimally effected by environmental actors. Tugger lines can be used for motion control during mating, they will be attached to the structure itself giving 3D motion compensation possibilities.

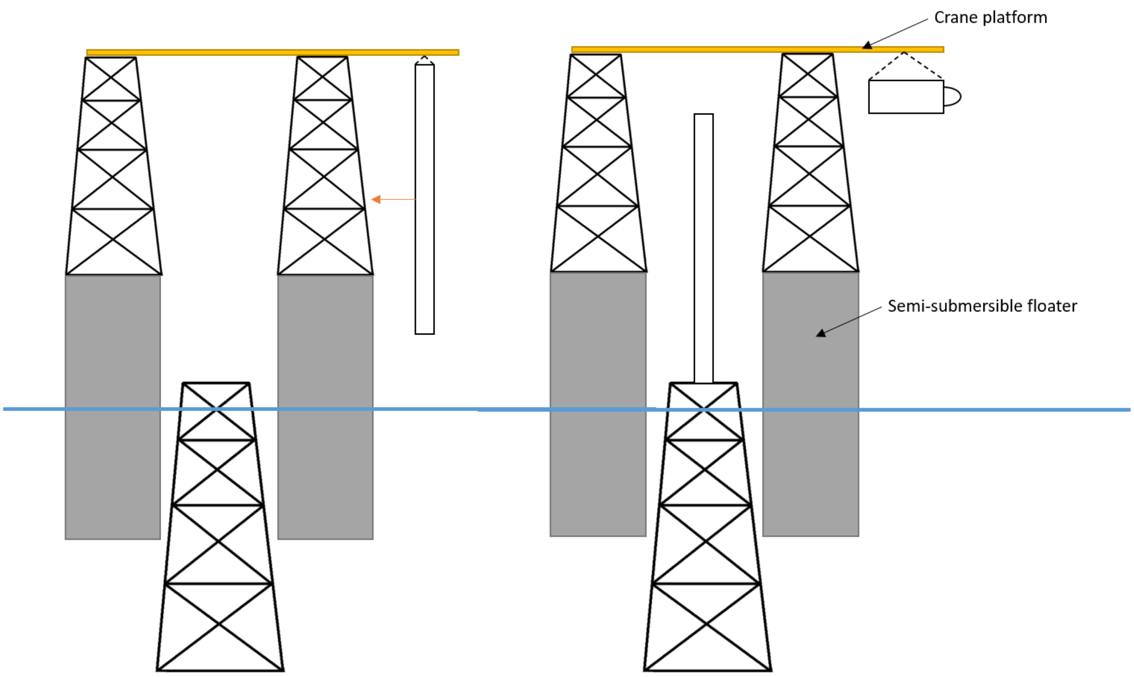

Figure C.3: Sketch of workings generated concept 3, installation tower.

C.4. Concept 4: Multi pivot tower to lower mating surface (tag: GC-4)

Table C.4: Morphological choices concept 4.

Reach needed height	Motion control	Methodology	Mating	Working platform
Lower mating surface	None / Active	Traditional split	Manual	Ship type vessel

General description: This concept does not try to reach a certain height, but revolves around lowering the height at which mating has to be performed. The tower construction will need to be altered to cater to this, inside the tower a mechanism will be placed which makes it possible to lower the tower top by pivoting it outwards. The tower top can then be horizontally placed on an installation vessel, where traditional installation of the nacelle and blades can take place. The mating and support of the tower top is performed on a pedestal on which the tower and nacelle can rest. This pedestal needs to be tall enough to install the blades, or a different method for blade installation should be used. This method mainly looks at the problem of upright nacelle installation at large heights, which is not possible with single pivot concepts.

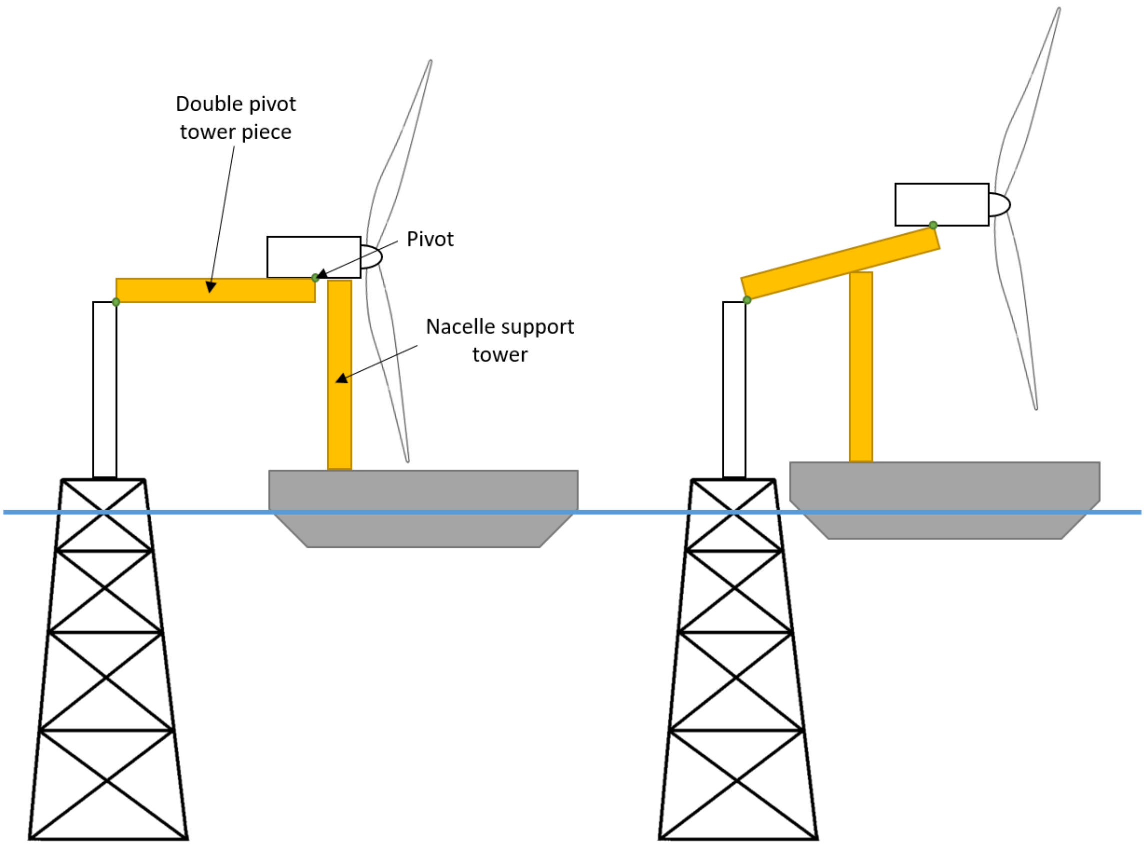

Figure C.4: Sketch of workings generated concept 4, double pivot.

C.5. Concept 5: elevator working platform (tag: GC-5)

Table C.5: Morphological choices concept 5.

Reach needed height	Motion control	Methodology	Mating	Working platform
Lift	fix	Modular split	Automatic	Attached to WT with feeder vessel

General description: This method is a different take on self-climbing mechanisms. The tower will be installed up to reachable height by traditional means of installation. A tower encircling mechanism is placed around the tower close to sea level. This platform is attached to lifting wires which run from the tower top where pulleys are present, to automatic winches placed either on the platform or on the transition piece of foundation. Using the automatic winches, the platform can be elevated and lowered, creating a mobile working platform. The platform is raised to the tower top and the tower is build up piece by piece. During installation of components, the platform clamps itself to the tower, so that component and platform lifting mechanisms are decoupled. Once a tower piece is installed, the top pulleys/attachment points of the lifting wires are moved upwards to the new tower top surface, and the platform can be moved upward again. This can be repeated up until all components are installed. A feeder vessel will deliver the components.

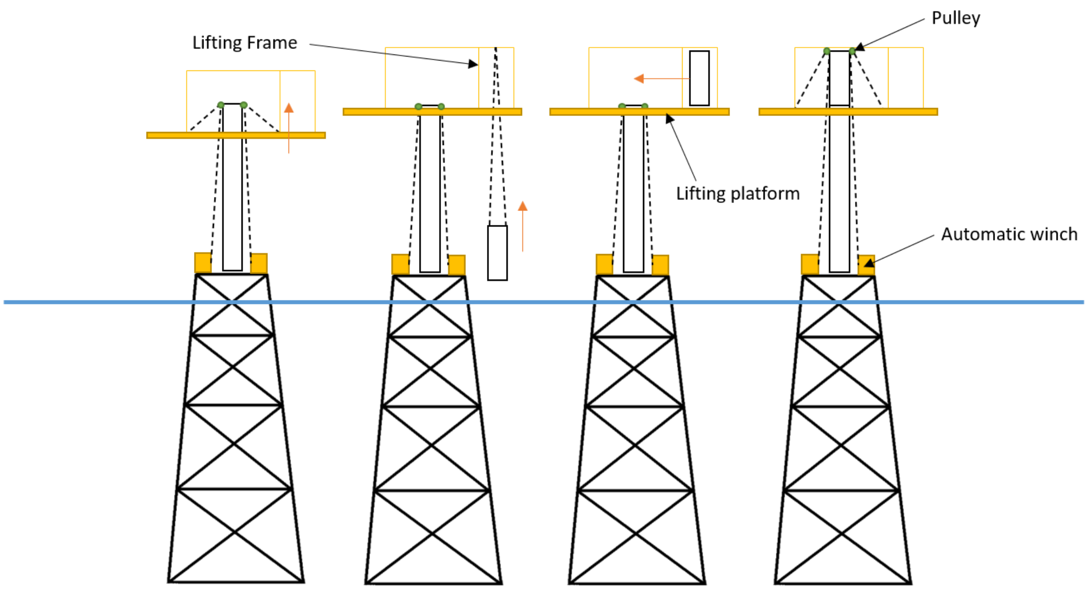

Figure C.5: Sketch of workings generated concept 5, elevator platform.

C.6. Concept 6: Integrated float out (tag: GC-6)

Table C.6: Morphological choices concept 6.

Reach needed height	Motion control	Methodology	Mating	Working platform
None of the specified options	none for stucture/ Active for installation vessels	Intergrated	None	Ship type

General description: This method is only possible for use with jackets or large gravity-based foundations. The entire wind turbine and foundation construction is already assembled in a dry dock or harbour. Next, it is floated from a dry dock or quay side. The construction is made buoyant and kept stable with carefully placed buoyancy tanks during transport. Using heavy offshore tugs, the entire structure is floated out to the intended location. The lowering process takes place by flooding the needed lower situated buoyant members. This both lowers the assembly as it uprights it. Once the structure is upright and lowered to the needed depth, the jacket can be attached to its pre-laid foundation.

Notes: As a wind turbine is a tall structure with a relatively heavy mass on top, it might be needed to add more weight at the bottom of the jacket to get it upright.

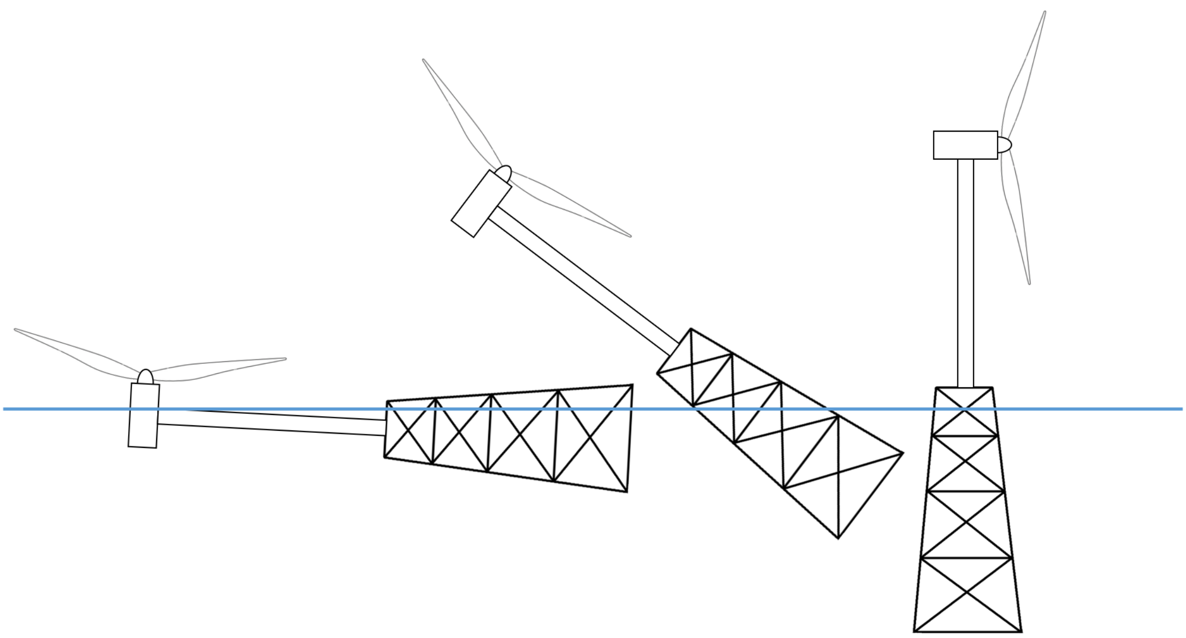

Figure C.6: Sketch of workings generated concept 6, integrated float out.

C.7. Concept 7: Tower ring with scissor platform (tag: GC-7)

Table C.7: Morphological choices concept 7.

Reach needed height	Motion control	Methodology	Mating	Working platform
Lift	Fix for paltform/ active for barge	modular split	Automatic	Attached to WT and placed on barge

General description: A large barge or other floating platform is attached to the foundation if loads allow, otherwise active motion compensation is needed. On this barge a scissor platform is placed. The platform can reach the needed height using the scissor system. On the platform on top of the scissor system components can be placed, either pieces of a modular tower, nacelle, or blade. The component is lifted to the needed height and mated automatically by use of guiding frames and hydraulic skidding systems that are present on the platform. The platform will have to be lowered for each operation, unless a few smaller parts can be stored on it. During lowering or scaling of the tower, the scissor platform will be guided along the tower using a guiding ring. The motions of the barge may become too large, thus an active motion control system may be needed or a decoupling of the motions of the scissor platform and the barge must be achieved by active or passive measures.

Note: This concept can be used with a modular tower concept, or can be utilized for the installation of nacelle and blades if a tower is already installed by other means.

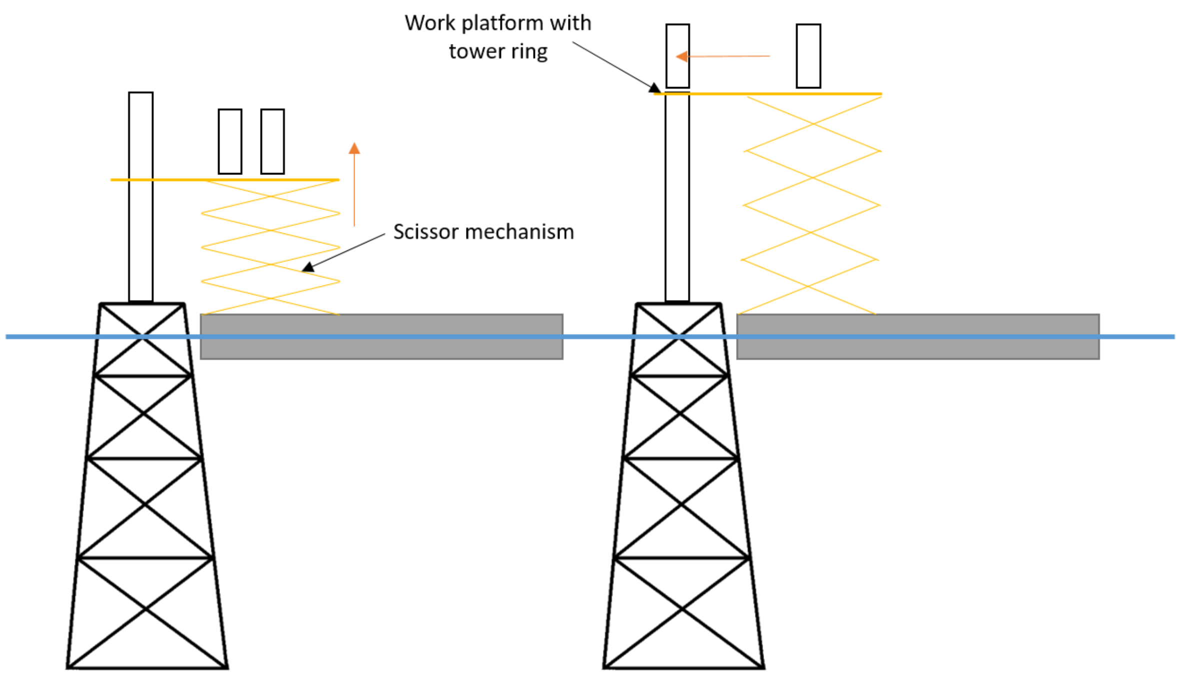

Figure C.7: Sketch of workings generated concept 7, scissor platform with tower ring.

C.8. Concept 8: Construction island (tag: GC-8)

Table C.8: Morphological choices concept 8.

Reach needed height	Motion control	Methodology	Mating	Working platform
Lift	None	Integrated	Automatic	Large man-made floating structure

General description: An enormous artificial island is created on which the entire assembly of wind turbines can be performed. An assembly line, like is used in the automotive industry, is present on the island. The entire turbine can be built up piece by piece using the on-board movable cranes that are placed on large movable tower structures. The assembly takes place using traditional top down means of installation. The turbine is moved along the assembly line where all components will be connected one by one. Once the turbine is completely assembled it has reached the aft of the island, here it is picked by grippers and placed on the foundation in a single lift. The island is then moved to another foundation while simultaneously assembling other wind turbines, so that (ideally) once the next foundation has been reached, a next turbine is ready and can be installed.

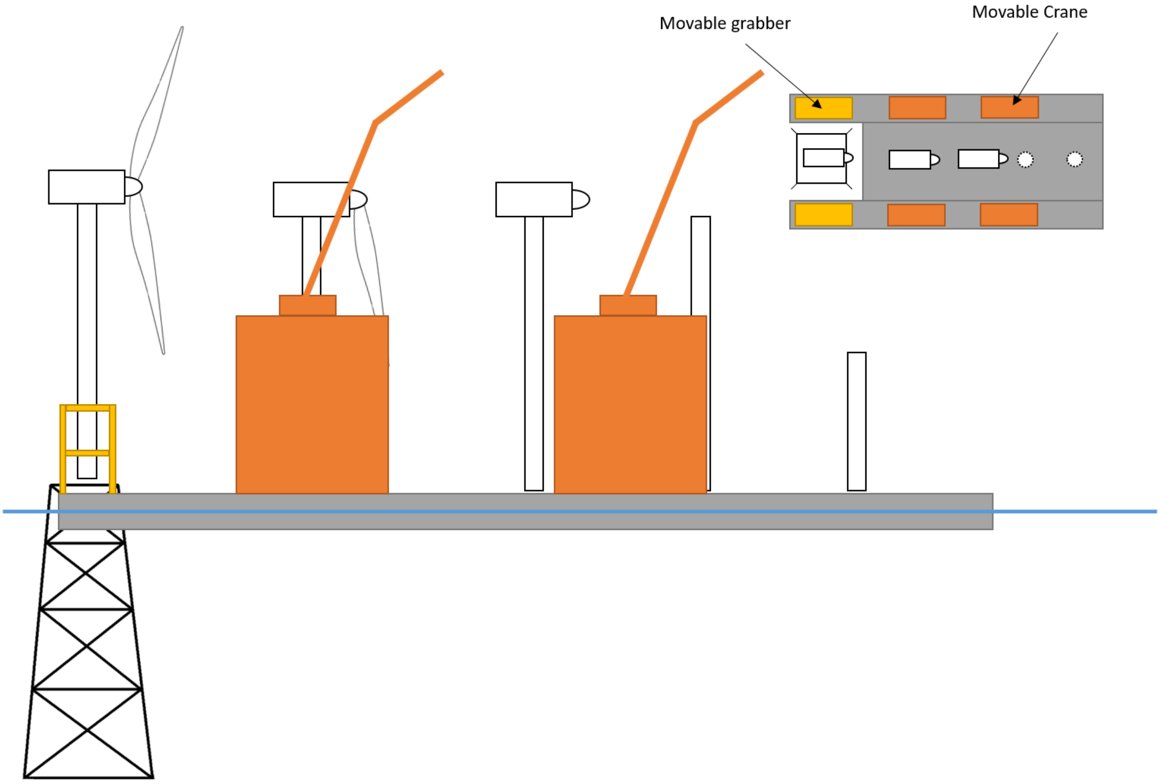

Figure C.8: Sketch of workings generated concept 8, installation island.

C.9. Concept 9: Telescopic tower (tag: GC-9)

Table C.9: Morphological choices concept 9.

Reach needed height	Motion control	Methodology	Mating	Working platform
Lower mating surface and self-erecting	None	'Traditional' Split	manual	Ship type vessel

General description: This method revolves around a major adaptation to the tower construction. The tower will be made telescopic, so that the mating surface can be lowered from hub height to a more workable height. This method uses a HLV that can install the telescopic tower on the foundation, after which the nacelle and blades can be attached in traditional fashion at a height of about 110 meters above LAT. Once everything is installed, the telescopic tower must be elongated and the nacelle will be brought to hub height. The telescopic pieces of the tower will lock in place and a fully rigid structure is achieved.

Notes: Might seem interesting, but telescopic towers have not been investigated or build yet by either the industry or academia.

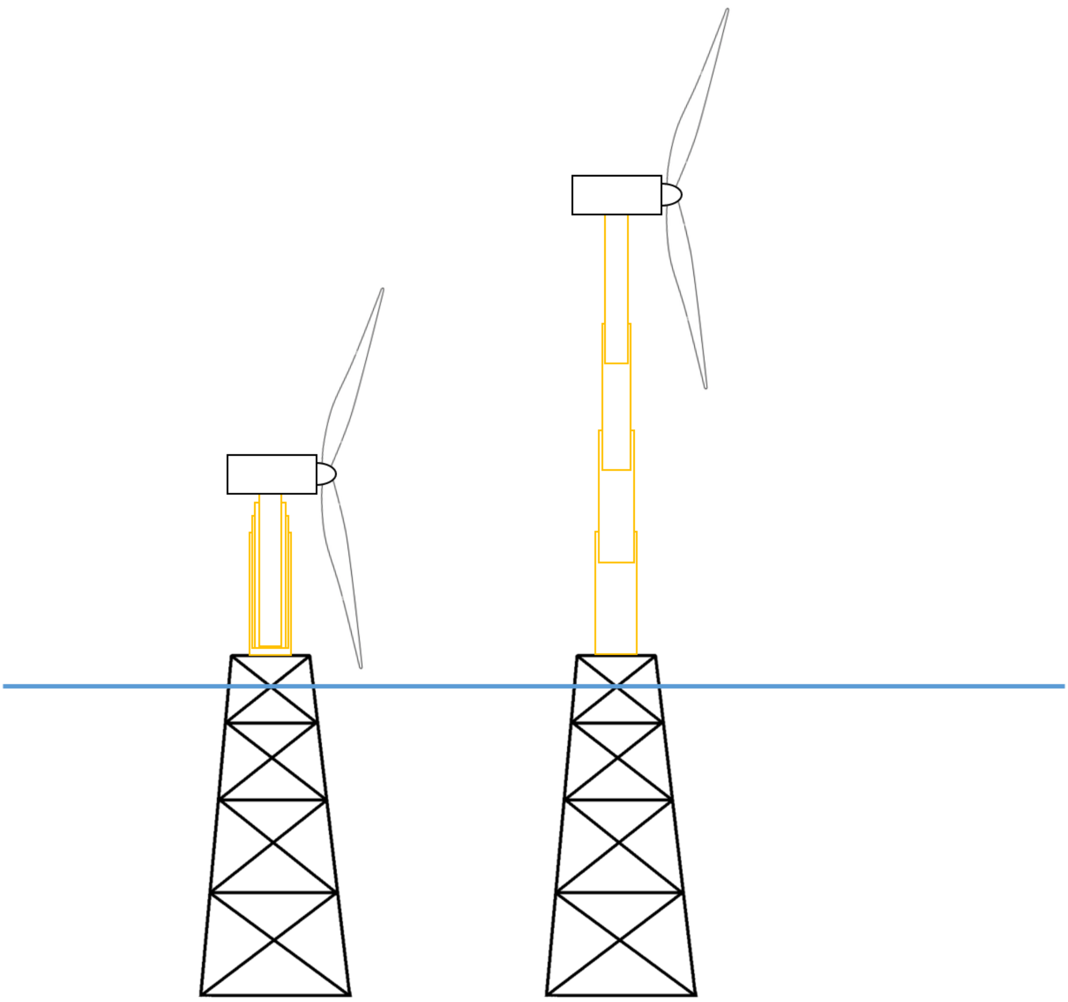

Figure C.9: Sketch of workings generated concept 9, telescopic tower.

C.10. Concept 10: Integrated pivot from installation vessel (tag: GC-10)

Table C.10: Morphological choices concept 10.

Reach needed height	Motion control	Methodology	Mating	Working platform
Pivot	Fix	Integrated	Automatic	Very large ship type vessel

General description: concept is the same as pivot from a barge, but now the whole procedure is performed from one single vessel. This to reduce the number of needed vessels. A fully assembles wind turbine is placed horizontally on a vessel, the vessel moves towards the foundation and attaches the flip frame to it. The on-board cranes of the vessel can now be used to upright the turbine. Once the turbine is upright, the frame carries the loads and automatically lowers the turbine onto the foundation. The ship detaches all equipment, and can pick up a next turbine.

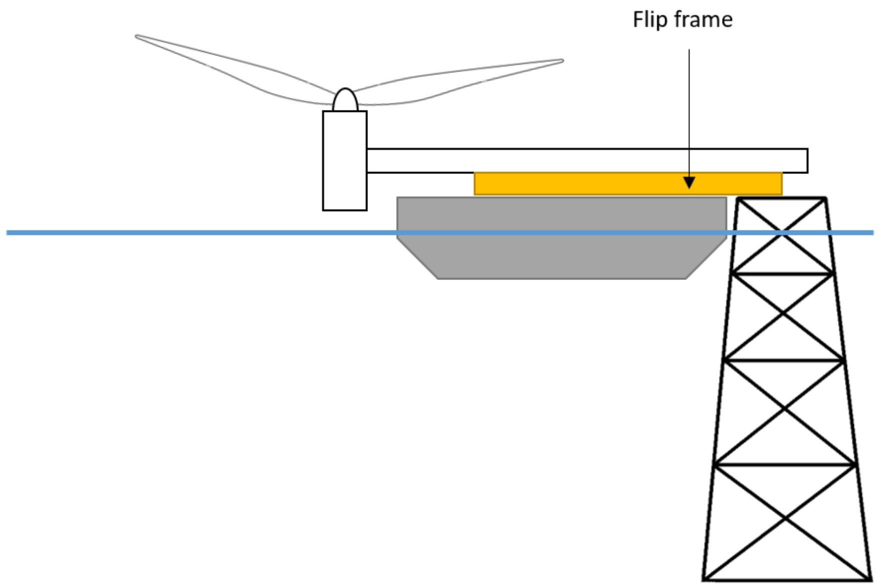

Figure C.10: Sketch of workings generated concept 10, pivot from installation vessel

C.11. Concept 11: Jack-up leg tower principle (tag: GC-11)

Table C.11: Morphological choices concept 11.

Reach needed height	Motion control	Methodology	Mating	Working platform
Self-erecting	None for mechanism/ active for vessel	Modular split	Manual	Ship type

General description: This method makes use of proven technology by imitating legs of jack-up vessels. For this method to succeed, the tower of the wind turbine must be altered to a jack-up leg like construction. This leg extends through the foundation up until the seabed. Like this, the mating surface can be lowered with around the same length as the water depth. When only using this, the mating surface will still be too high up. This can be decreased by making the tower also modular. So, one part of the tower is temporarily stored inside the jacket type foundation. A jack up system is in place which will hold a wind turbine tower. The nacelle and blades can be installed in traditional fashion. After this, a piece of tower is inserted in between the part that is stored inside the foundation and the tower that is already in the jack-up mechanism. This piece is connected to the tower and is jacked-up until enough space is available for the next piece. This is done up until the needed height can be reached using the tower piece that is stored inside the jacket. This piece is connected to the other parts of the tower and is jacked up. The jack-up leg like tower pieces will have to be fed into the system by a feeder vessel.

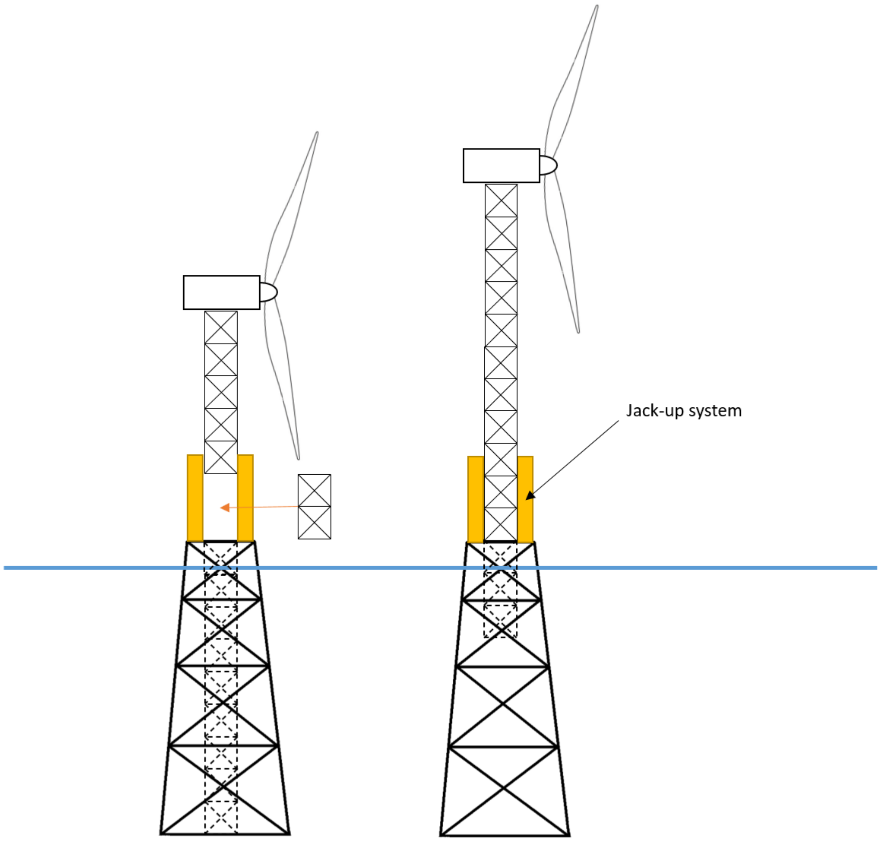

Figure C.11: Sketch of workings generated concept 11, Jack-up leg tower principle.

C.12. Concept 12: Combination between pivot and self-climbing (tag: GC-12)

Table C.12: Morphological choices concept 12.

Reach needed height	Motion control	Methodology	Mating	Working platform
Pivot and Self-climbing	Depends on phase	Traditional split	Depends on phase	Ship type and attached to tower

General description: The idea is to use a pivot like method for the installation of the tower, as then the nacelle and blades do not have to be considered when transporting and pivoting. Especially during transport, problems may arise as clearances of blades to the water are critical, and the nacelle does not have to be placed in a horizontal position. The tower is placed in a horizontal position on a barge with a flip frame on top of it. This barge is attached to the foundation and the ship uses its cranes in combination with a mooring or DP system to upright the tower. The tower is mated by use of a guiding frame and hydraulics in the flip mechanism. After the tower is connected to the foundation a self-climbing mechanism is attached to the tower, as high as safely possible using a heavy lift vessel. This mechanism climbs to hub height, locks in place, and lifts the nacelle from a feeder barge or vessel using its on board lifting mechanism. Once at hub height, it is placed on a horizontal skidding frame which moves the nacelle into position using hydraulic crawlers and is mated to the tower. Next, the blades are installed using the self-climbing platform as a working platform.

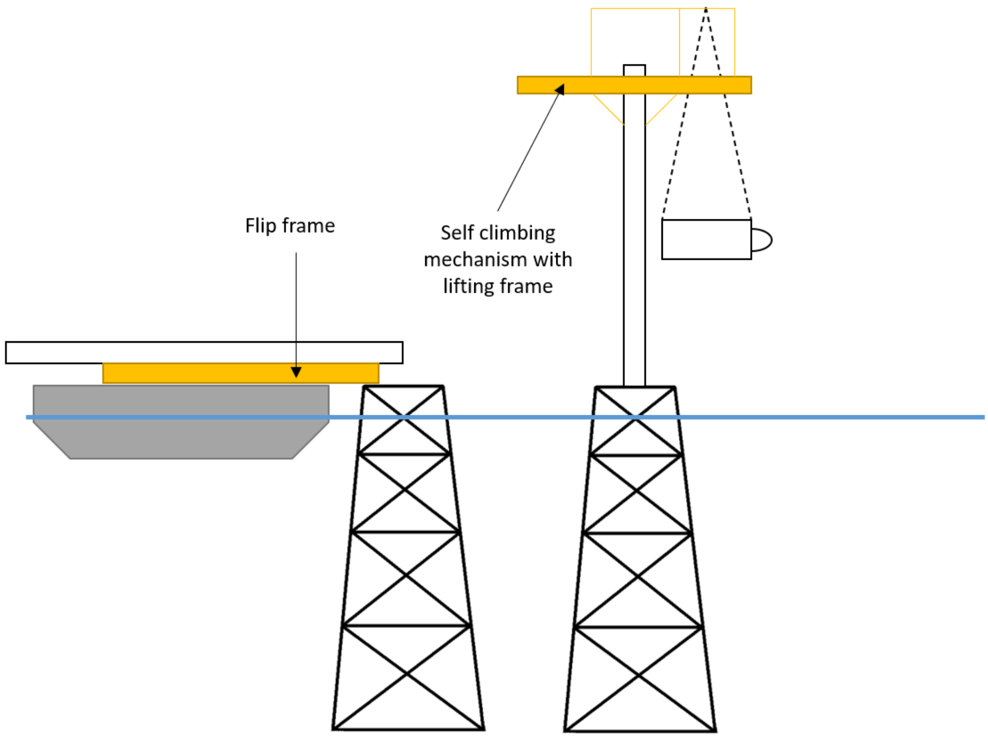

Figure C.12: Sketch of workings generated concept 12, Combination between pivot and self-climbing.

C.13. Concept 13: Integrated lift using traditional cranes and lifting frame (tag: GC-13)

Table C.13: Morphological choices concept 13.

Reach needed height	Motion control	Methodology	Mating	Working platform
Lift	Active	Integrated	manual with guiding frame	Super large ship type

General description: This method explores the possibility of using traditional installation vessels for the installation of ULWTs. The method revolves around a lifting frame in which a fully assembled ULWT can be placed in vertical position. The frame is a tower enclosing frame, and has attachment points for lifting equipment sticking out from the sides of the frame, so that the wind turbine can be held in between 2 cranes. The ULWT is pre-assembled on shore and placed in the lifting frame using quay side cranes. The entire assembly of frame and wind turbine is placed on the installation vessel. The vessel sails to the intended location and mores next to the foundation. The frame is lifted using 2 cranes in unison, all the while tugger lines and counterweights are used to keep the lifting frame balanced and upright. The two cranes move the turbine to the foundation and lower the entire assembly onto it. Mating takes place by using a guiding frame that is present on the lifting frame. The WT is connected, and the installation has been performed.

