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Master Thesis

Optimal offshore installation of floating wind turbines, using Mixed-Integer Linear Programming with AMPL

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Abstract

The demand for renewable energy in Europe is increasing. The largest potential is offshore wind energy where future wind farms consist of floating wind turbines. The wind is stronger at sea and the floating wind turbines must increase in size to generate more energy. These factors make the operation process challenging and costly without strategic planning.

This work aims to identify the logistic planning of transporting and installing floating offshore wind turbines to an offshore wind farm in Sørlige Nordsjø 1 in the North Sea. A Mixed-Integer Linear Programming (MILP) model is developed to optimize the total costs of operating from five different assembly sites on the west coast of Norway, where different vessel strategies are analyzed together with the installation process. Assembly sites are areas where mobilization and docking of vessels can take place and storage of partly assembled turbines. Vessel strategies are different methods of transportation from these sites to the final wind farm site. More on both concepts will be discussed in greater detail later. Weather windows and weather constraints are considered in the model to determine when operations can take place. Data for cost, vessel strategies, and operation time concerning the weather are implemented in AMPL, where several tests of the model are performed to determine the optimality of these. The main test consists of a different number of installed wind turbines in a time horizon of 30 days. This time horizon refers to the complete lifetime of our project, from parts or partly assembled wind turbines at assembly sites to the final finished wind farm at sea. Two additional tests where several assembly sites must be in use are also implemented. The main test and the two additional tests are analyzed in relation to each other, and total costs are compared between them. The results are valuable for future projects for the development of floating offshore wind farms, from a technical and economical view. We found that operating from one assembly site with transportation of partly assembled wind turbines is most optimal when parameters such as cost, weather, and time are considered.

Norway needs more investors for future development of floating wind farms, but to realize this, the total costs of projects must decrease. In this work, our model could help accelerate future project developments through better logistical strategic planning to save large costs.

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Benjamin Afzal
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Table of content

Abstract 2

Acknowledgments 3

Table of content 4

List of figures 6

List of tables 7

Abbreviations 8

1 Introduction 9

1.1 Outline of thesis 10

1.2 About offshore wind energy 10

1.3 Research questions 11

1.4 Objectives and motivation 12

2 Theory about floating offshore wind 13

2.1 Floating offshore wind in Europe and Norway 13

2.1.1 The floating offshore wind turbine 13

3 Literature review 16

3.1 Supply chain of offshore wind 16

3.1.1 Strategies for transportation 17

3.1.2 Weather implications 18

3.1.3 Exclusion zones 19

3.1.4 Sites of distribution 19

3.2 Business value factors 21

3.2.1 Cost trajectory of offshore wind and our contribution 21

3.2.2 LCOE ranges in the North Sea 22

3.2.3 Cost of floating elements using spar buoy structure 23

3.2.4 Other economic factors 24

3.2.4.1 Mass production 24

3.2.4.2 Economic effects 24

4 Methodology 25

4.1 Method 25

4.2 Data 25

4.2.1 Energy consumption and capacities of floating offshore wind 25

4.2.2 Fixed cost of operating from the assembly sites 26

4.2.3 Time charter and mobilization cost 27

4.2.4 Components 28

4.2.5 Location and weather data 29
4.2.5.1 Wind farm sites 29
4.2.5.2 Distance from assembly sites to the wind farm site 30
4.2.5.3 Transit time from the assembly sites 30
4.2.6 Loading and installation 31
4.2.7 Cycles 33
4.2.8 Weather restrictions for vessels and weather windows 33
4.2.9 Expected weather windows in 30 days 35
5 Constructing the MILP model 36
5.1 Input data assumptions 37
5.1.1 Vessel input 37
5.1.2 Days in the model 37
5.2 Sets 37
5.3 Parameters 38
5.4 Decision and continuous variables 39
5.5 Objective function and constraints 41
6 Testing the MILP model 45
6.1 Computation and tools 45
6.2 Main test (Test 1, Test 2, Test 3) and results 46
6.2.1 Test 1: 5 turbines and 30 days 46
6.2.2 Test 2: 9 turbines and 30 days 47
6.2.3 Test 3: 15 turbines and 30 days 47
6.2.4 Discussion of the main test 48
6.3 Using several assembly sites 49
6.3.1 3 assembly sites used 49
6.3.2 5 assembly sites used 51
6.4 Discussing several assembly sites-tests and comparing to the baseline (Test 3) 52
7 Limitations of the model, data & future work 52
7.1 Limitations of the model 53
7.1.1 Simplification of the model 53
7.2 Limitations on data 54
7.3 Future work 55
8 Conclusion 55
References 58
Appendix 62

List of figures

Figure 1: A growth in capacity ('Power production at sea re-emerges as Energiwende cornerstone', 2018) 14
Figure 2: Completely installed Spar-Buoy Foundation by Jochem Tacx ('Floating wind structures and mooring types', 2019) 15
Figure 3: Illustration of the assembly sites and the offshore wind farm in Sørlige Nordsjø 1 (by author) 17
Figure 5: Overview of sites. ('Delivery models for offshore wind', 2021) 21
Figure 6: Definition of LCOE ('Wind farm costs') 22
Figure 4: Relative LCOE for offshore wind in the North Seas. ('Our energy, our future. How offshore wind will help Europe go carbon-neutral', 2019) 23
Figure 7: Zones considered for offshore wind power in Western Norway (by author). 29
Figure 8: Max wind speed m/s ('Yr.no', 2022) 35

List of tables

Table 1: Fixed costs of operating from the assembly sites 26

Table 2: T/C and mobilization cost for vessel types. 28

Table 3: T/C and mobilization cost for vessel strategies. 28

Table 4: Data for IEA 15 MW turbine 29

Table 5: Distance from the assembly sites to the Sørlige Nordsjø 1 wind farm site 30

Table 6: Transit time for the vessel strategies 31

Table 7: Operation time for the vessel strategies 32

Table 8: Maximum cycles of 15 turbines for the vessel strategies 33

Table 9: Weather restrictions for the operation 33

Table 10: Wind and wave restrictions for the vessel strategies 35

Table 11: Number of weather windows for each vessel strategy. 36

Table 12: Sets and upper bound parameters for the model. 38

Table 13: Cost, weather windows, and time parameters for the model. 39

Table 14: Binary decision variables for the model. 40

Table 15: Continuous variables for the model. 41

Table 16: Result from Test 1 47

Table 17: Results from Test 2 47

Table 18: Cost and assembly site for Test 3 48

Table 19: Results of vessels strategies and duration of working days 48

Table 20: Cost and the 3 assembly sites used. 50

Table 21: Results for vessel strategies and duration of working days 50

Table 22: Cost and the 5 assembly sites used. 51

Table 23: Results for vessel strategies and duration of working days 51

Abbreviations

MILP	Mixed-Integer Linear Programming
LCOE	Levelized Cost of Energy
MW	Mega-Watt
GW	Giga-Watt
AMEP	Able Marine Energy Park
IEA	International Energy Agency
AMPL	A Mathematical Programming Language
NVE	Norwegian Water Resources and Energy Directorate
WTG	Wind Turbine Generator
T/C	Time Charter

1 Introduction

The rise of wind power is enormous worldwide. It is one of the fastest-growing renewable energy technologies. Global installed wind-generation capacity onshore and offshore has increased by a factor of around 75 in the past two decades, going from 7.5GW in 1997 to almost 565GW by 2018, according to IRENA's latest data. There are already several wind farms in existence, but the best locations for generating wind power are sometimes remote ones. Offshore wind power offers a large potential. (Irena, 2021)

A floating wind turbine is a wind turbine mounted on a floating structure that allows the turbine to generate power in water depths where fixed-foundation turbines are not feasible. (Thomas, T., 2014). The turbines are commonly constructed in relatively high-water depths (20 to 50 meters) and far distances (30 to 100 kilometers) from the coast. This implies large financial, technical, and logistical efforts, and profitability is difficult to achieve. (Lange et al., 2012).

The transportation of the multi-megawatt wind turbines on land and sea can be a technical and organizational challenge, which also must be considered from an economic point of view. The challenge arises when the weight and dimensions of the components increases. Several logistical concepts for transport and assembly have been developed, which will be discussed later.

The installation part is one of the biggest challenges due to the risk of bad weather, and all the known techniques can only be performed in a calm sea. Important criteria are wave height and wind speed. If these criteria are not satisfied, it can result in large financial setbacks. (Lange et al., 2012).

1.1Outline of thesis

Our thesis is structured into 8 chapters. In chapter 1, we introduce offshore wind energy and relevant concepts surrounding its technology and function and highlight our research questions and our motivation for the thesis. In Chapter 2, we introduce relevant theory about floating offshore wind and the structure of the floating wind turbine. In chapter 3, we introduce relevant theories and related work in supply chain and optimization that we will use later in our model. Chapter 4 is the methodology of how we gathered the needed data and explains the parameters in our model. In chapter 5, we explain the build-up of the Mixed-Integer Linear Programming (MILP) model in a detailed walk-through. Here, we minimize the total cost of operating and transporting wind turbine elements from different assembly sites to an offshore wind farm. Further in chapter 6, we are doing different tests on the model, where we have the main test, sending a different number of wind turbines to the wind farm in a fixed time horizon. Next, we force the model to choose several assembly sites that must be used during the operation. Chapter 7 talks about the limitations of the model with its data, and future work. Lastly, in chapter 8, we conclude our work and findings.

1.2 About offshore wind energy

According to experts from industry and analysis, the global offshore wind power capacity is set to increase 15-fold over the next two decades, turning it into a trillion-dollar business. People tend to ask if wind power is profitable and sustainable since the technology supplies only 0.3% of today’s global power generation. The answer is that the potential in the future is near limitless, according to experts. (Birol, 2019).

Offshore wind farms are growing fast. The possibilities to build larger wind turbines at sea are enormous compared to on land. In addition, it would not be sustainable in the long-term to place large wind turbines in the nature. “Bigger is better”, is a phrase that fits very well with offshore wind. The reason behind this is that bigger blades and turbines produce more electrical energy. (Irena, 2021).

1.3 Research questions

In general, the processes of transporting and installing floating offshore wind turbines are expensive. It is a time-consuming process where every step in the supply chain needs to be carefully planned and calculated. Offshore wind is relatively new, and the project costs are high. To reach the goal of 30GW installed capacity in Norway within 2040 in Sørlige Nordsjø 2 (Undheim, 2022), the total costs must be reduced for new investors to be willing to enter the market.

We have defined five potential assembly sites on the west coast of Norway and an offshore wind farm in Sørlige Nordsjø 1 in the North Sea. We consider three vessel strategies that loads the wind turbine elements in different ways. The plan is to transport wind turbine elements/partly assembled turbines to the offshore wind farm, where these elements/partly assembled turbines will be completely installed. The following research questions have been addressed in the thesis, where (1) is the main question, and (2) and (3) are follow-up questions from (1):

(1) *"What is the total cost of installing five, nine, and fifteen wind turbines within a fixed time horizon?"*
(2) *"Which assembly sites should be used to minimize the total costs?"*
(3) *"Which of the vessel strategies are most optimal to use based on the given time horizon and objective to minimize the total costs?"*

Our wish was to formulate the research questions that are realistic and in line with what actors in the industry today find relevant. The decision to pursue this research area and these exact research questions are therefore inspired by our contact with the company Elevon. Elevon is specializing in project logistics surrounding the offsore wind industry. They introduced us to the concepts of offshore wind, and the logistic difficulties and problems that exist in the field today.