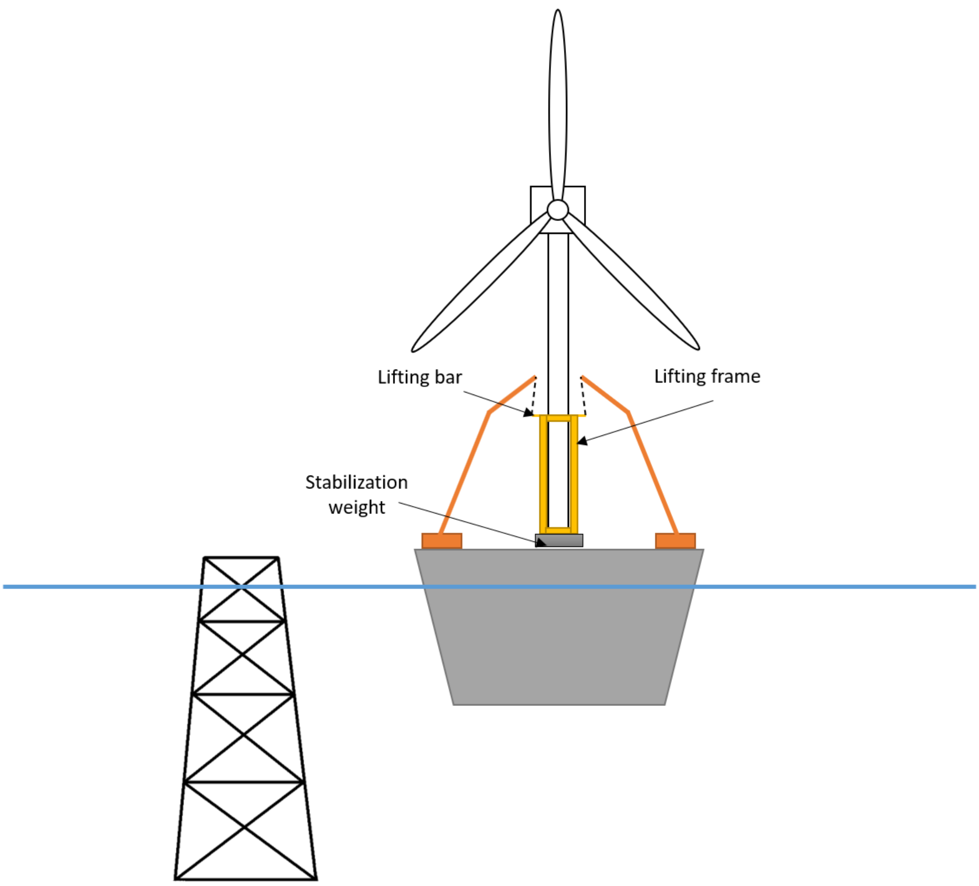

Figure C.13: Sketch of workings generated concept 13, Integrated lift using traditional cranes and lifting frame.

C.14. Concept 14: Pivot without cranes using specifically designed vessel (tag: GC-14)

Table C.14: Morphological choices concept 14.

Reach needed height	Motion control	Methodology	Mating	Working platform
Pivot	Fix for frame/ Active for vessel	Integrated	Automatic with guiding frame	Super large ship type

General description: This concept explores the crane less installation of ULWTs by use of a flip frame. The concept needs a purpose build catamaran like vessel, on which both the flip frame and the wind turbine can be placed. The flip frame is used in the same manner as described with other pivot concepts, the main difference here is that the upending of the wind turbine will not require a crane. The catamaran vessel must have enough clearance in between the two hulls to fit the entire foundation in between them. The up-righting mechanism will push the turbine up by sliding along the flip frame, during movement of the entire vessel in the direction of the foundation. The vessel will have active DP motion control to station keep and move forward, if The DP system cannot produce enough trust to upright the wind turbine, mooring lines can be used to support the system. This operation is the same as is done for e.g. pipe laying vessels.

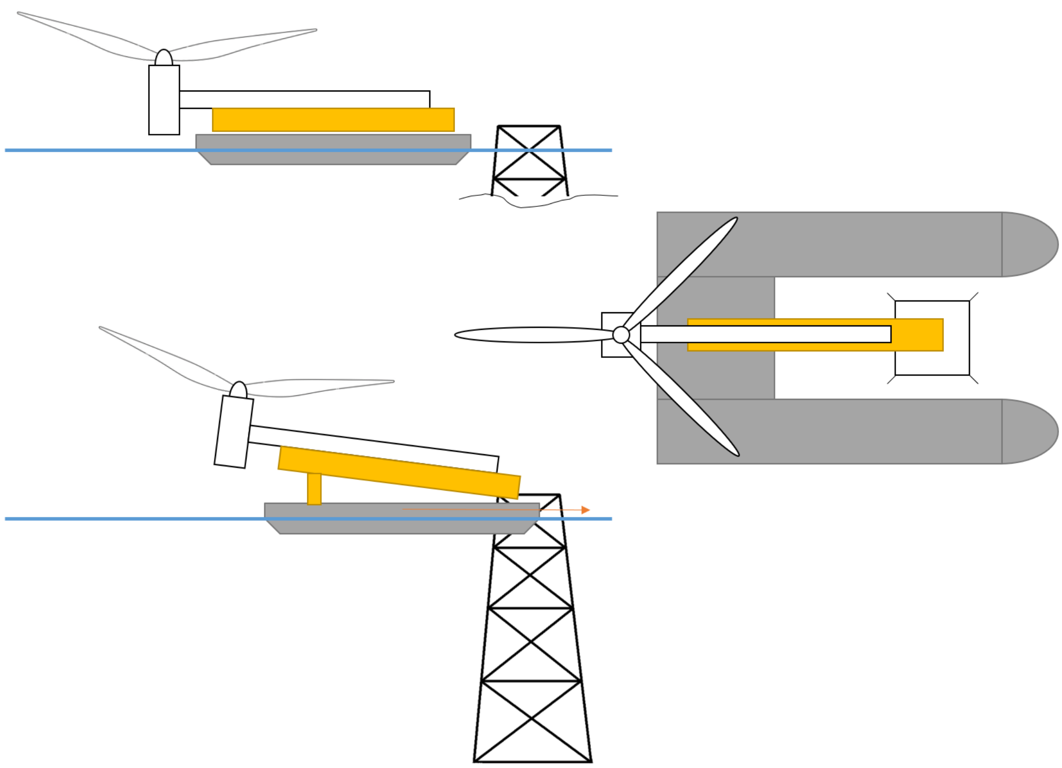

Figure C.14: Sketch of workings generated concept 14, Pivot without cranes using specifically designed vessel.

C.15. Concept 15: Scaffolding bottom-up modular tower (tag: GC-15)

Table C.15: Morphological choices concept 15.

Reach needed height	Motion control	Methodology	Mating	Working platform
Scaffolding	Fix	Modular Split	Manual	Attached to WT

General description: This concept is based around building practices that have already been in use in the civil industry for the construction of large buildings for decades. On the foundation of the ULWT a scaffolding like construction will be built up on which a relatively small crane with heavy lifting capacity is placed. This crane is then used to lift a tower piece of a feeder vessel and install the piece using traditional installation practices. The next step is to use the crane to build up the scaffolding to the next level. The crane is disassembled and moved to the higher allocated part of the scaffolding. During this, the lower part of the scaffolding will be fixed to the tower using clamps or other devices. Now the crane can be used to lift the next part of the construction and mate it to the already installed components of the wind turbine. This process continues up until all parts have been installed. After which the crane is used to piece by piece uninstall the scaffolding, and lower all parts to sea level.

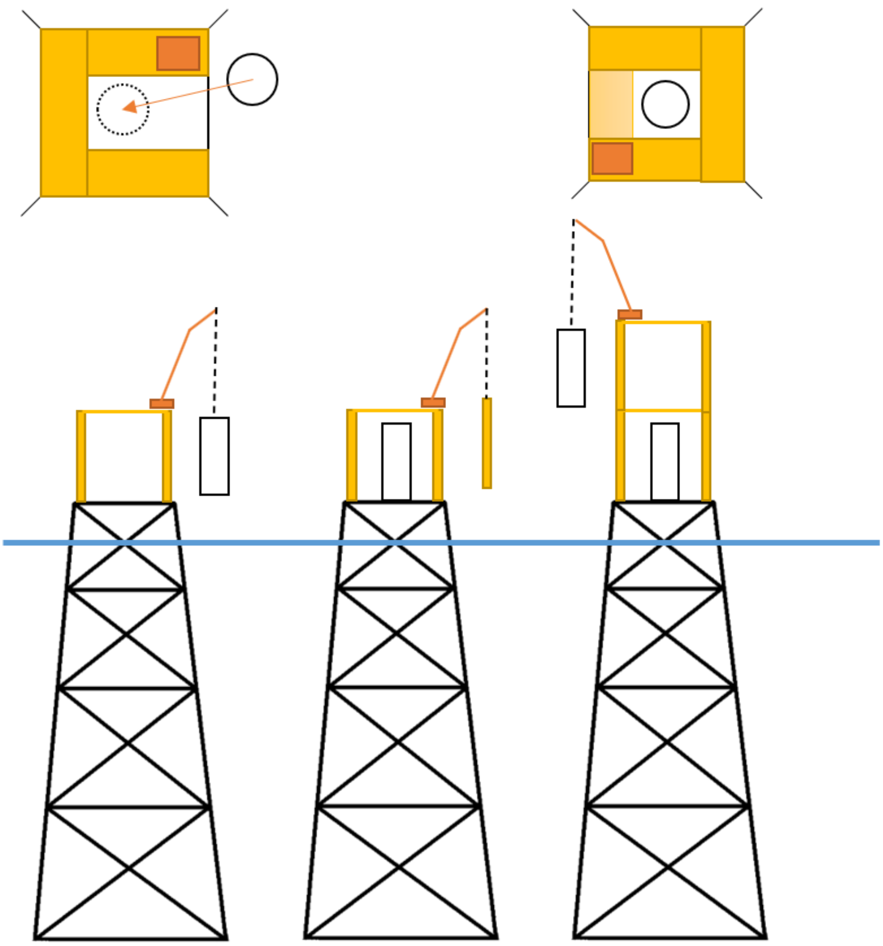

Figure C.15: Sketch of workings generated concept 15: Scaffolding bottom-up modular tower.

D

Appendix D: Screening of concepts tables and figures

In this appendix, tables and further figures describing the screening and grouping into branches of the novel concepts is shown. First, the grouping of concepts into branches is shown.

D.1. Grouping of concepts into branches

The branches that were defined are:

- Self-Climbing concepts;
- Self-Erecting concepts;
- Pivot like concepts;
- Integrated lift concepts;
- Super large man-made floating structures;
- Others.

All concepts are subdivided into these branches, see Table D.1 and Table D.2 for the entire subdivision of all concepts.

Table D.1: Academic and industry proposed novel methods with concept tag, description and branch.

Concept Tag	Description of concept	Branch
AC-1	Integrated installation method using inverted pendulum principle[1]	Pivot
AC-2	Novel blade installation method from K. De Groot[17]	N.a.
AC-3	Blade installation and replacement concept using tower[18] climbing apparatus	Self-climbing
AC-4	Floating dock principle for installation of spar type turbines[25]	N.a.
AC-5	Integrated lift installation using catamaran vessel[26]	Integrated lift
IC-1	Integrated lift installation vessel, Windlifter from Ulstein[54]	Integrated lift
IC-2	Integrated lift catamaran installation vessel, Wind turbine shuttle from Huisman Equipment[20]	Integrated lift
IC-3	Integrated lift Installation add-on support tower from Offshoretronic[41]	Integrated lift
IC-4	Integrated installation method for spar type turbines, from WindFlip[39]	N.a.
IC-5	Modular tower integrated installation method using self climbing system, from SMCC and Mammoet[33]	Self-climbing
IC-6	Self-climbing crane for onshore installation of wind turbines, from Lagerwey[30]	Self-climbing

Table D.2: Generated concepts tags, names and branches.

Concept Tag	Description of concept	Branch
GC-1	Wind turbine escalator	Other
GC-2	Self-erecting modular tower	Self-erecting
GC-3	Installation tower	Large man-made floating structure
GC-4	Multi pivot tower to lower mating surface	Pivot
GC-5	Elevator working platform	Self-climbing
GC-6	Integrated float out	Self-erecting
GC-7	Tower ring with scissor platform	Others
GC-8	Construction island	Large man-made floating structure
GC-9	Telescopic tower	Self-erecting
GC-10	Integrated pivot from installation vessel	Pivot
GC-11	Jack-up leg tower principle	Self-erecting
GC-12	Combination between pivot and self-climbing	Other
GC-13	Integrated lift using traditional cranes and lifting frame	Integrated lift
GC-14	Pivot without cranes using specifically designed vessel	Large man-made floating structure
GC-15	Scaffolding bottom-up modular tower	Other

An overview of the branches and the resulting concept that passed through the screening can be found in Table D.3. The screening of each branch and the selection of the best concept within each branch can be found in Section D.2.

Table D.3: Table showing branches, concepts within them, and the choice of concept.

Branch	Concepts	Choice
Self-climbing	AC-3, IC-5, IC-6, GC-5	GC-5
Self-erecting	GC-2, GC-6, GC-9, GC-11	GC-9
Pivot	AC-1, GC-4, GC-10	AC-1
Integrated lift	AC-5, IC-1, IC-3, GC-13	AC-5
Super large man-made floating structures	IC-2, GC-3, GC- 8, GC-14	GC-3
Others	GC-1, GC-7, GC-12, GC-15	GC-15

An overview of all the concepts and their subdivision into branches can be found in Figure D.1.

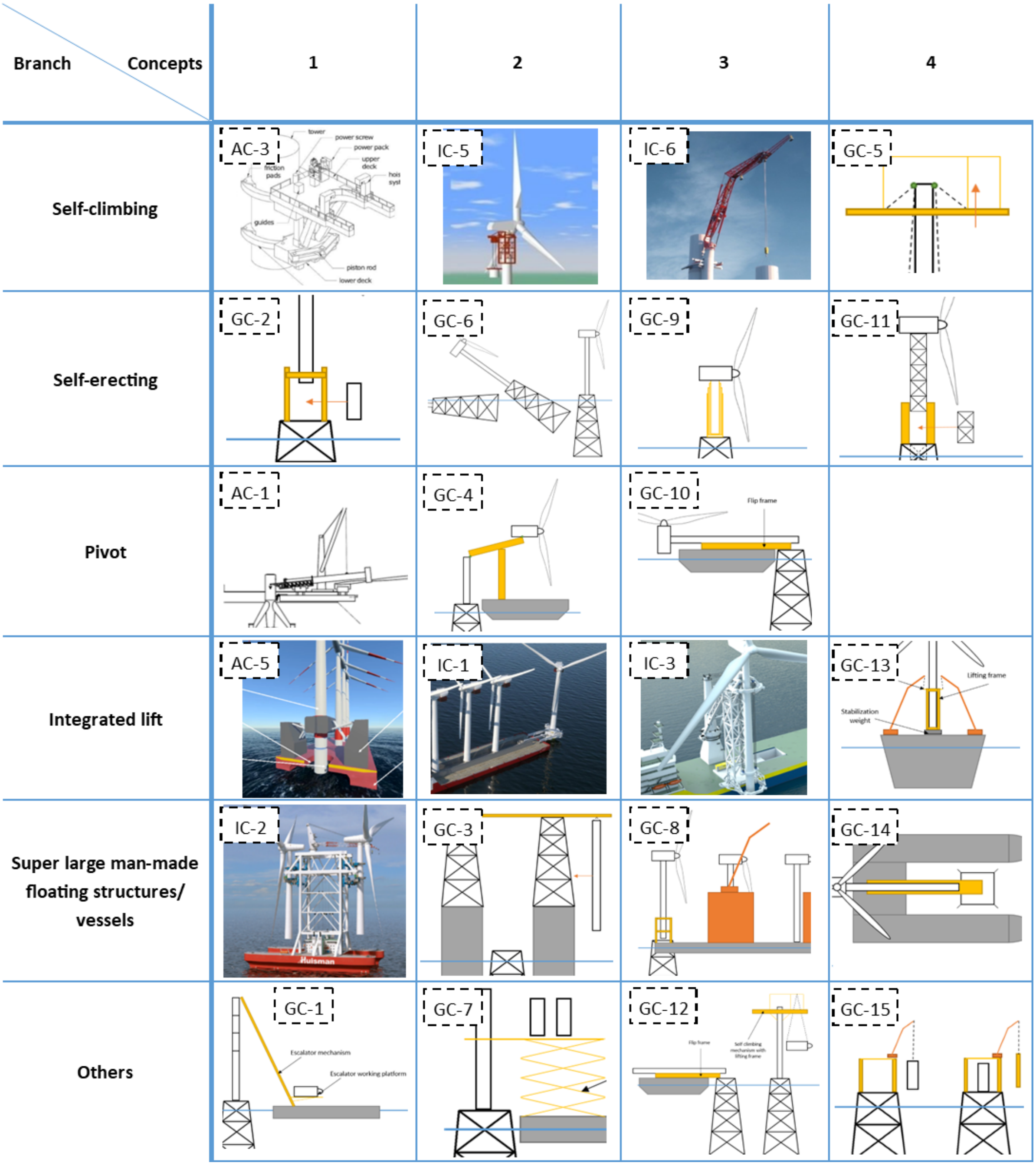

Figure D.1: Matrix showing all concepts, their tags, and branches.

D.2. Selecting concepts within each branch

In this part of the appendix, the screening of the concepts within each branch is further explained. In Table D.4 up until Table D.8 the screening tables of all branches can be found. The screening is based upon high level feasibility consideration evaluations and engineering sense. This might seem a bit arbitrary at some points, however, choices needs to be made to reduce the total amount of concepts that will be evaluated further.

D.2.1. Self-climbing

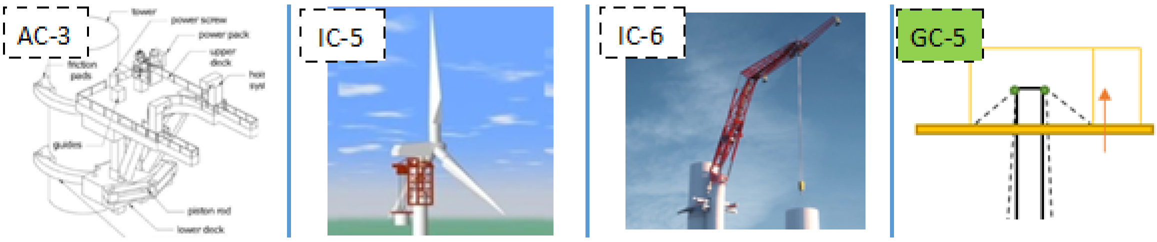

Figure D.2: Visual example of concept in branch, Self-climbing.

The first concept in the branch, AC-3, will not be considered as this method can only be used for installation of blades. Thus, This concept does not meet the boundary conditions.

Reasoning major mechanisms: All mechanisms have never before been used or build, so only a high level comparison about the complexity can be performed. The elevator system is deemed less complex, as it does not entail a self climbing system that has to be attached to the wind turbine tower. That leaves IC-5 and IC-6, from these two IC-5 is deemed less complex, as the climbing mechanisms is situated on top of the tower instead of attached to the side. Furthermore, IC-5 does not have a movable crane. So, GC-5>IC-5>IC-6

Reasoning complexity of process: GC-5 is deemed least complex, as here no dedicated climbing mechanism is needed, but only a guiding mechanism. resulting in an easier process of elevating and lowering compared to other two concepts. The other two are equally complex, as both have a complicated climbing process consisting of multiple steps. So, GC-5>IC-5=IC-6

Table D.4: Screening concepts within branch, self-climbing.

Tag	AC-3	IC-5	IC-6	GC-5
# of mating procedures	n.a.	>6	>6	>6
Relative score	n.a.	3	3	3
Normalized score	n.a.	1	1	1
Major mechanisms ranking	n.a.	2	1	3
Process ranking	n.a.	2	2	3
Relative score	n.a.	2	1	3
Normalized score	n.a.	0,67	0,33	1,00
Repair and replacement	n.a.	no	yes	yes
Foundation	n.a.	yes	yes	yes
Size of WT	n.a.	no	no	no
Relative score	n.a.	2	3	3
Normalized score	n.a.	0,67	1,00	1,00
Influence on WT construction	n.a.	0	0	0
Sum	n.a.	2,33	2,33	**3,00**

D.2.2. Self-erecting

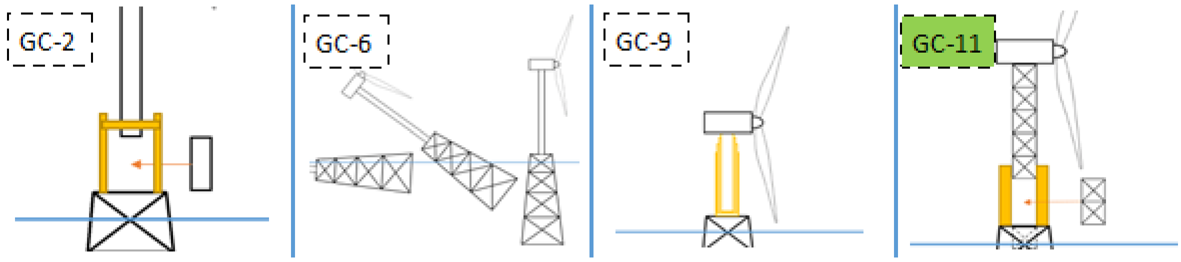

Figure D.3: Visual example of concept in branch, Self-erecting.

Reasoning major mechanisms: GC-9 is deemed to be based around the least proven technology, as a telescopic tower has never been made before and the entire internal structure of the turbine tower has to be made telescopic, or constructed after the erection of the turbine. GC-2 is deemed to be the second worst, as the mechanisms of raising the tower is based on technologies that have never been used before. Then GC-6 is the second best, as the mechanism needed for a float out are known and can be built. However, some mechanisms will be needed to lower the entire structure, which is deemed less favourable than GC-11. GC-11 is based upon proven technologies, as jack-up systems have been in use for decades already. So, GC-11>GC-6>GC-2>GC-9.

Reasoning complexity of process: The process of GC-11 and GC-2 are deemed equally complex, as both need supply of tower pieces, after which the tower is connected and further erected. They are deemed the easiest processes. The second-worst process is GC-9, where the tower has to be elongated by the telescopic mechanism. Due to the fact that the entire inside structure of the tower can only be installed after the elongation, it is deemed less favourable than GC-2 and GC-11. GC-6 is deemed worst as the process of lowering, up-righting and attaching to the pre-installed foundation piece has to be performed underwater. So, GC-11=GC-2>GC-9>GC-6.

Table D.5: Screening concepts within branch, self-erecting.

Tag	GC-2	GC-6	GC-9	GC-11
# of mating procedures	>6	1	4	>6
Relative score	2	4	3	2
Normalized score	0,50	1	0,75	0,5
Major mechanisms ranking	2	3	1	4
Process ranking	4	2	3	4
Relative score	3	2	1	4
Normalized score	0,75	0,50	0,25	1
Repair and replacement	no	no	yes	no
Foundation	no	no	yes	yes
Size of WT	yes	yes	no	yes
Relative score	3	3	4	4
Normalized score	0,75	0,75	1	1
Influence on WT construction	0	0	0	0
Sum	2,00	2,25	2,00	**2,50**

D.2.3. Pivot

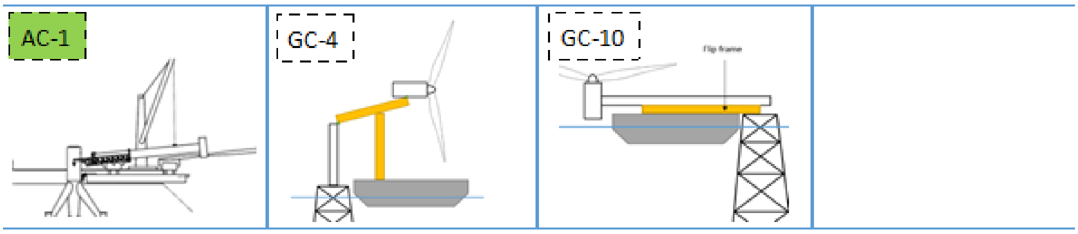

Figure D.4: Visual example of concept in branch, Pivot.

Reasoning major mechanisms: All concepts are not based upon proven technologies, GC-10 and AC-1 both consist of the same major mechanisms, which are deemed less complex than the double pivot of GC-4. Where two internal pivot mechanisms are needed. So, AC-1=GC-10>GC-4.

Reasoning complexity of process: AC-1 is deemed least complex as only one crane is needed and the barge can be attached to the foundation, making the installation easier than opposed to GC-10. Where two cranes are needed to upright the turbine and no rigid connection with the foundation can be made. GC-4 is deemed more complex, as the up-righting process of the double pivot will require multiple processes that have to be performed in unison. So, AC-1>GC-10>GC-4.

Table D.6: Screening concepts within branch, Pivot.

Tag	AC-1	GC-4	GC-10
# of mating procedures	1	1	1
Relative score	3	3	3
Normalized score	1	1	1
Major mechanisms ranking	3	2	3
Process ranking	3	1	2
Relative score	3	1	2
Normalized score	1	0,33	0,67
repair and replacement	no	yes	no
Foundation	no	yes	no
Size of WT	yes	no	yes
Relative score	2	3	2
Normalized score	0,67	1,00	0,67
Influence on WT construction	0	0	0
Sum	**2,67**	2,33	2,33

D.2.4. Integrated lift

Figure D.5: Visual example of concept in branch, Integrated lift.

Reasoning major mechanisms: GC-13 is deemed least complex because it only needs a frame, this is based upon proven technology, as frames have been used before but not for this size. All other concepts have never been used before, but have seen some development. IC-3 is deemed less complex than AC-5 and IC-1, as only one major mechanisms is in use, the tower construction in which the wind turbine is placed. AC-5 and IC-1 are deemed similarly complex, as they both have movable gripper systems. So, GC-13>IC-3>AC-5=IC-1.

Reasoning complexity of process: AC-5 is deemed least complex because the process is fully automated. IC-1 is deemed the second least complex because no connection to the foundation is made, and station keeping will have to take place to keep the installation vessel in place. GC-13 is the second most complex, because two cranes have to be operated at the same time and no automation is present. IC-3 is deemed most complex because the tower cannot be moved freely relative to the vessel, so the entire vessel has to be manoeuvred to line up the WT with the foundation. So, AC-5>IC-3>GC-13>IC-3.

Table D.7: Screening concepts within branch, integrated lift.

Tag	AC-5	IC-1	IC-3	GC-13
# of mating procedures	1	1	1	1
Relative score	3	3	3	3
Normalized score	1	1	1	1
Major mechanisms ranking	2	2	3	4
Process ranking	4	3	1	2
Relative score	4	3	2	4
Normalized score	1	0,75	0,50	1
repair and replacement	no	no	no	no
Foundation	no	yes	no	yes
Size of WT	no	no	no	no
Relative score	3	4	3	4
Normalized score	0,75	1,00	0,75	1
Influence on WT construction	1	1	0	1
Sum	3,75	3,75	2,25	**4,00**

D.2.5. Large man-made floating structures

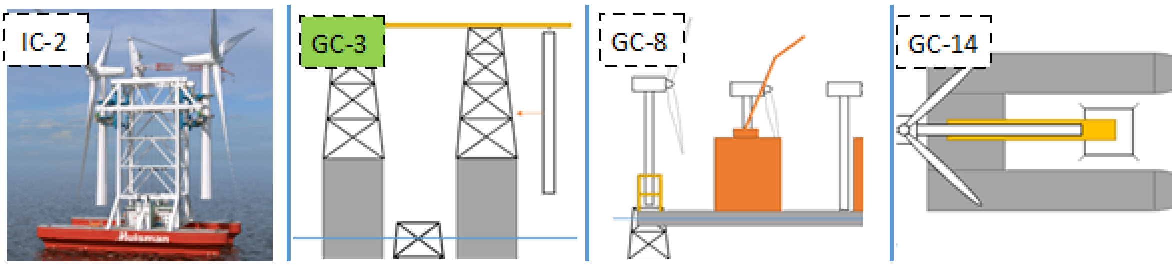

Figure D.6: Visual example of concept in branch, Large man-made floaters.

Reasoning major mechanisms: GC-3 is deemed the least complex, as all mechanisms are based on proven technologies. It is basically just a large floating crane platform. GC-8 is deemed second least complex, as large moving cranes and a gripper system are in use, the cranes are based upon proven technologies the gripper system is not. GC-14 is deemed the second most complex, because two never before developed mechanisms are needed, the flip frame and the up-righting mechanism. The most complex is IC-2, because it is based upon a double gripper system that has never before been used. So, GC-3>GC-8>GC-14>IC-2

Reasoning complexity of process: IC-2 is deemed the least complex, because only one procedure has to be performed, the lowering of the turbine onto the foundation. GC-3 is deemed second least complex, because multiple vessels are needed to supply the components. Even though only one vessel is needed for both GC-8 and GC-14, they are deemed more complex. GC-14 is deemed the second most complex, because the operation of up-righting requires the vessel to move and the ship has to be reloaded after every installation. GC-8 is the most complex, as both mating and construction will take place at the same time on one vessel, while also requiring supply vessels for feeding of components. So, IC-2>GC-3>GC-14>GC-8

Table D.8: Screening concept within branch, Large man-made floating structures.

Tag	IC-2	GC-3	GC-8	GC-14
# of mating procedures	1	5	6	1
Relative score	4	3	2	4
Normalized score	1	0,75	0,5	1
Major mechanisms ranking	1	4	3	2
Process ranking	4	3	1	2
Relative score	3	4	2	2
Normalized score	0,75	1,00	0,50	0,5
repair and replacement	no	yes	yes	no
Foundation	yes	yes	yes	no
Size of WT	no	yes	yes	no
Relative score	3	4	4	2
Normalized score	0,75	1,00	1	0,5
Influence on WT construction	1	1	1	0
Sum	3,5	**3,75**	3,00	2,00

D.2.6. Others

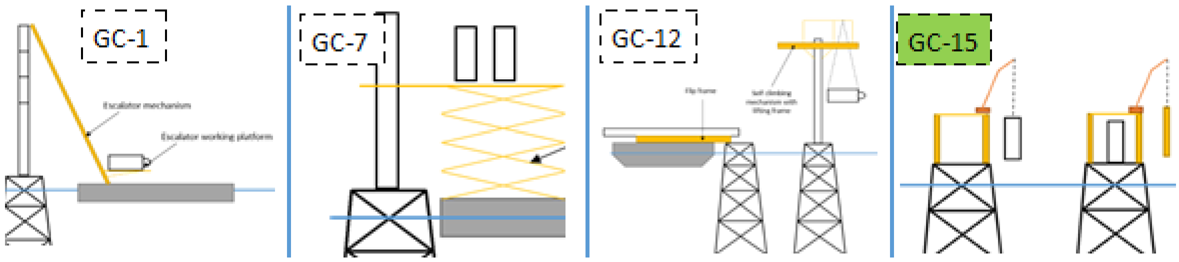

Figure D.7: Visual example of concept in branch, others.

Note that: GC-12 will not be taken into account further, as this is a combination method between two methods that are present in other branches. The feasibility of both methods still has to be determined, it is more interesting to look at them separately and afterwards determine the usability of the concepts with regard to installation of particular components.

Reasoning major mechanisms: GC-15 is deemed to be the least complex as the workings of the method are based on proven technology, except for the crane that has to be disassembled. GC-7 and GC-1 are both based on never before developed mechanisms. However, GC-7 is deemed less complex than GC-1, because the amount of moving parts in the construction is lower and fewer mechanisms are needed for the station keeping of the barge, as the barge can be kept at the same location during the entire operation. So, GC-15>GC-7>GC-1.

Reasoning complexity of process: GC-15 is again the least complex, as all operations can be performed by a crane which is rigidly connected to the tower and foundation. GC-7 is deemed the second least complex, because no re-positioning of the barge is needed in between the connection of tower pieces. So, GC-15>GC-7>GC-1.

Table D.9: Screening concept within branch, Others.

Tag	GC-1	GC-7	GC-12	GC-15
# of mating procedures	>6	>6	n.a.	>6
Relative score	3	3	n.a.	3
Normalized score	1	1	n.a.	1
Major mechanisms ranking	1	2	n.a.	3
Process ranking	1	2	n.a.	3
Relative score	1	2	n.a.	3
Normalized score	0,33	0,67	n.a.	1
repair and replacement	yes	yes	n.a.	yes
Foundation	yes	yes	n.a.	no
Size of WT	no	no	n.a.	yes
Relative score	3	3	n.a.	3
Normalized score	1	1	n.a.	1
Influence on WT construction	0	0	n.a.	0
Sum	2,33	2,67	n.a.	**3,00**

Appendix E: Wind turbine Particulars calculations and further information

In this appendix further information and calculations on the definition of the tower of a ULWT are provided. The starting point of the tower is the largest fully defined wind turbine tower the author could find, the IEA-15 MW academic turbine[14]. The tower will be scaled up by use of a constant stress assumption, as the main current failure mode of wind turbine towers is fatigue driven. To keep the fatigue life of towers within acceptable ranges, the tower natural frequency must be outside of the wind, wave and rotor excitation frequency ranges. This to lower the amount of stress cycles the construction experiences. Thus, when up-scaling towers 2 factors have to be taken into account, the number of cycles it sees and the stress range of the cycles. For now, only the stress range will be taken into account, thus the constant stress assumption is deemed acceptable. The discussion about the actual feasibility of this is presented in Subsection 5.2.3.