Our insights from the discussions with Elevon can be summarized by these bullet points:

- Different methods for transportation of wind turbines at sea can be used, however certain methods can only be implemented from areas on the coast that meets requirements of water depth and docking size.
- Transporting large wind turbines and floating elements require specialized vessels that might be expensive and have limited availability.
- Wind turbines are becoming larger to increase efficiency, which can force changes in transportation and installation methods at sea.
- Weather is an important factor in planning of a project, and can cause unforeseen delays and costs.

1.4 Objectives and motivation

This Master Thesis aims to give a perspective on the possibilities in the floating offshore wind industry. With our strong interest in optimization and supply chain analytics, the topic of floating offshore wind energy strongly motivates us due to its great future in generating energy. We will strive to minimize the total costs of operating from different assembly sites and transporting elements of wind turbines to an offshore wind farm, where these elements will be assembled and installed.

Offshore wind farms have been in existence since 1991, with the Danish project Windbyesis being the first of its kind. Europe now has an installed offshore wind capacity of about 22.000 MW. Offshore wind still accounts for a low percentage of Europe's power generation, but the potential to utilize offshore wind to a much higher degree is there. According to Equinor, about 80% of the world's offshore wind resource potential is in waters deeper than 60 meters. This means that the relatively new (Equinor being the first in 2017) floating wind turbine technology could account for 80% of the offshore wind resources in the future. (Equinor, 2020)

Some relevant research articles on inventory-routing-optimization, installation-optimization, and transportation analysis have been reviewed, such as Skår (2021), Uraz (2011), and Dauzère-Pérès, Nordli, Olstad, Haugen, Koester, Myrstad, and Reistad (2007).

With our analysis, we hope to show the potential of floating wind power economically and technically in terms of its optimal distribution of wind turbines. Our work differentiates itself from previous work through adding a cost minimizing aspect to floating offshore wind modelling. We want to be as transparent and unbiased as possible in presenting the effectiveness of floating wind turbines for insights and comparisons to other energy sources and optimization methods.

2 Theory about floating offshore wind

In this chapter we give a brief overview of floating offshore wind in Europe and Norway. Additionally, we introduce the structure and the capacity of a floating wind turbine.

2.1 Floating offshore wind in Europe and Norway

As mentioned earlier, the potential of offshore wind energy is huge. Future wind developments will likely be for the most offshore, and the multi-megawatt wind turbines will be floating. That means the demand will increase for onshore locations for storage and assembly of wind turbines. Different suppliers and actors in the offshore wind industry needs to cooperate to fulfill this demand.

The potential in Norway for floating offshore wind is tremendous. The knowledge from the oil industry and the port infrastructure makes Norway a potential leader in the wind industry market. The latest report from WindEurope states that the Norwegian Government will hold its first offshore wind auction with a capacity of 1.5GW in the second half of 2022. So far, the Norwegian wind industry is not yet satisfied with the terms, stating that political conditions are slowing down the development and future projects. (WindEurope, 2022).

2.1.1 The floating offshore wind turbine

The output of energy from the turbines is proportional to the dimensions of the rotor and the amount of wind speed. In theory, when wind speed doubles, potential wind power increases by a factor of eight. (Irena, 2021). As we can see from Figure 1, wind turbine capacity has increased over time. The steepness of the graph will continue in the next decades, as the offshore wind market is set to grow by 13% per year. The global wind capacity is estimated to increase 15-fold from 2018 to 2040. Annual offshore wind capacity additions are set to double over the next five years and increase almost five-fold by 2030 to over 20GW per year. (Birol, 2019).

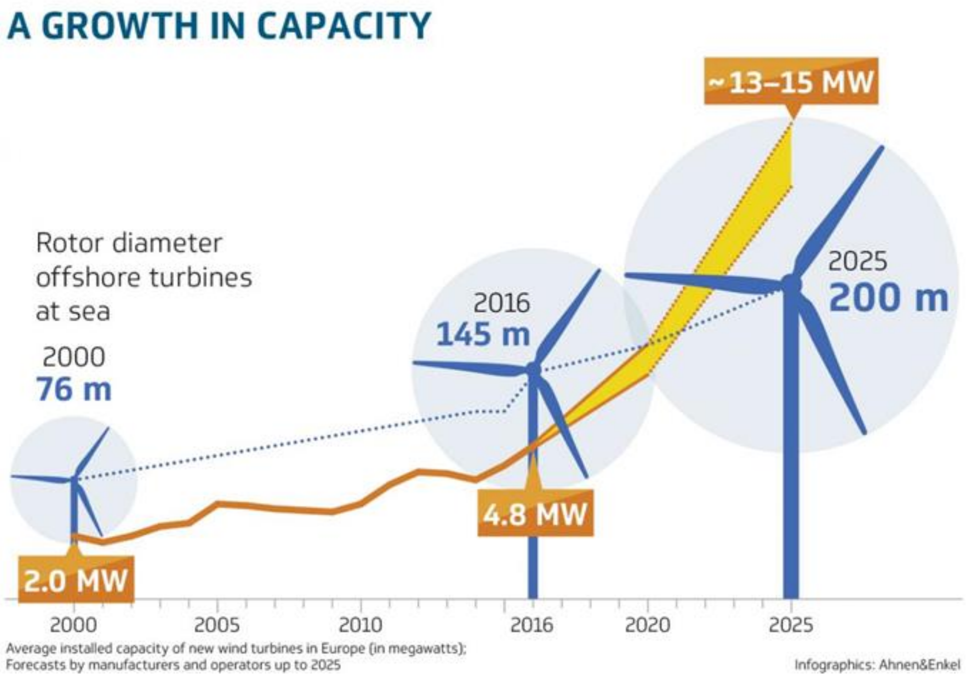

Figure 1: A growth in capacity ('Power production at sea re-emerges as Energiwende cornerstone', 2018)

In recent years, floating wind turbines have opened larger possibilities for offshore wind. With this technology, wind farms can be built far out in the sea where the water is deeper, and the wind is stronger. Most of the wind turbines that are already installed on the sea are anchored with the foundation to the seabed. That means the depth cannot be more than 50 meters.

The floating wind turbine type we will focus on is the spar buoy foundation. This is the type that is used and will be used in the future for offshore wind. The spar buoy foundation is a cylinder with a lower waterplane area, filled with heavy material to keep the center of gravity below the center of buoyancy. The mooring lines are connected to the suction caisson to provide additional tension. (Tacx, 2019). The spar buoy foundations will keep the wind turbines stable through big waves, which makes the rotation of the blades more effective and maximizes the production of energy.

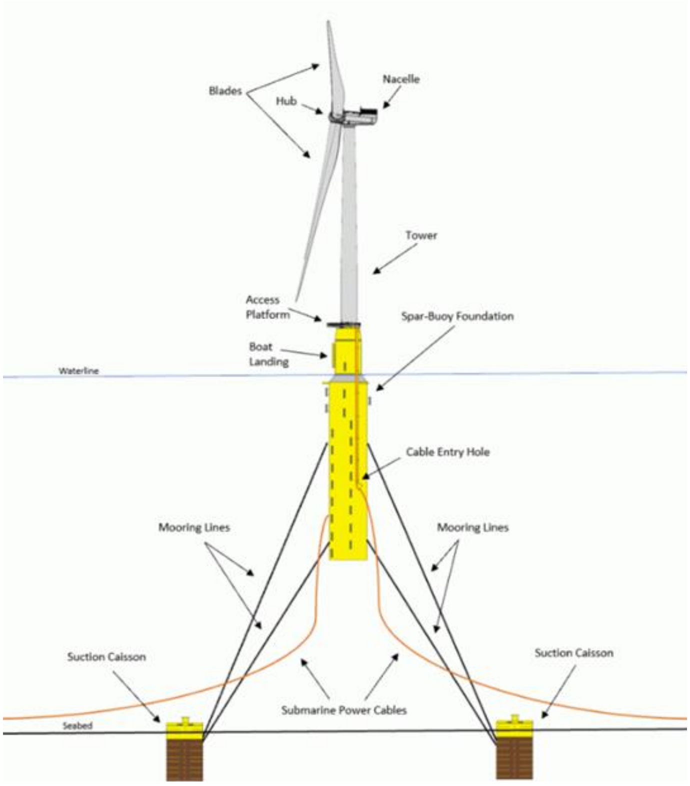

Figure 2: Completely installed Spar-Buoy Foundation by Jochem Tacx ('Floating wind structures and mooring types', 2019)

Equinor's project Hywind Scotland is the world's first offshore floating wind park located 29 kilometers outside Scotland. The farm has five 6 MW floating spar buoy foundation turbines with a total capacity of 30 MW. In a twelve months period to March 2020, the floating wind park set a new record in the UK, with an average capacity factor of 57.1%, which is quite good and proves that offshore wind energy works. In the two first years of operations, the farm achieved an average capacity of 54%, which is large in comparison to an offshore wind average in the UK of around 40%. The capacity factor is the ratio of actual energy output over a period, to the maximum possible output. A higher capacity factor means a higher value. (Equinor, 2021)

3 Literature review

We are not the first to investigate the technology and cost for floating offshore wind turbines. The literature review will give a proper understanding of the work that has already been published. We will elaborate on topics that fit our research on reducing costs in the floating offshore wind industry. First, we map out the supply chain of offshore wind projects, and specifically the strategies used to transport and install wind turbines. Then, we look at the business value side of things, with focus on relevant costs for our analysis.

3.1 Supply chain of offshore wind

In an offshore wind project, the parts necessary for wind turbines are first developed by international production specialists of wind turbine parts, an example being Siemens in Germany (Equinor, 2020). Parts are shipped to assembly sites with large enough docks to handle and store these, which could be Stavanger in Norway for instance.

From there, parts are either distributed to designated locations where some of the assembly is happening or stored in locations that can handle installation and distribution of all the parts altogether.

Wind turbines are then installed either partly, semi-finished, or in some cases finished at docks by the land at assembly locations. Distribution happens by vessels from assembly sites to the wind farm location (Uraz, 2011). We will go through the specific methods for distribution in our next subchapter.

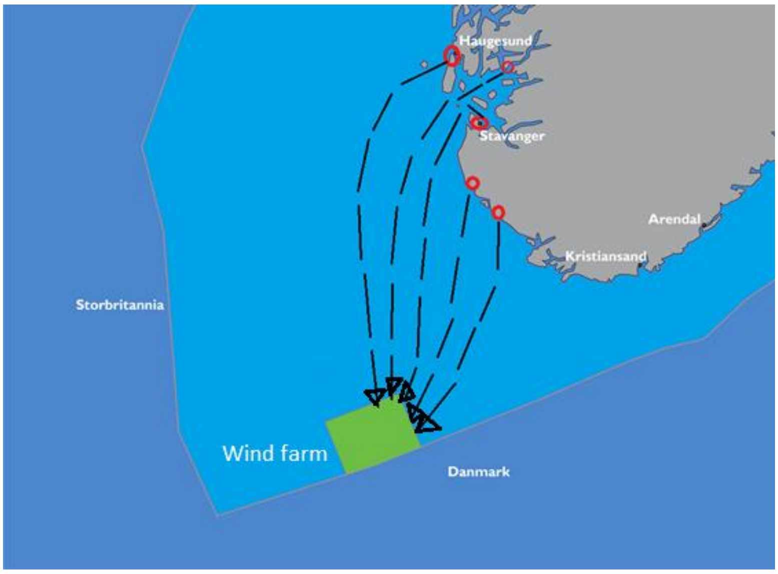

Figure 3: Illustration of the assembly sites and the offshore wind farm in Sørlige Nordsjø 1 (by author)

At the offshore wind farm location, the final installation happens by a jack-up vessel, that carries parts/or semi-finished wind turbines onto its foundation (spar buoy) by crane.