E.1. Tower dimension calculations

A first estimation of the tower dimensions has to be made using only the provided hub height of 250 meters. Taking into account the height of the foundation above the water line, the height of the transition piece and the height of the nacelle, the tower length of an ULWT becomes 212.5 meters, as described in Subsection 5.2.2. The first step is to identify the main causes of the stress in a wind turbine tower. This is caused by the moments in the tower due to the wind, the main point of interest here is the moment at the base of the tower as here the largest moments will occur. This moment can be subdivided into 2 components, the thrust due to the wind acting on the blades and drag on the tower, see Equation E.1. Here the assumption is made that there is no yaw error and the trust is in line with the wind direction.

$$M_{base} = T \cdot L_{tow} + \int_{0}^{L_{tow}} F_d(L) \cdot L dL \tag{E.1}$$

In which M_{base} is the moment at the base of the tower in [Nm], T is the thrust force in [N], L_{tow} is the length of the tower in [m], $F_d(L)$ is the drag force in the tower dependant on the height along the tower in [N] and L is the length along the tower in [m]. The thrust force is the main contributor to this moment, given by Equation E.2. The drag component will be neglected from here on.

$$T = \frac{1}{2}\rho C_t(\lambda) A_{rot} V_w^2 \tag{E.2}$$

In which T is the thrust in [N], ρ is the density of the air in [kg/m3], $C_t(\lambda)$ is the dimensionless tip speed ratio dependant thrust coefficient, A_{rot} is the swept area of the rotor in [m2] and V_w is the wind speed at hub height in [m/s]. Under the assumption of constant wind speed and thrust coefficient the thrust becomes relative to the rotor area of the wind turbine, Equation E.3.

$$T \propto A_{rot} \tag{E.3}$$

This results in, that the tower base moment is proportional to the area of the rotor and the length of the tower, as expressed in Equation E.4.

$$M_{base} \propto A_{rot} \cdot L_{tow} \tag{E.4}$$

The stress in the tower is guided by this moment and can be expressed as Equation E.5, using the well known bending stress relation.

$$\sigma_m = \frac{M \cdot y}{I} \tag{E.5}$$

In which σ_m is the stress due to a moment in [pa], M is the moment in [Nm], y is the location of the outer fiber of the cross section in [m] and I is the area moment of inertia of the cross section in [m4]. A wind turbine tower is a tubular structure, so the distance of the outer fiber and the area moment of inertia of the cross section can be expressed in terms of the diameter of the tower, see Equation E.6 and Equation E.7 respectively.

$$y = \frac{D_o}{2} \tag{E.6}$$

$$I_{tow} = \frac{\pi}{64}\left(D_o^4 - (D_o - 2t)^4\right) \tag{E.7}$$

In which D_o is the outer diameter of the wind turbine tower in [m] and t is the wall thickness of the tower in [m]. To determine the wall thickness the diameter over thickness(D/t) ratio will be kept constant when up-scaling the tower. The dependencies of the outer fiber and the area moment of inertia can be expressed as Equation E.8 and Equation E.9 respectively.

$$y \propto D_o \tag{E.8}$$

$$I_{tow} \propto D_o^4 \tag{E.9}$$

All needed proportionality' are known to express to diameter of the up-scaled tower in terms of tower length and rotor area under the constant stress assumption. Using Equation E.5 the ratio of the stress in the up-scaled and initial turbine can be expressed as Equation E.10.

$$\frac{\sigma_{m1}}{\sigma_{m2}} = \frac{M_1}{M_2}\frac{y_1}{y_2}\frac{I_2}{I_1} \tag{E.10}$$

In which 2 denotes the up-scaled turbine and 1 denotes the initial turbine. Using the found proportionality' of the moment, outer fiber distance and the area moment of inertia, a scaling factor can be expressed. The factor will be dependant on the ratio of the tower lengths and rotor areas.

$$\frac{\sigma_{m1}}{\sigma_{m2}} \propto \frac{A_1 L_{tow1}}{A_2 L_{tow2}}\frac{D_{o1}}{D_{o2}}\frac{D_{o2}^4}{D_{o1}^4} = \frac{A_1 L_{tow1}}{A_2 L_{tow2}}\frac{D_{o2}^3}{D_{o1}^3} \tag{E.11}$$

Thus, the incease in diameter under the constant stress assumption can be expressed in Equation E.12. Using this formula the tower diameter that suffices to the constant stress assumption can be found.

$$D_2 = D_1 \cdot \sqrt[3]{\frac{A_2 L_{tow2}}{A_1 L_{tow1}}} \tag{E.12}$$

Using this equation in combination with, the particulars of the IEA-15 and provided tower length and rotor diameter of the ULWT. The base and top diameters of the tower of an ULWT can be estimated. In Table E.1 the rounded of values for the diameters can be found.

Table E.1: Parameters of IEA-15 and ULWT found using constant stress assumption.

Parameter	IEA15	ULWT
Tower length [m]	135	212.5
Rotor diameter [m]	240	410
Base Diameter tower[m]	10	16.5
Top Diameter tower[m]	6.5	10.5
D/t at base[-]	250	250
D/t at top[-]	310	310
t at base[mm]	21	34
t at top[mm]	40	66
Tower weight[ton]	860	3600

The assumption was made that the D/t ratio will is similar for both towers to not exceed local plate buckling stresses. Lowering these values will require more in depth design of the tower to determine the local and global buckling resistances. Furthermore, both the D/t ratio and the diameter are assumed to have a linear relation between the tower top and bottom. Normally a single plate within a tower structure will have the same diameter and thickness without a slope, as that is more practical for the construction of the plates. However, it is deemed acceptable as a first estimation, and will not be optimized any further. In Figure E.1 the tower diameter and wall thickness along the tower can be found.

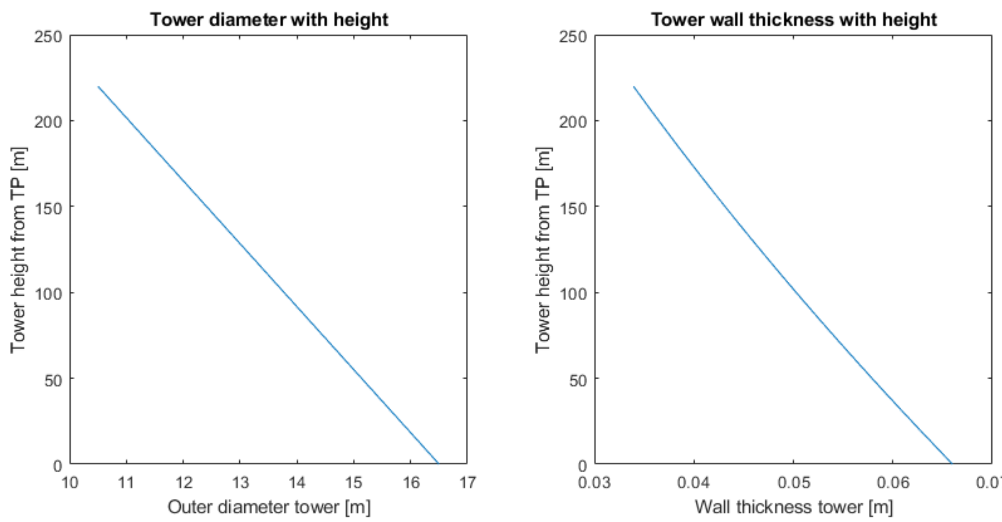

Figure E.1: Tower diameter and wall thickness along tower height of ULWT.

E.2. Wind turbine drawings and dimensions

As was discussed in Section 5.2 the height of the foundation above LAT is chosen to be 15 meters, with a TP height of 15 meters as well. The choice was made to use the same blade cone angle as the IEA-15 of 5 degrees. When using these parameters the size of all parts of the turbine are set and are depicted in Figure E.2.

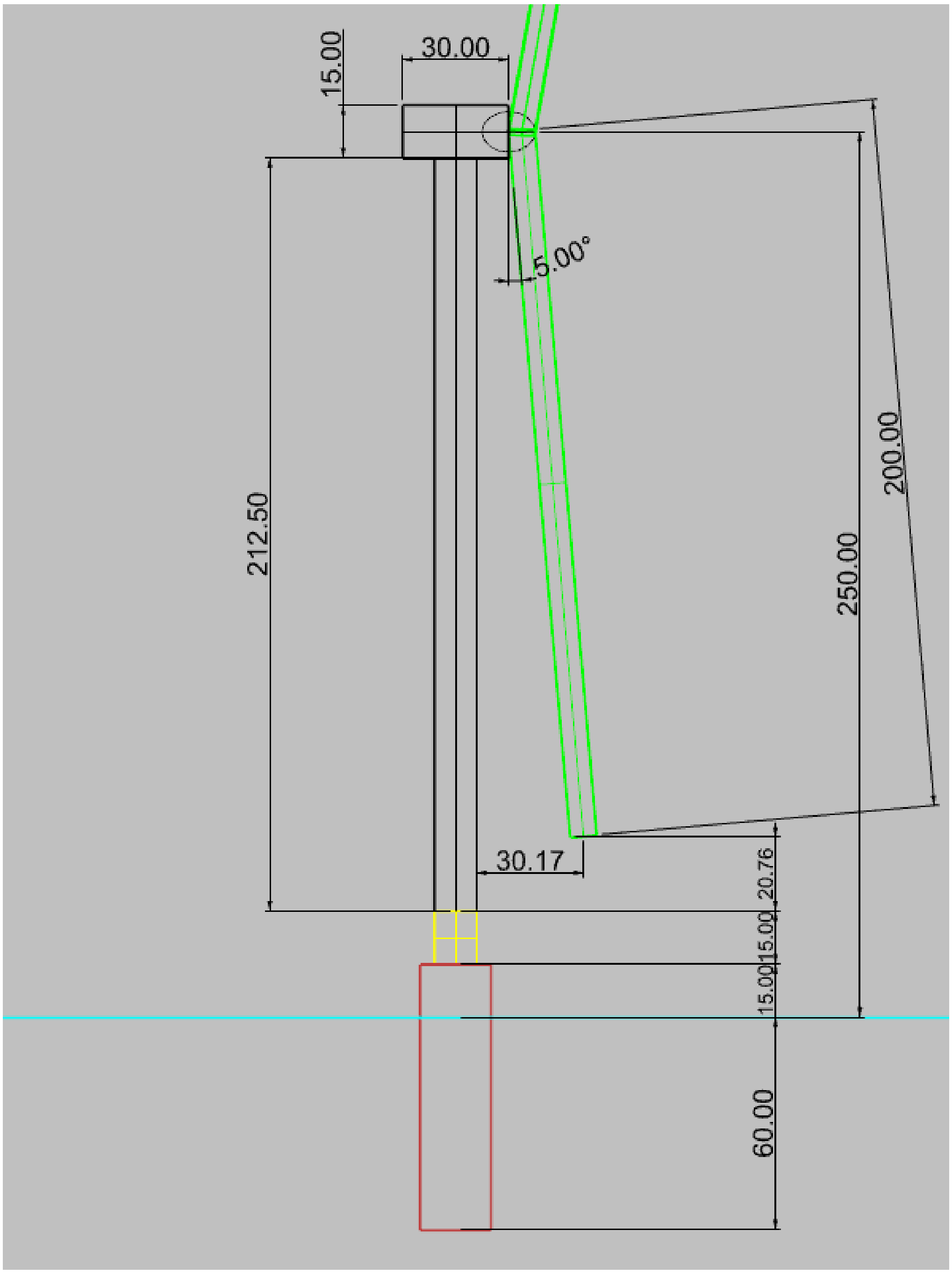

Figure E.2: Wind turbine side view with all dimensions.

F

Appendix F: Elevator platform calculations and storyboard

In this appendix, further information on the concept of the elevator platform is provided. The entire process of initial sizing and assessment of the size and strength defining critical factors will be shown.

F.1. Initial sizing and mass estimate

In this section, the initial sizing and weight estimate will be worked out into detail. The steps taken are:

- Initial sizing of concept around size of nacelle & blade clearance;
- Selection of equipment on platform using maximum load;
- Mass estimate of platform using initial size, equipment and maximum load;
- Determine load on tower due to lifting of nacelle and assess buckling and ultimate strength of tower;

In the following sections, the entire concept design process will be described and worked out. Starting with the initial sizing, after which the feasibility of the design can be assessed at a high level. The final concept design of the Elevator platform is visualized in Figure F.1.

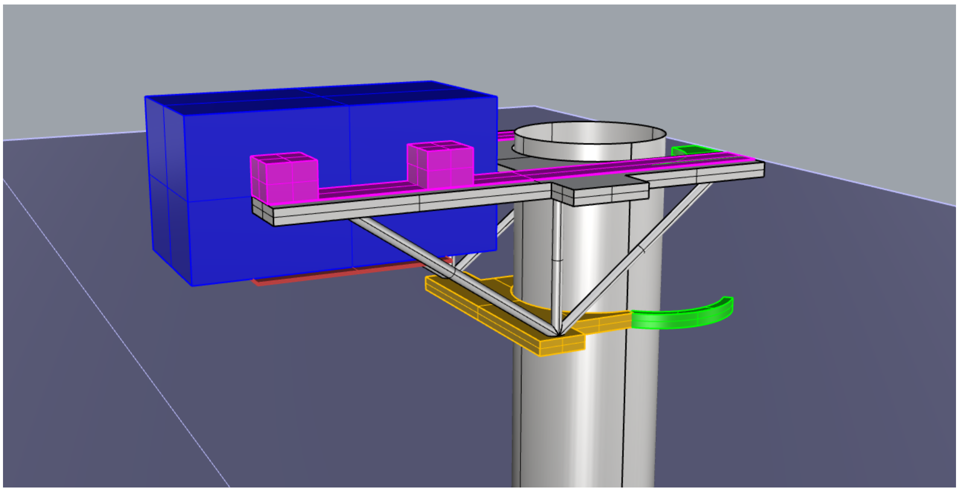

Figure F.1: Perspective view of artist impression elevator platform attached to tower while lifting nacelle.

F.1.1. Initial sizing upper platform due to nacelle size

The initial sizing of the concept revolves around the size of the nacelle and blade clearance during the installation of the blades. The first, as that is the largest and heaviest component that has to be lifted by the platform and the latter, as interference between blades and platform is unacceptable. Those in combination with the minimal lifting tolerances specified in guidelines[16] will guide the initial sizing. The tolerances must be 5 meters from a floating vessel to fixed structure during lifting and 3 meters between the lifted object and stationary parts of the structure.

The first choice that was made during the design was to place the nacelle in longitudinal direction next to the tower. This does increase the eccentricity of the load, but makes that the same lifting mechanism can be used for the installation of all components. If this orientation is achievable, it will become clear when evaluating the loads on the tower due to the lifting of the nacelle, after the weight estimation has been performed. All choices made regarding the sizing and orientation of components influence the eventual weight and feasibility of a concept, as everything influences each other. A starting point must be taken from which further iterations can be made, this starting point is the goal of this concept design.

The minimal distance of the Centre Of Gravity (COG) of the nacelle to the centre of the tower can then be expressed as Equation F.1. This distance is important, as it can be related to the global moment on the tower due to the lifting of the nacelle. This should always be minimized to lower the moment arm and thus the stresses introduced in the tower.

$$COG_{nac} = \frac{W_{foundation}}{2} + X_{clear} + \frac{L_{nacelle}}{2} = 30..5[m] \quad \text{(F.1)}$$

In which COG_{nac} is the distance of the COG of the nacelle to the centre of the tower in [m], $W_{foundation}$ is the width of the foundation at water level in [m], X_{clear} is the clearance stated in guidelines in [m] and $L_{nacelle}$ is the length of the nacelle in [m]. The COG of the nacelle is assumed to be at the volumetric centre. The situation is sketched out in Figure F.2.

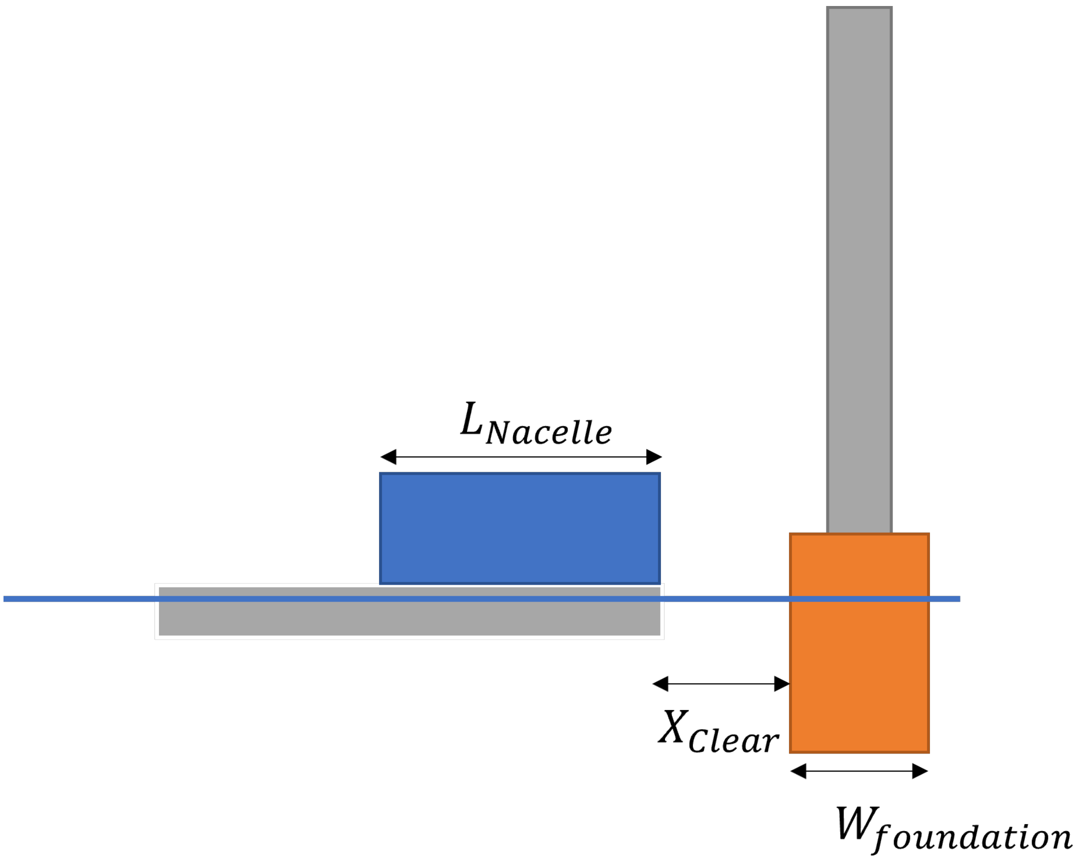

Figure F.2: Depiction distance of nacelle to centre of tower.

Using the minimal lifting distance determined with Equation F.1, the initial dimensions of the platform in length wise direction can be determined. In Figure F.3 the top view of the platform with parameterized dimensions can be found. Using the minimal distance from the centre of the tower to the COG of the nacelle, L_{sub} can be calculated using Equation F.2.

$$L_{sub} = COG_{nac} - \frac{D_{tower}}{2} - \frac{L_{nac}}{2} - L_{clear} \tag{F.2}$$

In which L_{sub} is the distance between the U-frame and the tower ring in [m], D_{tower} is the tower base diameter in [m], L_{nac} is the length of the nacelle in [m], and L_{clear} is the length of the clearance gap in [m], taken to be 1.5 meters. This leads to an L_{sub} of 5 meters. The distance of the nacelle to the tower during lifting exceeds 5 meters at all time, thus all lifting guidelines are met.

The other dimensions were chosen so that the COG of the nacelle is always within the lifting structure, the equipment can be placed on top of the upper platform, some space is left over for personnel and some space that is reserved for an auxiliary crane. However, all these dimensions are open to change as they are just a first estimation based on the mentioned factors and engineering feeling. In Figure F.3 the top platform with parameterized dimensions can be found and the values of all parameters can be found in Table F.1.

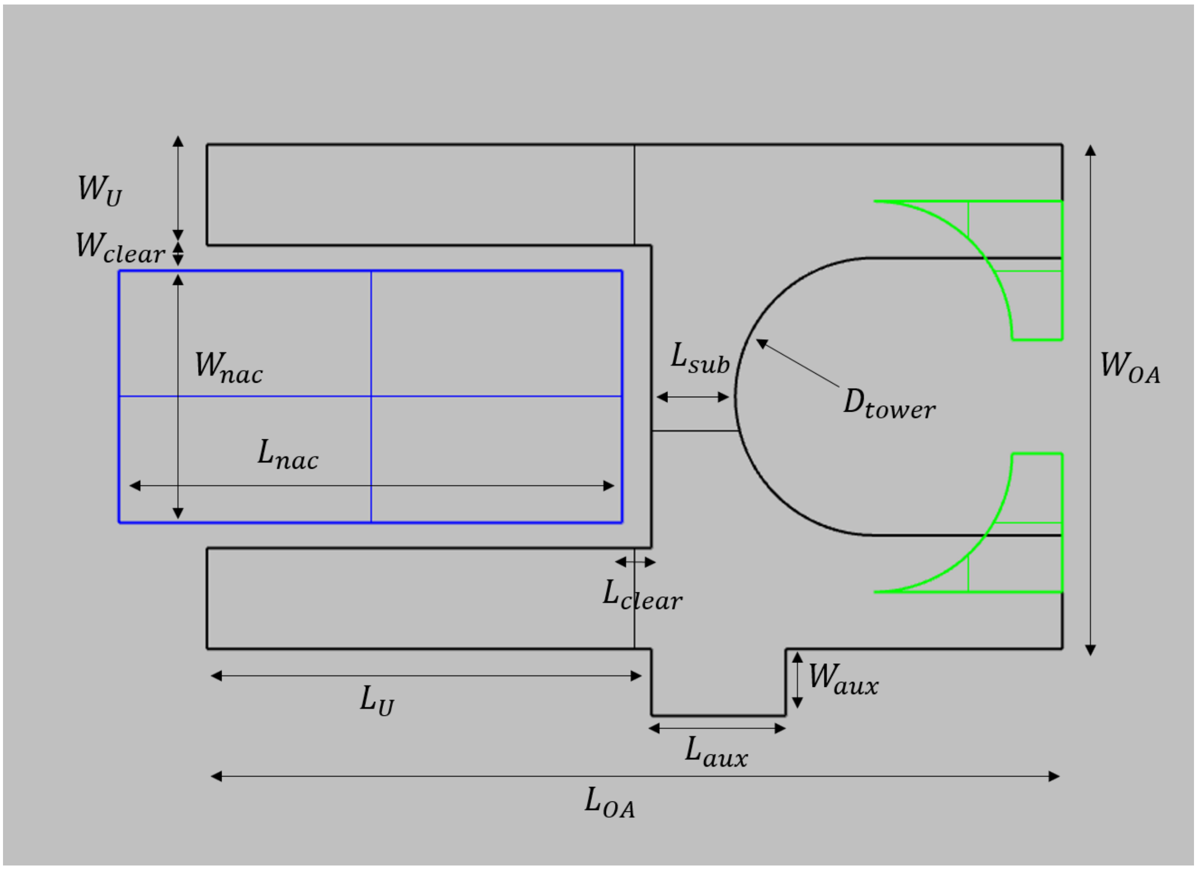

Figure F.3: Top view of upper platform of the elevator with parameterized dimensions.

Table F.1: Values of all parameters of top platform in meters.

Parameter	**Value**	**Parameter**	**Value**
L_{nac}	30	W_{nac}	15
L_{OA}	51	W_{OA}	30
L_U	26.5	W_U	6.0
L_{aux}	8.0	W_{aux}	4.0
L_{clear}	1.5	W_{clear}	1.5
L_{sub}	5.0	D_{tow}	16.5

Initial sizing lower platform

The lower platform can be significantly smaller, as only the tower ring and tower attachment system must be included. The goal of the secondary platform is to provide stability to the entire structure. The visualization and parameterized dimensions of the lower platform can be found in Figure F.4, the values of the dimension can be found in Table F.2. All dimensions have been determined in accordance with the size of the upper platform.

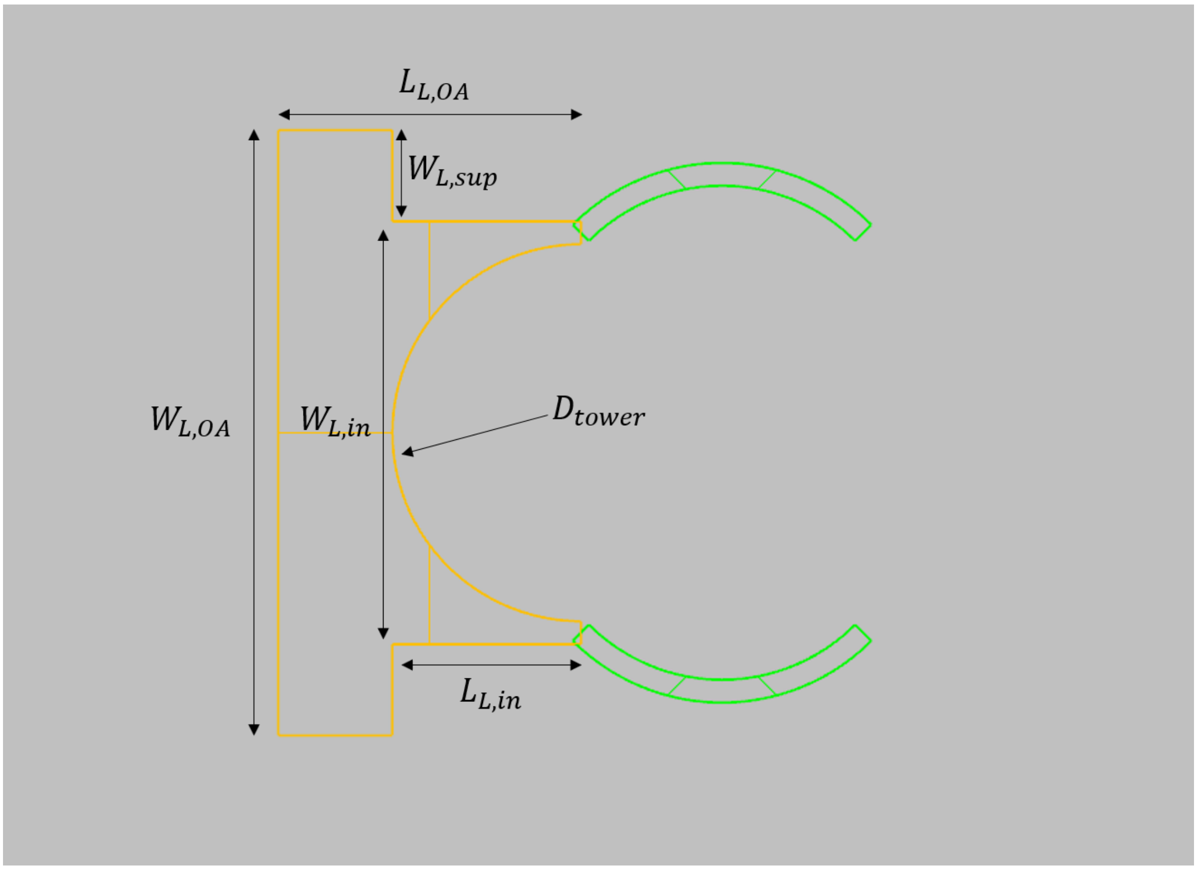

Figure F.4: Top view of lower platform with parameterized dimensions.

Table F.2: Values parameters of lower platform in meters.

Parameter	Value	Parameter	Value
$L_{L,OA}$	13.25	$W_{L,OA}$	26.5
$L_{L,in}$	8.25	W_{L_in}	18.5
D_{tower}	16.5	$W_{L,sup}$	4

Platform height and clearance of blades

The distance in-between the upper and lower platform is determined by the clearance of the blades and the effective angle at which the braces can be placed. The distance between the upper and lower platform must be as small as possible to allow for clearance with the blades, but should not be too small that the support braces have an angle below 30 degrees. A lower angle will result in less effective braces, increasing the weight of said braces. The choice has been made to use an initial distance of 15 meters between the upper and lower platform. This results in a bracing angle of 35 degrees, which is acceptable.

The height of the boxes, which make up the upper and lower platform, is determined during the weight estimation of the platform in Subsection F.1.3. The values of the parameters can be found in Table F.3.

The lifting and skidding equipment can be moved over the platform and placed such that, there is no interference with the blades. The total height of the platform becomes 18 meters and the length measured perpendicular to the tower 31.5 meters. This results in sufficient blade clearance when using the dimensions of the wind turbine provided in Section E.2. In the case that the transition piece is smaller, even more clearance can be attained, as the lower platform can then be placed on the smaller transition piece. If larger blades are used, the clearance of the blades becomes problematic. The distance between the lower and upper platform must then be decreased. In the later case, a different bracing structure must be designed, as brace angles of less than 30 degrees cannot be accepted.

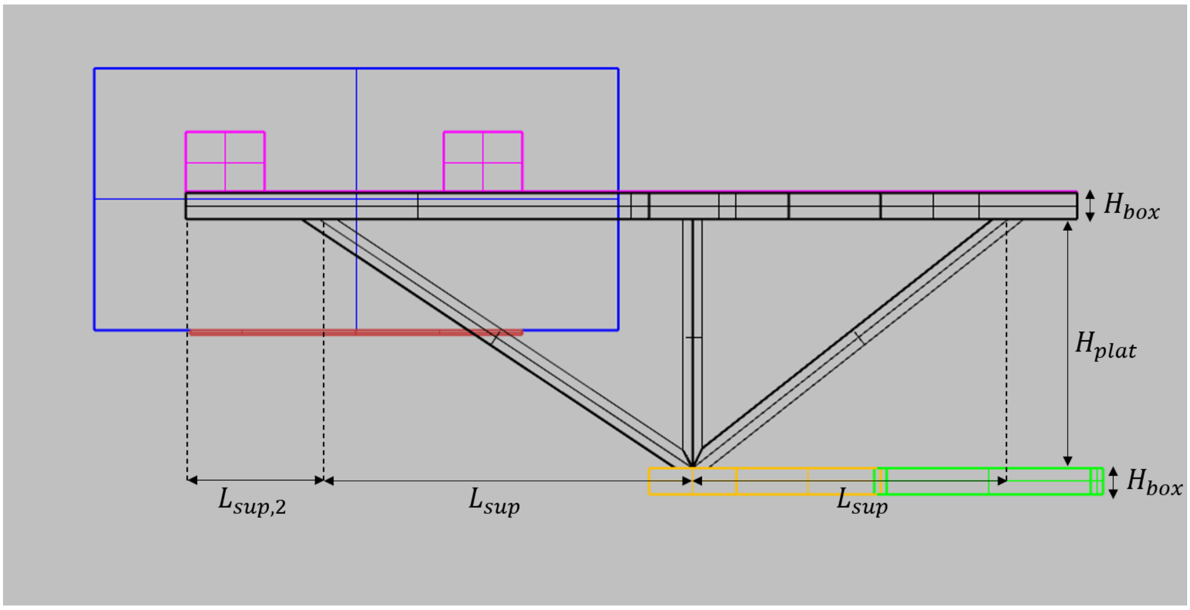

Figure F.5: Side view of elevator platform with parameterized dimensions.

Table F.3: Values parameters side view of platform in meters.

Parameter	Value
L_{sup}	21.0
$L_{sup,2}$	6.5
H_{plat}	15
H_{box}	1.5

Tower ring

In this section, the tower ring is described and depicted. In the tower rings, which are located in both the upper and lower platform, 3 main components are present.

- The wire guides of the lifting wires of the platform: The wires reach from tower top to bottom, where the automatic winches are located and must be guided through the platform. The wires are parallel to the tower and are guided through by use of wire guide rollers.
- The platform guiding system: the platform must be centred around the tower and guided during the lowering and lifting of the platform. The exact design of these will not be performed, as that is part of the detailed design.
- The platform locking system: during the lifting of the wind turbine components, the entire load of the platform and component combined must be carried by the system. This to fully decouple the platform lifting and component lifting operations. During detailed design, possibly it is beneficial to use the platform lifting system and locking system in unison to bear the extra loads on the platform during lifting. The system consists of hydraulically unlocked spring friction pads.

All 3 mechanisms are part of the tower rings, one major issue arises, the changing diameter of the tower. Due to this, all 3 systems must be movable perpendicular to the tower, as at the tower bottom the diameter is larger than at the tower top. The difference of the diameter is about 6 meters, so on either side of the tower rings must be able to reduce about 3 meters in size. It could possibly be attained by hydraulic systems which slide the systems in and out of the platform depending on the height of it. If this is attainable must be researched further. Another option to work around this issue is to have a constant diameter tower. Which one of these choices is more beneficial to the overall picture must be investigated further.

F.1.2. Selection of equipment

The selection of the lifting and skidding equipment is based around the weight of the nacelle, as this is the heaviest component that must be lifted. The choice is made to only look at equipment which is already in use in the heavy lifting industry, as weights and sizes of this equipment are known. So, they can be used during the initial sizing and weight estimation of the elevator platform. The maximum weight that has to be lifted is 2000 tons, the choice is made to use 4 attachment points on the lifting frame of the nacelle. Thus, each lifting device needs to bear a static load of 500 tonnes. The choice has been made to utilize strand jacks due to their high capacity to size and weight ratio. Further discussion can be had about this choice, as the strands of strand jacks are normally used for singular or a low number of lifts. How often they can be used could not openly be found, thus further research into this is needed.

The strand jacks that were selected are the HLS series of Enerpac with a lifting capacity of 650 tons[10]. The skidding system that was chosen is the skidding system heavy of Mammoet[36] which has a skidding capacity of 125 tons. So that would mean that 4 skidding units are needed per strand jack.

The automatic winches which lift and lower the platform can be further defined after the platform mass has been determined. And will be discussed after this has been performed.

F.1.3. Mass estimation

The mass estimation of the platform is performed using a top-down approach, first the equipment is selected and the mass is determined. Next, the forces in the platform due to the equipment mass and nacelle are calculated using basic statics. The highest moment in the platform is selected and a box structure is designed which can withstand the moment. The mass is sequentially determined by expressing the box structure mass in tons per square meter and then multiplied by the area of the platform. The final step is to determine the forces in the supports and design the supports such that there will be no global buckling of said supports.

Mass of equipment

In this section, the mass estimation of the equipment which is placed on the platform is discussed. A top-down approach is used, starting with the component lifting mechanism and working down to the skidding mechanism.

The component lifting mechanisms were selected to be the HLS650 strand jack system from ENERPAC[10]. The mass of the lifting mechanism is determined by the mass of the strands(lifting wires) and the stand jacks themselves. The entire mass of the strand jacks is determined using Equation F.3.

$$m_{sj,total} = n_{sj}\left(m_{sj} + n_{strands} w_{strand} L_{strand}\right) \tag{F.3}$$

In which $m_{sj,total}$ is the total mass of the strand jacks and strands combined in [kg], n_{sj} is the number of strand jacks, m_{sj} is the mass of one strand jack in [kg], $n_{strands}$ is the number of strands in one strand jack, w_{strand} is the mass per running meter of strand in [kg] and L_{strand} is the length of a single strand in [m]. The values used for all parameters and result can be found in Table F.4.

Table F.4: Inputs and output strand jack mass calculations elevator platform.

Parameter	Value
n_{sj}[-]	4
m_{sj}[ton]	4
$n_{strands}$[-]	43
$w_{strands}$[ton/m][11]	$1.74E^{-}3$
$L_{strands}$[m]	250
$m_{sj,total}$[ton]	90

Next the skidding system mass is determined, The skidding system is the Mammoet heavy 700/867 tonnes[36]. They have a push and pull capacity of 125 tons, and a single strand jack will have a load of 500 tons. Thus, 4 of these skidding systems are needed per stand jack. The total mass of the skidders is determined using Equation F.4.

$$m_{skid,total} = n_{skid}\,(m_{skid} + w_{track}L_{track}) \tag{F.4}$$

In which $m_{skid,total}$ is the total mass of the skidding system including the skidders and tracks in [kg], n_{skid} is the number of skidders in use, m_{skid} is the mass of one single skidder in [kg], w_{track} is the mass per running meter of skidding track in [kg] and L_{track} is the length of a single track in meters. This length is taken to be the same as the overall length of the platform. The inputs and outputs can be found in Table F.5.

Table F.5: Inputs and output of skidder system mass determination elevator platform.

Parameter	Value
n_{skid}[-]	16
m_{skid}[ton][36]	16
w_{track}[ton/m][36]	0.33
L_{track}[m]	50
$m_{skid,total}$[ton]	395

Then finally, 21 more systems have to be placed on the platform, the power packs for all hydraulics and an auxiliary crane. The auxiliary crane will be able to lift 20 tons, which will also be its mass, as was determined after deliberation with the project supervisors. The rule of thumb that can be used is that the mass of a crane is about the same as the maximum load of the crane. That leaves the power packs, No information can be found on the needed power pack output power for the systems, as that is in house knowledge. So a guess is made that the 8 highest power, power packs of ENERPAC[12] are used. The total equipment mass is then determined by Equation F.5.

$$m_{equ,total} = n_{pp}m_{pp} + m_{aux} + m_{sj,total} + m_{skid,total} \tag{F.5}$$

In which $m_{total,equ}$ is the total equipment mass in [kg], n_{pp} is the number of power packs used, m_{pp} is the mass of a single power pack in [kg], m_{aux} is the mass of the auxiliary crane in [kg] and the other parameters are stated above. The inputs and outputs can be found in Table F.6.

Table F.6: Inputs and outputs final mass determination equipment elevator platform.