The part of interest in our thesis is the distribution and installation part from the assembly sites to the offshore wind farm. This means that we take it as given that parts required for the wind turbines are in place at each assembly site, as illustrated in the areas in red in Figure 3 above.

3.1.1 Strategies for transportation

We will define three vessel strategies. These are methods in how wind turbines are loaded on the vessels, distributed, and installed at the offshore windfarm. Each vessel strategy will require a given vessel or a given set of vessels to perform the strategy. The strategies are all known and tested in real-life projects. Our inspiration for the strategies is taken from the work of Emre Uraz, where he presented different vessel strategies in his Master thesis in 2011. (Uraz, 2011).

The first strategy is the Feed. A large cargo barge vessel “feeding” a jack-up installation vessel with components at the offshore wind farm. The Feed strategy can carry up to a maximum of 8 turbines in seven different components: one tower, three blades, one nacelle, and the spar buoy (floating) foundation in two parts. This strategy allows for a lot of turbines to be carried at once. However, it also requires a designated assembly vessel at the wind farm site, and two tugboats to drag a large cargo vessel.

The next strategy is the 2-blade formation. This is a self-propelled installation vessel that can carry a maximum of 3 wind turbines in one trip. The turbine is half-installed by two blades and one nacelle and then loaded on the vessel in a “bunny-ear” configuration. The 3 fully assembled floating foundations are placed on both sides and one in the back of the vessel. At the offshore wind farm, the spar buoy foundation will be lowered into the water first. After this is done, the rest of the tower will be assembled onto the spar buoy foundation where the last blade will be installed at the end. Since this is a self-propelled installation vessel, both transportation and installations are done by this vessel.

The last strategy is the Unmounted. This is also a self-propelled installation vessel that can carry a maximum of 6 wind turbines in one trip. The strategy transport towers that are assembled, and the top part are loaded in 4 separate elements (3 blades and 1 nacelle). Belonging these 6 wind turbines, 6 spar buoy foundations can be carried. The foundations are standing vertically, loaded in two parts to not exceed the height limitations. A total of 12 foundation parts will be carried along with the other elements.

3.1.2 Weather implications

Operations on the open sea can be challenging if the weather is tough. Lifting operations and maintenance need to be scheduled concerning the weather, and the exact weather forecast must be considered.

Weather is a factor that can affect the cost of a wind farm project greatly. Lacal-Arántegui et al. states that weather is the most crucial factor for the activities of loading, transportation to wind farm site (and back), and installation (Lacal-Arántegui et al., 2018). This means that all the cost elements related to the transportation and installation at the wind farm site will potentially change by a large margin in the presence of “bad weather”. This highlights the importance of accurate weather forecasting not just as a technical issue, but also as an economical one too.

Better weather window estimates lead to better results in the accessibility predictions and reduce the operational cost and make the offshore wind industry more profitable. Each vessel has different wave and wind handling capabilities. To ensure that operations are taken place when it should, and by the strategy that fits best, the accurate weather forecast needs to be in place and in consideration for a model. In the data part of our thesis, we will go through the exact limitations of each vessel in terms of wind speeds and wave heights, and ultimately how each vessel strategy is affected by the limitations.

3.1.3 Exclusion zones

According to WindEurope, 85% of the total capacity by 2050 will be developed in the North Seas, based on supply chain efficiencies and good wind resources. Some areas in the North Seas are protected from project development because of fishing, military activities, shipping, and environmental reasons. These are called "exclusion zones". Due to this, it is not possible to build offshore wind farms in at least 60% of the North Seas. (Walsh, 2019).

3.1.4 Sites of distribution

Assembly sites in Norway can be divided and described by physical characteristics as done by Industri Norge (Industri Norge, 2020), which indicates what kind of wind power-related activities may be conducted there. The characteristics they are evaluated by are:

- Vessel accessibility as indicated by air draft (bridges, power lines hindering wind turbine generator (WTG)- movement), horizontal clearance (narrow fjords, aquaculture), and vessel draft (draft by quayside and sea depth in access route between quay and open sea).

- Available areas at the waterfront, taking elevation into account. Also evaluated the ability to work 24/7 at the waterfront

- Quay lengths and ability to accommodate various types of vessels. Quayside strength – enabling heavy loads and use of cranes.

- Storage areas
- Access from shore, most often by access and distance to national roads ‘riksvei’ and distance to airports for transfer of specialized personnel
- Core utilities available, such as gas, power, and water
- Load-bearing capacity at the assembly site

Another important factor to account for in the strategic location choices is the development of wind power technology. The trend is that wind turbines become larger, and equipment to deal with the turbines needs increased capacities. It is therefore not given that an assembly site today is sufficient in 5 or 10 years from now.

Western Norway is the area that will host the Hywind Tampen, a floating offshore wind farm that will have a capacity of 88MW. According to Industri Norge, this area has several sites suitable for floating offshore wind assembly. Furthermore, it is an area located strategically for the European offshore wind industry in the future, and an area with knowledge from the oil industry (Industri Norge, 2020). Therefore, we decided to use this as our modeling area.

Florø, Lutelandet, Gulen, Bergen, Stord, Karmsund, Stavanger, Jelsa, and Eigersund are the locations that could be utilized for offshore wind in some sense. Following are the characteristics of these locations indicating what use case they fit:

PORT	Logistics	Assembly (shallow)	Assembly (deep)	Construction (shallow)	Construction (deep)	O&M SOV	O&M CTV
Bergen - Ågotnes & Hanøytangen	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Eigersund	Yes	No	No	No	No	Yes	Yes
Florø Fjordbase	Yes	Yes	No	Yes	No	Yes	Yes
Haugaland Næringspark	Yes	Yes	No	Yes	No	Yes	Yes
Jelsa	Yes	Yes	Yes	Yes	Yes	No	No
Karmsund havn	Yes	No	No	Yes	No	Yes	Yes
Lutelandet Offshore	Yes	Yes	No	Yes	No	Yes	Yes
Sandnes	Yes	No	No	No	No	Yes	Yes
Stavanger - Dusavika	No	No	No	No	No	Yes	Yes
Stavanger - Forsand	Yes	No	No	Yes	No	Yes	Yes
Stavanger - Mekjarvik	Yes	Yes	No	No	No	Yes	Yes
Stavanger - Risavika	Yes	No	No	No	No	Yes	Yes
Stord Base	Yes	Yes	No	Yes	No	Yes	Yes

Figure 4: Overview of sites. ('Delivery models for offshore wind', 2021)

We have chosen the assembly sites to be Bergen, Stavanger - Forsand, Stord, Eigersund, and Jelsa for our analysis.

3.2 Business value factors

It is important that initiated projects are economically beneficial, with properly estimated costs, and value generated. Furthermore, it is important to look at what the drivers of costs are, what scale of projects does to overall costs, and whether the projects carry over value elsewhere.

3.2.1 Cost trajectory of offshore wind and our contribution

In 2020, Equinor started building Hywind Tampen. Comparing this project to the previous Equinor project, Hywind Scotland from a cost trajectory perspective, Equinor has estimated that the cost for Hywind Tampen will drop around 40 % compared to Hywind Scotland. The reasons are higher knowledge from the industry, new technology, use of larger turbines, and concrete fundaments. (Equinor, 2020).

A common practice when observing the costs of offshore wind farms is by looking at the Levelized Cost of Energy (LCOE). This is the revenue required to earn a rate of return on investment equal to the discount rate over the life of the wind farm. In other words, it is the lifetime average cost.

The technical definition of LCOE is:

$$LCOE = \frac{\sum_{t=-5}^{n+1} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=-5}^{n+1} \frac{E_t}{(1+r)^t}}$$

Where:

I_t : Investment expenditure in year *t*
M_t : Operation, maintenance and service expenditure in year *t*
E_t : Net energy generation in year *t*
r : Discount rate (or WACC), and
n : Lifetime of project in years

Figure 5: Definition of LCOE ('Wind farm costs')

Where basically the sum of the investment, operation, maintenance, and service costs discounted for t years, over all years from year -5 to the end of the project lifetime are in the numerator. The energy generated, also discounted for t years, over all years from -5 to the end of the project lifetime is in the denominator. We then end up with an estimate of the cost of the energy produced and the goal should be to minimize the LCOE.

According to Catapult, the largest cost drivers are the service/maintenance field, the installation of cables, including foundation, substations, etc., and the parts for the wind turbine. (Catapult, 2021).

Our analysis will focus solely on transportation and installation cost, which will impact the financial decision through the investment expenditure and the expense of operation in the LCOE calculation. Which is to be used in addition to purchasing models, and models for optimizing maintenance and power generation in a final investment decision. More specifically, we will minimize cost of the time charter for the vessels for the period, mobilization cost of vessels, and operating cost from each assembly site. These ultimately add up to an estimated transportation and installation cost of a wind farm project.

3.2.2 LCOE ranges in the North Sea

Figure 6 illustrates the LCOE ranges from very low to high, where very low is below 50€/MWh in 2030 and high is above 80€/MWh in 2030. It assumes 15MW-turbines and a connection with the nearest onshore point. The areas with high LCOE are located far from the shore where the supply chain process is longer, and the weather window prediction is harder to estimate. This naturally increases the costs.

Norway has a larger potential to establish more sites in the southern waters. These areas have a lower LCOE range and are closer to the demand centers in Europe. Half of Norway's potential is to export the electricity but establishing sites in the northern waters would require expensive grid investments.

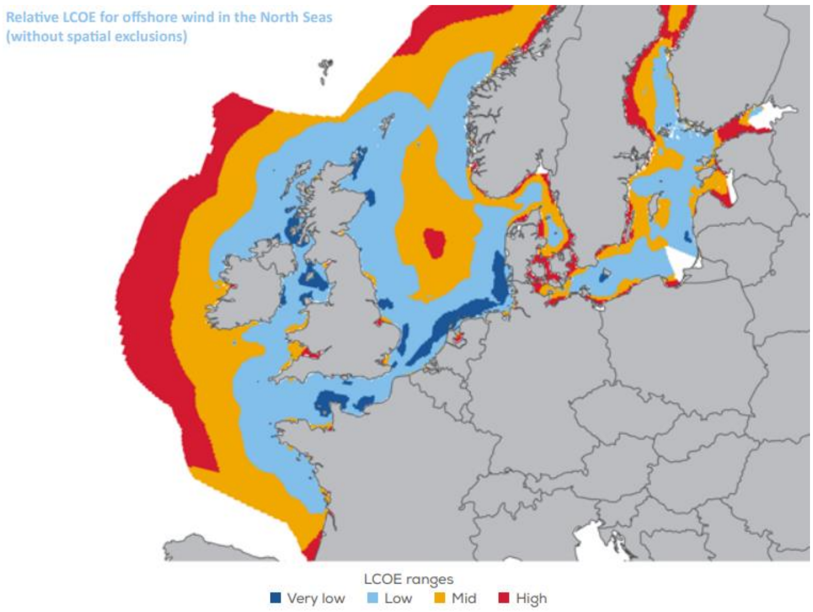

Figure 6: Relative LCOE for offshore wind in the North Seas. ('Our energy, our future. How offshore wind will help Europe go carbon-neutral', 2019)

3.2.3 Cost of floating elements using spar buoy structure

Constructing a wind turbine and the technology behind this has been done for many years. Offshore wind turbines are not a new technology but putting a floating foundation together with a wind turbine is rather new. A floating fundament is already well known in the oil and gas industry, but the combination can be costly since it has not yet been mass-produced. In addition, the development can improve from a technological perspective, and this can also bring down the costs.

3.2.4 Other economic factors

When doing projects of high complexity, and with a lot of factors to consider, one can expect economic impacts beyond the cost of investment and the revenue generated. For instance, can the technology used, and experience gathered in one project be a steppingstone for similar projects in the future, like we have seen with Equinor’s projects Hywind Scotland and Hywind Tampen.

3.2.4.1 Mass production

One crucial factor to lower costs and increase profitability of floating offshore wind is mass production. It is estimated by 2050 that offshore wind costs will be down somewhere between 37% and 49%. This decline of cost will be due to competition boosting efficiency, larger scale of turbines and larger scale of projects, according to experts. (Wiser et al., 2021).

Furthermore, we have seen trial and errors, and test farm sites from companies like Equinor, which lead to better understanding of the technology and industry. These trials and tests will allow for more, and bigger projects in the future.

3.2.4.2 Economic effects

There are several after-effects of wind farm technology and development. In a press release by the Government of Norway, the prime minister talks about the offshore wind initiative and its consequences (Regjeringen, 2022). Among the highlighted benefits are affordable electricity for people and businesses. The opportunity to be more self-sufficient in energy, and to have the option to export larger amounts of energy for profits is a great benefit for companies, and the Norwegian economy.

Furthermore, offshore wind energy can act as a springboard for existing labor to transition to new work, which in turn increases employment and takes advantage of existing competency. A lot is said about the downfall of the oil and gas industry, especially with environmental focus gaining stronger grounds. A transition of labor and competency from the oil and gas sector to the offshore wind sector could decrease the risk of taking massive economical hits from a declining industry that Norway is heavily invested in.

4 Methodology

4.1 Method

Having the literature review in mind we have determined what questions are most relevant to our problem, as defined in the introduction. To answer these questions, we need to construct a Mixed-Integer Linear Programming (MILP) model that can optimize the decision variables and total costs. We will present the MILP model in chapter 5. The inputs of our optimization model were based on realistic parameters for vessel data, wind turbine component data, and weather/location data. The plan was to receive the data from Elevon, but the company was founded in 2020, which means they do not possess any historical data for us to use. Acquiring the data was done by researching already written reports and theses, as well as contacting people with knowledge of the segment. It was of importance to fact-check and exercise source criticism, as wrongful assumptions could lead to critical errors in the analysis. We, therefore, use sources that we consider highly respectable and professional.

4.2 Data

4.2.1 Energy consumption and capacities of floating offshore wind

When it comes to the assumptions of how much energy production is needed in future years, and specifically how much of the energy should come from offshore wind, we use IEA's offshore wind outlook from 2019 as an indication. (Birol, 2019). It provides data for growth rates for the offshore wind market from 2010 to 2018, as well as future aims and growth potential from 2019 until 2040. The report states among other things that EU offshore wind capacity will multiply by 4 over the next 2 decades. With these numbers in mind, we made assumptions about how Norwegian offshore wind capacity would fall in line with global and European growth potentials.

To further elaborate on our decision for growth rates in the Norwegian market we looked at sources from Norwegian articles and official statements from the government as well. With the current plan being that the Norwegian Government will hold its first offshore wind auction with a capacity of 1.5GW in the second half of 2022, we have a sensible scenario of energy production from offshore wind in Norway soon. The Master thesis from Martin Skår (Skår, 2021) suggests that a 0.5GW, 3GW, and 7GW installed wind capacity by 2030, 2040, and 2050 is a low scenario, and a 1GW, 7GW, and 19GW installed wind capacity is a high scenario. These numbers are based on DNV's energy transition report. (DNV, 2020).

The scenarios for installed wind capacities suggest higher growth rates in Norway than what IEA suggests for Europe as a whole. IEA's suggestion for growth in the EU market is from 19GW in 2018 to 127GW in 2040 or a multiplication of about 6.5, whereas Skår's article suggests a growth for Norway of 19GW in 30 years. (Skår, 2021). We do however see the slow growth rate from 2020 to 2040, and the higher expected growth rate from 2040 to 2050. The is due to the market is yet not fully established in Norway.

4.2.2 Fixed cost of operating from the assembly sites

The fixed costs of operating from the assembly sites are presented in Table 1 below. There is a lack of information on how much this cost is from the industry. We have been in contact with several actors in the industry where these fixed costs have been presented. Due to confidentiality, we wish to keep these actors anonymous.

Assembly sites	Fixed cost
Bergen	$1,000,000
Stord	$2,000,000
Eigersund	$3,000,000
Jelsa	$1,500,000
Stavanger – Forsand	$1,800,000

Table 1: Fixed costs of operating from the assembly sites

4.2.3 Time charter and mobilization cost

Total prices for time charter rental and mobilization of jack-up installation vessels vary with season and the time horizon of the mobilization. However, for a summertime rental and a short mobilization period, it is estimated to be $215,000 per day in daily time charter (T/C) cost and $1,190,000 for mobilization. (Dalgic et al. 2015). For a jack-up installation vessel with a larger crane weight capacity, the estimated cost is $356,000. (Dalgic et al., 2013).

The daily T/C rates for a jack-up installation vessel that can handle heavy lifts are estimated to be around $166,000. (Dalgic et al. 2013). Mobilization happens similarly to jack-up installation vessels, only docking at the sites is not required. We assume a cut cost of $100.000 in mobilization. Heavy lift cargo barge vessels are assumed to be around $8.000 per day in 2022. (Toepfer Transport, 2022).

Tugboat rates vary from $290 to about $850 according to Hans Schramm & Co. (Hans Schramm, 2017). Using this estimate we can assume a daily rate of $5,250 for each tugboat.

There is not much information about mobilization costs of cargo barge vessels and tugboats in a given period. However, the Interreg North Sea region estimates mobilization costs of $181,400 for cargo barge vessels and no cost for tugboats (North Sea Region, 2022).

Vessel costs	Jack-up installation vessel	Jack-up for cargo barge	Cargo barge vessel	Tugboat (towing)
T/C	$215,000 per day. (heavy) $356,000 per day (heavy + large crane cap.).	$166,000 per day	$8,000 per day	$5,250 per day
Mobilization	$1,190,000 (for a 2-month period)	$1,090,000 (for a 2-month period)	$215,000 (one-time-pay)	N/A

Table 2: T/C and mobilization cost for vessel types.

If we convert from cost per vessel to cost per strategy, we can estimate the mobilization cost for a given vessel strategy. The 2-blade formation and the Unmounted strategies only require the jack-up installation vessel for installation, but the 2-blade formation strategy use one with a larger crane capacity due to heavier elements being carried at once. The Feeding strategy requires one jack-up, one cargo barge vessel, and two tugboats. The estimated prices will be as follows:

Vessel strategy	Feed	2-blade formation	Unmounted
T/C	$184,000 per day	$356,000 per day	$215,000 per day
Mobilization	$1,305,000 per day	$1,190,000 per day	$1,190,000 per day

Table 3: T/C and mobilization cost for vessel strategies.

4.2.4 Components

The wind turbines we will use for the study are conceptual turbines following the properties of the IEA 15 MW turbine. (Gaertner et al., 2020). The blades have a rotor diameter of 240 meters and a total weight of 65 metric tons. The tower has a hub height of 150 meters, leaving a 30-meter clearance for the blades and the water. The tower mass is 860 tons, and the rotor-nacelle assembly mass is the sum of three blades and the tower mass. We had to estimate the spar buoy depth from Fylling et al. where they have material assumptions for a 5MW turbine. We used this information to estimate the depth of the spar buoy of a 15MW turbine by also looking at the hub height. A feasible spar buoy depth is 170 meters. We also assume that the heavy ballast section (bottom) of the spar buoy from Figure 2 in Chapter 3 is not filled with heavy material. This process happens at the offshore wind farm.

Following is a table of relevant parameters for the different parts:

Parameter	Unit	IEA 15 MW turbine
Rotor diameter	Meter	240
Hub height	Meter	150
Spar buoy depth	Meter	170
Blade mass	Ton	65
Tower mass	Ton	860
Rotor-nacelle assembly mass	Ton	1070

Table 4: Data for IEA 15 MW turbine

4.2.5 Location and weather data

4.2.5.1 Wind farm sites

According to the Norwegian Water Resources and Energy Directorate (NVE), the category A locations for offshore wind in Norway are Utsira Nord, Sørlige Nordsjø 1, and Sørlige Nordsjø 2. Category A means the areas which are best suited economically and have the least conflicts. (NVE, 2013). Here is a representation of the most important areas, according to NVE:

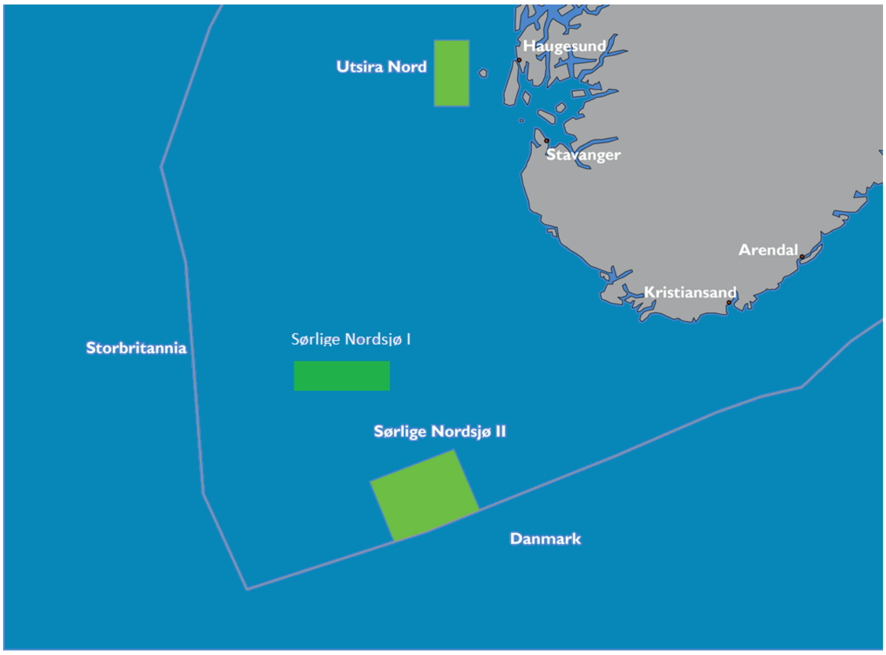

Figure 7: Zones considered for offshore wind power in Western Norway (by author).