Parameter	Value
n_{pp}[-]	8
m_{pp}[ton]	2
m_{aux}[ton]	20
$m_{equ,total}$[ton]	520

Determination of the largest moment in structure of elevator platform
The simplified model used for the force calculations can be found in Figure F.6. The goal is to find the location of the largest moment. Three locations are of interest, the moment at the support and

the moments at both of the lifting points. The lifting points can move over the platform, thus multiple scenarios must be checked to find the scenario in which the maximum load on the platform occurs. The first scenario is when $L_1 => 0$, the second scenario is when the lifting point passes the support, thus when $L_1 < 0$.

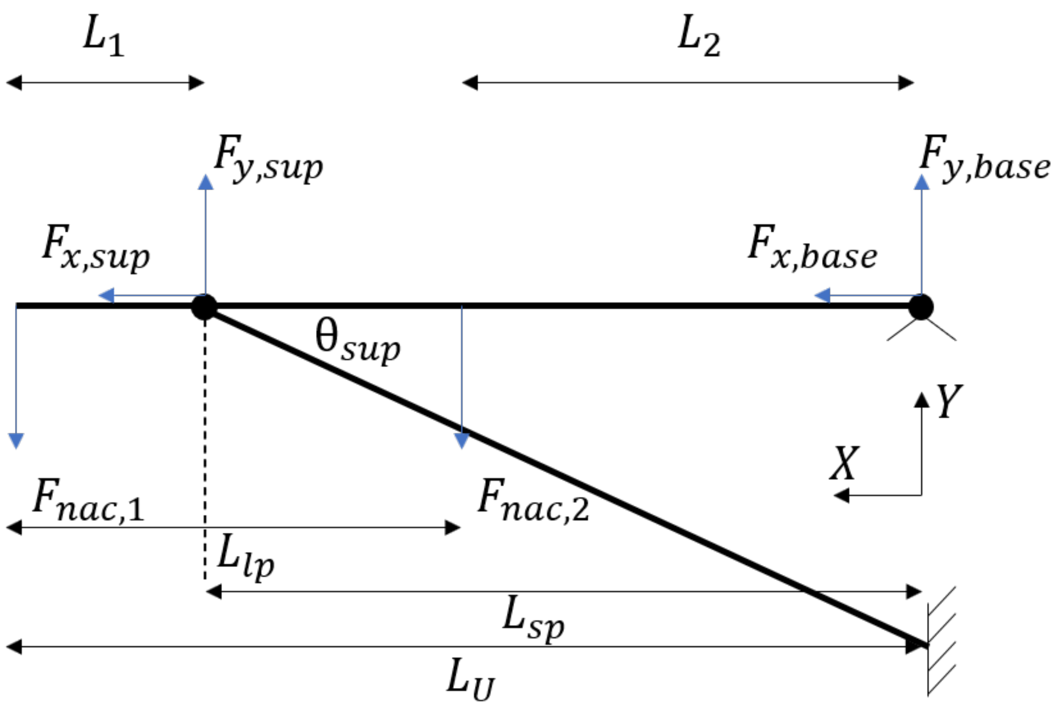

Figure F.6: Simplification of system used for force calculation.

Case1
The equations used to define case 1 are:

$$M_{sup} = F_{nac,1}L_1 \tag{F.6}$$

$$M_{lp,1} = 0 \tag{F.7}$$

$$M_{lp,2} = F_{nac,1}L_{lp} - F_{y,sup}(L_{sp} - L_2) \tag{F.8}$$

In which M_{sup}, $M_{lp,1}$ and $M_{lp,2}$ are the internal moments in the upper platform at the support, left most lifting point and second lifting point respectively in [Nm]. $F_{y,sup}$, $F_{nac,1}$ and $F_{nac,2}$ are the force due to the nacelle at the support and lifting points respectively in [N]. L_1 is the distance of the left most lifting point to the support expressed as Equation F.9 in [m], L_2 is the distance of the second lifting point to the base of the platform in [m] expressed as Equation F.10 in [m]. L_{lp} is the distance between the lifting points in [m] and L_{sp} is the horizontal length of the support from the base in [m].

$$L1 = L_U - L_{sp} - X_{lp} \tag{F.9}$$

$$L2 = L_U - L_{lp} - X_{lp} \tag{F.10}$$

In which L_U is the length of the U-shape in the upper platform in [m] and X_{lp} is the location of the left most lifting point measured from the edge of the platform in [m]. The reaction force in the support can be determined using a moment balance around the base, which results in Equation F.11 in which all parameters are as described for the equations above.

$$F_{Y,sup} = \frac{F_{nac,1}(L_{sp} + L_1) + F_{nac,2}L_2}{L_{sp}} \tag{F.11}$$

Case 2

The equations used to determine the moments for case 2 can be found in Equation F.12 up until Equation F.14. All parameters are the same as described in the section above.

$$M_{sup} = 0 \tag{F.12}$$

$$M_{lp,1} = -F_{Y,sup}(-L_1) \tag{F.13}$$

$$M_{lp,2} = -F_{Y,sup}(-L1 + L_{lp}) + F_1 L_{lp} \tag{F.14}$$

The support reaction can again be determined by a moment balance around the base and changes to Equation F.15.

$$F_{Y,sup} = \frac{F_{nac,1}(L_2 + L_{lp}) + F_{nac,2}L_2}{L_{sp}} \tag{F.15}$$

Using the moment equations the maximum moment can be found by increasing X_{lp}, the moments due to the skidding of the nacelle can be found in Figure F.7. From this figure, the extreme case can be identified for the dimensions sated in Subsection F.1.1. This results in, the most extreme case being, when the nacelle is at maximum eccentricity from the tower, so when $X_{lp} = 0$[m] and $L_1 = L_{sup,2} = 6.5$[m]. This moment will now be used to design the box structure that has to withstand it.

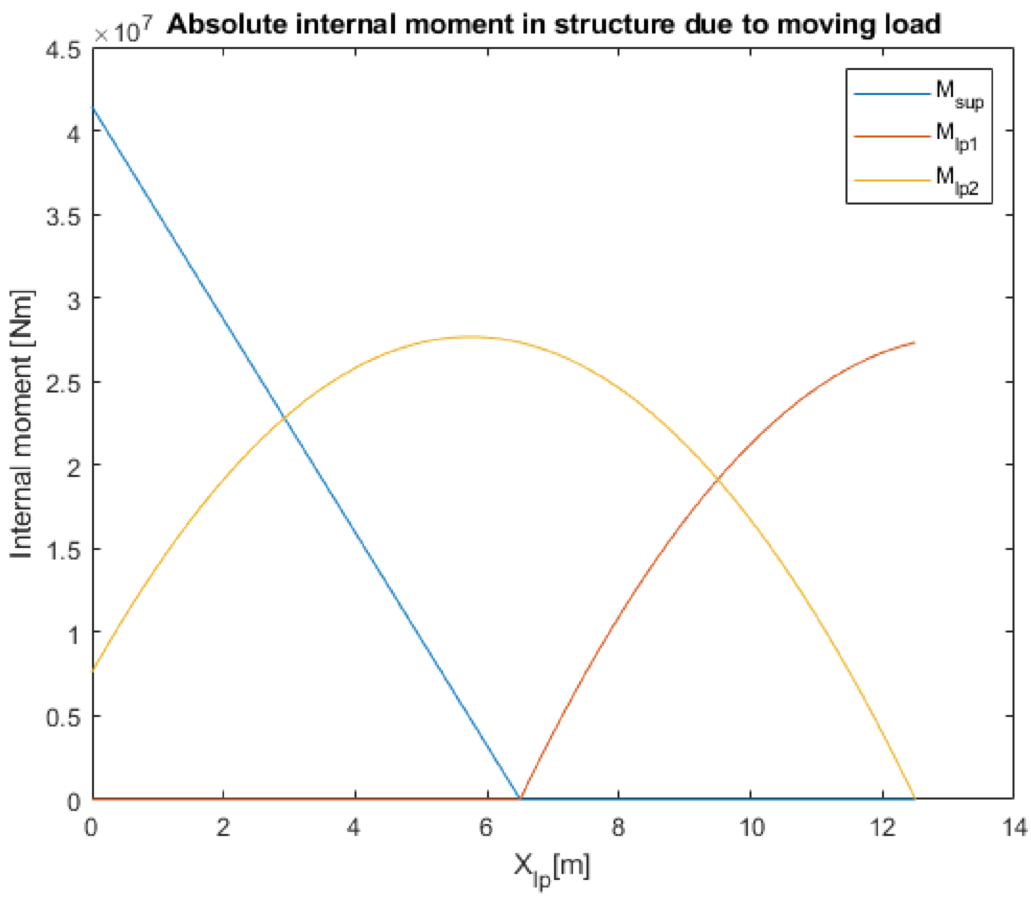

Figure F.7: Moments at the support and both lifting points of elevator platform due to skidding of nacelle.

Box structure design

The initial design of the box structure is formulated using a parameterization of a box structure, and comparing the attained area moment of inertia to the needed area moment of inertia. The latter is determined by the maximum moment, which was determined in the section above. The parameterization used can be found in Figure F.8.

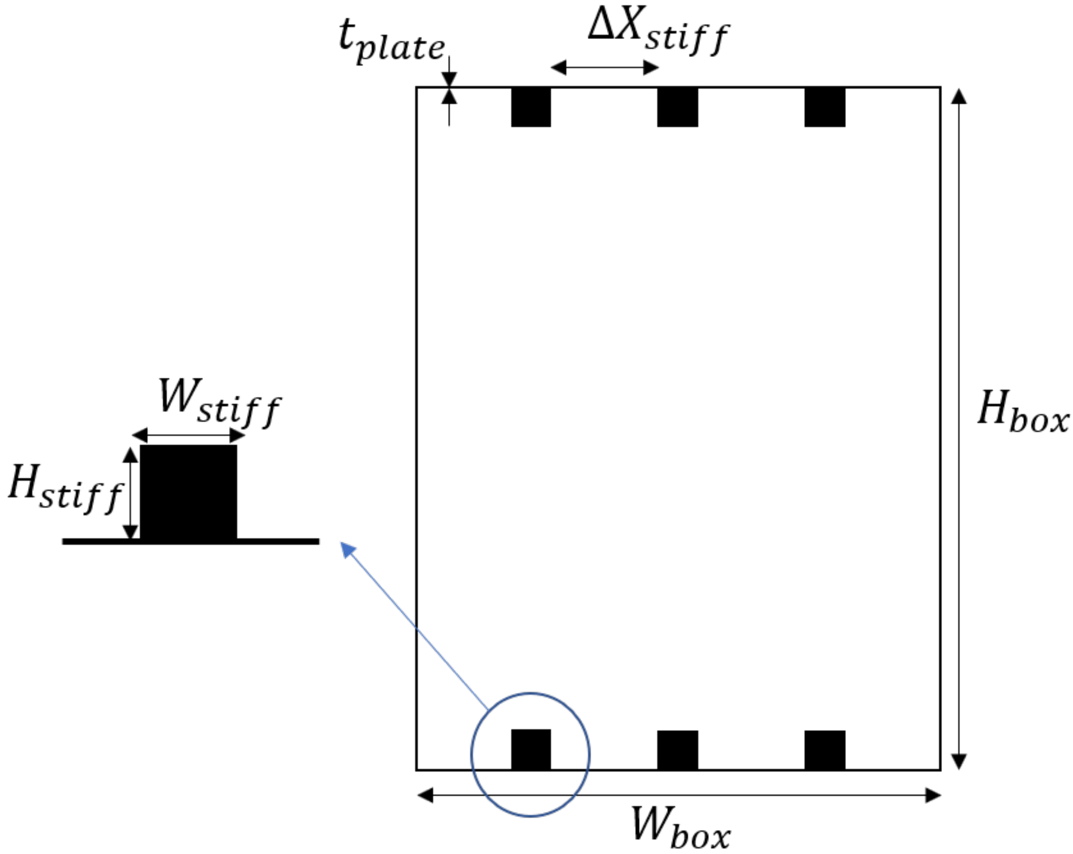

Figure F.8: Parameterization used for box structure design.

In the figure, H_{box}, W_{box}, H_{stiff} and W_{stiff} are the height and width of the cross-section of the box and stiffeners respectively, t_{plate} is the plate thickness and ΔX_{stiff} is the used stiffener spacing determined by Equation F.16.

$$\Delta X_{stiff} = \frac{W_{box} - n_{stiff} W_{stiff}}{n_{stiff} - 1} \tag{F.16}$$

In which all parameters are the same as described above and n_{stiff} is the number of stiffeners. These parameters are used to calculate the attained area moment of inertia. By initializing and altering them, the needed moment of inertia due to the moment in the structure can be reached. The assumption is made that both the upper and lower plate of the box have the same amount of stiffeners. The stiffeners on the right and left sides of the box contribute relatively little to the overall area moment of inertia and will thus be omitted during the determination of it. Resulting in a conservative box design, as those stiffeners will in fact add some area moment of inertia. The moment of inertia of the box structure is determined by Equation F.17 up until Equation F.21.

$$I_{total} = I_{box} + I_{stiff} \tag{F.17}$$

$$I_{box} = \frac{W_{box} H_{box}^3}{12} - \frac{(W_{box} - 2t_{plate})(H_{box} - 2t_{plate})^3}{12} \tag{F.18}$$

$$I_{stiff} = n_{stiff}\left(\frac{W_{stiff}H_{stiff}^3}{12} + A_{stiff}D_{stiff}^2\right) \tag{F.19}$$

$$A_{stiff} = W_{stiff}H_{stiff} \tag{F.20}$$

$$D_{stiff} = \frac{H_{box}}{2} - t_{plate} - \frac{H_{stiff}}{2} \tag{F.21}$$

In which A_{stiff} is the surface area of the cross-section of the stiffeners in [m2], D_{stiff} is the distance of the normal line of the box structure to the normal line of a stiffener and all other parameters are the same as mentioned at Equation F.16. The area moment of inertia that must be reached can be calculated using the well known bending stress formulae Equation F.22.

$$I_{needed} = \frac{(M_{box} + M_{box,sw})H_{box}}{2\sigma_{y,steel}}SF \tag{F.22}$$

In which M_{box} is the moment on the box in [Nm], $M_{box,sw}$ is the moment due to the self weight of the box in [Nm], $\sigma_{y,steel}$, taken to be 355[MPa] is the yield stress of steel in [Pa] and SF is a safety factor, here taken to be 1.5. Equation F.23 and Equation F.24 show the formulae for the moment determination.

$$M_{box} = \left(F_{nac,1}DAF + F_{eq}\right)L_{box} \tag{F.23}$$

$$M_{box,sw} = gw_{box}\frac{L_{box}^2}{2} \tag{F.24}$$

In which DAF is the dynamic amplification factor on the static load, taken to be 1.2[16], F_{eq} is the force due to equipment in [N] taken to be 100 tons, L_{box} is the length of the box structure in [m] taken to be the same length as was determined for the most critical case of 6.5[m], g is the gravitational constant and w_{box} is the mass of the box per meter in [kg/m] determined using Equation F.25 and Equation F.26.

$$w_{box} = \left(A_{box} + 2n_{stiff}A_{stiff}\right)P_fS_f\rho_s \tag{F.25}$$

$$A_{box} = W_{box}H_{box} - (W_{box} - 2t_{plate})(H_{box} - 2t_{plate}) \tag{F.26}$$

In which A_{box} is the surface area of the box in [m2], P_f and S_f are factors used to include the mass of cross stiffeners and longitudinal stiffeners on the sides of the box structure, both taken to be 1.3 after discussion with project supervisors of GustoMSC NOV. ρ_s is the density of structural steel in [kg/m3] and all other parameters are the same as described in Equation F.16. The factors used in the calculations can be found in Table F.7

Table F.7: Factors used during box design.

Parameter	Value
$SF[-]$	1.5
$P_f[-]$	1.3
$S_f[-]$	1.3
$DAF[-]$	1.2
ρ_s[kg/m3]	7850
σ_s[MPa]	355

The mass of the box is determined by changing the parameters stated in Figure F.8 to suffice to the needed area moment of inertia. Once that is achieved, the dimensions of the box are determined and the mass is calculated using Equation F.27.

$$m_{box} = w_{box}L_{box} \tag{F.27}$$

Weight estimation upper and lower platform

Using the formulae presented in Figure F.1.3 and the critical case presented in Table F.1.3 the box structure design could be performed. The mass of the upper and lower platform are determined by, using the found box mass per meter to express the mass of the platform per square meter and multiplying it by the surface area of the upper and lower platform. This is deemed acceptable as a first estimation because the box mass is determined using the largest moment found in the elevator platform.

The final dimensions of the box and the mass of the lower and upper platform can be found in Table F.8.

Table F.8: Box structure parameters of elevator platform and final masses of lower and upper platform.

Parameter	Value	Parameter	Value
H_{box}[m]	1.5	W_{box}[m]	6.0
H_{stiff}[m]	0.18	W_{stiff}[m]	0.06
n_{stiff}[-]	9	t_{plate}[m]	0.01
I_{needed}[m4]	0.145	I_{total}[m4]	0.155
w_{box}[ton/m]	4.5	$w_{box,2}$[ton/m2]	0.8
m_{Upper}[ton]	650	m_{Lower}[ton]	220

Mass estimation supports

The mass of the supports is determined using the maximum compressive force on the supports. It is found using the formulae Equation F.11 and Equation F.15, for case one and 2 respectively. It was found that the maximum compressive force occurs at the same time as the maximum moment in the box structure, thus when $L_1 = 6.5$ [m]. The compressive force can then be calculated using Equation F.28.

Next, the needed area moment of inertia to withstand global buckling is determined using the well known global buckling formula, see Equation F.29. The support is assumed to be a tubular member, so the area moment of inertia can be determined using Equation F.30.

$$F_{comp,sup} = \frac{F_{Y,sup}}{\sin\frac{H_{sp}}{L_{sp}}} \tag{F.28}$$

$$I_{comp} = SF\frac{F_{comp,sup}(K_{supp}L_{supp})^2}{\pi^2 E_s} \tag{F.29}$$

$$I_{tube} = \frac{\pi}{64}\left(D_t^4 - (D_t - 2t_t)^4\right) \tag{F.30}$$

In which $F_{comp,sup}$ is the compressive force in the support in [N], H_{sp} and L_{sp} are the height and length of the support respectively in [m], K_{supp} is the K-factor for pinned-pinned supports of 1, E_s is the Young's modulus of steel in [Pa], D_t and t_t are the diameter and wall thickness of the tubular in [m]. The wall thickness is determined using a D/t ratio of 60, as is commonly used for jacket type structures. Using these formulae, the dimensions of the supports can be determined and used to calculate the mass using Equation F.31.

$$m_{supp} = A_t L_t \rho_s \tag{F.31}$$

In which m_{supp} is the mass of a single support tubular in [kg], A_t is the cross-sectional surface area of the tubular in [m2], L_t is the length of the tubular in [m] and ρ_s is the density of steel mentioned in Table F.7. As a first estimation, all six tubular members of the supports are assumed to have the same mass, resulting in Table F.9.

Table F.9: Mass estimation tubular supports elevator platform.

Parameter	Value	Parameter	Value
D_t[m]	1.1	t_t[m]	0.18
I_{tube}[m4]	0.009	I_{comp}[m4]	0.007
m_{sup}[ton]	11	$m_{total,sup}$[ton]	66

Total mass of elevator platform

The total mass of the platform can now be determined by summing all the masses of the individual parts, resulting in a total mass of about 1500 metric tons. Using this mass, an estimation can be made of the automatic winches that lift and lower the entire platform. Automatic winches that can lift 300 tons[48] already exist, so a total of 5 of these can lift the platform. If using a pulley system, this can be further reduced to 2 or 3, depending on the amount of pulleys used. So, it is deemed feasible but will not be worked out into further detail, as that is part of detailed design.

F.1.4. Load on tower due to lifting of nacelle and platform

In this subsection, the load on the tower due to the weight of the platform and the lifting of the nacelle will be assessed, to determine the technical feasibility of the design. The first check that will be performed is a global column buckling check. Using Equation F.32, originating from the Euler buckling formula Equation F.33 and the assumption that a wind turbine is fixed at the bottom of the tower, the critical mass can be calculated.

$$m_{cr} = \frac{P_{cr}}{g \cdot SF} \tag{F.32}$$

$$P_{cr} = \frac{\pi^2 E_s I_{tow}}{(KL_{tow})^2} \tag{F.33}$$

In which m_{cr} is the critical mass the tower can bear in [kg], P_{cr} is the critical compressive force in [N], g is the gravitational constant, SF is a safety factor, again chosen to be 1.5, E_s is the Young's modulus of steel in [Pa], I_{tow} is the smallest area moment of inertia of the tower, K is the Euler K-factor taken to be 2 and L_{tow} is the length of the tower in [m].

The Euler buckling formula assumes that a beam has a constant cross-sectional area, the tower of a wind turbine has a changing diameter and wall thickness thus does not meet this criterium. However, if the smallest cross-section of the tower is used, a first estimation of the buckling strength can be made. The increase in diameter and wall thickness will only make that the buckling strength increases, thus this is a conservative check. The moment of inertia is determined using Equation F.30 and the dimensions of the tower top found in Table E.1. In Table F.10 the critical compressive force, mass and input parameters can be found.

Table F.10: Critical compressive force and weight on tower.

Parameter	Value	Parameter	Value
E_s[Pa]	$210E^9$	I_{tow}[m4]	15.27
K[-]	2	L_{tow}[m]	212.5
P_{cr}[MN]	175	m_{cr}[ton]	11900

In the table above it becomes clear that the critical global buckling mass is about 3 times larger than the weight of the platform and the nacelle combined, thus global buckling will not become a problem.

The second check is a local buckling and yield strength check due to the global moment acting on the tower. The local buckling moment can be determined using Equation F.34 [7].

$$M_{lb} = \frac{0.939 E_s R t^2}{\sqrt{1-\nu_s^2}} \frac{1}{DAF \cdot SF} \tag{F.34}$$

In which M_{lb} is the buckling moment of a tower section in [Nm], R and t are the radius and wall thickness respectively of the tower in [m], ν_s is the poisons ratio of steel taken to be 0.3. The safety factor and dynamic amplification factor are defined in Table F.7.

Using the well known bending stress formula, the maximum moment that can be applied to the tower before exceeding the yield strength of steel can be expressed as Equation F.35. Extra yield capacity is added due to the normal stresses introduced into the tower by the own weight of the tower and the weight of the nacelle and platform.

$$M_y = \frac{(\sigma_y + \sigma_{z,tow} + \sigma_{z,nac} + \sigma_{z,plat}) I_{tow}}{R \cdot SF \cdot DAF} \tag{F.35}$$

In which M_y is the maximum moment of a tower section determined by the yield stress in [Nm]. σ_y, $\sigma_{z,tow}$, $\sigma_{z,nac}$ and $\sigma_{z,plat}$ are the yield stress of steel and stresses in the tower structure introduced by the tower's own weight, the nacelle and the platform respectively in [Pa]. They are added up, as a compressive stress increases the yield capacity while under bending. This because the yield stress is a tensile stress. I_{tow} is determined by Equation F.30 and all other factors are the same as in Equation F.34. The compressive stresses in the tower can be determined by Equation F.36 up until Equation F.38 and depend on the location along the length of the tower due to the changing tower diameter and wall thickness.

$$\sigma_{z,tow}(y) = \frac{\int_y^{L_{tow}} A_{tow}(L)\rho_s g dL}{A_{tow}(y)} \tag{F.36}$$

$$\sigma_{z,nac/plat}(y) = \frac{W_{nac/plat} g}{A_{tow}(y)} \tag{F.37}$$

$$A_{tow}(y) = \frac{\pi D(y)^2 - (D(y) - 2t(y))^2}{4} \tag{F.38}$$

In which y is the location along the tower measured from the base to the top in [m], A_{tow} is the cross-sectional area of the tower in [m2], $m_{nac/plat}$ is the mass of the nacelle or platform in [kg], D and t are the diameter and wall thickness of the tower in [m].

Using the formulae for the maximum local buckling and yield moment, the maximum eccentricity of the COG of the nacelle can be determined, the choice was made to express this as the distance to the centre of the tower, so that it can be compared to the determined distance of the nacelle to the tower.

$$COG_{nac,lb/y}(y) = \frac{M_{lb/y}(y)}{m_{nac}} + R(y) \tag{F.39}$$

In which $COG_{nac,lb/y}$ is the maximum distance of the COG of the nacelle to the centre of the tower, to reach the local buckling criterion or the yield criterion in [m]. In Figure F.9 the maximum distance of the COG of the nacelle to the tower centre can be found. It shows that the most critical point is at the tower top. This is logical, as the diameter and wall thickness of the tower are lowest here. This shows that the lifting of the nacelle is possible as the max COG is at 37 meters while the COG of the nacelle is at 30 meters from the tower centre.

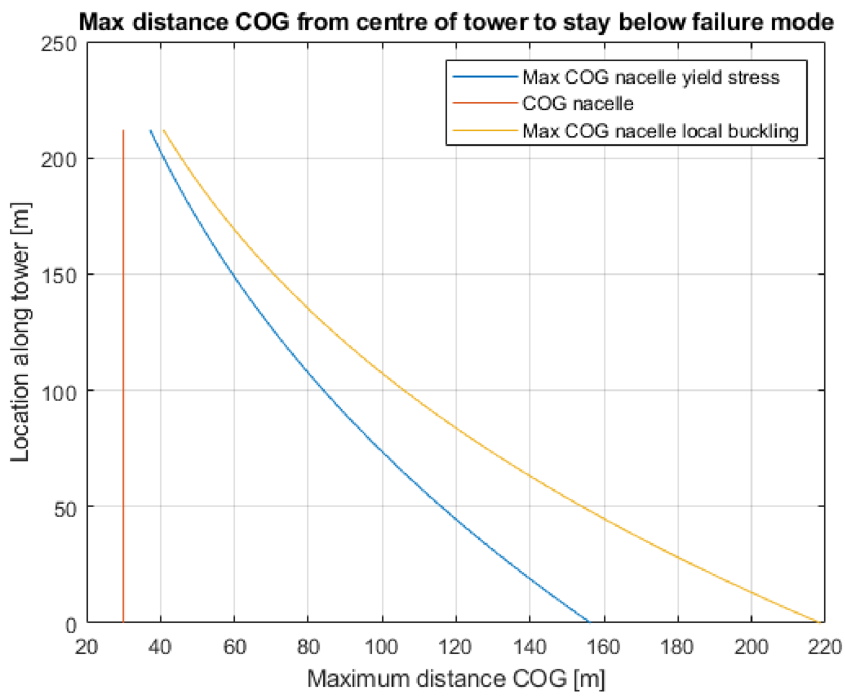

Figure F.9: Max distance of COG of nacelle for local buckling and yield criterion due to nacelle weight.

The distance of the COG of the platform to the centre of the tower can then be determined by using a utilization ratio. Which is determined using the moment due to the nacelle and the maximum moments on the tower. The utilization ratio is expressed as Equation F.40 and the maximum distance of the COG of the platform is expressed as Equation F.41.

$$U_{lb,y}(y) = \frac{COG_{nac}}{COG_{nac,lb/y}(y)} \tag{F.40}$$

$$COG_{plat,lb/y}(y) = \frac{M_{lb/y} * (1 - U_{lb/y}(y))}{g \cdot W_{plat}} \tag{F.41}$$

In which $U_{lb,y}(y)$ is the utilization ratio of the local buckling or yield criterion, COG_{nac} is the distance of the COG of the nacelle to the centre of the tower in [m], determined to be 30 meters in Subsection F.1.1 and m_{plat} is the total mass of the platform determined to be 1500 tonnes. In Figure F.10 the maximum distance of the COG of the platform to the centre of the tower can be found. A maximum distance of 14 meters was found.

No detailed design of the platform is performed, so no further conclusion can be drawn. However, as most material of the platform is located close to the tower, it is deemed possible to place the COG of the platform within this distance. Furthermore, the global buckling of the tower only occurs at around 12000 tons, so it is also possible to include a counterbalance into the platform which extends during the lifting of the nacelle to reduce moments on the tower. This does increase the platform weight and is thus not preferable.

Using all information gained, the concussion can be drawn that the platform is mechanically feasible. It should be noted that the design of the tower has a large influence on the technical feasibility of the elevator platform. If the choice falls on a soft-stiff design of the tower, as the reference tower, or a stiffer design, the lifting of the nacelle and attachment of the platform is possible. But if a soft-soft design is used, yield or local buckling stresses will be exceeded making the lifting of the nacelle impossible, resulting in an infeasible concept.

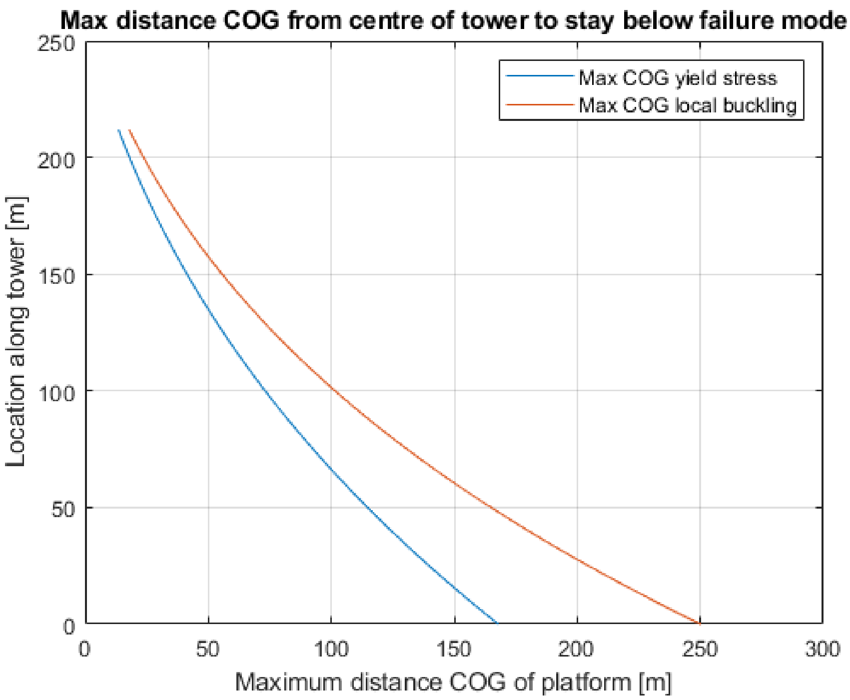

Figure F.10: Max distance of COG of platform for local buckling and yield criterion due to nacelle and platform weight.

F.2. Story board installation

In this section, a story board is presented to show the workings of the elevator platform concept. In Figure F.11 the installation of the nacelle using the elevator platform is depicted. Only the installation of the nacelle is shown, as the installation of a tower piece is performed in the exact same manner.

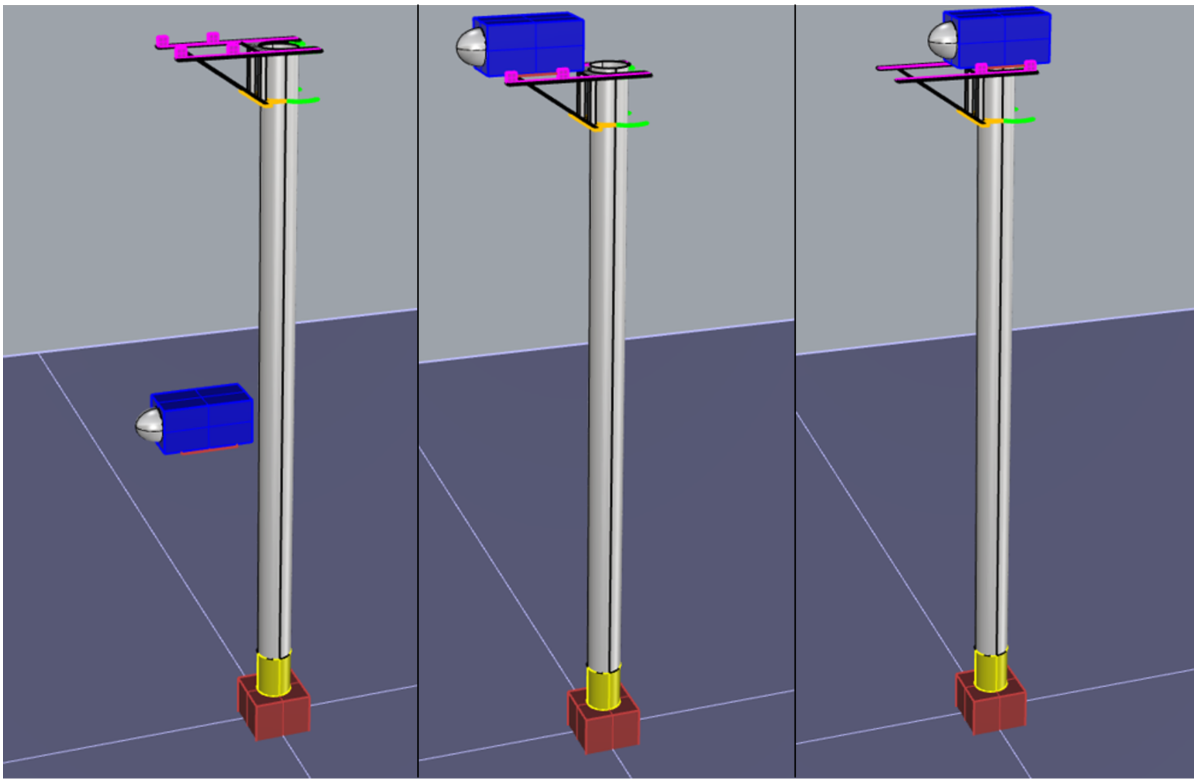

Figure F.11: Installation of Nacelle using the elevator platform, Left lifting of nacelle from barge to tower top, Middle nacelle at maximum elevation, Right skidding of nacelle over tower top.

In Figure F.12 the steps taken for blade installation are depicted. The blade is picked up from a barge, skidded over the barge while being lifted by the elevator platform. Next, the mating of the blade is depicted where the barge will also support the blade with lifting wires to angle the blade appropriately, and finally the platform is lowered to the minimum height and the blade is rotated outward. Now the next blade can be installed, this is repeated until all blades are attached.

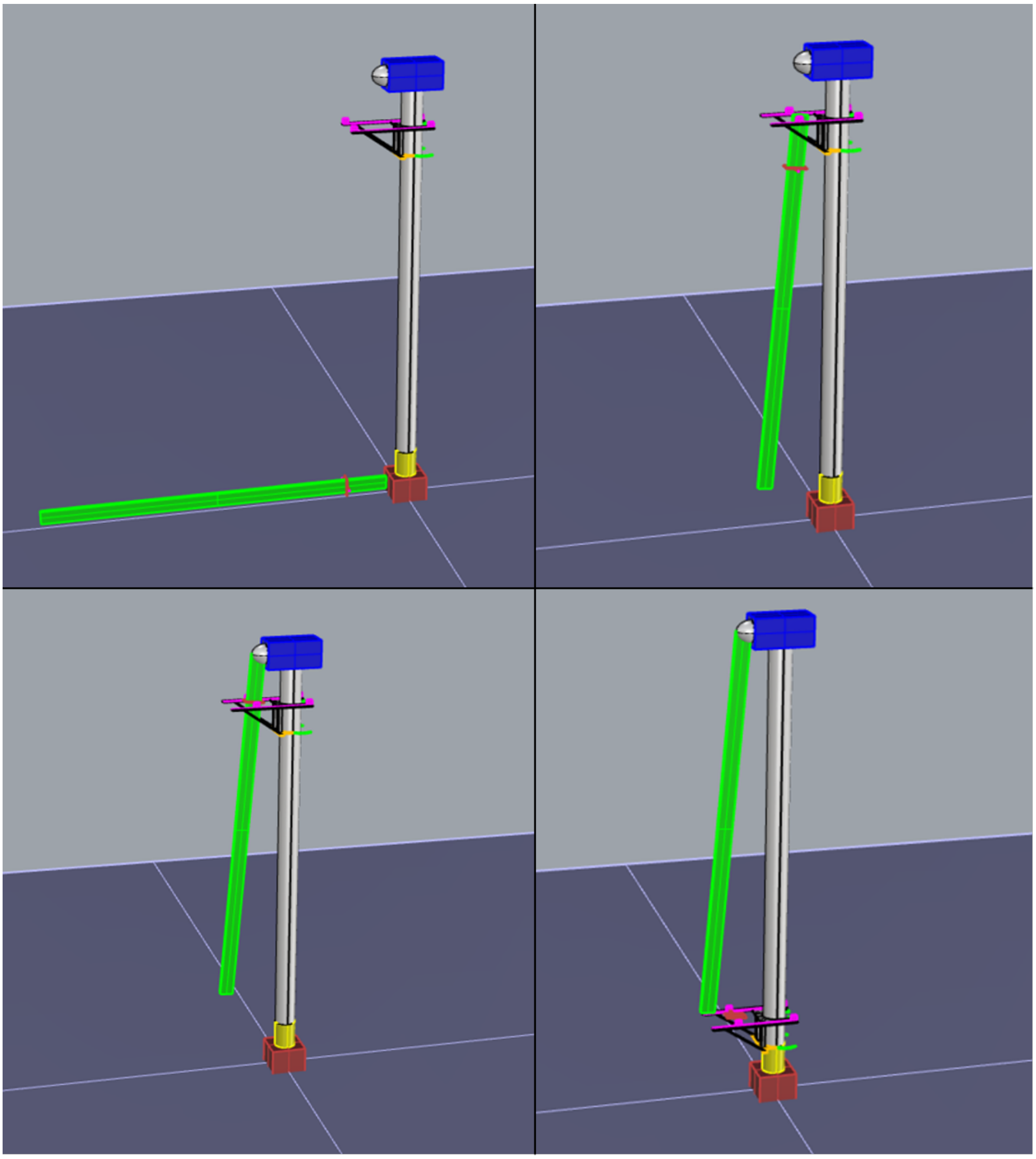

Figure F.12: Blade installation using the elevator platform, top left blade on barge, top right blade during lifting, bottom left Blade during mating, bottom right platform at lowest position so that blade can rotate.

G

Appendix G: Jack-up tower calculations and storyboard

In this appendix, more information is provided on the second screened concept, the jack-up tower concept. First, a discussion on the choice of jack up mechanisms is presented. After which, an evaluation of vessel motions using RAO's of an already existing vessel is performed to assess the feasibility of installation of the nacelle and blades at initial tower height. In Figure G.1 a 3D drawing for the overview of the concept can be found.

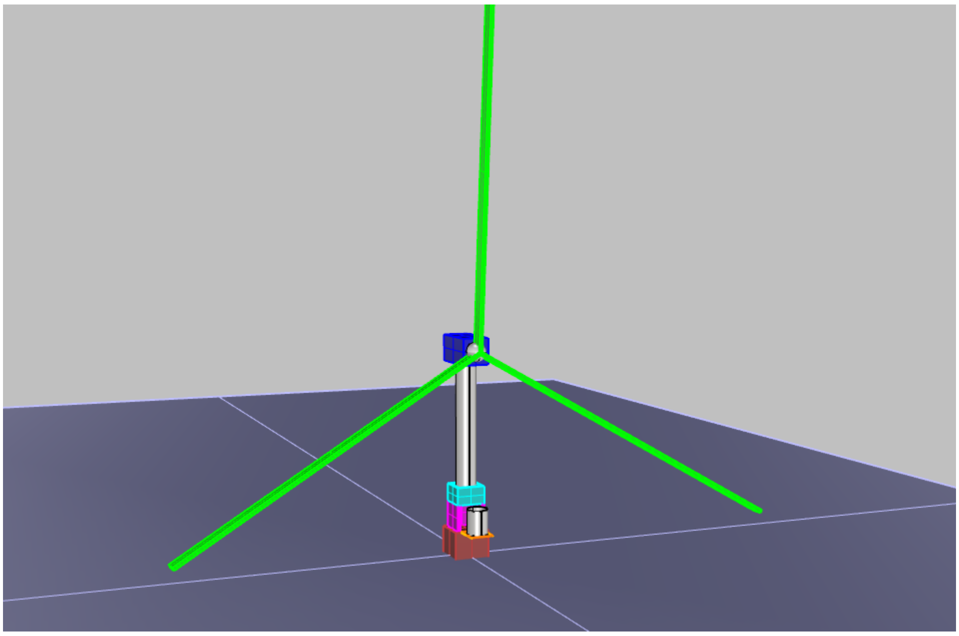

Figure G.1: Overview of jack up tower concept.

G.1. Jack-up mechanism choice

In this section of the appendix, the choice for the type of jack-up mechanism is presented. Even though the concept is deemed in-feasible in the end, it is good to show the considerations going into the choice of jack-up mechanisms.

A multitude of jacking mechanisms can be used, two of the most common methods nowadays are the Rack and Pinion and the Hydraulic Pinhole[6]. Which one is preferable depends on design considerations of wind turbine towers. Pinion and rack mechanisms are mainly in use with lattice like legs and pin and hole methods with circular tubular legs. One of the main down sights of using these jack-up mechanisms is that, no jack up systems exist yet which can deal with conical tubulars like a traditional wind turbine tower. So, either new jacking systems will need to be developed or the tower needs to have the same dimensions at all elevations to deal with this. This would lead to a non-ideal tower, as the diameter of the entire tower will then be guided by the base diameter, causing larger diameters at the tower top than needed. This discussion only serves to show effects of the chosen jack-up mechanism to the tower structure.

The rack and pinion system requires racks to be present on the lower part of the tower. To facilitate a rack and pinion system, a full redesign of the tower is needed, as 3-4 radially placed racks need to be present in the tower's structure for the pinions to grab onto. This will increase the weight and probably stiffness of the tower significantly. One of the feasibility considerations is the influence on the construction of the wind turbine. So, this alone is already a big disadvantage of applying rack and pinion to wind turbine towers, as a lightweight solution is always preferable. Furthermore, rack are expensive and heavy components which will only be used once or twice during the lifetime of the turbine, the exact effect on the CAPEX of this method cannot be expressed in numbers now, but it can be said that this will increase it significantly.

The pinhole system requires a different kind of alteration to the tower design, holes need to be present in the tower to accommodate the pins of the hydraulic jacking system. This is arguably less severe than adding racks to the tower, as this will not significantly increase the mass and stiffness of a tower. It will most probably lower those slightly, as material is taken out of the tower. However, as the design of towers is fatigue driven (especially for larger turbine towers), the effect of holes in the tower must be assessed. Assuming circular holes and using rules and regulation on fatigue design[40], a first estimation of fatigue strength reduction due to the cut-out holes can be made.

To assess the influence of holes in the tower construction, the well known S-N formula can be used, see Equation G.1.

$$log(N) = log(\bar{a}) - mlog(\Delta\sigma) \tag{G.1}$$

In which N is the number of cycles till failure, a and m are empirical factors based on material properties, plate geometry and finishing of welds[40] and $\Delta\sigma$ is a stress range in [MPa]. The inclusion of holes into a plate will cause localized stress hot spots. In guidelines, the Stress Concentration Factor (SCF) is defined for commonly used hole shapes, which is multiplied with a global stress level in the material to obtain the actual stress level using Equation G.2.

$$\Delta\sigma_{hs} = SCF \cdot \Delta\sigma_{glob} \tag{G.2}$$

In which $\Delta\sigma_{hs}$ is the hot spot stress level in [MPa], SCF is the Stress Concentration Factor (SCF) determined by the shape of the hole and $\Delta\sigma_{glob}$ is the global stress level in the material in [MPa]. Using the formulae defined above, the influence of holes on the fatigue life of a tower can be investigated.

The fatigue strength of transverse welds in the tower will be compared to the fatigue strength of a plate with 2 types of holes, one with a circular hole and one with an ovalized hole. The S-N-curves provided by DNV[40] in air are used. A plate without welds is classified as a B2 curve, and a transverse continuous weld is classified as a C1 curve. An $\Delta\sigma$ of 100 [MPA]is chosen to study the effect of the holes. In Table G.1 the values found using for the parameters and the number of cycles for all cases can be found.

Table G.1: Fatigue assessment of introducing holes into wind turbine tower.

	a	**m**	**SCF**	**N**
Weld	12.449	3	1	$2.8E^6$
Plate	14.885	4	1	$7.7E^6$
Plate & round hole	14.885	4	3	$9.4E^4$
Plate & ovalized hole	14.885	4	2.4	$2.3E^5$

It was found that round holes in the wind turbine tower will, as expected, decrease the fatigue life of the tower. It is decreased by a factor of 81 compared to a plate without holes, which is obviously not acceptable. To decrease the SCF it is possible to use ovalized holes, this reduces the SCF to 2.4. However, this is still not acceptable, as this gives a reduction of fatigue life with a factor of 33

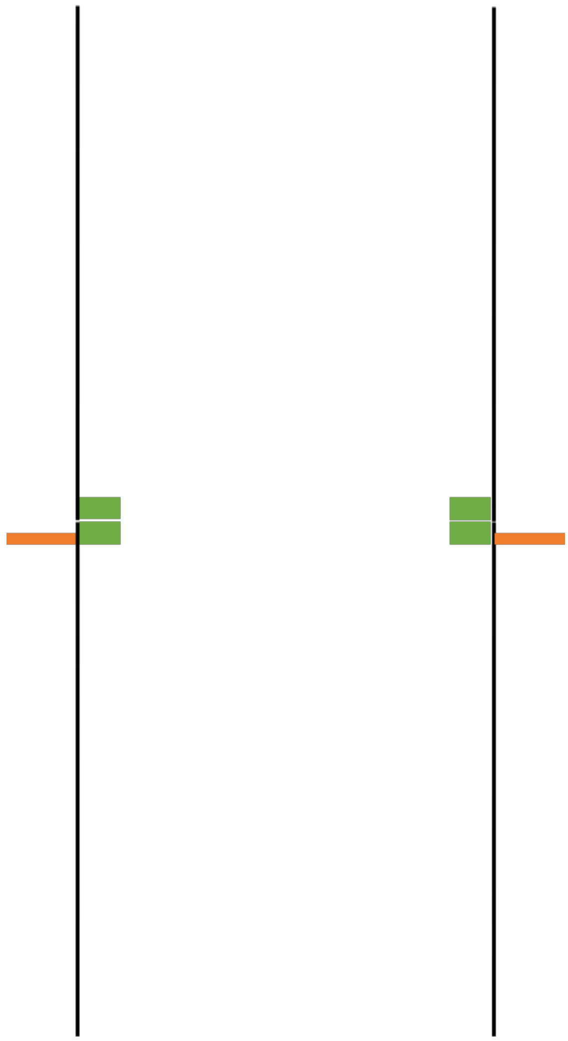

Figure G.2: Cross-section of tower with flanges and a protruding edge on which a pinhole system can be attached.

relative to a plate. Which means that significant strengthening of the tower will be needed to reduce the stress in the tower, so that the intended fatigue life of a tower is reached. This can also be achieved by strengthening the holes, as can be found in DNV-RP-C203[40]. However, this will add mass and extra work on the tower, further increasing the price, which is also not preferable. Furthermore, the holes in the tower cannot be left open after the jacking has taken place, as this would expose the inner components of the tower to the environment. The main problem would be the incursion of salt and water, leading to corrosion related problems. Thus, the holes would have to be welded shut after jacking. This would work around the SCF problem, but needs high quality welding and smoothening of the weld to reach acceptable fatigue behaviour, adding to the costs of a tower. The closing of the holes would also have to take place at large height and offshore, complicating the procedure. The author of the research does not have enough knowledge about welding procedures to say anything about the feasibility of this, however, a workaround can be formulated.

This workaround is the addition of protruding flanges to the tower piece connection flange, on which pins of a pinhole jacking system can be placed. This circumvents the need of creating holes in the tower structure, but does increase the total steel volume of the tower slightly. This is deemed the best option, as this results in the least effect on the construction of the tower, and it is still based on proven technology, albeit somewhat different in application. In Figure G.2 an artist impression is given on where the protruding edge is located along the tower.

Concluding, an adapted pinhole jack-up system will be used, as this has the least effect on the tower structure and does not needlessly add steel weight and costs to the tower construction. A normal pinhole jack-up system can be used, which will rest its pins underneath the protruding edges that are placed at the flanges of each tower piece.

G.2. Mono hull vessel motions while installing initial tower piece, nacelle and blades

This section has been removed, as it contained confidential information provided by the research's partner GustoMSC NOV.

G.3. Story board installation using jack-up tower concept

In this section of the appendix, the story board of the Jack-up tower concept is presented. In Figure G.3 the first part of the story board is presented, here the jack-up mechanisms and support frame with open side are installed first, after which the tower with initial tower height is installed followed by the nacelle.

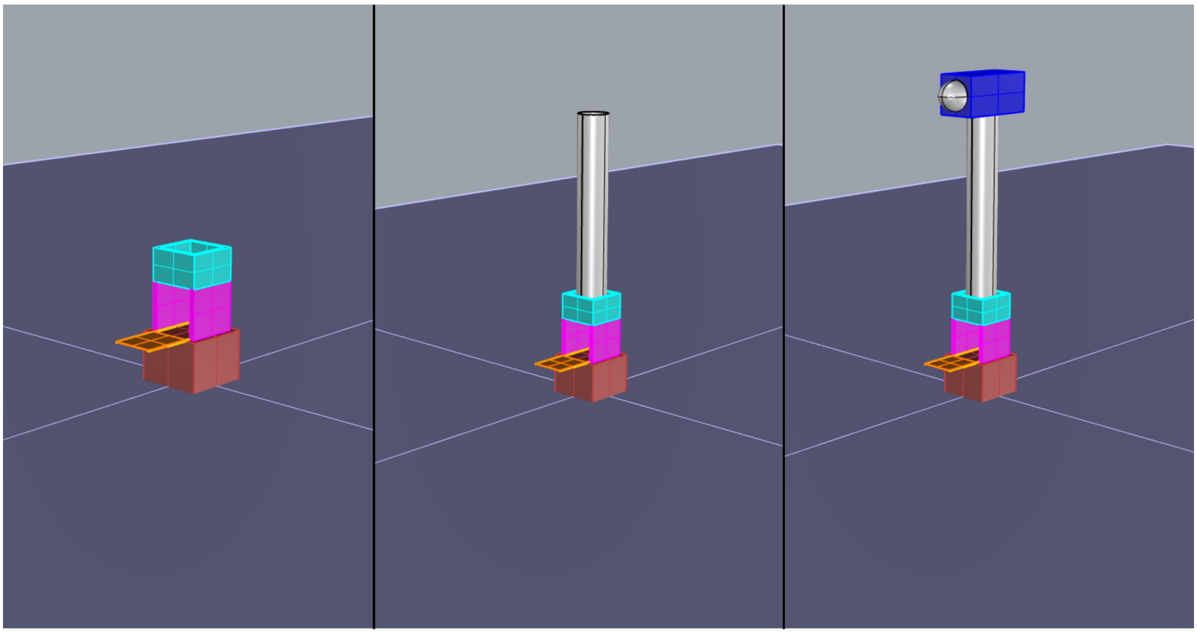

Figure G.3: Story board installation using jack-up tower concept, part 1, Left: installation of jack-up mechanism and support frame on foundation, Middle: installation of tower piece with initial tower height, Right: installation of nacelle.

In Figure G.4 the second part of the story board can be found. Here the installation of the blades is depicted, which is done by use of inclined blade installation tools. The next step is to feed in the tower pieces into the skidding and jack-up mechanism, after which the piece is connected and jacked-up. This is repeated until the tower is at the needed height.

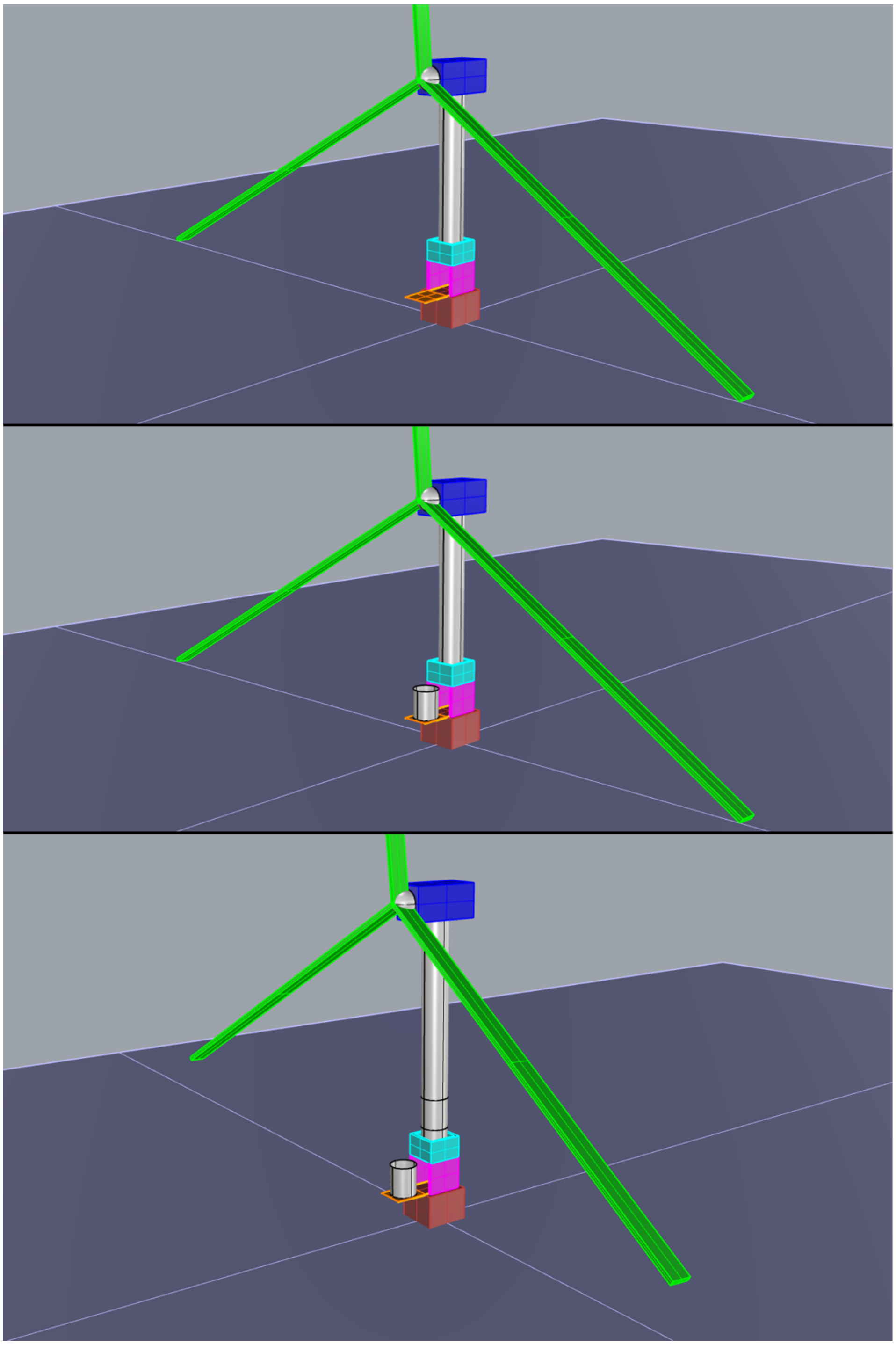

Figure G.4: Story board installation using jack-up tower concept, part 2, top: installation blades at initial tower height using inclined blade tool, Middle: Feeding in and skidding of tower piece, bottom: Tower during erecting, almost fully erected.

H

Appendix H: Inverted pendulum principle calculations and storyboard

In this appendix, further information and calculations regarding the inverted pendulum principle are presented. The concept was deemed infeasible during the assessment of the critical factors listed below, due to this no initial weight and size estimation of the flip-frame and transportation barge have been performed. An overview of the concept can be found in Figure H.1. The critical factors are listed below:

- Moment in the tower during up-righting;
- Needed crane capacity to overcome gravitational forces on turbine and frame.

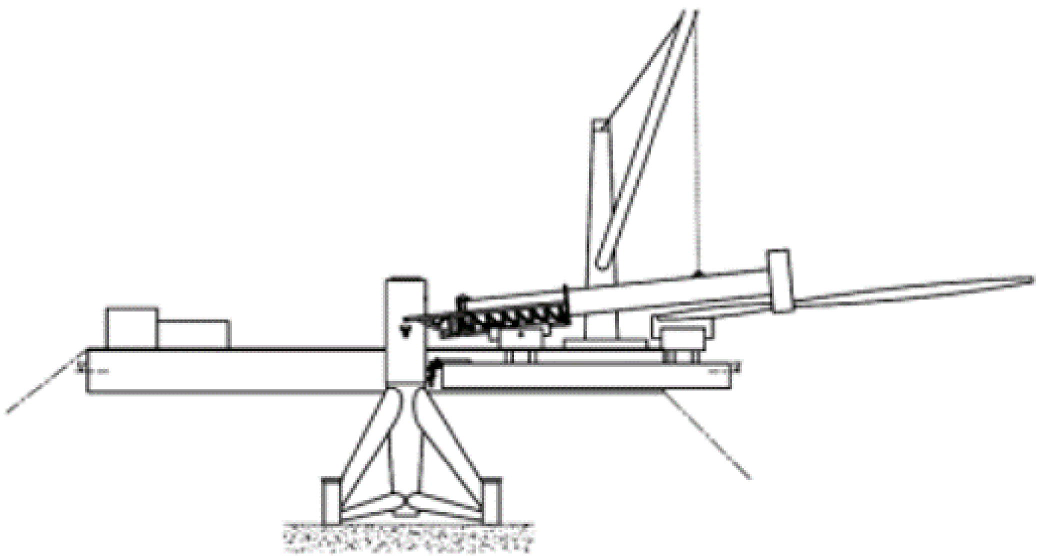

Figure H.1: Overview of inverted pendulum principle, taken from paper[1].

H.1. Assessment of critical factors

In this section, the critical factors which have been mentioned above are assessed. The flip frame has been simplified to identify the critical moments in the tower construction and the needed lifting capacity to perform the up-righting of the wind turbine. See Figure H.2 for a depiction of the simplification and parameterization used for the assessment of the critical factors. The first step is to identify the situation in which the largest moments and forces occur. This is just after the lifting frame is mated to the foundation and lifted off from the pivoting support on the barge stern. The needed lifting capacity is the largest in this case, as the moment due to gravity on all components will be largest. The internal moments in the tower due to gravity and the lifting force will be largest at the same time. This due to the eccentricity of the masses of nacelle, blades and own weight of the tower. So, only one case must be investigated, the case when the tower is almost horizontal and has lifted off from the barge stern support. For simplicity, the lift-off is assumed to take place when the barge is fully horizontal.

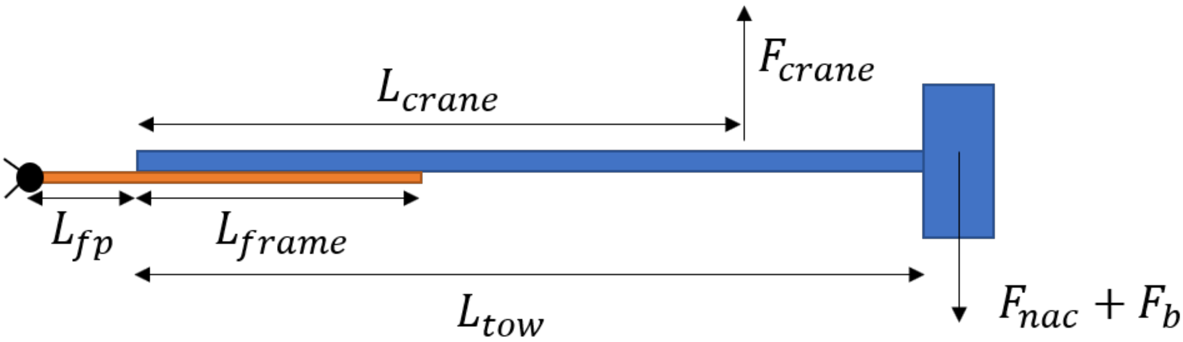

Figure H.2: Simplification and parameterization used for determining the critical factors of the inverted pendulum concept.

H.1.1. Critical moment identification

In this subsection, the location of the largest moment in the tower will be investigated. The two critical factors can be assessed simultaneously, as the moment in the tower is dependent on the lifting force of the crane. First, the lifting force of the crane is determined. The needed lifting force is derived by taking the moment balance around the pivot point depicted on the far left in Figure H.2, and is expressed as Equation H.1. During this assessment, the weight of the frame itself is not yet taken into account. First, the feasibility has to be assessed before the initial sizing will take place.

$$F_{crane} = \frac{g\left(m_{tow}\left(COG_{tow} + L_{fp}\right) + \left(m_{nac} + 3m_B\right)\left(L_{fp} + L_{tow} + \frac{H_{nac}}{2}\right)\right)}{L_{fp} + L_{crane}} \tag{H.1}$$

In which, F_{crane} is the force the crane has to exert to start lifting in [N], m_{tow}, m_{nac} and m_B are the mass of the tower nacelle and blades respectively in [kg], COG_{tow} is the location of the COG of the tower along the length of it in [m], here found to be 90 meters, L_{fp} is the length of the flip-frame in-between the tower bottom and pivot points in [m], L_{tow} is the length of the tower in [m], H_{nac} is the height of the nacelle in [m] and L_{crane} is the length along the tower of the attachment point of the crane in [m]. The input parameters can be found in Table H.1. L_{fp} is estimated to be 20 meters to get enough clearance to the jacket when pivoting. This is accepted as a first estimation, as only high level feasibility is assessed here. If the first two critical factors are passed, it should be defined more in-depth. Two assumptions are made here, that the mass of the blades is located at the same spot as that of the nacelle and that the COG of the nacelle is located at the volumetric centre of the nacelle.

Table H.1: Input parameters used for evaluating critical factors of inverted pendulum principle.

Parameter	Value	Parameter	Value
m_{tow}[ton]	3600	L_{tow}[m]	212.5
m_{nac}[ton]	2000	L_{fp}[m]	20
m_B[ton]	140	H_{nac}[m]	15
COG_{tow}[m]	90		

Using the definition of the crane force, the moments at the 2 critical points in the tower can be defined, the moment at the top of the frame and the moment at the lifting point. See Equation H.2 and Equation H.3 respectively, the formulae are defined using static relations around the pivot point.

$$M_f = g\left(m_{nac} + 3m_B\right)\left(L_{tow} - L_{frame} + \frac{H_{nac}}{2}\right) + g\frac{m_{tow}}{L_{tow}}\frac{\left(L_{tow} - L_{frame}\right)^2}{2} - F_{crane}\left(L_{crane} - L_{frame}\right) \tag{H.2}$$

$$M_{lp} = g\,(m_{nac} + 3m_B)\left(L_{tow} - L_{crane} + \frac{H_{nac}}{2}\right) + g\frac{m_{tow}}{L_{tow}}\frac{(L_{tow} - L_{crane})^2}{2} \tag{H.3}$$

In which M_f and M_{lp} are the internal moments in the tower at the frame and lifting point respectively in [Nm] and all other variables and parameters are the same as defined in Equation H.1. A few assumptions have been made to simplify the formulae. The own weight of the tower is included by dividing the total weight over the length and using the assumption that the own weight is evenly divided over the length of the tower. This is not entirely true because the weight to length ratio is smaller at the top than at the bottom of the tower. However, as the majority of the moment in the tower is caused by the nacelle and blades, this first estimation is accepted. Furthermore, the same assumptions still hold that have been described at Equation H.1.

Using these two formulae, the moments at the two critical points in the tower can be determined and investigated to see which one will be the largest. It was found that for each and every combination of L_{frame} and L_{crane} under the bounds of $L_{crane} > L_{frame}$, resulted in the moment at the lifting point being the largest. Thus, the strength of the tower at this location must be looked into further. This is independent of the length of the frame, which will not be included anymore into the assessment. Only the distance at which the lifting point should be located along the tower will be looked into.

H.1.2. Tower strength assessment

In this section, the needed strength of the tower to stay below yield stresses will be determined. This to investigate the feasibility of a small frame with a lifting point high up along the tower. The needed wall thickness to stay below yield stresses in the tower will be determined using the well known bending stress formula, and the well known area moment of inertia formula for tubulars, Equation H.4 and Equation H.5 respectively.

$$\sigma_y = \frac{My_{max}}{I_{tow}} \tag{H.4}$$

$$I_{tow} = \frac{\pi(D_{tow}^4 - (D_{tow} - 2t_{tow})^4}{64} \tag{H.5}$$

In which σ_y is the yield strength of structural steel in [Pa], y_{max} is the distance of the most outer fibre of the material to the centroid of the cross-section in [m], I_{tow} is the area moment of inertia of the tower in [m4], D_{tow} is the diameter of the tower in [m] and t_{tow} is the wall thickness of the tower in [m]. Using these two formulae, the needed wall thickness to withstand a certain moment can be expressed as Equation H.6.

$$t_{needed} = \frac{SF}{2}\left(D_{tow} - \left(D_{tow}^4 - \frac{64My_{max}}{\sigma_y\pi}\right)^{0.25}\right) \tag{H.6}$$

In which t_{needed} is the needed wall thickness given a certain tower diameter and moment in [m], SF is an assumed safety factor of 1.5 and all other parameters are the same as defined in Equation H.4. To investigate if the tower can bear the moment during up righting due to gravity, Equation H.3 is used. It will be expressed in terms of needed wall thickness of the tower, for all possible L_{crane}. This to find the minimum length along the tower at which the lifting point must be located to withstand the moments.

The needed thickness is both a function of the tower diameter, the diameter of the tower defined in Appendix E is used to determine the needed wall thickness. It is also possible to determine the needed tower diameter for a given wall thickness and moment. Due to buckling criteria of wind turbine towers the choice is made to use wall thickness, as increasing the diameter for a given wall thickness lowers the D/t ratio of the tower. This is not preferred, as local and global buckling will become more prevalent. Either way, the location at which the tower should be supported can be determined. It is done by investigating the needed wall thickness versus the actual wall thickness as determined in Appendix E, in Figure H.3 the results of the calculations can be found. Three cases have been investigated, one with variable wall thickness and tower diameter, one with constant tower diameter and variable wall thickness, and one with both the wall thickness and diameter constant from tower bottom to top. This to investigate the effect of strengthening the tower on the minimal length along the tower of the lifting point.

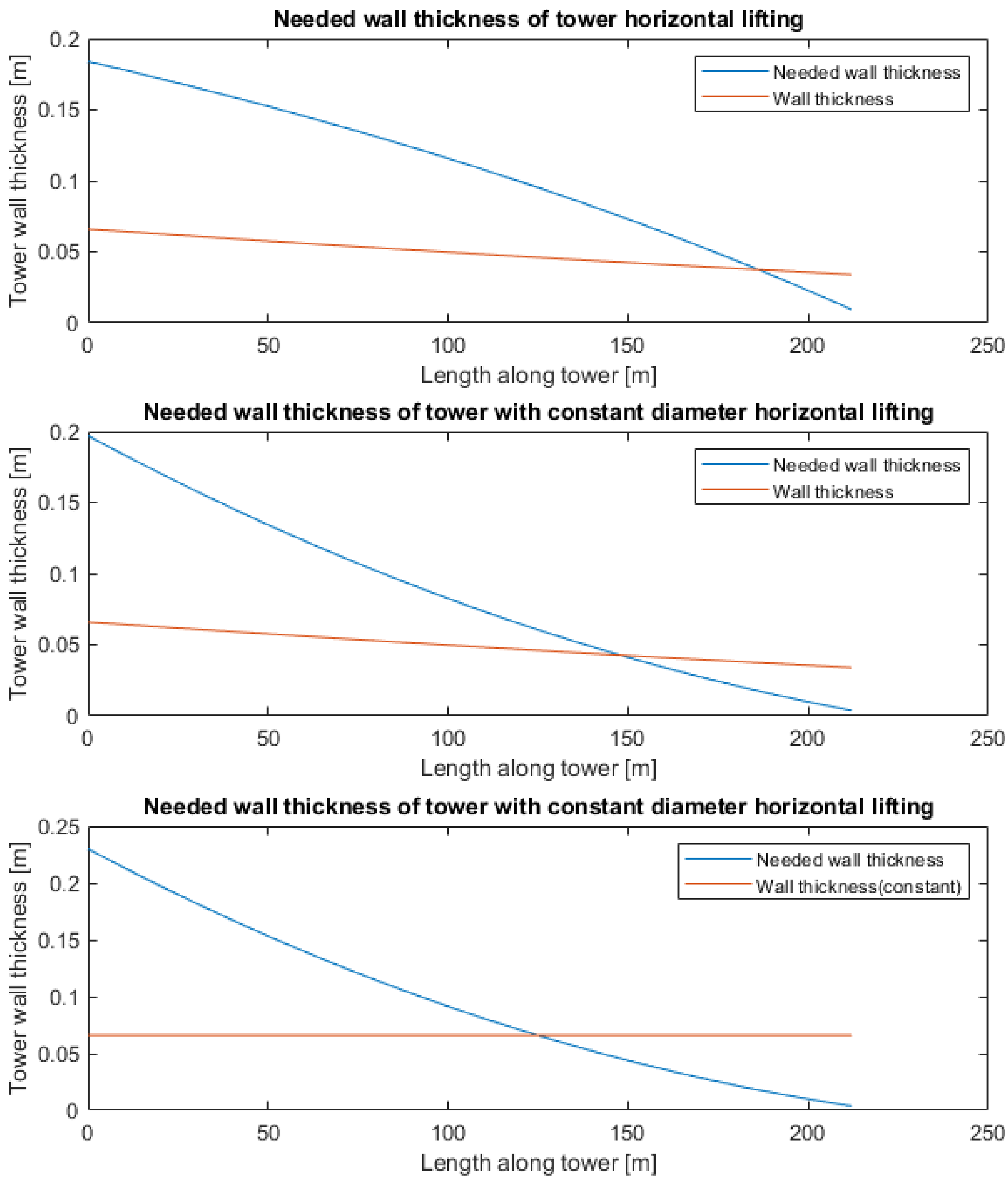

Figure H.3: Needed wall thickness to withstand moment on tower during horizontal lifting of wind turbine vs the actual wall thickness. Top: needed wall thickness for given diameter, Middle: needed wall thickness with constant diameter tower, bottom: needed wall thickness with constant diameter tower and constant wall thickness.

In the figure, it becomes clear that the tower must be lifted at around 185 meters along its length, to not exceed the yield stress of steel. This is obviously too high up, as that would mean a crane height of at least 215 meters above LAT is needed. To investigate the effects on the minimal lifting point length from the base of the tower due to the tower diameter and wall thickness, 2 more cases were set up. One with constant tower diameter from tower bottom to top, and one with constant wall thickness and tower diameter from tower bottom to top. The results of all 3 cases can be found in Table H.2.