These zones are feasible for grid connection and are technically and economically feasible for offshore wind projects. Utsira Nord is located about 22 km off the coast, west of Haugesund. The zone covers an area of 1010 km^2 with an average wind speed of 10.2 m/s. Sørlige Nordsjø 1 is located approximately 150 km from the coast. This zone covers an area of 1375 km^2 with an average wind speed of 10.5 m/s. Sørlige Nordsjø 2 is located close to Sørlige Nordsjø 1 and 140 km from the coast with the same average wind speed. Sørlige Nordsjø 2 has a total area of 2591 km^2.

We have chosen Sørlige Nordsjø 1 to be our wind farm destination in our model. This area fits our model best since our assembly sites are on the Southwest coast of Norway.

4.2.5.2 Distance from assembly sites to the wind farm site

Eigersund is located approximately in the closest straight line from Sørlige Nordsjø 1 to the coast with 150 km (NVE, 2013). From there we estimated the distance using google maps distance measure from our given point at sea.

We then ended up with the distances as follows:

Assembly sites	Distance from the assembly site to the wind farm site
Eigersund	150 km
Stavanger - Forsand	200 km
Jelsa	227 km
Stord	270 km
Bergen	320 km

Table 5: Distance from the assembly sites to the Sørlige Nordsjø 1 wind farm site

4.2.5.3 Transit time from the assembly sites

With the distances, transit time in hours can be calculated using the speed of each vessel. Then a simple transformation of hours to days, with one day being a full 24 hours, we get our transit time as days. With this, we assume that offshore workers follow shifts that ensures that someone is at work at every hour of the day. As an example, from Eigersund to the wind farm site using the Feed strategy is calculated as 150 km / 7.4 km/h (4 knots) = 20.27 = 0.84 days.

Following are the transit times from each assembly site with each vessel strategy:

Vessel strategy	Eigersund	Stavanger – Forsand	Jelsa	Stord	Bergen
Feed	0.84	1.11	1.28	1.52	1.80
2-blade formation	0.34	0.45	0.56	0.61	0.72
Unmounted	0.34	0.45	0.56	0.61	0.72

Table 6: Transit time for the vessel strategies

4.2.6 Loading and installation

According to Lacal-Arántegui's paper (Lacal-Arántegui et al., 2018) about offshore wind installation, the process of turbines and foundations could roughly be divided into the processes:

1) Adaption of the vessel for the job
2) Assembly site loading of turbines/foundations
3) Transport to wind farm site
4) Installation
5) Vessel returns to assembly site
6) Removal of installation equipment

Given that vessels could be obtained from anywhere in the world, and with different schedules and availabilities, we do not model for the process of adapting each vessel other than the mobilization cost that we already stated. We, therefore, assume that mobilization is already done at a fixed cost. The same thing goes for the removal of installation equipment. This is a part of the demobilization of the project, and we do not consider the time measures of this action.

The remaining processes could be divided into four time-parameters, namely loading time, transit time, installation time, and jack-up time. Where transit time is the time to travel from one assembled turbine to the next. Vessel transportation to the wind farm site and vessel returning to assembly site is treated with the same time parameters in the model, see section 4.2.5.3.

When it comes to the estimations of loading and installation times based on historical data, there are difficulties and variations in terms of previous projects being different in size, location, weather, technical difficulties, etc. This results in some assumptions in defining the time parameters. However, Lacal-Arántegui's paper states that Hywind Scotland used about 1.87 days per turbine of complete installation time. If we use this as a baseline for total loading and installation time using the Feed strategy, we can assume that the Unmounted strategy uses the same time approximately for loading and installation but has a higher transit speed (10 knots compared to 4), and a slightly faster jack-up speed due to parts not being fed to another jack-up. The 2-blade formation strategy has a faster loading and installation time as fewer parts need to be loaded and installed, and the jack-up and speed are the same as the Unmounted strategy because the vessel is the same.

We assume about a 1/3 faster installation and loading for the 2-blade formation strategy than the others, a turbine transit time reflecting the speed of each vessel, and a jack-up time twice as fast for the non-feeding strategies. The time in working days needed for loading and installation processes are approximated as follows:

Operation in working days	**Feed**	**2-blade formation**	**Unmounted**
Loading time	0.75	0.50	0.75
Installation time	1.0	0.67	1.0
Turbine transit time	0.020	0.008	0.008
Jack-up time	0.10	0.050	0.050

Table 7: Operation time for the vessel strategies

4.2.7 Cycles

Vessel strategies can be used multiple times and on multiple assembly sites within the time horizon. The maximum number of cycles per strategy is defined as how many cycles would be needed to set up, transport, and install all turbines with this strategy alone. For safety reasons, we add room for a bit more cycles in case the batches are smaller than maximum capacity in some of the cycles. For 15 turbines installed, the 2-blade formation strategy would need 5 maximum capacity cycles to complete, the Feed strategy would need 2 maximum capacity cycles to complete, and the Unmounted strategy would need 3 maximum cycles to complete.

We then get maximum cycles for 15 turbines completed as follows:

Vessel strategy	Feed	2-blade formation	Unmounted
Maximum cycles of 15 turbines	2	5	3

Table 8: Maximum cycles of 15 turbines for the vessel strategies

4.2.8 Weather restrictions for vessels and weather windows

There are certain weather restrictions for the different vessels, where each has a different limit on doing operations when it comes to wind speed and wave height. Through the work of Emre Uraz (Uraz, 2011), we have estimated updated weather restrictions ranges for the vessel operations:

Operation	Wind speed (m/s)	Wave height (m)
Transit	22 – 27	2.0 – 3.5
Setup	17 – 22	2.0 – 3.0
Installation	10 – 17	4.0 – 6.5

Table 9: Weather restrictions for the operation

Updates are done assuming there are some improvements in the vessel and jack-up/jack-down carrying abilities over the last decade.

Considering these vessel restrictions, weather windows are produced to fit our model as time intervals. Only when wind speed and wave height are within these limits, we can fit the data in our model. Furthermore, we assign a specific restriction of wind speed (m/s) and wave height (m) for each vessel strategy. The assumptions made in assigning wind speed restrictions are quite simple, both the Feed and the Unmounted setup, transit and install turbines in parts, whereas the 2-blade formation strategy carries almost fully assembled turbines in each step of the process. Therefore, the Feed and the Unmounted strategy get assigned the upper bound of the wind speeds, and the 2-blade formation strategy gets assigned to the lower bound.

Assigning wave height restrictions to each strategy we look at the vessels in use. The 2-blade formation and Unmounted strategy use the same type of self-propelled installation vessels that can handle the upper bound of the wave height in all steps of the process. The Feed strategy uses smaller tugboats in the transit and setup parts of the process, but a larger jack-up vessel for installation. The feed strategy gets assigned the lower bound for transit and setup wave height, and the upper bound for installation.

Wind and wave restrictions	Feed	2-blade formation	Unmounted
Wind transit	27 m/s	22 m/s	27 m/s
Wind setup	22 m/s	17 m/s	22 m/s
Wind installation	17 m/s	10 m/s	22 m/s
Wave transit	2 m	3.5 m	3.5 m
Wave setup	2 m	3 m	3 m

Wave installation	6.5 m	6.5 m	6.5 m

Table 10: Wind and wave restrictions for the vessel strategies

4.2.9 Expected weather windows in 30 days

Wind data is taken from Eigerøya, which is the closest weather point to Nordsjøen, while at the same time representing weather close to our assembly sites on the west coast. (yr.no, 2021).

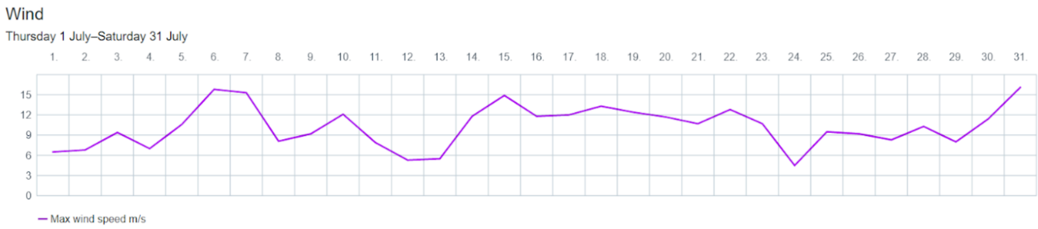

Figure 8: Max wind speed m/s ('Yr.no', 2022)

The maximum wind speed in July 2021 is 16.1 m/s, with 6 days having an average wind speed higher than 10 m/s, and no days having wind speeds over 17 m/s.

It is quite difficult to model for correct weather, as nothing is certain, and nothing can be predicted with 100% accuracy. Assumptions based on July 2021 however tell us that there will be no days where setup, transit, or installation in the Feed strategy and the Unmounted strategy is impossible due to wind. Around 6 days, the installation of the 2-blade formation strategy is impossible due to wind. Considering planners would have to work around the days where installation is impossible, it is a safe choice to assume about 3 weather windows where all processes can be accomplished with the 2-blade formation strategy in 30 days. For example, days 0-6, 9-15, and 18-24. The days in between each period are then the down days due to wind.

For wave heights, Kystvarslingssenteret shows historical wave heights in given areas around the Norwegian coast. For a point near the coastline of Eigersund, which we use as a reference, the wave heights for July 2021 were above 2 meters five days in the period and above 3 meters one day. This leaves us with 5 days where transit and setup for the Feed strategy are impossible and 1 day where setup is impossible for the 2-blade formation and Unmounted strategies. (Kystvarslingssenteret, 2022).

Furthermore, we establish weather windows for setup, transit, and installation of each vessel strategy. We assume that with time restrictions to finish every step of the process and get ready for a new cycle in mind, the maximum number of weather windows for a vessel strategy is 5. This is the maximum number of cycles any strategy can accomplish. The weather window for a setup, transit, and installation will be a time of 6 days with no delays. This would result in exactly 5 windows ending in 30 days.

The number of weather windows for each process and each vessel strategy are as follows:

Number of weather windows	Feed	2-blade formation	Unmounted
Transit	3	5	5
Setup	3	4	4
Installation	5	3	5

Table 11: Number of weather windows for each vessel strategy.

5 Constructing the MILP model

The model is inspired by the work of Dauzère-Pérès et al. where they optimized the supply chain for delivering calcium carbonate slurry to European paper manufacturers for Omya Hustadmarmor. (Dauzère-Pérès et al., 2007). The model is a distribution-optimization model that later was developed to a complex inventory-routing problem. We will only focus on the distribution-optimization part of their model. We have adjusted their mathematical model to have a "one-way" distribution to a single target: the offshore wind farm, as opposed to a distribution between tank farms in their case. Instead of a fleet of vessels, we are using the vessel strategies as mentioned. This means we eliminate the need to add loading capacity on the vessels in our model, because we already have a fixed number of elements each strategy can carry.

5.1 Input data assumptions

5.1.1 Vessel input

The model does not take vessels as input, but rather the vessel strategies – which could be combinations of different vessels in use at the same time. Furthermore, the calculations of time charter and mobilization cost are calculated based on what each complete set of vessels in use would cost.

5.1.2 Days in the model

The European Wind Energy Association states that a smaller wind farm can easily be built in less than two months. Furthermore, they state that a larger wind farm can be built in less than six months. (WindEuropeAssociation, 2022). To both be in line with realistic time horizons and test the model capacity we choose 30 days as a time horizon. We consider a full project duration from start to finish to be longer than the stages of the supply chain that we model for. This time horizon will be used throughout our different tests.