The calculation was performed again with a constant tower diameter of 16.5 meters, and changing wall thickness. Then the needed lifting point length becomes 150 meters along the tower, thus a crane of about 185 meters would be needed. This is still too high up. Thus, the next case of further strengthening the tower was investigated, keeping both the tower diameter and wall thickness constant from tower bottom to top. In this case, the lifting point would be at a 125 meters high along the tower. Thus, a crane of about 155 meters above LAT would be needed to up-right the turbine. This seems more achievable from a crane height perspective, however, there are only a hand-full of cranes which can reach this height. The main problem that arises when strengthening the tower is that the tower weight will increase tremendously, for case 3 to about 5700 tonnes. This is unacceptable due to the added costs this would entail during construction of the tower. Furthermore, the increase in mass would enlarge the already existing logistical problems with on shore crane capacity and handling of the turbine.

From this calculation, it can be concluded that the proposed concept using a relatively small frame and high up lifting point cannot be pulled off. The tower needs to be supported at the mentioned distance from the tower base to withstand the gravitational forces put on the tower. Resulting in, that the concepts can only be used when the flip-frame reaches along the tower to at least the minimal stated L_{crane}. Leading to that the lifting point can be moved downward to a more attainable height, circumventing the problems that arise with the strength of the tower. This then becomes a purely capacity driven problem, the needed capacity is still to be determined.

Table H.2: Results calculations minimal lifting point location along length of tower for 3 cases, needed crane height and tower weight.

Parameter	Case 1	Case 2	Case 3
D_{tow}[m]	Variable	Constant(16.5)	Constant(16.5)
t_{tow}[m]	Variable	Variable	Constant(0.065)
L_{crane}[m]	185	150	125
H_{crane}[m]	215	185	155
m_{tow}[ton]	3600	4200	5700

H.1.3. Assessment of the needed lifting capacity

If the flip frame is increased in length, the lifting point can be at any height along the tower. To assess this the critical factor of the needed lifting capacity, a vessel must be chosen. The needed lifting capacity obviously depends on crane height, as the higher up the crane, the lower the needed capacity will be. The Sleipnir will be used for the assessment of this critical factor, as this is the largest and strongest lifting vessel in the world. It has a crane height above LAT of 115 meters at a lifting radius of 48 meters, thus a L_crane of 80 meters is possible[19] to reach.

The largest needed capacity will occur when the turbine lifts off from the aft support and pivots around the pivot point depicted in Figure H.2. During the lift-off, the frame will have a small angle relative to the foundation, lowering the needed crane capacity. This angle is assumed to be 15 degrees, as no information on this could be found in the paper describing the concept[1]. Both the fully horizontal case and the angled case will be shown to show that the effect of this will be minimal. The lifting force under an angle is determined using Equation H.7, in Table H.3 the results of the calculation can be found.

$$F_{crane,\theta} = F_{crane} \cos\theta \tag{H.7}$$

Table H.3: Results lifting force calculation, expressed in metric tonnes.

Parameter	Case 1	Case 2	Case 3
$F_{crane}[ton]$	9700	10500	12000
$F_{crane,\theta}[ton]$	9400	10100	11600

From the above table it becomes clear that the needed lifting capacity can not be reached by the Sleipnir, as during the calculations the DAF is not taken into account and the weight of the frame is omitted for simplicity. In real applications the frame weight will also add to the needed capacity, surpassing the maximum capacity of 10000 tons of the Sleipnir.

The effect of L_{fp} on this is also significant, as the height along the tower at which the lifting point can be attached is directly related to this. If L_{fp} needs to be larger to accommodate the flipping of the frame, the lifting capacity is increased even further. Furthermore, it is debatable if the stated crane capacities can be reached, as the crane will not be loaded in a traditional fashion. Normally, cranes are mostly loaded in vertical direction, however, the crane will also be loaded in horizontal direction. It has to "pull" the flip frame into place while the vessels moves forward. Due to this, the crane capacity is most likely lower, as cranes are not designed for such a load case. The combination between these factors makes this concept is deemed mechanically infeasible. Furthermore, one key selling point of this concept, using relatively small floating vessels to install a ULWT, does not hold anymore. Further confirming the in-feasibility of this concept.

H.2. Story board installation using inverted pendulum principle

In this section, the story board for the installation using the inverted pendulum principle is presented. The method was originally described and developed for use with tripod foundations, so the depiction only includes this. The story board is taken directly from the paper in which the concept is presented[1].

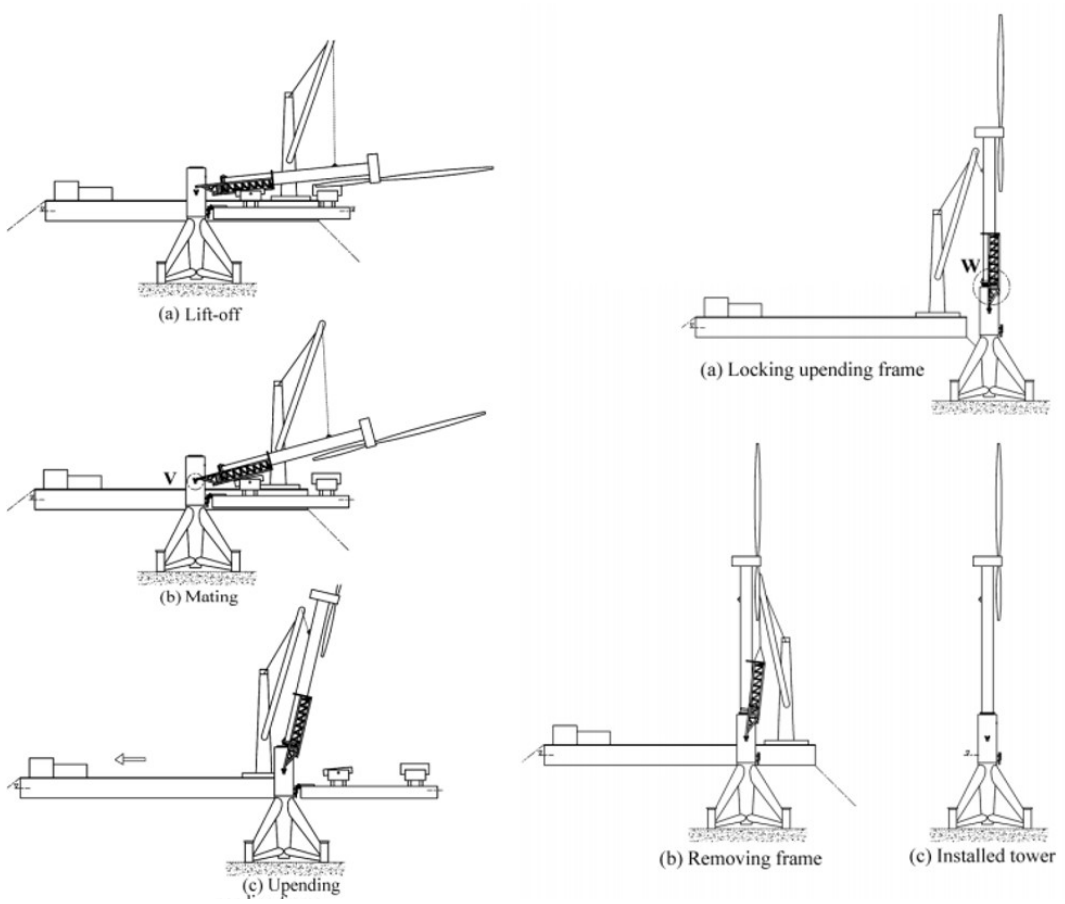

Figure H.4: Story board installation using the pivot principle, taken from paper[1] and edited by author.

Appendix I: Lifting frame calculations and storyboard

In this appendix, further information and calculations used for the definition of the lifting frame concept can be found. The approach taken for the concept design and feasibility assessment can be found below, and a depiction of the frame with turbine inside can be found in Figure I.1.

- Choose vessel;
- Determine frame size due to max crane height above deck using load curves;
- Simplify frame and calculate frame weight;
- Set target COG height of assembly;
- Determine weight counterbalance to reach target COG height;
- Redefine strength and weight of frame to include counterbalance weight.

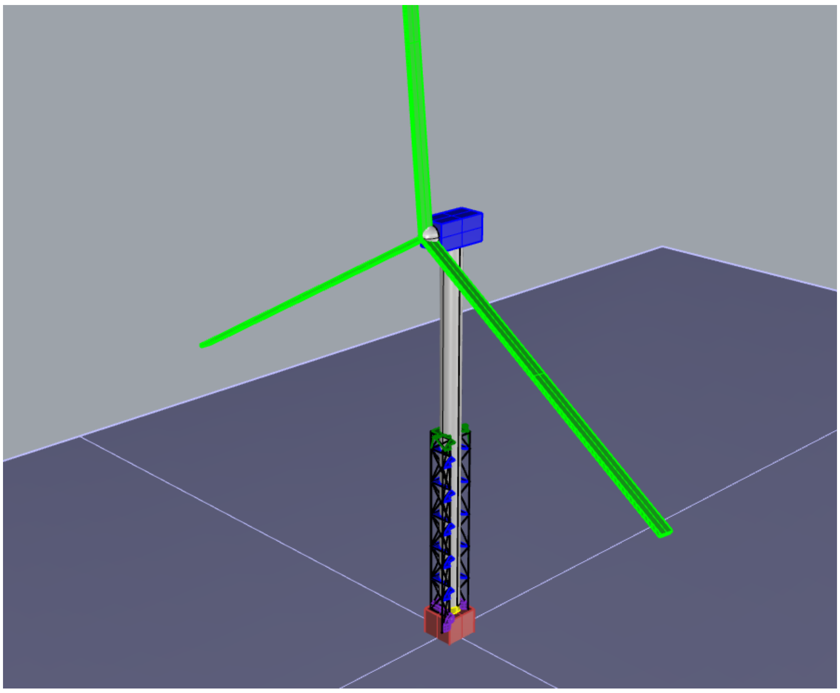

Figure I.1: Artist impression of opened up lifting frame with tower after mating.

I.1. Initial sizing lifting frame concept

In this section, the initial sizing of the lifting frame concept will be presented. The first critical factor that will be looked into is the height of the lifting frame. This is limited by the height of cranes above the deck of the installation vessel. The Sleipnir[19] is chosen for the concept design of the lifting frame. It has a crane height above deck of 110 meters of the main hoist, which will be the height of the frame. The capacity of a tandem lift is claimed to be 20000 tonnes, so that should be more than enough to lift the wind turbine and frame assembly. Using this height as a starting point, the initial frame weight will be determined using the parameterization defined in Figure I.2. The width and depth of the frame are estimated to be 17.5 meters, as the maximum diameter of the tower will be 16.5 meters. The assumption is made that the frame is constant in width and depth along its length as a first estimation. The found dimensions are listed in Table I.1.

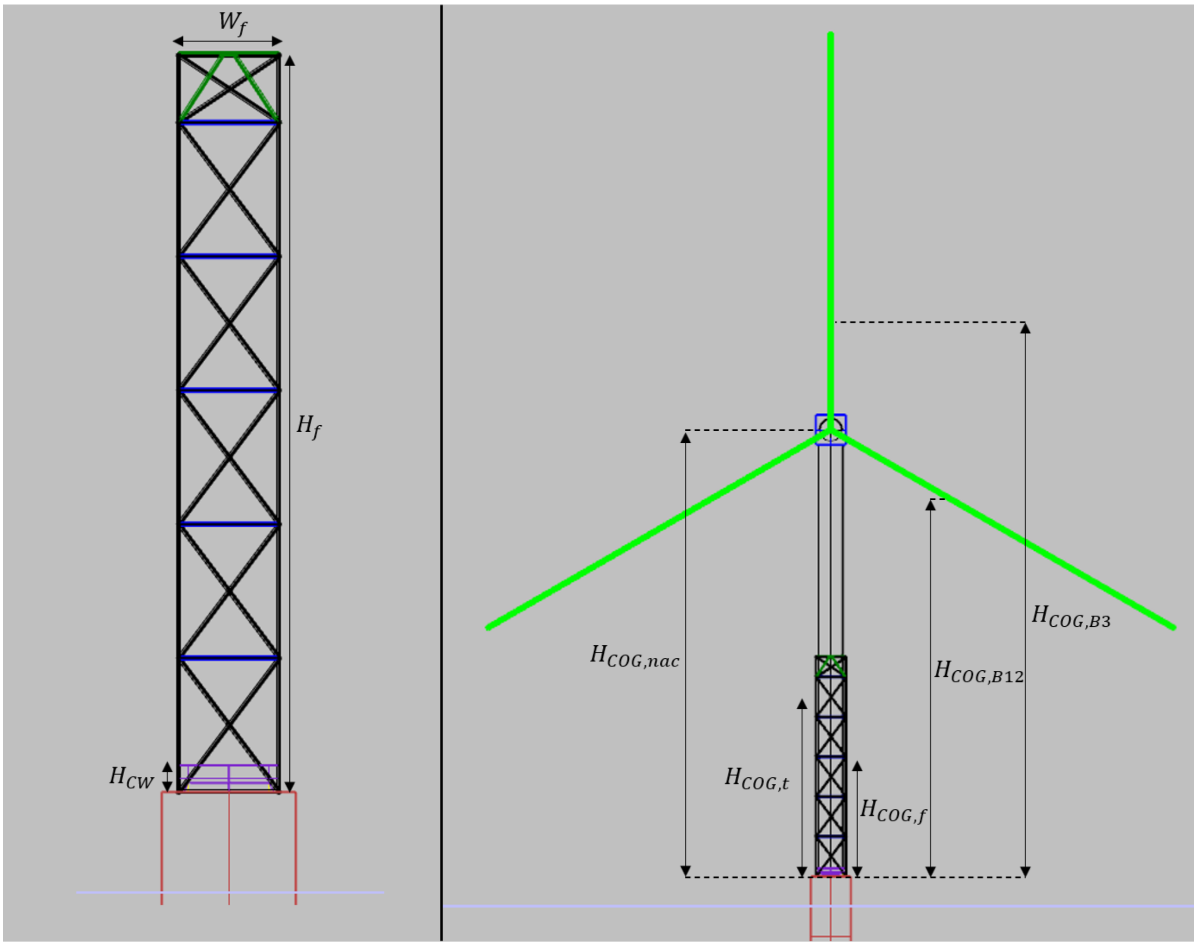

Figure I.2: Parameterization used for calculation of lifting frame, Left dimensions of lifting frame and counterweight, Right heights of COGs of all components.

Table I.1: Height and width of lifting frame.

Parameter	Value	Parameter	Value
$H_f[m]$	110	$W_f[m]$	17.5

I.1.1. Centre of gravity determination of wind turbine

In this subsection, the height of the COG above the deck of the wind turbine will be determined. The goal is to lower the centre of gravity of the entire assembly below the lifting points, so that the frame is stable while lifting. The choice is made to face 2 of the blades downward with a 60-degree angle to the tower, as depicted in Figure I.2. This lowers the COG of the blades as far as possible. The weight of the blades is relatively small compared to the other components, so the significance of the effect of this can be debated. It might be beneficial to rotate the blades upward so that more clearance of crane booms and blades can be achieved, in spite of a bit larger counterweight. This is vessel dependant and will thus not be looked into any further, but should be mentioned nonetheless.

The COG of the blades is assumed to be at 1/3 of the total length along the blade measured from the root. The COG of the tower is determined by integrating the mass density over the length of the tower with was defined in Section 5.2 and the COG of the nacelle is assumed to be at half height of the provided nacelle size. With Equation I.1 up until Equation I.3 the height of the COGs above deck of all components can be determined. Which can then be used in the determination of the COG of the wind turbine, using Equation I.4. Only the height of the COG is assessed here, the transverse and longitudinal location will not be determined, as the weight of the wind turbine is centred in the frame. The effect of eccentricities of the weights of the wind turbine components on the load on the cranes, should be assessed at a later stage of development.

$$H_{COG,B12} = L_{tow} - \frac{L_b}{3}\cos\frac{60\pi}{180} \tag{I.1}$$

$$H_{COG,B3} = L_{tow} + \frac{L_b}{3} \tag{I.2}$$

$$H_{COG,nac} = L_{tow} + \frac{H_{nac}}{2} \tag{I.3}$$

$$H_{COG,WT} = \frac{\sum_{i=1}^{n} m_n \cdot COG_n}{\sum_{i=1}^{n} m_n} \tag{I.4}$$

In which $H_{COG,B12}$, $H_{COG,B3}$, $H_{COG,nac}$ and $H_{COG,WT}$ are the height of the COGs above the bottom of the frame of the lower blades, upper blade, nacelle and the entire wind turbine respectively in [m]. L_{tow} is the length of the tower in [m], determined to be 212.5 meters, L_b is the length of the blade in [m], provided to be 200 meters, H_{nac} is the height of the nacelle in [m], provided to be 15 meters and m_n is the mass of a component in [kg]. Using these equations the height of the COG of the wind turbine can be determined, the results can be found in Table I.2.

Table I.2: Weights and COGs of all wind turbine components.

Parameter	Value	Parameter	Value
m_{tow}[ton]	3600	m_{Blade}[ton]	140
m_{nac}[ton]	2000		
$H_{COG,tow}$[m]	90	$H_{COG,B12}$[m]	179
$H_{COG,nac}$[m]	220	$H_{COG,B3}$[m]	287
W_{WT}[ton]	6020	$H_{COG,WT}$[m]	141.9

I.1.2. Mass determination of lifting frame and counterweight

The next step is to determine the mass of the frame and counterweight required to place the COG of the entire assembly below the lifting point height. Both masses affect each other, as the weight of the frame effects the needed counterweight mass and the mass of the counterweight effects the strength of the frame. Ending up with a recursive problem, as both masses have to be determined still. The choice is made to approach this problem by, first, determining the mass of the frame to withstand only the load of the wind turbine. After which the mass of the counterweight is determined by setting a target height of the COG of the entire assembly. However, now the frame weight must be redefined, as the initial weight is based on the strength assessment without the counterweight weight. All used formulae will be derived, including the counterweight mass, which will be set to 0 to find the initial strength and weight of the frame. So, this section will assess the critical factors of, stability and frame strength simultaneously.

The system is simplified to a single beam under pure tension, see Figure I.3. The counterweight is depicted in purple, the lifting point in green and the frame in blue. The maximal tension found in the beam is equal to the force the crane exerts on the lifting points while lifting it and is determined using

Equation I.5. The forces due to the weight of the frame, wind turbine and ballast are determined using Equation I.6 up until Equation I.8.

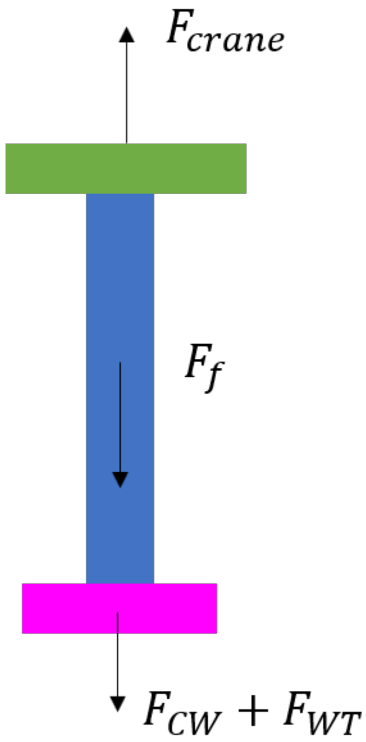

Figure I.3: Simplification used for calculations lifting frame.

$$F_{crane} = F_f + F_{CW} + F_{WT} = F_{t,beam} \tag{I.5}$$

$$F_f = A_f H_f \rho_s g \tag{I.6}$$

$$F_{WT} = m_{WT} g \tag{I.7}$$

$$F_{CW} = m_{CW} g \tag{I.8}$$

In which F_{crane} is the force on the crane [N]. F_f, F_B and F_{WT} are the forces on the frame due to the self mass of the frame, the ballast and wind turbine respectively in [N]. A_f and H_f are the surface area and length of the frame in [m2] and [m] respectively, ρ_s is the density of steel in [kg/m3], as defined inTable F.8 and m_{CW} is the mass of the counterweight in [kg]. All other parameters can be found in Table I.2.

The goal is to determine the mass of the frame by investigating the needed cross-sectional area of the beam to withstand the tension loads put on it. This can be done using solving Equation I.9 for the area of the frame using the "solve" function in Matlab.

$$\sigma_y = \frac{F_{t,beam}}{A_f} = \frac{(m_{WT} + m_{CW})g + A_f H_f \rho_s g}{A_f} \tag{I.9}$$

In which σ_y is the yield strength of steel in [Pa] taken to be 355[MPa] and all other factors are the same as described in the paragraph directly above. The mass of the frame can subsequently be determined with Equation I.10, the COG of the frame is assumed to be halfway up along the length of the frame.

$$m_f = A_f L_f \rho_s SFH_{fac} \tag{I.10}$$

In which SF is the safety factor taken to be 1.5, H_{fac} is a correction factor to also include the weight of the horizontals and braces of the frame, taken to be $4/3$, and all other parameters are defined at Equation I.9.

The system of equations is a recursive problem, as the mass of the ballast influences the mass of the frame and the mass of the frame influences the mass of the ballast. To determine the mass of the frame, initially the mass of the ballast is set to zero to get rid of the recursiveness of the problem. Resulting in a initial mass of the frame which can be used in the determination of the mass of the counterweight, the results can be found in Table I.3.

Table I.3: Initial mass of frame determined without counterweight mass.

Parameter	Value
m_{CW}[ton]	0
A_f[m2]	0.167
m_f[ton]	288

The mass of the counterweight can subsequently be determined by setting a goal for the COG of the entire assembly, and solving Equation I.11 for the mass of the ballast, m_{CW}, using the "solve" function in Matlab.

$$H_{COG,ass} = \frac{m_{WT}H_{COG,WT} + m_f H_{COG,f} + m_{CW}H_{COG,B}}{m_{WT} + m_f + m_{CW}} \tag{I.11}$$

In which $H_{COG,ass}$ is the target height of the COG of the entire assembly above the bottom of the frame in [m], which is assumed to be 105[m]. $H_{COG,f}$ is the height of the COG of the frame in [m], which is assumed to be at half height of the frame. $H_{COG,B}$ is the height of the COG of the counterweight in [m], this is assumed to be 1.5 meters, as this depends on the still unknown volume of the ballast. This results in a mass of the counterweight of about 2000 tonnes. This intermediate step results can be found in Table I.4.

Table I.4: Intermediate Mass of frame and counterweight.

Parameter	Value
m_{CW}[ton]	2000
A_f[m2]	0.167
m_f[ton]	288
$H_{COG,ass}$[m]	105

The next step is to re-assess the strength of the frame, as the needed area of the frame has initially been determined using only the wind turbine weight. Equation I.9 is used again, this time including the mass of the counterweight into the strength assessment. Thus, resulting in a slightly heavier frame. This lowers the COG of the assembly further, as the mass of the frame increases due to the added weight of the counterweight. The final height of the COG of the assembly is recalculated including the final weight of the frame using Equation I.11. The results can be found in Table I.5. The approach sketched in this section can be repeated multiple times to converge to an optimum mass of frame and counterweight. Only one iteration is performed, as the gains in mass reduction are not significant enough to matter during the concept design.

Table I.5: Final mass of frame and counterweight.

Parameter	Value
m_{CW}[ton]	2000
A_f[m2]	0.2224
m_f[ton]	385
$H_{COG,ass}$[m]	104.4

The final check that must be performed is, to confirm the estimated height of the COG of the counterweight is acceptable. This is done by determining the height of the counterweight using Equation I.12.

$$H_{CW} = \frac{V_{CW}}{A_{CW}} = \frac{\frac{m_{CW}}{\rho_s}}{W_f^2 - \frac{D_{tow}^2 \pi}{4}} \tag{I.12}$$

In which, H_{CW}, V_{CW} and A_{CW} are the height, volume and cross-sectional area of the ballast in [m], [m3] and [m2] respectively. Wi_f is the width of the frame, as the assumption is made that the ballast will be placed in the frame around the tower and D_{tow} is the bottom diameter of the tower, defined to be 16.5 meters. The found height of the counterweight is 2.76 meters, so the initial assumption of $H_{COG,B}$ of 1.5 meters is deemed acceptable. This because the actual COG of the counterweight is lower than the assumed one, further decreasing the attained COG of the entire assembly. The total mass of the wind turbine plus assembly then becomes, 8405 metric tons.

I.2. Motions of semi submersible in transit

This section has been removed, as it contained confidential information provided by the research's partner GustoMSC NOV.

I.3. Story board installation using lifting frame.

In this section, a story board is presented depicting the installation procedure using the lifting frame concept. For simplicity, the installation vessel is omitted in the depiction. In Figure I.4 the lifting and mating of the wind turbine in the lifting frame is depicted, and in Figure I.5 the opening up and detachment of the frame is depicted.

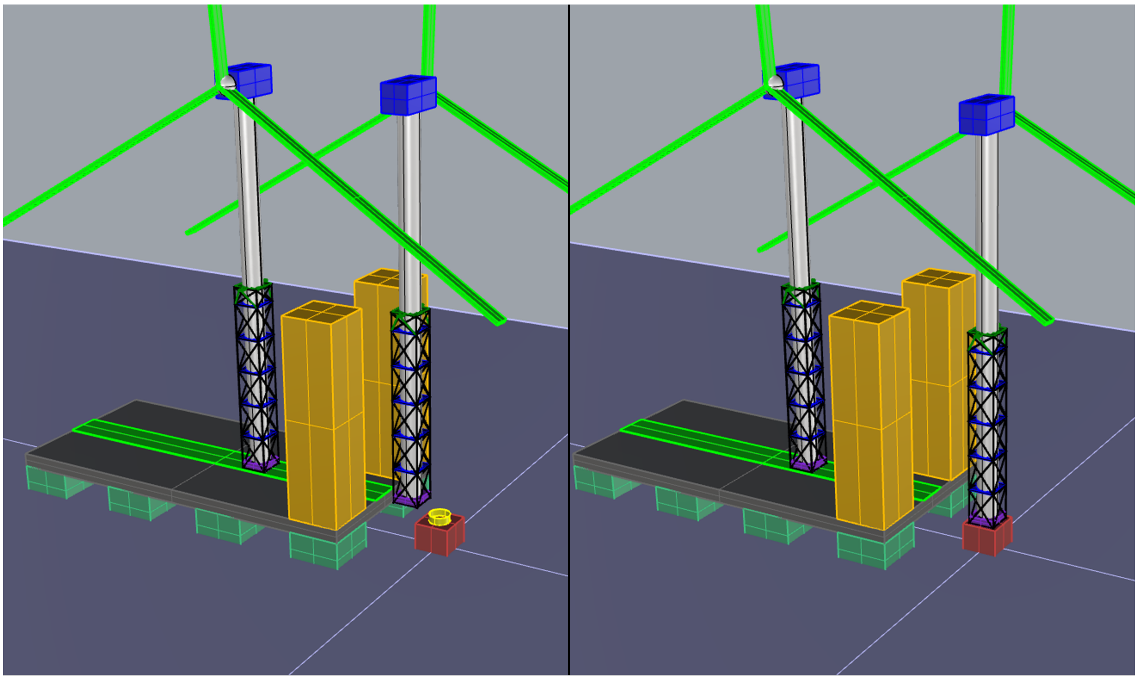

Figure I.4: Story board installation using lifting frame part 1, Left wind turbine in frame during lift, Right mating of wind turbine to foundation.

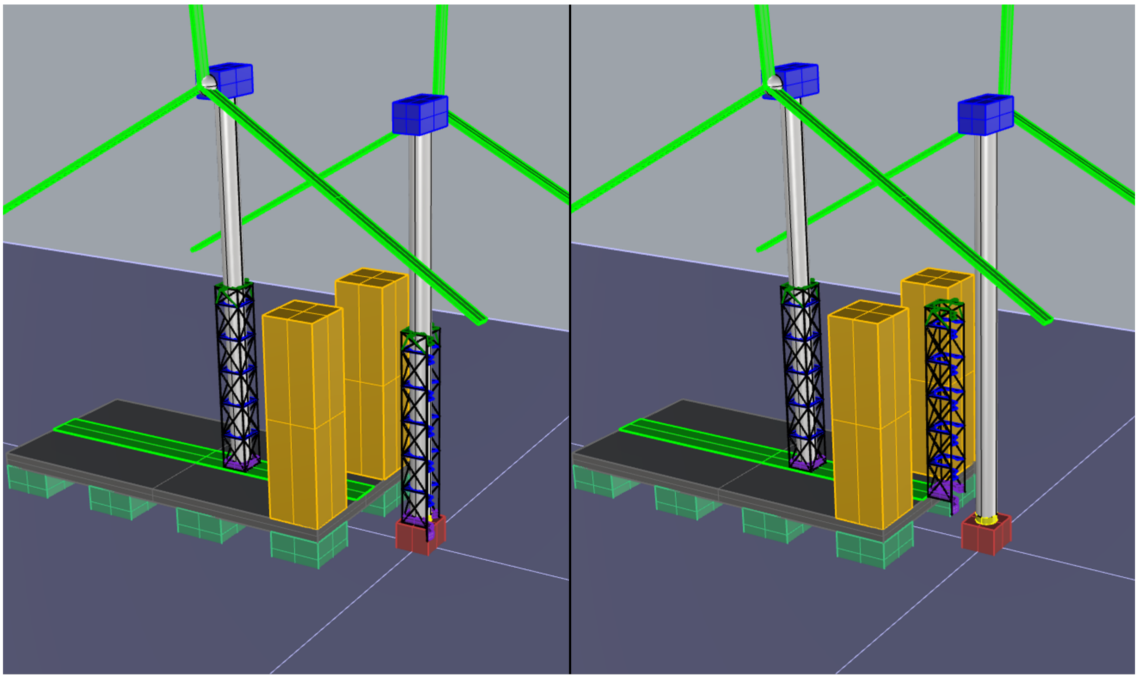

Figure I.5: Story board installation using lifting frame part 2, Left wind turbine with opened up frame, Right detachment of frame.

J

Appendix J: Installation tower calculations and storyboard

In this appendix, the calculations regarding the concept of the installation tower semi submersible are presented. The procedure followed and used formulae for the initial sizing will be discussed into detail. The procedure followed is listed below. The process of finding a vessel that is stable is an iterative one, as a change in one of the parameters will affect a plethora of others. In this appendix only the approach, used formulae and final dimensions are presented. The iterative process is left out as it adds little value. An overview of the vessel can be found in Figure J.1.

- Choose initial layout of semi submersible vessel;
- Parameterize semi submersible vessel dimensions;
- Choose initial dimensions;
- Determine size topside;
- Design crane platform for size topside and lifting capacity of 2000 metric tons;
- Set size tower lattice structure;
- Determine size and weight of lattice structure using rules of thumb for jackets;
- Check tower leg stability;
- Determine stability of the vessel during lifting of nacelle;
- Redefine dimensions to reach positive GMs in all direction;
- Check all dimensions of all parts if still plausible;
- If yes, no problem. If not, redefine dimension and check stability again.

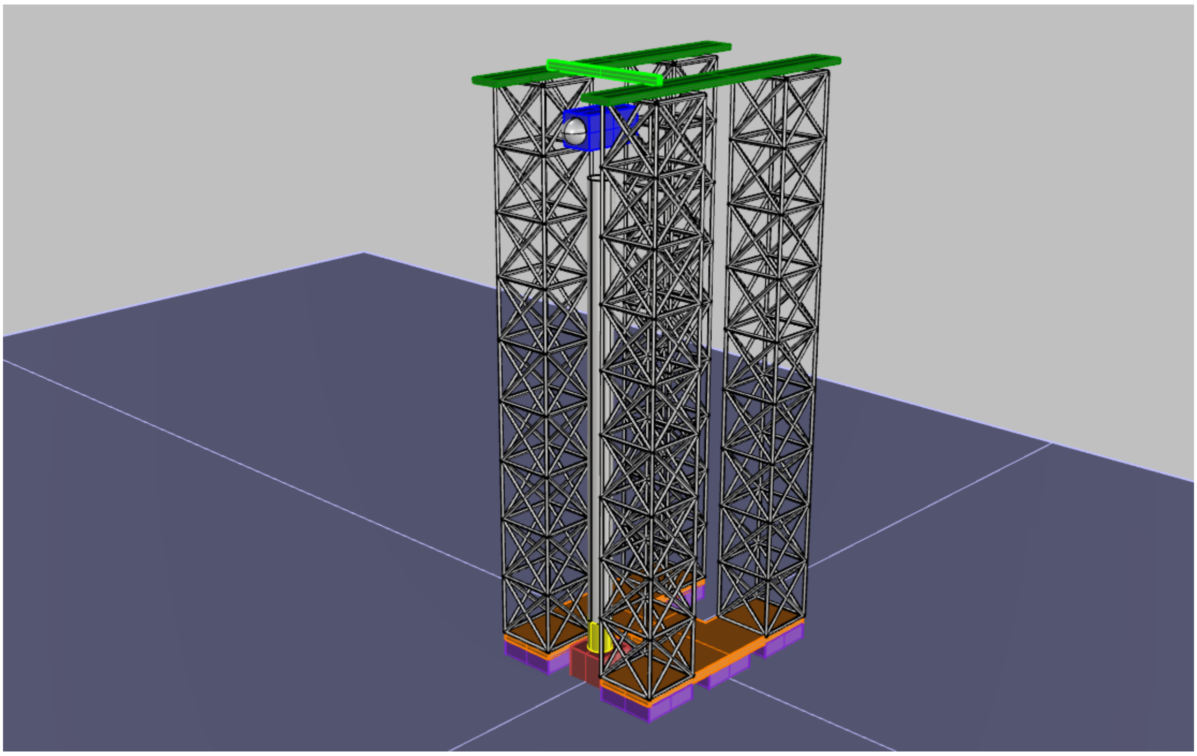

Figure J.1: Overview of installation tower semi-submersible concept.

J.1. Initial weight and size estimation

In this section, the initial weight and size estimate of the semi-submersible tower installation vessel is presented. The concept design revolves around the stability of the vessel, to determine this the above listed process was used. First, the parameterization of the semi submersible vessel is presented followed by the design of the gantry crane, the design of the towers on top of the semi submersible and finally the determination of the stability of the vessel.

J.1.1. Parameterization and weight estimate of Semi submersible vessel hull

The entire parameterization of the semi submersible vessel's hull will be discussed first. The design of semi-submersibles always starts with the choice of the layout of the vessel. The decision was made to start with a layout consisting of 3 columns on each side of the vessel with a pontoon underneath and a deck box on top, as can be seen in Figure J.2 up until Figure J.4.

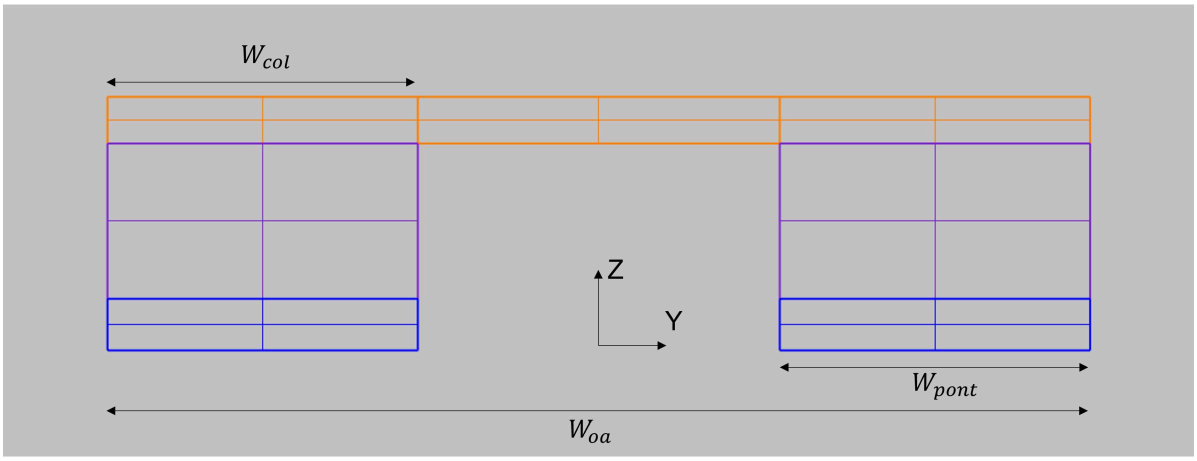

Figure J.2: Front view of hull semi submersible vessel with parameterization. Orange is the deck box, purple the columns and blue the pontoons.

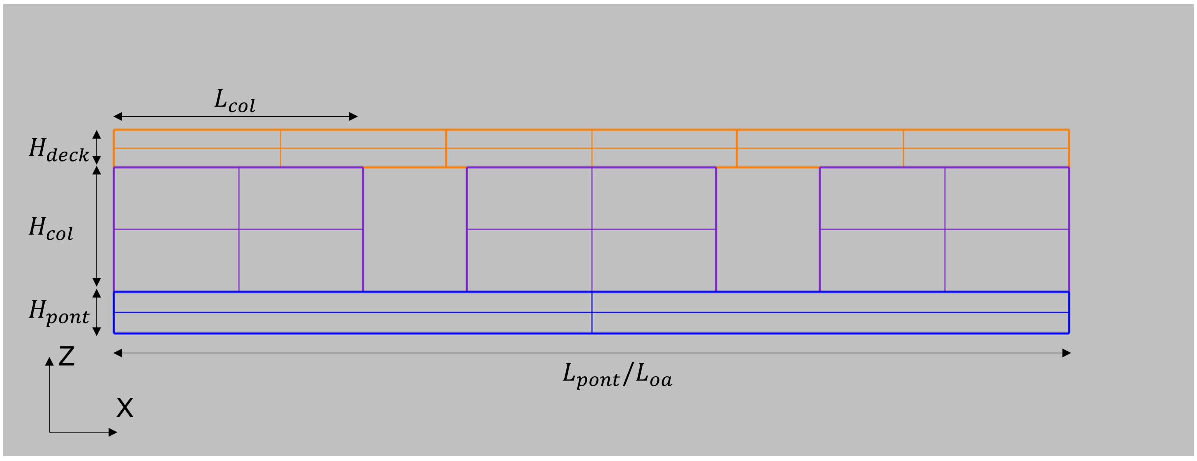

Figure J.3: Side view of hull semi submersible vessel with parameterization.Orange is the deck box, purple the columns and blue the pontoons.

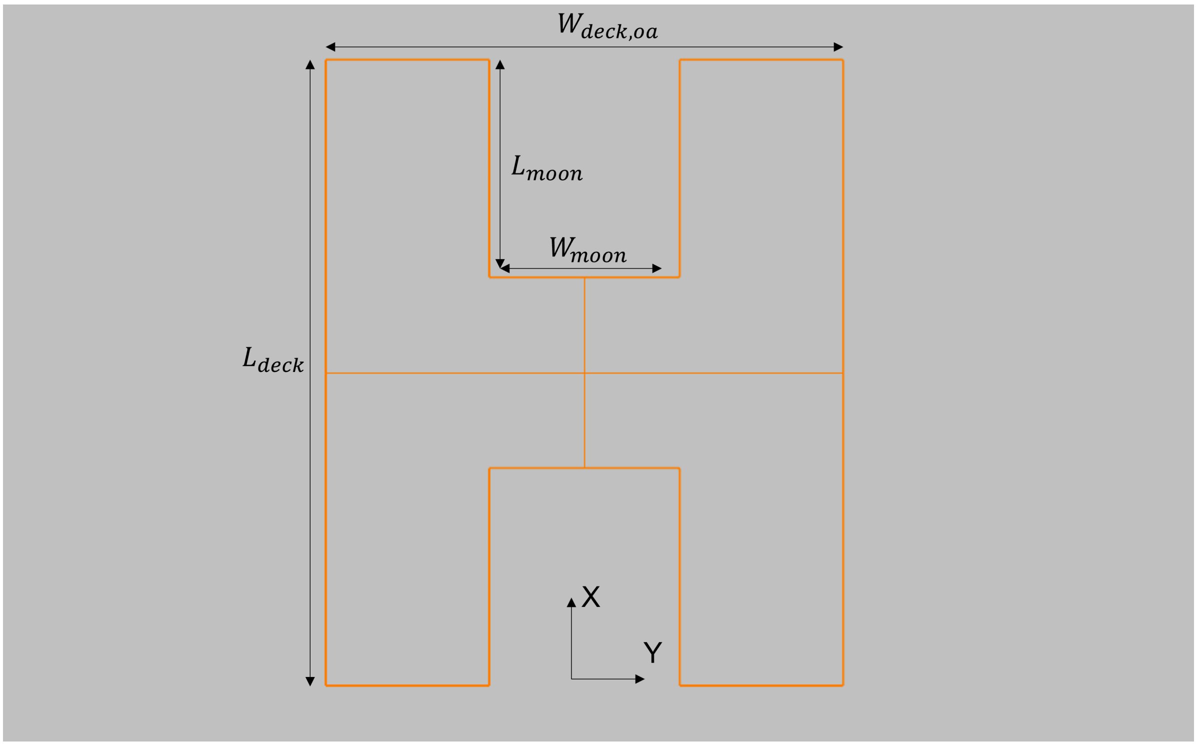

Figure J.4: Top view of hull semi submersible vessel with parameterization.

A tool was written in Matlab in which all parameters of the semi-submersible hull could be varied, to in the end find a design which is stable during the lifting of the heaviest component of the wind turbine, the nacelle. In Table J.1 the parameters are described and is provided if they are fixed or variable. The goal was to reduce the amount of variables as much as possible, so that a first estimation of hull sizes could be made without creating too much work. It can be seen in the table that the main parameters which are varied are the overall width and length of the vessel, the width & height of the pontoon and the height of the columns. This all to reach a vessel which has positive GMs in all directions, has more than enough free-board and will never have pontoons above the water line in operation conditions. The strength assessment of the deck is performed using the box structure design approach described at Figure F.8.

Table J.1: Description and Determination of all parameters in hull design of semi-submersible hull, all in meters.

Parameter	Denotation	Determination
Overall length of hull	L_{oa}	Variable
Overall width of hull	W_{oa}	Variable
Length of deck	$L_{deck,oa}$	$= L_{oa}$
Width of deck	$W_{deck,oa}$	$= W_{oa}$
Height of deck	H_{deck}	Strength assessment
Length of pontoons	L_{pont}	$= L_{oa}$
Width of pontoons	W_{pont}	Variable under constraint $2W_{pont} < W_{oa} - 35$
Height of pontoons	H_{pont}	Variable but should never reach above waterline during loaded condition
Length of columns	L_{col}	$= W_{pont}$
Width of columns	W_{col}	$= W_{pont}$
Height of columns	H_{col}	Variable taken to be less than length or width
Length of moon pools	L_{moon}	Variable under constraint of $2L_{moon} < 0.3L_{oa}$
Width of moon pools	W_{moon}	Variable under constraint of $W_{moon} < L_{deck} - 2W_{bay}$

Weight estimation of hull

The weight estimation of the hull is performed using an initial design approach in which a volume to mass ratio is assumed[42]. This is common practice in the industry and is thus assumed to be a proper initial estimate. The mass of a part of the semi-submersible hull can be determined using Equation J.1, under the assumption that all parts of the hull are perfectly rectangular. In reality this is not the case as that would lead to problems with open water behaviour and localized loads, however, as a first estimate this is deemed acceptable. Furthermore, because the actual volume will not be that far off from this estimation due to the fact that normally only corners are rounded off.

$$w_{hull} = \sum_{n=1}^{i} L_n W_n H_n \rho_{hull} \tag{J.1}$$

In which w_{hull} is the mass of the hull in tonnes, n denotes a particular part of the hull, L_n, W_n, H_n are the length, width, and height of a certain part of the hull in [m] and ρ_{hull} is the assumed mass density of the hull in [ton/m3]. The initial hull density is assumed to be 0.270 [ton/m3], which means that 27% of the hull is mass and the other 83% will be pure buoyancy. Like this, an initial estimate of the mass of the hull can be attained, without the in-depth design of the hulls structure.

Deck box structure design

For the deck box structure mass determination, the same approach is taken as outlined at Figure F.8. The only difference is the manner in which the maximum moment on the box is determined. The deck is assumed to be fixed at both ends and assumed to be designed for a deck load of 20 tonnes per square meter. This is common for large heavy lift semi submersibles, as was discussed with the project supervisors. The initial assumption is made that the deck is only loaded by the deck load and its own weight, as braces in-between the pontoons will carry the hydrodynamic forces put on the hull. In this concept design, the braces have not yet been included.

More strengthening of the deck might be needed during transit, as torsional moment will act on the hull and braces. This can be attained by placing beams on the fore and aft of the vessel which span the entire width and can be opened up, so that during installation and mooring of feeder barges the beams do not interfere with the process. This is also done on the Pioneering Spirit of Allseas. It is left out of the calculations, as in depth hydrodynamic analysis of the hull is needed to determine the exact loads on the hull and deck. Furthermore, if the weight of the deck must be increased, to bear these loads, it will only positively influence the stability of the vessel. Due to fact that the COG of the entire vessel is situated above the deck, as there are large towers on top of it.

The simplification used for the determination of the moment in the deck due to the deck load of 20 tonnes per meter squared and its own weight can be found in Figure J.5. Due to the assumption of either end of the deck being clamped, the maximum moment can be found using the well known forget-me-not formulae for moments in clamped-clamped beams.

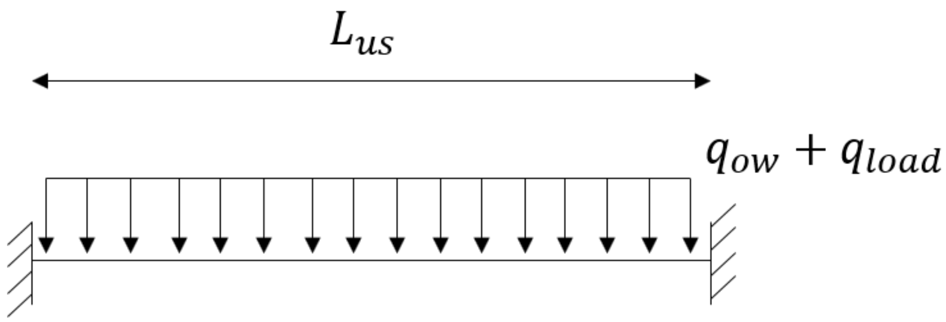

Figure J.5: Simplification used for determination of maximum moments in deck.

$$M_{max,hull} = \frac{(q_{ow} + q_{load})\, L_{us}^2}{12} \tag{J.2}$$

In which $M_{max,hull}$ is the maximum moment found in the hull in [Nm], q_{ow} is the distributed force put on the deck due to its own weight in [N/m], as is described at Figure F.8, q_{load} is the distributed force on the deck due to the assumed maximum deck load of 20 [tons/m2] in [N/m] and L_{us} is the unsupported length of the deck in meters. q_{load} is determined by Equation J.3 and L_{us} is determined by Equation J.4.

$$q_{load} = w_{load} g W_{box} \tag{J.3}$$

$$L_{us,deck} = W_{oa} - 2W_{col} \tag{J.4}$$

In which w_{load} is the predetermined deck load in [kg/m2], g is the gravitational constant, W_{box} is the width of the box structure in [m], W_{oa} is the overall width of the vessel in meters and W_{col} is the width of the columns of the vessel in meters. W_{box} is set to be 5 meters wide initially, as a larger width would most likely result in plate buckling. Furthermore, all forces put on the deck box are defined as distributed forces, thus the eventual estimation of the entire mass of the deck will not be affected significantly by the choice of box width. The mass per meter that surfaced from the box structure calculation is expressed as a mass per square meter and multiplied by the total deck area, determined by Equation J.5, to find the mass of the deck with Equation J.6.

$$A_{deck} = L_{oa} W_{oa} - 2L_{moon} W_{moon} \tag{J.5}$$

$$w_{deck} = A_{deck} w_{deck,2} \tag{J.6}$$

In which A_{deck} is the deck area in [m2], w_{deck} is the mass of the deck in [kg], $w_{deck,2}$ is the weight per area of the deck, found using the above described approach in [kg/m2] and all other parameters are the same as defined in Table J.1.

The mass of the deck can be determined by multiplying the deck area by the found deck weight per meter squared. Note that, the found mass per square meter is rounded up to an integer, as no detailed design has been performed, resulting in a conservative estimate. Here the entire deck is designed to withstand the largest moment put on it and can probably be reduced when optimizing. However, localized strengthening will be needed to support the towers on the deck, which will increase the weight again. But as a first estimation, this is deemed acceptable.

J.1.2. Parameterization and weight estimate of gantry crane.

The design of the gantry crane is described in this subsection. The same box structure design approach that has been described at Figure F.8 has been used to define the gantry crane upper- and the support boxes. The gantry crane rests on these support boxes, which both are located at the top of the lattice towers. Within the box the moving equipment for the gantry is located, this will not be worked out into detail as that is part of detailed design.

The parameterization of the gantry crane and its support structure can be found in Figure J.6 up until Figure J.8. In Table J.2 all parameters and their definition can be found.

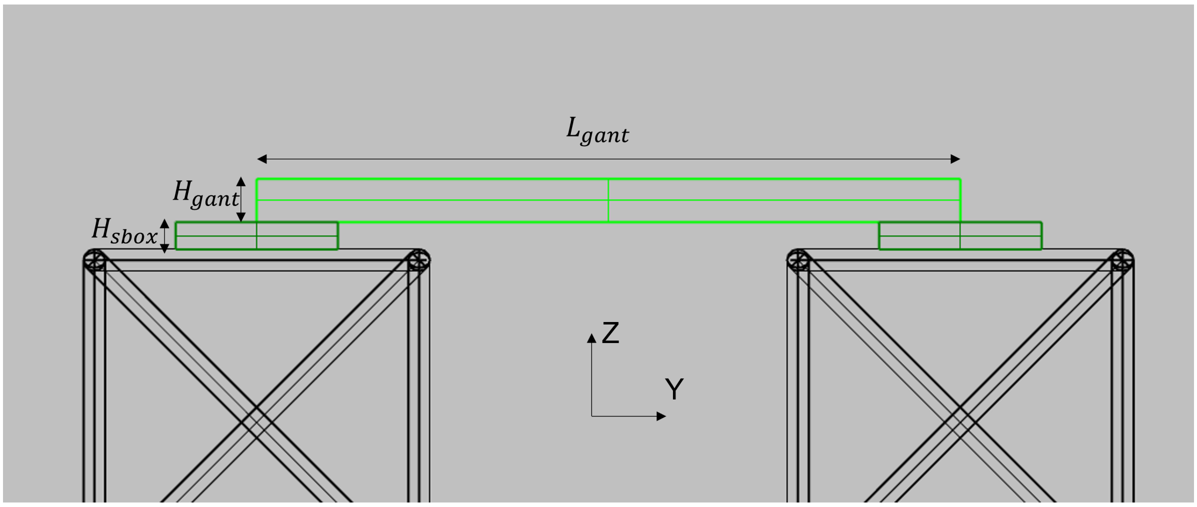

Figure J.6: Front view of the gantry like crane platform, light green is the movable gantry crane and dark green the support structure.

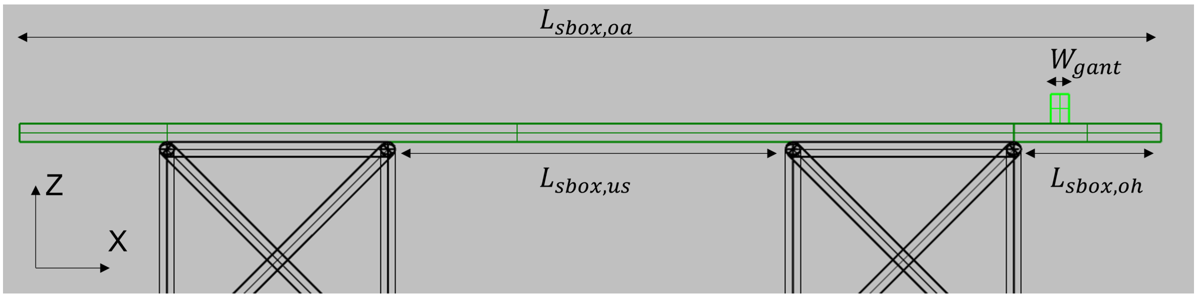

Figure J.7: Side view of the gantry like crane platform, light green is the movable gantry crane and dark green the support structure.

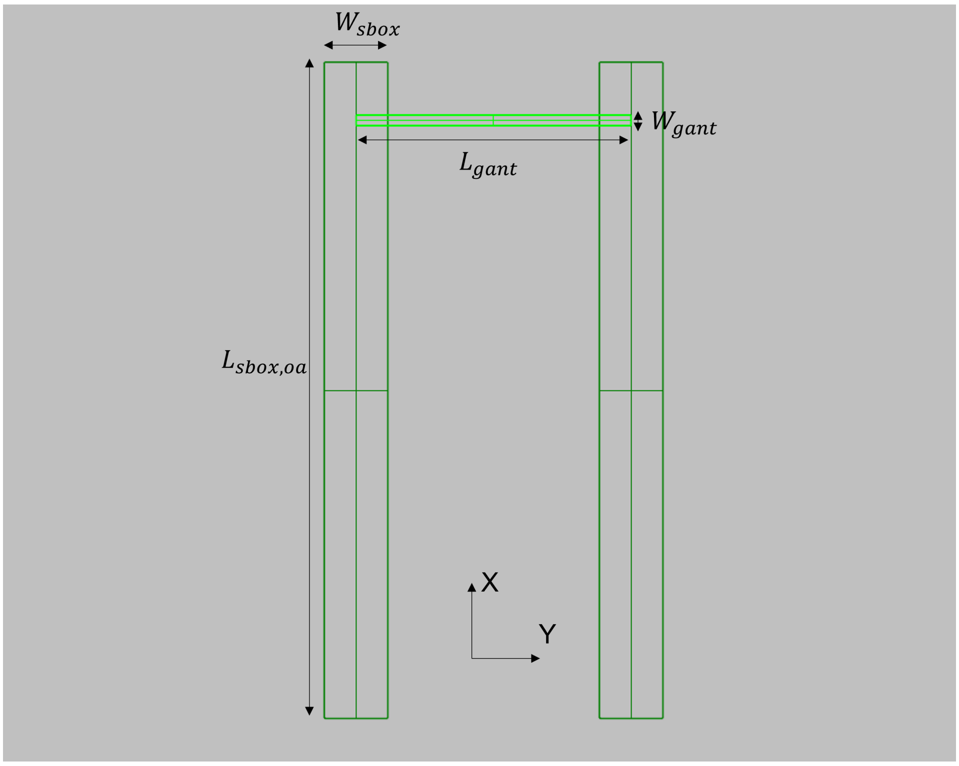

Figure J.8: Top view of the gantry like crane platform, light green is the movable gantry crane and dark green the support structure.

Table J.2: Description and determination of all parameters gantry platform and support boxes all parameters are in meters.

Parameter	Denotation	Determination
Length of the gantry like crane platform	L_{gant}	$= W_{oa} - W_{bay}$
Width of gantry like crane platform	W_{gant}	Strength assessment box
Height of gantry like crane platform	H_{gant}	Strength assessment box
Unsupported length of gantry	$L_{gant,us}$	$= L_{gant}$
Length support boxes	$L_{sbox,oa}$	$= L_{oa} + 2L_{sbox,oh}$
Width support boxes	W_{sbox}	Strength assessment box
Height support boxes	H_{sbox}	Strength assessment box
Unsupported length support boxes	$L_{sbox,us}$	$= L_a o - 2W_{bay}$
Overhang length of support boxes	$L_{sbox,oh}$	Variable but taken to be 20 meters

Weight estimation gantry like crane and support boxes
The same approach is taken for the design of both of the support box structures, as described in the section above. The main difference is, again, how the maximum moment in the box structures is determined. The box structure is assumed to be clamped at both ends of the unsupported length of the box, the simplification used for finding the maximum moment can be found in Figure J.9.

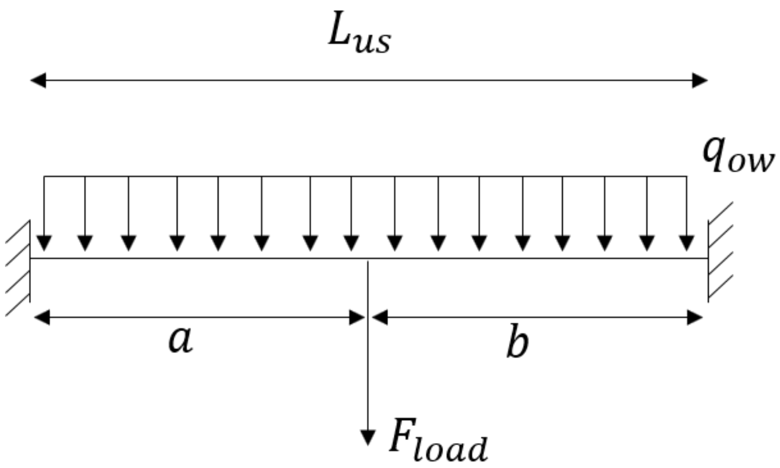

Figure J.9: Simplification used for determination of maximum moment in Gantry like crane and support structure of crane.

The load can move over the support structure in lengthwise direction and on the gantry crane in transverse direction. The location of the load has an effect on the moment at the bases of the boxes, the maximum moment must thus be derived using forget-me-nots. The moments at the base of the simplified beam will again be the leading moments, the moment due to the own weight can be determined using Equation J.2 and setting the deck load to zero. Now only the moment due to the lifting load, F_{load}, must be determined. The moment can be expressed as Equation J.7, by rewriting, differentiating and setting equal to 0 the maximum moment can be found. See Equation J.8 for the entire process of differentiating and finding the location of the load at which the maximum moment occurs. This results in a maximum moment when $a = \frac{2L_{us}}{3}$, thus, the maximum moment can be expressed as Equation J.9.

$$M_{load,crane} = \frac{F_{load} a^2 b}{L_{us}^2} \tag{J.7}$$

$$\frac{\mathrm{d}M_{load,crane}}{\mathrm{d}a} = \frac{\mathrm{d}}{\mathrm{d}a} \frac{F_{load} a^2 (L_{us} - a)}{L_{us}^2} = 0 \tag{J.8}$$

$$M_{max,crane} = \frac{F_{load} \left(\frac{2L_{us}}{3}\right)^2 \frac{L_{us}}{3}}{L_{us}^2} \tag{J.9}$$

In which, $M_{load,crane}$ is the moment in the crane due to the load put on it in [Nm], F_{load} is the force due to the load on the box structure in [N], a and b describe the location of the load on the box structure in [m], L_{us} is the unsupported length of the box structure in [m] and $M_{max,crane}$ is the maximum moment on the box structure due to the load in [Nm]. The force due to the load can be determined for each of the members, the gantry like crane platform and the support structure boxes.

First, the mass of the gantry crane box is determined. The load on the gantry crane is expressed as Equation J.10.

$$F_{load,gc} = m_{nac} g DAF \tag{J.10}$$

In which $F_{load,gc}$ is the load on the gantry crane due to the lifting of the nacelle in [N], m_{nac} is the mass of the nacelle in [kg], g is the gravitational constant an DAF is the Dynamic Amplification Factor (DAF), taken to be 1.2[16]. Using the above determined maximum moment and the box design approach described at Figure F.8, the mass per running meter of the gantry crane box can be expressed. It is used to determine the total mass of the gantry crane box using Equation J.11

$$m_{gc} = L_{gant} w_{gant,m} \tag{J.11}$$

In which m_{gc} and L_{gant} are the mass and length of gantry like crane in [kg] and [m] respectively and $w_{gant,m}$ is the gantry crane mass per running meter in [kg/m] found using the box design approach. Note that, the found ton per running meter is rounded up to an integer, as no detailed design has been performed, resulting in a conservative estimate.

The next step is to determine the mass of the support boxes of the gantry crane, which are placed on top of the lattice towers. This was done in the exact same manner as for the gantry crane. The only difference is the load force, F_{load} in Equation J.9, as for the support boxes this load also includes the mass of the gantry crane. The load force is expressed as Equation J.12. It is assumed that the full load of the nacelle must be carried by one support box, which is the case when the nacelle is close to the support. Furthermore, half of the weight of the gantry crane box is also on one support box, as the gantry crane is always supported by 2 boxes.

$$F_{load,sup} = F_{load,gc} + \frac{m_{gc} g}{2} \tag{J.12}$$

In which $F_{load,sup}$ is the force due to the load on the supports of the gantry crane in [N], m_{gc} is the mass of the gantry crane box in [kg] and all other parameters are the same as defined at Equation J.10. Using this load, the maximum moment in the supports of the gantry crane was determined and used to find the mass per meter. This is again multiply with the overall length of the support box to find the final mass of the supports using Equation J.13.

$$m_{sbox} = L_{sbox} w_{sbox,m} \tag{J.13}$$

In which m_{sbox} and L_{sbox} are the mass and length of the support boxes in [kg] and [m] respectively and $w_{sbox,m}$ is the support box mass per running meter in [kg/m] found using the box design approach. The found mass per running meter is rounded up to an integer, as no detailed design has been performed, resulting in a conservative estimate.

J.1.3. Lattice tower design, weight estimate and unity check

In this section, the parameterization and definition of the tower structures on top of the deck of the semi submersible is presented. They are designed last, as the check on stability of the legs requires the mass of the gantry crane and supports. The choice is made that the towers consist of entirely square bays supported by x-bracings on all sides. The length, height, and width of these bays are equal, so that the design of them is relatively easy and fast. Furthermore, this simplifies the calculations to only one variable that can be changed while determining the stability of the vessel. This will by no means result in an optimized structure and should thus be looked into further if deeper level design is done on the concept. In Figure J.10 the parameterization of the tower is depicted and in Table J.3 the denotation and determination of the variables can be found.

Table J.3: Parameterization and determination of tower structure on top of hull, all parameters are in meters.

Parameter	Denotation	Determination
Length of bay	L_{bay}	Variable
Height of bay	H_{bay}	$= L_{bay}$
Width of bay	W_{bay}	$= L_{bay}$
Height of entire tower	H_{tow}	Variable but H_{tow}/L_{bay} must be an integer, taken to be 270 meters
Number of bays	n_{bay}	$= H_{tow}/L_{bay}$

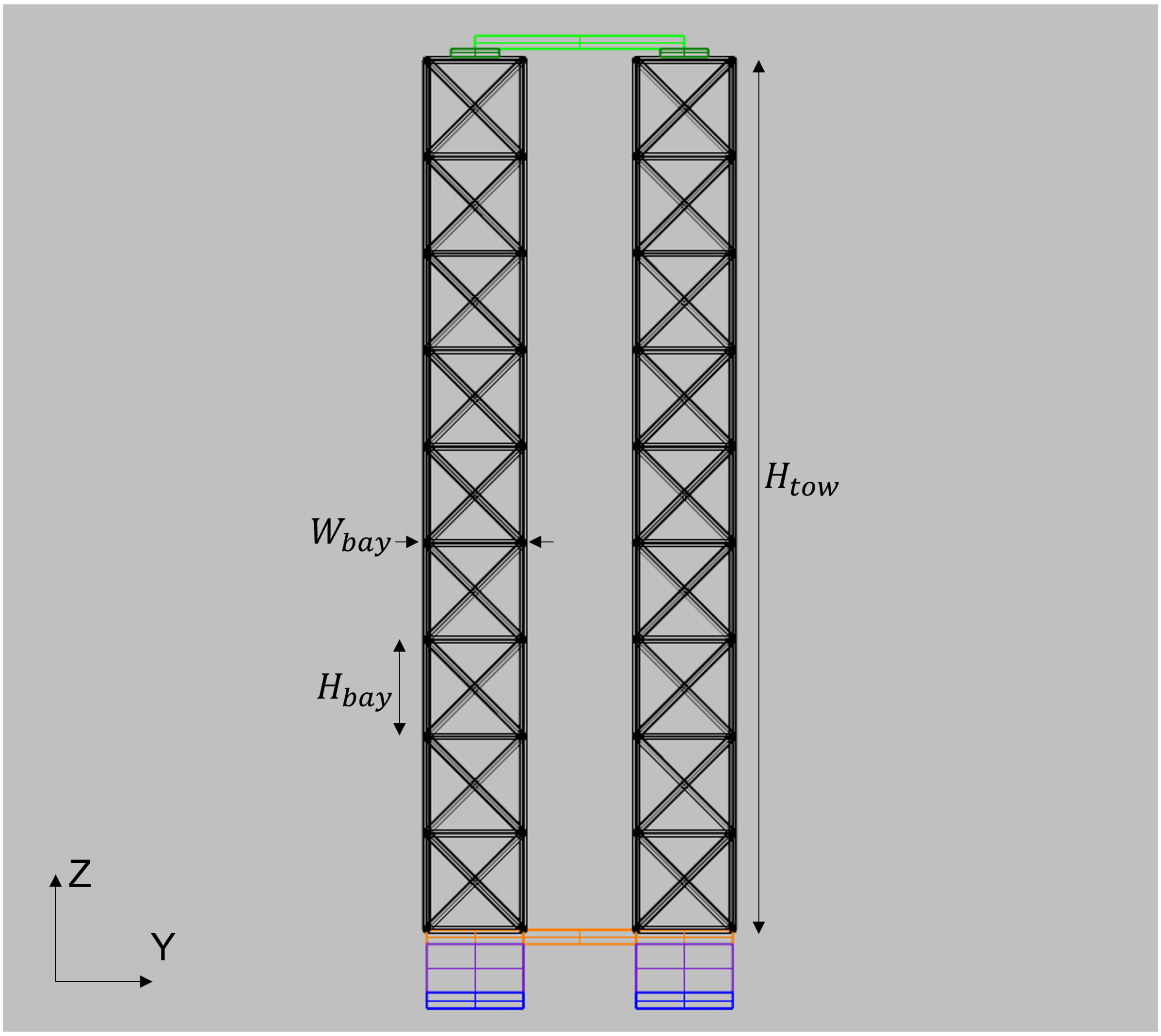

Figure J.10: Front view of semi-submersible with parameterization of towers.

Design of tower structure and weight estimate

For the design of the tower structure, rules of thumb found in the handbook for offshore engineering[57] for jackets are used. Jackets are under more loads than these tower structures, as they are not located underwater. Drag due to wind will cause significantly fewer forces on the members of the tower structure, thus, as a first estimation, this is deemed acceptable. The main difference between an underwater jacket structure and the tower structures is that all members are loaded due to gravity, as opposed to underwater, where members can be buoyant as well. So, buckling checks on all members should be performed to see if they can withstand the loads due to their own weight. During the design, this is only be done for the legs of the tower structure, as these members will take up the most load. However, it is safe to assume that the other members have sufficient strength, as the rules of thumb take wave loading into account, which is significant as well.

First, the diameters of all members must be determined using rules of thumb based on the slenderness of the member. The diameter of the x-braces and horizontals are determined using Equation J.14 and Equation J.15 respectively and the diameter of the leg has to be sufficiently larger than the diameters of the other members so that welding is possible, denoted in Equation J.16.

$$D_x = 0.018L_x \tag{J.14}$$

$$D_h = 0.023L_h \tag{J.15}$$

$$D_l > D_h \& D_x \tag{J.16}$$

In which D_x, D_h and D_l are the diameters of the x-bracing, horizontals and legs respectively in [m], L_x and L_h are the length of the x-bracing and horizontals respectively determined by Equation J.17 and Equation J.18.

$$L_x = \sqrt{H_{bay}^2 + W_{bay}^2} \tag{J.17}$$

$$L_h = L_{bay} \tag{J.18}$$

In which all variables are defines as in Table J.3. The next step is to determine the wall thicknesses of all members, again by using rules of thumb on the diameter over thickness(D/t) ratio of the tubular members. The D/t ratios used can be found in Table J.4 and using Equation J.19 the wall thickness of the members can be determined.

Table J.4: used D/t ratios for tower design semi-submersible concept.

Part	**D/t ratio**
Tower leg[-]	60
X-bracing[-]	40
Horizontals[-]	40

$$t_{wall,n} = \frac{D_n}{Dt_{ratio,n}} \tag{J.19}$$

In which $t_{wall,n}$ is the wall thickness of a member in [m], n denotes the type of member, D_n is the diameter of a certain member in [m] and $Dt_{ratio,n}$ is the dimensionless D/t ratio of a certain member. To determine the total weight of a tower, the volume of steel needed for the construction of the tower is determined. This is done by assuming all members of a certain type are of equal diameter and wall thickness, next the cross-sectional area of each type is calculated, followed by the calculation of the steel volume of each type of member. The steel volume of a single member of a certain type is multiplied by the number of members of that type to find the weight of the tower structure, see Equation J.20 up until Equation J.22.

$$A_n = \frac{1}{4}\pi\left(D_n^2 - (D_n - 2 * t_{wall,n})^2\right) \tag{J.20}$$

$$V_n = A_n L_n \tag{J.21}$$

$$V_{total} = V_{leg} n_{leg} + V_x n_x n_b + V_h n_h (n_b + 1) \tag{J.22}$$

In which, A_n is the cross-sectional steel area of a member in [m2], n denotes a type member, D_n is the diameter of a certain type of member in [m], $t_{wall,n}$ is the wall thickness of a type of member in [m], V_n is the steel volume of a certain type of member in [m3], L_n is the length of a type of member in [m], $V_t otal$ is the total steel volume of one tower in [m3]. V_{leg}, V_x, V_h are the steel volumes of one leg, one x-brace, one horizontal respectively in [m3] and n_{leg}, n_x, n_b and n_h are the number of legs, x-braces in one bay, number of bays and number of horizontals in one bay respectively. The weight of one towers is determined using Equation J.23.

$$m_{tow} = V_{total} \rho_s \tag{J.23}$$

In which m_{tow} is the mass of the tower in [kg], ρ_s is the density of steel in [kg/m3], opposed to all other designs of components of the semi-submersible no safety factor is used here as that will be included later on during the stability check.