5.2 Sets

The model consists of two sets. V is about the different vessel strategies we already have introduced in Chapter 4: Feed, 2-blade formation, and Unmounted. K is the different assembly sites we have chosen. These assembly sites are Bergen, Stavanger - Forsand, Stord, Jelsa, and Eigersund as already introduced.

The two upper bound parameters need to be introduced now for better understanding when presenting the variables. U_v consists of a maximum number of cycles, where one cycle is the process from when a vessel strategy is leaving the assembly sites until it returns to the same assembly site. Y_v is how many turbines that can be installed per cycle with a given vessel strategy.

Category:	**Set/parameter:**	**Description:**

Sets:	V	Set of different strategies for vessels
	K	Set of assembly sites
Upper bound parameters:	U_v	Maximum number of cycles with vessel strategy $v \in V$
	Y_v	Maximum number of turbines installed per cycle with vessel strategy $v \in V$

Table 12: Sets and upper bound parameters for the model.

5.3 Parameters

We have defined three cost parameters. The first one is the cost of operating from an assembly site, and the two others are costs related to the vessel strategies. One for time chartering in the project period, and one for mobilization of the vessel strategies. The aim is to minimize these costs in the objective function. Next are the weather windows parameters for transiting, positioning, and installation which define the number of weather windows in working days and when these can start and must end. These numbers are calculated with respect to the weather forecasts. The parameters WW_v^I, $start_{vn}^I$, and end_{vn}^I are only for complete turbine installations, not for each component. The time parameters are carefully estimated from the installation process with the different vessel strategies. Lastly, all turbines are defined by one parameter R, which means the total number of wind turbines to be installed.

Category:	**Parameter:**	**Unit:**	**Description:**
Cost	$cost_k^K$	$	Fixed cost operating from assembly site $k \in K$
	$cost_v^{TC}$	$	Time charter cost for each working day for vessel strategy $v \in V$
	$cost_v^M$	$	Mobilization cost to start the chartering of vessel strategy $v \in V$
	WW_v^T	$\mathbb{R}_+$	Number of weather windows for transiting with vessel strategy $v \in V$
	WW_v^P	$\mathbb{R}_+$	Number of weather windows for positioning with vessel strategy $v \in V$

Weather windows	WW_v^I	$\mathbb{R}_+$	Number of weather windows for installing turbine with vessel strategy v ∈ V
	$start_{vn}^I$	$\mathbb{R}_+$	Start of weather window n ∈ {1, …, WW_v^I} for installing with vessel strategy v ∈ V
	end_{vn}^I	$\mathbb{R}_+$	End of weather window n ∈ {1, …, WW_v^I} for installing with vessel strategy v ∈ V
	$start_{vn}^P$	$\mathbb{R}_+$	Start of weather window n ∈ {1, …, WW_v^P} for positioning with vessel strategy v ∈ V
	end_{vn}^P	$\mathbb{R}_+$	End of weather window n ∈ {1, …, WW_v^P} for positioning with vessel strategy v ∈ V
	$start_{vn}^T$	$\mathbb{R}_+$	Start of weather window n ∈ {1, …, WW_v^T} for transiting with vessel strategy v ∈ V
	end_{vn}^T	$\mathbb{R}_+$	End of weather window n ∈ {1, …, WW_v^T} for transiting with vessel strategy v ∈ V
Time	$time_v^L$	$\mathbb{R}_+$	Time to load one turbine with vessel strategy v ∈ V
	$time_v^I$	$\mathbb{R}_+$	Time it takes to install a turbine with vessel strategy v ∈ V
	$time_v^T$:	$\mathbb{R}_+$	Time for turbine transits with vessel strategy v ∈ V
	$time_v^{PJ}$	$\mathbb{R}_+$	Time to jack-up/jack-down with vessel strategy v ∈ V
	$time_{kv}^K$	$\mathbb{R}_+$	Time for assembly site transits from assembly site k ∈ K with vessel strategy v ∈ V
Turbines	R	$\mathbb{R}_+$	Total number of turbines

Table 13: Cost, weather windows, and time parameters for the model.

5.4 Decision and continuous variables

We have defined eight binary decision variables: The first four variables in Table 13 addresses the different assembly sites and vessel strategies in the model. The last four variables include an additional index *n*: weather windows. These last four only operate after the vessel strategies have left the assembly sites, since they do not include the index *k*. Note that in the variable NT_{vuyn}, the last turbine will be accounted for when the vessel returns to the assembly site.

Category:	**Variable:**	**Description:**

Vessel strategies and assembly sites	W_k	1: If assembly site k ∈ K is in use. 0: Otherwise.
	X_{kvu}	1: If vessel strategy v ∈ V is going from assembly site k ∈ K on u ∈ {1, …, U_v} or more cycles. 0: Otherwise.
	T_v	1: If vessel strategy v ∈ V is in use. 0: Otherwise.
	Z_{vuy}	1: If vessel strategy v ∈ V is going u ∈ {1, …, U_v} or more cycles installing y ∈ {1, …, Y_v} or more turbines. 0: Otherwise.
Weather windows	NI_{vuyn}	1: If turbine y ∈ {1, …, Y_v} on cycle u ∈ {1, …, U_v} is installed with vessel strategy v ∈ V in weather window n ∈ {1, …, WW_v^I}. 0: Otherwise.
	$NP1_{vuyn}$	1: If vessel strategy v ∈ V enter position at turbine y ∈ {1, …, Y_v} on cycle u ∈ {1, …, U_v} in weather window n ∈ {1, …, WW_v^P}. 0: Otherwise
	$NP2_{vuyn}$	1: If vessel strategy v ∈ V exit position at turbine y ∈ {1, …, Y_v} on cycle u ∈ {1, …, U_v} in weather window n ∈ {1, …, WW_v^P}. 0: Otherwise
	NT_{vuyn}	1: If vessel strategy v ∈ V transit to turbine y ∈ {1, …, Y_v + 1} on cycle u ∈ {1, …, U_v} in weather window n ∈ {1, …, WW_v^T}. 0: Otherwise

Table 14: Binary decision variables for the model.

Seven continuous time variables are defined. These are closely connected with the binary decision variables of weather windows and measure the time in working days (24h). These must be greater or equal than zero.

Category:	Variable:	Description:
Time	q_{vu}	Time when cycle u ∈ {1, …, U_v} start with vessel strategy v ∈ V
	e_{vu}	Time when u ∈ {0, …, U_v} ends with vessel strategy v ∈ V
	s_{vuy}	Time when jack-up at turbine y ∈ {1, …, Y_v} start with vessel strategy v ∈ V on cycle u ∈ {1, …, U_v}
	f_{vuy}	Time when installation of turbine y ∈ {1, …, Y_v} start with vessel strategy v ∈ V on cycle u ∈ {1, …, U_v}
	g_{vuy}	Time when jack-down at turbine y ∈ {1, …, Y_v} start with vessel strategy v ∈ V on cycle u ∈ {1, …, U_v}
	h_{vuy}	Time when transit away from turbine y ∈ {1, …, Y_v} start with vessel strategy v ∈ V on cycle u ∈ {1, …, U_v}
	E_v	Total time vessel strategy v ∈ V is time chartered

Table 15: Continuous variables for the model.

5.5 Objective function and constraints

$$\min \sum_{k \in K} cost_k^K W_k + \sum_{v \in V} cost_v^M T_v + \sum_{v \in V} cost_v^{TC} E_v \qquad (1)$$

Subject to:

$$\sum_{v \in V} \sum_{u=1}^{Uv} \sum_{y=1}^{Yv} Z_{vuy} \geq R \qquad (2)$$

$$Z_{vuy} \leq T_v, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{1, \ldots, Y_v\} \qquad (3)$$

$$X_{kvu} \leq W_k, \quad \forall\, k \in K, v \in V, u \in \{1, \ldots, U_v\} \qquad (4)$$

$$\sum_{k \in K} X_{kvu} \leq 1, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\} \qquad (5)$$

$$Z_{vu1} \leq \sum_{k \in K} X_{kvu}, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\} \qquad (6)$$

$$X_{kvu} \leq X_{kv(u-1)}, \qquad \forall\, k \in K, v \in V, u \in \{2, \ldots, U_v\} \tag{7}$$

$$Z_{vuy} \leq Z_{vu(y-1)}, \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{2, \ldots, Y_v\} \tag{8}$$

$$Z_{vuy} \leq Z_{v(u-1)1}, \forall\, v \in V, u \in \{2, \ldots, U_v\}, y \in \{1, \ldots, Y_v\} \tag{9}$$

$$e_{v(u-1)} + \sum_{y=1}^{Yv} time_v^{\,L}\, Z_{vuy} \leq q_{vu}, \ \forall\, v \in V, u \in \{1, \ldots, U_v\} \tag{10}$$

$$q_{vu} + \sum_{k \in K} time_{kv}^{\,K}\, X_{kvu} \leq s_{vu1}, \ \forall\, v \in V, u \in \{1, \ldots, U_v\} \tag{11}$$

$$s_{vuy} + time_v^{\,PJ}\, Z_{vuy} \leq f_{vuy}, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{1, \ldots, Y_v\} \tag{12}$$

$$f_{vuy} + time_v^{\,I}\, Z_{vuy} \leq g_{vuy}, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{1, \ldots, Y_v\} \tag{13}$$

$$g_{vuy} + time_v^{\,PJ}\, Z_{vuy} \leq h_{vuy}, \ \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{1, \ldots, Y_v\} \tag{14}$$

$$h_{vu(y-1)} + time_v^{\,T}\, Z_{vuy} \leq s_{vuy}, \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{2, \ldots, Y_v\} \tag{15}$$

$$h_{vuy} + \sum_{k \in K} time_{kv}^{\,K}\, X_{kvu} \leq e_{vu}, \forall\, v \in V, u \in \{1, \ldots, U_v\} \tag{16}$$

$$e_{vu} \leq P, \qquad \forall\, v \in V, u \in \{0, \ldots, U_v\} \tag{17}$$

$$e_{vu} - e_{vo} \leq E_v, \qquad \forall\, v \in V, u \in \{1, \ldots, U_v\} \tag{18}$$

$$\sum_{n=1}^{WWvT} NT_{vu1n} = Z_{vu1}, \qquad \forall\, v \in V, u \in \{0, \ldots, U_v\} \tag{19}$$

$$\sum_{n=1}^{WWvT} NT_{vuyn} = Z_{vuy}, \qquad \forall\, v \in V, u \in \{0, \ldots, U_v\}, y \in \{1, \ldots, Y_v\} \tag{20}$$

$$\sum_{n=1}^{WWvT} NT_{vu1n} \leq q_{vu}, \qquad \forall\, v \in V, u \in \{0, \ldots, U_v\} \tag{21}$$

$$q_{vu} + \sum_{k \in K} time_{kv}^{\,K}\, X_{kvu} - P\,(1 - Z_{vu1}) \leq \sum_{n=1}^{WWvT} NT_{vu1n}\, end_{vn}^{\,T}, \quad \forall\, v \in V, u \in \{0, \ldots, U_v\} \tag{22}$$

$$\sum_{n=1}^{WWvT} NT_{vuyn}\, start_{vn}^{\,T} \leq h_{vu(y-1)}, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{2, \ldots, Y_v + 1\} \tag{23}$$

$$h_{vu(y-1)} + time_v^{\,T} - P\,(1 - Z_{vuy}) \leq \sum_{n=1}^{WWvT} NT_{vuyn}\, end_{vn}^{\,T}, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\}, y \in \{2, \ldots, Y_v\} \tag{24}$$

$$h_{vuy} + \sum_{k \in K} time_{kv}^{\,K}\, X_{kvu} - P\,(1 - Z_{vu1}) \leq \sum_{n=1}^{WWvT} NT_{vu(y+1)n}\, end_{vn}^{\,T}, \quad \forall\, v \in V, u \in \{1, \ldots, U_v\} \tag{25}$$