Strength check on leg of tower structure

To check if the designed tower can bear the loads on it due to the lifting of the nacelle and weight of the gantry crane, a buckling unity check is performed. The check is performed on one of the lower parts of the legs of one tower, as is proposed in the handbook for offshore engineering part2, section 2.4.5[57]. The compressive load on one leg due to the gantry crane, support box of the gantry crane and nacelle is determined by Equation J.24. The assumption is made that the weight is evenly taken up by each leg on one side of the vessel, as no in depth lifting analysis was performed. The compressive load on one leg due to the own weight of the tower is determined by Equation J.25 under the assumption that the entire weight of the structure is evenly taken up by all legs of the tower.

$$P_{c,gc} = \frac{g(m_{gc} + m_{nac} + m_{sb})}{n_{leg}\frac{n_{tow}}{2}} \tag{J.24}$$

$$P_{c,ow} = \frac{g m_{tow}}{n_{leg}} \tag{J.25}$$

In which $P_{c,gc}$ and $P_{c,ow}$ are the compressive load on one leg due to the gantry crane and own weight of the structure respectively in [N], m_{gc}, m_{nac}, m_{sb} and m_{tow} are the mass of the gantry crane box, nacelle, gantry crane support box and tower respectively in [kg], n_{leg} is the number of legs in one tower and n_{tow} is the total number of towers on the vessel. The compressive stress is then calculated using Equation J.26 which is then used in the check denoted by Equation J.27.

$$\sigma_c = \frac{P_{c,gc} + P_{c,ow}}{\frac{\pi}{4}D_l^2 - \left(D_l - 2t_{leg}\right)^2} \tag{J.26}$$

$$\frac{\sigma_c}{F_c \phi_c} < a_c \tag{J.27}$$

In which σ_c is the compressive stress in a leg in [Pa], D_l and t_{leg} are the leg diameter and wall thickness in [m], F_c is the maximum compressive buckling stress in [Pa], phi_c is a safety factor, defined to be 0.85, a_c is the unity check factor taken to be 0.6 as no lateral loads have been included into the evaluation. F_c is determined by Equation J.28.

$$F_c = \begin{cases} (1 - 0.25\bar{\gamma}^2)\sigma_y & \text{if } \bar{\gamma} < \sqrt{2} \\ \frac{1}{\bar{\gamma}^2}\sigma_y & \text{if } \bar{\gamma} \geq \sqrt{2} \end{cases} \tag{J.28}$$

In which $\bar{\gamma}$ is the buckling factor and σ_y is the yield strength of steel in [Pa]. $\bar{\gamma}$ is determined by Equation J.29 using Equation J.30 to determine the radius of gyration.

$$\bar{\gamma} = \frac{K H_{bay}}{\pi r}\sqrt{\frac{\sigma_y}{E_s}} \tag{J.29}$$

$$r = \sqrt{\frac{I}{A}} \approx \frac{D_l - t_l}{2\sqrt{2}} \tag{J.30}$$

In which K is the buckling length factor of a leg taken to be 1, as proposed in the handbook[57], H_{bay} is the height of the bay and thus unsupported length of the leg in [m], r is the radius of gyration in [m], E_s is the Young's modulus of steel in [Pa] and all other factors have been described in this section. In Table J.5 the used safety factor, unity check factor, yield strength and Young's modulus of steel are repeated.

Table J.5: Parameters used in strength calculation of tower leg.

Parameter	Value
ϕ_c[-]	0.85
a_c[-]	0.6
σ_y[MPa]	355
E_s[GPa]	210

Using the above defined strength check, an initial assessment of the strength of the legs of the towers can be conducted. Using this, the diameter of the legs can be checked and scaled to find a leg diameter that will provide sufficient strength and thus find the tower mass in the process. The determination of the compressive force put on the leg can be considered conservative, as the assumption is made that all forces are taken up by the legs and the braces and horizontals do not affect this. While in reality they will also take up a part of the force, if the choice is made to work out this concept further the detailed design of the towers should be included.

J.1.4. Stability check vessel

In this subsection, the masses and sizes of all parts of the semi submersible vessel are used to perform an small angle intact stability check. Using this stability check, the vessel will be dimensioned, as the overall stability of the vessel is the critical factor that is assessed here. The approach to calculating the stability is:

- Set size vessel and components;
- Determine weight of all components;
- Determine draft of vessel using weight and size hull;
- Determine BM, KB, and KG in roll and pitch;
- Calculate intact small angle stability.

Only the intact small angle stability is assessed, as this already give a good first estimate of the initial stability of the vessel. After this has been performed, other stability cases must obviously be worked out to determine if the design is safe. However, that is outside the scope of this research, as only concept design is performed.

Stability of ships

The stability of ships is expressed using the well known stability formula given in Equation J.31[50].

$$GM_i = KB + BM_i - KG \tag{J.31}$$

In which GM_i is the distance between the meta centre of the ship and the Centre Of Gravity (COG) of the ship in direction i in meters. KB is the distance between the keel of the ship and the centre of buoyancy in meters, BM_i is the distance of the Centre Of Buoyancy (COB) to the meta centre of the ship in direction i in meters and KG is the distance of the meta centre to the keel of the vessel in meters. The design is non-symmetrical in roll and pitch, so directions the GM of these two have to be determined separately as BM will be different for both directions. Thus, GM_{xx} and GM_{yy} will be determined denoting, roll and pitch respectively.

Determination of KB vessel

The distance of the COB to the keel can be determined by investigating the volumetric centre of the underwater part of the vessel. The draft of a vessel can vary, so the draft must be determined first. Two cases can be defined, one for when the pontoon is not fully submerged and one fully submerged. This difference is due to the fact that once the pontoon is fully submerged, less underwater volume is added per meter draft, as the columns are smaller than the pontoons. The mass and volume of all components of the hull can be determined as described in the sections above. Using these, the draft of the vessel can be calculated for each of the cases stated. To determine the draft, first the total weight of the vessel is determined by Equation J.32.

$$w_t = w_{hull} + w_{deck} + w_{gc} + 2w_{sbox} + n_{tow}w_{tow} \tag{J.32}$$

In which m_t is the total mass of the vessel in tons. m_{hull}, m_{deck} , m_{gc} and m_{sbox} are the masses of the hull, deck, gantry crane and support boxes of the crane respectively in tons. n_{tow}, m_{tow} are the number and mass of the towers on top of the hull. Next, it has to be determined which of the two stated cases will occur due to the total weight of the vessel. This is determined using Archimedes's principle in Equation J.33, where x_{case} determines if the mass of the total displaced volume of the pontoons is larger than the total mass of the vessel. Thus, if $x_{case} \leq 0$ the total mass of the displaced water volume of the pontoons is larger than the total mass of the vessel and if $x_{case} > 0$ the pontoons are fully submerged. The draft is calculated for each case using Equation J.34 and the free board is determined using Equation J.35.

$$x_{case} = w_t - V_p \rho_w \tag{J.33}$$

$$T = \begin{cases} \frac{m_t}{\left(\frac{\partial V}{\partial H}\right)_p \rho_w} & \text{if } x_{case} \leq 0 \\ \frac{m_t - V_p \rho_w}{\left(\frac{\partial V}{\partial H}\right)_c \rho_w} + H_{pont} & \text{if } x_{case} > 0 \end{cases} \tag{J.34}$$

$$FB = H_{pont} + H_{col} + H_{deck} - T \tag{J.35}$$

In which x_{case} is the dimensionless variable describing the case in which the vessel operates, V_p is the total volume of the pontoons in [m3], ρ_w is the density of water in [kg/m3], T is the draft of the vessel in [m], $\left(\frac{\partial V}{\partial H}\right)_n$ is the underwater volume per meter draft of n, where n here denotes either the pontoons(p) or the columns(c), H_{pont}, H_{col} and H_{deck} are the height of the pontoon column and deck, as defined in Table J.1 and FB is the free board of the vessel in [m]. The underwater volume per meter draft is determined using Equation J.36.

$$\left(\frac{\partial V}{\partial H}\right)_n = n_n L_n W_n \tag{J.36}$$

In which $\left(\frac{\partial V}{\partial H}\right)_n$ is the added underwater volume per meter draft for either the pontoons(p) or the columns(c) in [m3/m], n_n is the number of pontoons or columns set to be 2 and 6 in this design. L_n and W_n are the length and width of one pontoon or column as defined in Table J.1. Using the draft and the distance of the COB to the keel, the KB is determined using Equation J.37. Where KB is half of the draft when the pontoons are not fully submerged and is the height of the volumetric centre of both pontoons and the columns if the draft is larger than the height of the pontoons.

$$KB = \begin{cases} \frac{T}{2} & \text{if } x_{case} \leq 0 \\ \frac{V_{uw,p}(0.5H_p) + V_{uw,c}(H_p + 0.5(T - H_p))}{V_{uw,p} + V_{uw,c}} & \text{if } x_{case} > 0 \end{cases} \tag{J.37}$$

In which KB is the vertical distance from keel to COB, $V_{uw,p}$ and $V_{uw,c}$ are the underwater volume of the pontoon and the columns respectively in the case that the pontoons are fully submerged in $[m3]$ and all other variables are the same as defined in Equation J.34. Determined using Equation J.38 and Equation J.39 respectively.

$$V_{uw,p} = \left(\frac{\partial V}{\partial H}\right)_p H_p \tag{J.38}$$

$$V_{uw,p} = \left(\frac{\partial V}{\partial H}\right)_c (T - H_p) \tag{J.39}$$

In which all variables are the same as defined in Equation J.34. The second part of the stability calculation, the BM of the vessel, is determined in the next section.

Determination of BM vessel

The BM of the vessel is the vertical distance of meta centre to the COB and is calculated using Equation J.40.

$$BM = \frac{I_i}{\nabla} \tag{J.40}$$

In which I_i is the area moment of inertia of the water plane in [m4] in either roll or pitch and ∇ is the volumetric displacement of the ship. The area moment of inertia also depends on the draft, as the pontoons and columns have a different water plane area. The area moment of inertia in roll I_{xx} and in pitch, I_{yy} and volumetric displacement for both cases, can be found in Equation J.41 up until

Equation J.43. Under the assumption that the columns and pontoons are perfectly square and always centred around the volumetric centre of the entire vessel.

$$I_{xx} = \begin{cases} \frac{n_p L_p W_p^3}{12} + n_p L_p W_p (0.5(W_{oa} - W_p))^2 & \text{if } x_{case} \leq 0 \\ \frac{n_c L_c W_c^3}{12} + n_c L_c W_c (0.5(W_{oa} - W_c))^2 & \text{if } x_{case} > 0 \end{cases} \tag{J.41}$$

$$I_{yy} = \begin{cases} \frac{n_p W_p L_p^3}{12} & \text{if } x_{case} \leq 0 \\ \frac{n_c W_c L_c^3}{12} + (n_c - 2) W_c L_c (0.5(L_{oa} - L_c))^2 & \text{if } x_{case} > 0 \end{cases} \tag{J.42}$$

$$\nabla = \begin{cases} T\left(\frac{\partial V}{\partial H}\right)_p & \text{if } x_{case} \leq 0 \\ V_p + (T - H_p)\left(\frac{\partial V}{\partial H}\right)_c & \text{if } x_{case} > 0 \end{cases} \tag{J.43}$$

In which I_{xx} and I_{yy} are the water plane area moment of inertia's of roll and pitch respectively in [m4]. n_p , L_p and W_p are the number, length and width in meters of the pontoons respectively, n_c , L_c and W_c are the number, length and width in meters of a column respectively. Where all other parameters are defined in Equation J.36 and Table J.1. The last part of the stability assessment is to determine the height of the COG above the keel, which will be done in the next subsection.

Determination of KG vessel

The KG of the vessel is the vertical distance of the COG of the entire vessel to the keel of the vessel. Opposed to the other 2 variables in the stability equation, the KG does not depend on the draft, but only on the mass and location of the COGs of individual parts and cargo. For this estimation, the COGs of all components are assumed to be in the volumetric centre of said component. The KG is determined using Equation J.44.

$$KG = \frac{\sum n^{i=1} m_i H_{cog,i}}{\sum n^{i=1} w_i} \tag{J.44}$$

In which n denotes a certain part, m_i is the mass of that certain part in tons and $H_{cog,i}$ is the height of the COG of said part above the keel in [m]. The height of the COG of all parts can be determined using Equation J.45 up until Equation J.50.

$$H_{cog,p} = 0.5H_p \tag{J.45}$$

$$H_{cog,c} = H_{cog,p} + 0.5H_c \tag{J.46}$$

$$H_{cog,d} = H_{cog,c} + 0.5H_d \tag{J.47}$$

$$H_{cog,t} = H_{cog,d} + 0.5H_t \tag{J.48}$$

$$H_{cog,crane} = H_{cog,d} + H_t + 0.5H_{gc} \tag{J.49}$$

$$H_{cog,cargo} = H_{cog,cargo,wl} + T \tag{J.50}$$

In which $H_{cog,p}$, $H_{cog,c}$, $H_{cog,d}$, $H_{cog,t}$ and $H_{cog,crane}$ are the heights of the COGs above the keel of the pontoon, columns, deck, towers, gantry crane plus support boxes and cargo respectively in meters. $H_{cog,cargo,wl}$ is the height of the COG of the cargo above the water line and all other parameters are defined in Equation J.34, Table J.1 and Table J.2. Using these equations and the defined masses of all components, the KG of the vessel can be determined.

With this, all components that make up the intact stability of the vessel can be determined and the design of the vessel can be performed. The idea is to end up with positive GMs in both the roll and pitch direction, by scaling the variables which are described in Table J.1, Table J.2 and Table J.3, the final concept design is presented in the next section.

J.1.5. Found size and weight

In this section, the final concept design of the semi-submersible vessel is presented. The only criteria used to determine the size of the concept design is the initial intact small angle stability, as this gives a good initial idea about the stability of the vessel. More design steps and optimization will be needed to end up with a final design, but as a first estimate, this is accepted. The approach taken to end up with a stable design is listed below and repeated up until a stable vessel design is reached.

- Initialize sizes of hull components;
- Initialize size of towers and determine amount;
- Determine size and weight of gantry crane & support boxes;
- Perform stability check on legs tower and alter dimensions if needed;
- Determine draft to see if pontoons are fully submerged;
- Determine stability of vessel using found draft;
- Check stability if GMs are all above 0, if not redefine sizes of hull, components, and repeat procedure.

All dimensions of all parts of the semi-submersible installation tower concept can be found in Table J.6 up until Table J.11.

Table J.6: Hull particulars of the semi submersible installation tower concept final concept design.

Parameter	Value	Parameter	Value	Parameter	Value
L_{pont}[m]	120	L_{col}[m]	25	n_{pont}[-]	2
W_{pont}[m]	25	W_{col}[m]	25	n_{col}[-]	6
H_{pont}[m]	5	H_{col}[m]	15	n_{deck}[-]	1
L_{deck}[m]	120	L_{moon}[m]	40	m_{pont}[ton]	4050
$W_{deck,oa}$[m]	100	W_{moon}[m]	40	m_{col}[ton]	2530
H_{deck}[m]	4.5			m_{deck}[ton]	13200

Table J.7: Main particulars of the deck box design.

Parameter	Value	Parameter	Value
L_{box}[m]	40	t_{plate}[m]	0.015
H_{box}[m]	4.5		
W_{box}[m]	5	I_{needed}[m4]	1.4
W_{stiff}[m]	0.06	I_{box}[m4]	1.9
$Hstiff$[m]	0.18	$w_{box,found}$[ton/m2]	1.3
n_{stiff}[-]	20	$w_{box,m,used}$[ton/m2]	1.5

Table J.8: Main particulars of the gantry crane and support boxes.

Parameter	Value	Parameter	Value	Parameter	Value
L_{gant}[m]	70	$L_{gant,us}$[m]	70	n_{gant}[-]	1
W_{gant}[m]	3	$L_{sbox,us}$[m]	60	n_{sbox}[-]	2
H_{gant}[m]	5			$w_{gc,m}$[ton/m]	10
$L_{sbox,oa}$[m]	160			m_{gc}[ton]	700
$W_{sbox,oa}$[m]	15			$w_{sbox,m}$[ton/m]	15
H_{sbox}[m]	3			m_{sbox}[ton]	2400

Table J.9: Main particulars gantry crane box structure design.

Parameter	Value	Parameter	Value
L_{box}[m]	70	t_{plate}[m]	0.02
H_{box}[m]	5		
W_{box}[m]	3	I_{needed}[m4]	2.95
W_{stiff}[m]	0.09	I_{box}[m4]	3.00
H_{stiff}[m]	0.27	$w_{box,found}$[ton/m]	8.7
n_{stiff}[-]	14	$w_{box,m,used}$[ton/m]	10

Table J.10: Main particulars support boxes of gantry crane, box structure design.

Parameter	Value	Parameter	Value
L_{box}[m]	60	t_{plate}[m]	0.02
H_{box}[m]	3		
W_{box}[m]	15	I_{needed}[m4]	1.8
W_{stiff}[m]	0.05	I_{box}[m4]	2.0
H_{stiff}[m]	0.15	$w_{box,found}$[ton/m]	13.5
n_{stiff}[-]	40	$w_{box,m,used}$[ton/m]	15

Table J.11: Main particulars tower structure on top of semi submersible vessel.

Parameter	Value	Parameter	Value
L_{bay}[m]	30	D_l[m]	1.15
W_{bay}[m]	30	D_h[m]	0.7
H_{bay}[m]	30	D_x[m]	0.76
H_{tow}[m]	270	a_c[-]	0.55
n_{tow}[-]	4	m_{tow}[ton]	2000

The found dimensions of all components of the semi submersible installation tower concept pass all checks and result in a stable vessel with main particulars described in Table J.12 .

Table J.12: Main particulars of semi submersible vessel.

Parameter	Value	Parameter	Value
L_{oa}[m]	120	∇[m3]	50000
W_{oa}[m]	100		
T[m]	10.5	GM_{xx}[m]	6.7
FB[m]	14.0	GM_{yy}[m]	13.9

J.2. Motion estimate using comparable vessel

This section has been removed, as it contained confidential information provided by the research's partner GustoMSC NOV.

J.3. Story board installation using the semi-submersible tower installation vessel

In this section, the story board of installing a wind turbine using the installation tower semi-submersible is presented. In Figure J.11 the installation of the tower in two pieces is depicted. In Figure J.12 The installation of the nacelle is depicted and in Figure J.13 the blade installation is shown.

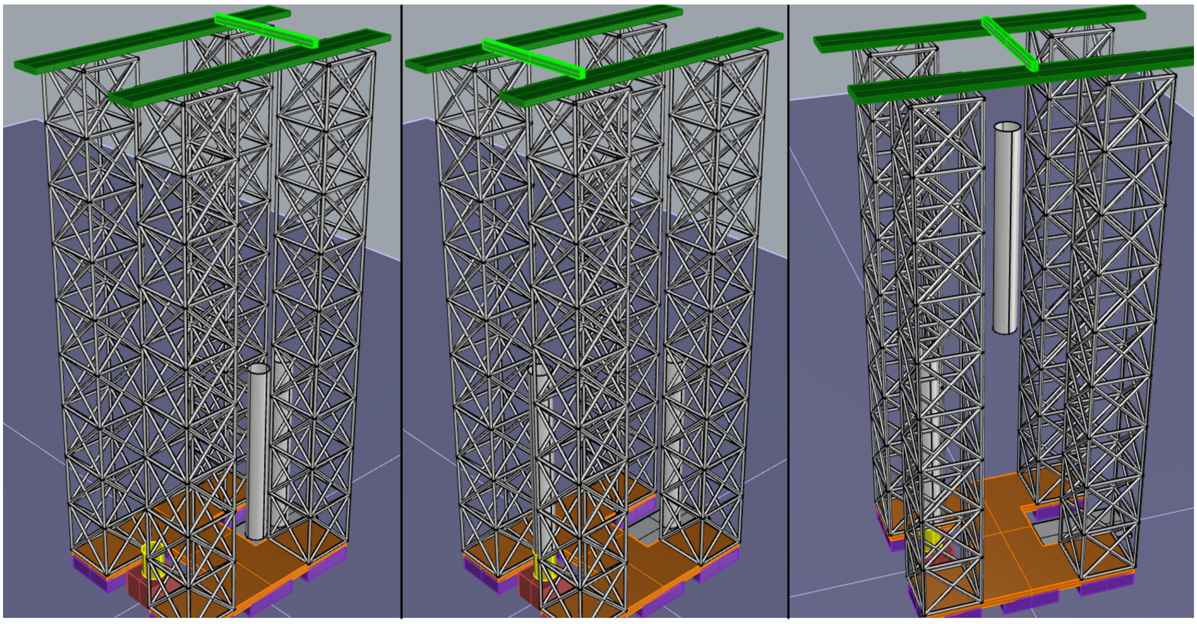

Figure J.11: Part one of story board installation using installation tower semi-submersible concept. Left, 2 tower pieces on barge at aft of vessel, Middle first tower piece installation, Right lifting of second tower piece.

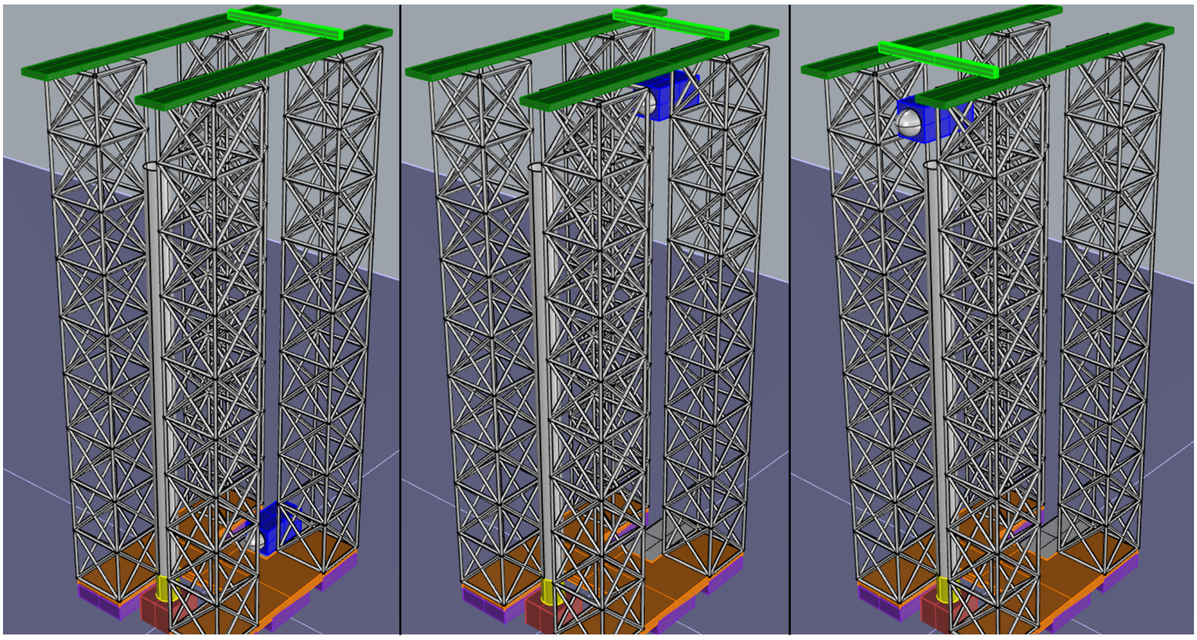

Figure J.12: Part two of story board installation using installation tower semi-submersible concept. Left, nacelle on barge at aft of vessel, Middle Lifting of nacelle, Right lifting and mating of nacelle.

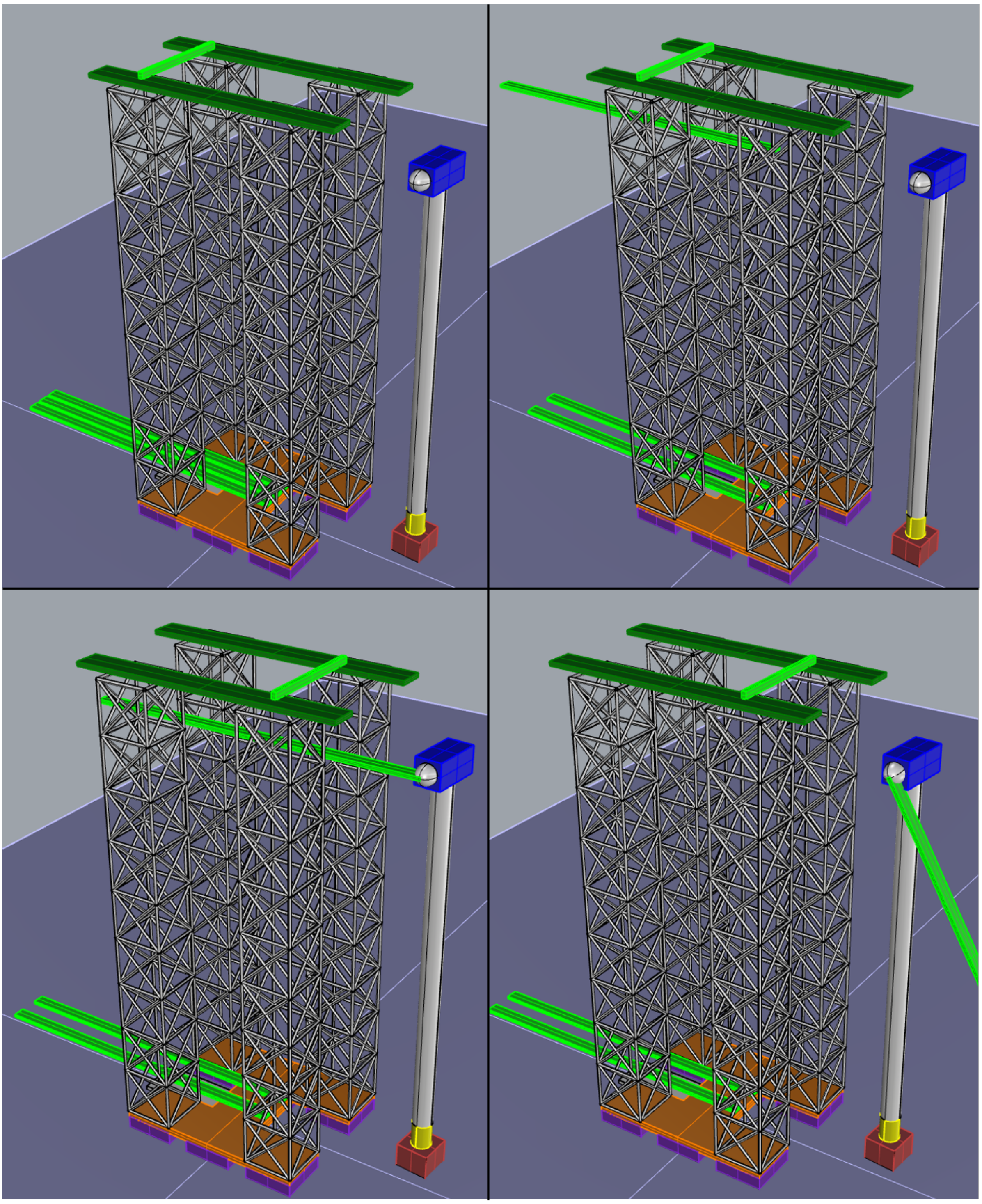

Figure J.13: Part three of story board installation using installation tower semi-submersible concept. Top-Left, Three blades on barge at aft of vessel. Top right, lifting of blade. Bottom left, Mating and bolting of blade. Bottom right, Rotation of first blade to make installation of next blade possible.

K

Appendix K: Cost-effectiveness of feasible concepts

In this appendix, the calculation and reasoning behind the cost-effectiveness calculations are presented. First the installation time estimation will be shown followed by the estimations of the costs of the vessels and equipment.

K.1. Installation time estimate

The estimation of the installation time is performed by investigating comparable operations and the time those take. Not a lot of information is publicly available, as installation time estimates are mostly confidential in house knowledge. The market is a highly competitive one, and small reductions in installation time can have a snowball effect on the eventual LCOE of a project. The reduction on time to first energy, in combination with lower rental costs of vessels and equipment, result in lower costs and earlier power generation. To get an idea of common installation times for certain action, some papers can be used[17] [1] [18]. To get a fair comparison, steps that have to be taken by all concepts, like the mooring of the vessel, will have the same duration for all concepts. The idea is to create “building blocks” of actions describing the time they take to complete, which are all based on the same underlying principles. The actions that are similar for all concepts are the connection procedures where bolting takes place and the mooring procedures. For the mooring procedures, 3 hours is assumed to be sufficient and the bolting of all parts is assumed to take 1 hour per bolting procedure. Here the similarities between the methods end, as different lifting devices are used by each of them. First, the elevator platform installation time will be estimated, followed by the lifting frame and the installation tower semi-submersible. Note that the estimations here are not based on in-depth analysis’s of each activity, but only serve as an estimation which can be used to relatively compare the methods.

K.1.1. Installation time elevator platform concept

For the estimation of the installation time of the elevator platform, first the lifting speeds of the platform and component lifting mechanism have to be estimated. The lifting speed of automatic winches is set to be 150 meters per hour, as high capacity automatic winches can reach up to 5 meters per minute[48]. They can in theory reach up to 300 meters per hour, but the assumption was made that 1 pair of pulleys is used to lower the needed capacity of the winches by half, the lifting speed is also halved.

High-powered strand jacks can reach lifting speeds up to 50 meters per hour, depending on the weight of the cargo and the power of the hydraulic power packs, as is claimed by producers[8]. Tower pieces and the nacelle are heavier than the blades it is assumed that, the stand-jacks can lift 40 meters per hour when lifting the nacelle or tower pieces and 50 meters per hour when lifting the blades. The latter because the maximum capacity of the strand jacks is way above the weight of the blades, so power can be used for speed as opposed to lifting capacity. If these lifting speeds cannot be reached then the use of strand jacks will not be feasible anymore, as installation times blow up immensely and automatic lifting winches must be used. The lifting speeds are summarized in Table K.1.

Table K.1: Lifting speeds of automatic winches platform and strand-jacks.

Lifting speeds components	Speed[m/h]
Elevator speed	150
Lifting speed heavy lift	40
Lifting speed blade	50

To now determine the time needed for the installation, two factors have to be defined. First, the initial tower length and the length of the tower pieces. The initial tower piece length is set to be 50 meters, reaching to around 80 meters above LAT when taking the height of the jacket and transition piece into account. This height is deemed reachable by floating vessels which have the needed lifting capacity, around 2000 tonnes, to lift the elevator platform. The following tower pieces are set to be around 32 meters so that the tower can be installed in 6 pieces. The goal is to get an estimate on installation time, so no details on the splitting of the tower are further provided and only approximate dimensions are used.

In Table K.2 the time estimates for all activities and sub activities of the installation using the elevator platform can be found. All estimated times for the actions have been rounded up to the next integer to end up with a conservative estimate and for simplicity. After the installation of the first tower piece(step 5) each following tower pieces takes 2 hours longer to install than the previous, as the lifting distance increases with 32 meters. Leading to approximately 1 hour extra lifting time and 1 hour longer lowering of the lifting mechanisms. Resulting in a final lifting time of 6 hours for the nacelle. The total time for the installation of the tower is noted separately to stress that tower installation is about half of the total installation time.

Three types of actions are not specifically stated, as they take place simultaneously with other actions. The first one is the skidding backwards of the lifting frame after the mating of components has taken place. This is performed simultaneously with the bolting of a component. The second action is the moving up of the lifting points, which takes place during the lowering of the lifting frame after a tower piece has been installed. The third one is the mooring of the feeder barges, which takes place during the lowering of the lifting frame as well. Actions as the detachment and attachment of lifting wires to the frames are also not stated specifically, but are included by rounding up the action times to the nearest integer.

Table K.2: Installation time estimate of all activities and sub-activities, Elevator platform.

Step	Activity	Time [h]
1	Mooring vessel	3
2	Initial tower piece installation	3
3	Attaching platform to tower	4
4	Elevate platform	1
5	Install tower piece	4
6	Install next tower piece	6
7	Install next tower piece	8
8	Install next tower piece	10
9	Install final tower piece	12
10	Install nacelle	14
11	Install blade	8
12	Rotate blade	1
13	Elevate platform	2
14	Install blade	8
15	Rotate blade	1
16	Elevate platform	2
16	Install blade	8
17	Detach platform	4
	Total	99
	Total tower	43

Platform (de)attachment

Sub activities	Time[h]
Lift & mate platform	2
Attach & tension lifting wires	2
Total	4

Tower piece installation(1st)

Sub activities	Time[h]
Lift tower piece	1
Skid tower piece	1
Bolt tower piece	1
Lower lifting mechanism	1
Total	4

Nacelle installation

Sub activities	Time[h]
Lift nacelle	6
Skid nacelle	1
Bolt nacelle	1
Lower lifting mechanism	6
Total	14

Blade installation

Sub activities	Time[h]
Lift blade	4
Mate & Bolt blade & detach lifting tool	2
Lower entire platform	2
Total	8

K.1.2. Installation time integrated Lifting frame concept

The installation using the integrated lifting frame is a less complicated procedure than the elevator platform and is thus a lot faster. That said, the lifting procedure of the frame assembly is estimated to take a lot longer than lower weight lifting operations, as 2 cranes have to be utilized at the same time. The estimation of the time needed for all activities can be found in Table K.3.

Table K.3: Installation time estimate of all activities, Lifting frame concept.

Step	Activity	Time[h]
1	Mooring	3
2	Move turbine to lifting location on vessel / mooring of barge	3
3	Install turbine with frame	5
4	Detach & storage frame	2
	Total	13

K.1.3. Installation time Semi-submersible installation tower concept

The last concept for which the installation time will be estimated is the semi-submersible installation tower. The estimation is based on the same found information as the other concepts and can be found in Table K.4.

Table K.4: Installation time estimate of all activities, installation tower concept.

Step	Activity	Time[h]
1	Mooring semi sub	3
2	Mooring feeder barge	2
3	Tower piece installation	3
4	Tower piece installation	4
5	Nacelle	4
6	Relocate for blade installation	3
7	Install blade	3
8	Rotate blade	1
9	Install blade 2	3
10	Rotate blades	1
11	Install blade 3	3
	Total	30

K.2. Cost estimation of vessels and equipment

In this section, the cost estimation which has been performed for all the concepts is discussed. The cost estimation is based on 2 rules of thumb which have been provided by the researches partner GustoMSC NOV. The first of which is that the cost of equipment can be estimated by multiplying the steel weight of a structure by 15-20, depending on the complexity of the equipment. If the equipment has loads of hydraulics and combinations of systems the upper bound is to be taken, and if the equipment is mostly just steel with some smaller additional systems then the lower bound is to be taken.

The second rule of thumb is that the day-rate of vessels and equipment can be determined by dividing the cost by 1000. Suggesting that a total of 1000 active days are needed to reimburse the development and construction costs of the equipment and vessels, not taking into account operational and maintenance costs. This is wholly dependent on the assumed lifetime a vessel or piece of equipment has, if it is designed to only function for a few years this number has to be lowered. To make the compression fair, the same rule of thumb is used for all vessels and equipment in concepts.

For the determination of the costs of the vessels used by the lifting frame concept and the installation tower concept, a different approach is used. The estimated construction and development costs of the Sleipnir are used as a baseline, as the lifting frame concept is based on this vessel. To determine the costs of the semi-submersible installation, tower concept Equation K.1 is used.

$$C_{ITSS} = \frac{\partial C_{SS}}{\partial \nabla} \nabla_{ITSS} \tag{K.1}$$

In which C_{ITSS} is the cost of the installation tower semi submersible in Euro and & ∇_{ITSS} is the displacements of the installation tower semi-submersible in [m3] and $\frac{\partial C_{SS}}{\partial \nabla}$ is the cost of semi submersibles per cubic meter displacement. The Sleipnir has an approximate displacement of, 250000 [m3] and the costs of the Sleipnir are approximately 1 billion[46], resulting in a cost per cubic meter displacement of 4000 euros. This is rounded up to 5000 euros per cubic meter displacement for the installation tower semi submersible, to account for the development of the novel gantry crane. The total displacement of the concept is approximately 50000 [m3]. The vessel costs for each concept can be found in Table K.5.

Table K.5: Approximate vessel costs for all concepts.

Concept	**Vessel**	**Costs**[€]	**Day rate**$[\frac{k€}{day}]$
Elevator platform	HLV	n/a	150-300
	Feeder barges	n/a	6-10
Lifting frame	Sleipnir	$10E^9$	1000
Installation tower	Semi-submersible	$250E^6$	250
	Feeder barges	n/a	6-10

The estimated equipment costs can be found in Table K.6. Note that the equipment costs for the installation tower semi submersible are included into the vessel's costs, as the gantry crane is part of the vessel.

Table K.6: Estimated equipment costs for all concepts.

Concept	**Equipment**	**Weight[ton]**	$\frac{€}{kg}$	**Costs**[€]	**Day rate** $[\frac{k€}{day}]$
Elevator Platform	Platform	1500	20	$30E^6$	30
Lifting frame	Frame	4000	15	$60E^6$	60
Installation tower	n.a.	Included in the vessel costs			