$\sum_{n=1}^{WWvP} NP1_{vuyn}\, start_{vn}^{P} \leq s_{vuy},$

$\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (26)

$s_{vuy} + time_{v}^{PJ} - P\,(1 - Z_{vuy}) \leq \sum_{n=1}^{WWvP} NP1_{vuyn}\, end_{vn}^{P},$

$\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (27)

$\sum_{n=1}^{WWvP} NP1_{vuyn} = Z_{vuy},$ $\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (28)

$\sum_{n=1}^{WWvP} NP2_{vuin}\, start_{vn}^{P} \leq g_{vuy},$

$\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (29)

$g_{vuy} + time_{v}^{PJ} - P\,(1 - Z_{vuy}) \leq \sum_{n=1}^{WWvP} NP2_{vuyn}\, end_{vn}^{P},$

$\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (30)

$\sum_{n=1}^{WWvP} NP2_{vuyn} = Z_{vuy},$ $\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (31)

$\sum_{n=1}^{WWvI} NI_{vuyn}\, start_{vn}^{I} \leq f_{vuy},$

$\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (32)

$f_{vuy} + time_{v}^{I} - P\,(1 - Z_{vuy}) \leq \sum_{n=1}^{WWvI} NI_{vuyn}\, end_{vn}^{I},$

$\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (33)

$\sum_{n=1}^{WWvI} NI_{vuyn} = Z_{vuy},$ $\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (34)

$W_k \in \{0,1\}$ $\forall$ k $\in$ K (35)

$X_{kvu} \in \{0,1\}$ $\forall$ v $\in$ V, u $\in$ {1, …, U_v}, k $\in$ K (36)

$T_v \in \{0,1\}$ $\forall$ v $\in$ V (37)

$Z_{vuy} \in \{0,1\}$ $\forall$ v $\in$ V, u $\in$ {1, …, U_v}, y $\in$ {1, …, Y_v} (38)

$NI_{vuyn} \in \{0,1\}$ $\forall$ y $\in$ {1, …, Y_v}, u $\in$ {1, …, U_v}, v $\in$ V, n $\in$ {1, …, WW_v^I} (39)

$NP1_{vuyn} \in \{0,1\}$ $\forall$ y $\in$ {1, …, Y_v}, u $\in$ {1, …, U_v}, v $\in$ V, n $\in$ {1, …, WW_v^I} (40)

$NP2_{vuyn} \in \{0,1\}$ $\forall$ y $\in$ {1, …, Y_v}, u $\in$ {1, …, U_v}, v $\in$ V, n $\in$ {1, …, WW_v^I} (41)

$NT_{vuyn} \in \{0,1\}$ $\quad \forall$ y ∈ {1, …, Y_v}, u ∈ {1, …, U_v}, v ∈ V, n ∈ {1, …, WW_v^I} (42)

$q_{vu} \geq 0$ $\quad \forall$ v ∈ V, u ∈ {1, …, U_v} (43)

$e_{vu} \geq 0$ $\quad \forall$ v ∈ V, u ∈ {1, …, U_v} (44)

$s_{vuy} \geq 0$ $\quad \forall$ v ∈ V, u ∈ {1, …, U_v}, y ∈ {1, …, Y_v} (45)

$f_{vuy} \geq 0$ $\quad \forall$ v ∈ V, u ∈ {1, …, U_v}, y ∈ {1, …, Y_v} (46)

$g_{vuy} \geq 0$ $\quad \forall$ v ∈ V, u ∈ {1, …, U_v}, y ∈ {1, …, Y_v} (47)

$h_{vuy} \geq 0$ $\quad \forall$ v ∈ V, u ∈ {1, …, U_v}, y ∈ {1, …, Y_v} (48)

$E_v \geq 0$ $\quad \forall$ v ∈ V (49)

The objective function (1) minimizes the total costs. Constraint (2) make sure that all turbines are transported and installed with some vessel strategy v ∈ V. Constraint (3) make sure secure that vessel strategy v ∈ V can be used only if mobilized. Constraint (4) make sure that assembly site k ∈ K can be used if opened. Constraint (5) make sure that vessel strategy v ∈ V is going from only one assembly site on cycle u ∈ {1, …, U_v}. Constraint (6) make sure that vessel strategy v ∈ V starts the cycle u ∈ {1, …, U_v} from an assembly site if at least one turbine is installed. Constraint (7) make sure that vessel strategy v ∈ V continues to go from no other assembly site k ∈ K than where it started. Constraint (8) specify that y ∈ {2, …, Y_v} turbines can only be installed with vessel strategy v ∈ V if y-1 turbines also are installed on cycle u ∈ {1, …, U_v}. Constraint (9) specify that u ∈ {2, …, U_v} cycles only can be made with vessel strategy v ∈ V if u-1 cycles are made where at least one turbine is installed. Constraints (10)-(11) explains loading and assembly site transit to wind farm. Constraints (12)-(15) explains jack-up, installation and jack-down at each turbine visited during a cycle. Constraint (16) explains transit in between turbines, and these are only restricted if y ∈ {2, …, Y_v} or more turbines are installed with vessel strategy v ∈ V on cycle u ∈ {1, …, U_v} only if Z_{vuy} = 1. Constraint (17) transits from wind farm back to assembly site and the end of cycle u ∈ {1, …, U_v} with vessel strategy v ∈

V. Constraint (18) make sure that vessel strategy $v \in V$ cannot return to an assembly site after time P. P is the length of working days, an integer number that will decide the length of our experiments later. Constraints (19) is the total charter period of vessel strategy $v \in V$ is at least as long as the time when operation is performed. Constraints (20)-(21) make sure that all transits happen within one weather window. Constraint (22)-(23) make sure that the first transit with vessel strategy $v \in V$ from assembly site to wind farm is within one weather window. Note that in this case, the P defines an integer number in working days through all the constraints. Constraint (24)-(25) make sure that the transit between turbines is made within one weather window. Constraint (26) make sure that any transit is done after a weather window has started for turbine $y \in \{1, \ldots, Y_v\}$. If the vessel strategy $v \in V$ cannot load the maximum number of turbines on cycle $u \in \{1, \ldots, U_v\}$ due to different reasons, then constraint (27) will transit back to the assembly site. Constraint (28)-(29) are made for the installation position and secure that jack-up happens within one weather window for each turbine. Constraint (30)-(31) are made for installation position exit and secure that jack-down happens within one weather window for each turbine. Constraints (32)-(34) are made so installations apply to each wind turbine and secure that installation of each complete turbine is performed within one weather window.

6 Testing the MILP model

In this chapter, we will go through all the tests we have performed to answer our research questions. In addition, the optimization tool used for the MILP model is introduced.

6.1 Computation and tools

All tests were conducted on a 1.50-GHz Intel Core i5 PC with 8 GB of RAM. The MILP model was implemented in the software AMPL, which is a modeling language to solve complex problems for large-scale mathematical computing. It is effective in solving optimization problems using data of both smaller and larger scales. Additionally, it deals well with continuous variables and models that require a lot of run-throughs to find an optimal solution.

The model was run in a *.mod* file where the data was connected in a *.dat* file. (See Appendix). To find the optimal solutions from our tests, we used the CPLEX solver. CPLEX is a software package for optimization developed by IBM. It solves inter programming problems, and large linear problems. (IBM, 2017). The more variables in a model, the longer the execution time take. It is a fast solver and gives a feasible solution within seconds. It may use longer execution time when parameters are increased, and because the model have a combination of binary decision variables and continuous time variables.

6.2 Main test (Test 1, Test 2, Test 3) and results

We are testing how the model is performing with an input of 5, 9, and 15 completely installed turbines to an offshore wind farm within 30 days, called Test 1, Test 2, and Test 3 respectively. We chose these numbers of turbines because of what we can expect from future floating offshore wind farms. The model assumes that these three combinations will be completed during the fixed time horizon, in other words, all the components will be transported and installed during this time.

The most important outputs of the model are the total cost, the assembly sites used, and how many of these sites the model chooses. The model will optimize the best vessel strategies in relation to the number of completely installed turbines. Lastly, the model tells us how many working days it takes before all the turbines are completely installed.

6.2.1 Test 1: 5 turbines and 30 days

Our first test is when the wind farm consists of 5 completely installed turbines with the time horizon of 30 days. As mentioned in Chapter 5 when the model was presented, we defined 5 assembly sites: Bergen, Stord, Jelsa, Stavanger-Forsand, and Eigersund. Only Bergen proves to be the optimal assembly site, and the total cost for this assembly site and transportation offshore is $4,495,230.

The optimal vessel strategy is the Unmounted. The total duration of this operation from start to finish is 10.72 working days.

Test 1	Total costs	Vessel strategy	Duration of working days	Assembly site
5 turbines and 30 days	$4,495,230	Unmounted	10.72	Bergen

Table 16: Result from Test 1

6.2.2 Test 2: 9 turbines and 30 days

The second test is when the wind farm consists of 9 completely installed turbines with the same time horizon as before. Of the 5 assembly sites, Bergen still shows to be optimal, with a total cost of $6,953,110. The increase in total costs relative to the increase in number of turbines from Test 1, is lower in Test 2. Despite the increase in the number of turbines, the CPLEX solver has no problem finding the optimal solution within seconds.

Here, the optimal vessel strategy is still the Unmounted. The total duration is 22.15 working days.

Test 2	Total costs	Vessel strategy	Duration of working days	Assembly site
9 turbines and 30 days	$6,953,110	Unmounted	22.15	Bergen

Table 17: Results from Test 2

6.2.3 Test 3: 15 turbines and 30 days

The last test we are analyzing is when the wind farm consists of 15 completely installed turbines with the same time horizon. Again, Bergen shows to be the most optimal assembly site. The total cost has increased to $11,544,200. The model has still no problem finding the optimal solution with the CPLEX solver.

For Test 3, the model finds two optimal vessel strategies: The Feed and the Unmounted. One of the reasons for this is the low time charter cost for these strategies. In addition, the Feed and the Unmounted strategy can carry more turbines in one trip. The duration is different for the two strategies, the Feed used 15.55 working days and the Unmounted strategy used 24.13 working days.

Two tables are shown for Test 3 to give a clear overview:

Test 3	Total costs	Assembly site
15 turbines and 30 days	$11,544,200	Bergen

Table 18: Cost and assembly site for Test 3

Vessel strategy	Used/Not used	Duration of working days
Feed	Used	15.55
2-blade formation	Not used	0
Unmounted	Used	24.13

Table 19: Results of vessels strategies and duration of working days

6.2.4 Discussion of the main test

In Test 1 – Test 3, Bergen proves to be the optimal assembly site and the vessel strategy used is the Unmounted in Test 1 and Test 2, and Unmounted and Feed in Test 3.

The optimal solutions for vessel strategy and assembly site make sense for Test 1 and Test 2 since the total number of turbines is low, and the strategy of Unmounted seems to be the most cost and time efficient at lower quantities. The increased number of turbines from Test 3 shows different results. The operation is much larger, and it requires two vessel strategies: Feed and Unmounted. It can be argued that the total number of turbines is much higher in Test 3, so two vessel strategies are needed to hold the deadline of 30 days. Furthermore, the Feed strategy has the highest mobilization cost, but at higher quantities it starts to get more cost efficient. The Feed has a higher transit time but can transport a larger number of elements to the wind farm site. This could explain that this strategy is used in combination with the Unmounted strategy. The two vessel strategies will run in parallel, where the Feed is done after 15.55 days, and the Unmounted is done after 24.13 days.

The increase in total cost from Test 1 to Test 2 is 34.52%, while the increase in the number of turbines from 5 to 9 is 44,50%. Looking at Test 2 and Test 3, the increase in total cost is 39.68%, while the increase in the number of turbines from 9 to 15 is 40%. To compare the total cost against the total number of turbines, it can be argued that Test 2 is the best economical choice since the increase in total cost is the lowest, while the increase in turbines is the highest.

The computational power in our main test is good, it gives feasible solutions in only seconds. Test 3 takes around 6 seconds longer than Test 1 and Test 2 to find the optimal solution. We have experimented with an even larger number of turbines and extended the time horizon. The CPLEX solver struggles to find the optimal solution when the number of turbines and time horizon is increased. 35 turbines in 3 months need to be run for 2 minutes to find the optimal solution. Increasing the number of turbines to 50 while keeping the same time horizon of 3 months will cause problems for the model. After 10 minutes, the run time was interrupted with an optimality gap of 11% which means the feasible solution is proved to be within 11% of optimal. This means the model performs poorly on a very large number of turbines over a longer time horizon.

6.3 Using several assembly sites

The next tests we are analyzing are several assembly sites used, meaning that we are forcing the model to choose a given number of assembly sites operated from. We are going to minimize the total cost of two new tests where we force the model to choose 3 assembly sites to be in operation, and 5 assembly sites (all) to be in operation. This requires some changes in the constraints in our model, where we force the model to choose the most optimal sites to be in operation and force the vessel strategies to connect with these sites. Our baseline model for these tests will be Test 3 from the main test with 15 turbines and 30 days.

6.3.1 3 assembly sites used

The model needs to understand that we are forcing 3 assembly sites to be in operation. The model will optimize the 3 best assembly sites. To solve this, we have introduced 2 new constraints in our model:

$$\sum_{k \in K} W_k = 3, \qquad (6.1.1)$$

$$\mathrm{W_k} \leq \sum_{v \in V} \sum_{u=1}^{Uv} X_{kvu}, \quad \forall\ \mathrm{k} \in \mathrm{K} \qquad (6.1.2)$$

Constraint (5.1.1) makes sure that exactly three assembly sites are in use. Constraint (5.1.2) makes sure that if an assembly site is used, at least one vessel strategy v ∈ V with one cycle u ∈ {1, …, U_v} must be used from that site.

The total cost for 3 assembly sites in use is $14,804,800 which is higher compared to the optimal solution from Test 3 in the main test with $11,544,200 operating from only 1 assembly site. The 3 most optimal assembly sites are Bergen, Jelsa, and Stavanger-Forsand. These assembly sites have the lowest fixed costs. All three vessel strategies are running in parallel, where the Feed is done with its operation after 13.95 days, the 2-blade formation used 1.44 days, and the Unmounted used 22.93 days. The total duration time is 22.93 days.

Two tables are shown for 3 assembly sites to give a clear overview:

3 assembly sites	Total costs	Assembly sites
15 turbines and 30 days	$14,804,800	Bergen, Jelsa, and Stavanger-Forsand

Table 20: Cost and the 3 assembly sites used.

Vessel strategy	Used/Not used	Duration of working days
Feed	Used	13.95
2-blade formation	Used	1.44
Unmounted	Used	22.93

Table 21: Results for vessel strategies and duration of working days

6.3.2 5 assembly sites used

Lastly, we test for 5 fixed assembly sites used. This means that we are forcing the model to use all the assembly sites that are available at least once during the time horizon. For this test to be feasible we must relax the constraint that designates only one vessel strategy to each location for the duration of the time horizon (constraint (7)).

From the 3 assembly sites-test we keep constraint (6.1.2) to ensure that at least one vessel strategy $v \in V$ is used in one cycle $u \in \{1, \ldots, U_v\}$ from each assembly site in use. Furthermore, we modify constraint (6.1.1) to:

$$\sum_{k \in K} W_k = 5, \qquad (6.1.3)$$

Constraint (6.1.3) ensures that all five assembly sites are in use.

The total cost for all 5 assembly sites in use is \$19,715,800. This is higher than the optimal solution from Test 3 and higher than the 3 assembly sites-test, which is to be expected from the trend of previous results. The Feed strategy used 14.42 days and the Unmounted used 24.50 days.

5 assembly sites	Total costs	Assembly sites
15 turbines and 30 days	\$19,715,800	All

Table 22: Cost and the 5 assembly sites used.

Vessel strategy	Used/Not used	Duration of working days
Feed	Used	14.42
2-blade formation	Not used	0
Unmounted	Used	24.50

Table 23: Results for vessel strategies and duration of working days

6.4 Discussing several assembly sites-tests and comparing to the baseline (Test 3)

It is natural to compare the baseline (Test 3) from the main tests with the several assembly sites-tests. Overall, the baseline (Test 3) outperforms the several assembly sites-tests. The total cost for the baseline (Test 3) is $11,544,200 while the 3 assembly sites used has a cost of $14,804,800, and 5 assembly sites used has a cost of $19,715,800. In the 3 assembly sites-test, the chosen assembly sites are sensible because these sites have the lowest fixed costs. Also, in both several assembly sites-tests the optimal vessel strategies seem to be the Feed and Unmounted strategy, which is in line with the baseline (Test 3). The reasoning for this is the same as previously discussed in main test.

The conclusion from a cost-minimizing perspective would be to operate from only 1 assembly site as in the baseline (Test 3), because the total costs are lower. From a time saving perspective, it is not significantly different compared to the baseline (Test 3). The 3 and 5 assembly sites-tests have similar time horizons to the baseline (Test 3) with 22.93 and 24.50 days. However governmental or municipal regulations and policies could change the project decisions.

The main reasoning for testing several assembly sites was to include potential political factors. For example, it can be decided that at least 3 of 5 sites must be in use to ensure Norway's escalation in the offshore wind industry. Another ultimatum could be that municipalities allow for operation of offshore wind industry only if the project manages to include local labor and businesses in the process. Lastly, we want to showcase that our model is changeable and flexible, where it is possible to do adjustments to achieve other outputs and results.

7 Limitations of the model, data & future work

We have been working hard to develop our MILP model and consider our experiments relevant to real-world scenarios and future developments. Optimizing costs is difficult in the offshore wind industry because the operations are complex and time consuming. Also, there are several unforeseen factors like bad weather and delays of elements that we have not included in our model. The model considers most of the important factors like cost, time, and weather windows, but there are still considerations we have not discussed. We will describe some of the weaknesses and limitations below.

7.1 Limitations of the model

The model we have developed contains parameters and decision variables from a real-life perspective. It contains several constraints that describe the whole process from loading elements/turbines at the assembly sites to installing the wind turbines at the wind farm. The whole process is based on time in working days (24h). We think this is the smartest way to model because we consider the weather window parameters that are also based on time. However, no model is 100% realistic, but rather a simplified version of the reality. The model could be more accurate and precise if several cost parameters were included like the number of workers at each vessel and their hourly pay rate. Another cost parameter that could make the model more accurate is fuel cost for the vessel, but we have simplified this with a time charter cost per vessel strategy. We have based the model on some assumptions by ourselves, like for example a vessel must come back to the same assembly site it left. In the real world, this may be different.

As briefly mentioned in subchapter 6.2.4 Discussion of main test, the model struggles to find a feasible solution when the number of turbines and the time horizon is increased. We increased the number of turbines and the time horizon way above our main test to check the capability of the model. With 35 turbines and a 3-month horizon, the model manages to find an optimal solution within 2 minutes. Increasing the number of turbines to 90 and a 5-month horizon is too much for the model, we had to interrupt the kernel after 20 min with an optimality gap of 11% using the CPLEX solver. We do not know if a feasible solution would be obtained within 20 minutes with a more powerful computer. The model did not struggle when we added new constraints that forced 3 and 5 assembly sites to be in operation.

7.1.1 Simplification of the model

The model is based on assumptions from a perfect world. This means the model does not consider delays or other factors causing problems in the supply chain. It is not possible with a single model to make the whole process perfect. Unforeseen factors like equipment damage may happen, and this would result in a higher cost for the project.

The transportation of the wind turbines from the assembly sites to the offshore wind farm is limited by number of elements for each vessel strategy in the model. In the real world, factors like loading capacity in tons and square meters on the vessels could give more precise outputs. Another factor is the crane load capacity. One of the largest crane ships in the world is the Saipem 7000 with two cranes with a load-lifting capacity of 7,000 tons each. (Mambra, 2022). Estimations of the weight on the floating spar buoy foundation of a 5MW turbine are 7,081 tons (consider if the heavy ballast section is filled with heavy material), which exceeds the crane capacity in the largest crane ships in the world. (Fylling et al., 2011). We rely on 15MW turbines, which have at least 60 meters higher tower than the 5MW turbine. This means that the depth of the spar buoy of a 15MW turbine must increase. The mass of this would reach up to 10,000 tons because the size is almost doubling. Transporting and lifting operations of these heavy elements would cause problems for the biggest vessels, even if the spar buoy is transported in several parts where the installation of the spar buoy foundation happens at the offshore wind farm.

The factors mentioned above are hard to estimate in one model. The offshore wind industry is complex, so more than one model is needed in the real world for the operation. We suggest a separate model for modeling the transportation of only the floating spar buoy foundations. These are heavy floating elements, so dividing these into three parts would make it possible to tow them to the offshore wind farm by tugboats. The fully assembly process would happen at the wind farm where a jack-up installation vessel could handle the floating spar buoy foundations since they arrive in smaller parts.

7.2 Limitations on data

Most of the input data for the model is inspired by Emre Uraz's Master thesis. (Uraz, 2011). This data is over 10 years old, and the market has changed a lot since 2011. On one side, prices have increased due to inflation. However, on the other side the knowledge in the industry has become better. Considering this, the model could have more accurate inputs. It is difficult to come across real data in the offshore wind industry. There are two reasons for this: the offshore wind industry is relatively new, so there are few data sources directly linked to the operation of transporting and installing wind turbines. The other reason is due to industry confidentiality. One could take inspiration from the oil industry, where offshore transportation of equipment to oil platforms is well known.

We have done estimations on the cost data, by researching relevant reports and papers. Better estimations and more accurate data will improve the output from our model and lead to even better results. This is important since more accurate data can save millions of dollars in the long run.

7.3 Future work

The relevance for future work is for the researchers and scientists in this field. We propose that future work acquire as accurate data as possible. The overall cost for real offshore wind projects is higher than in this model, and accurate data is crucial.

In addition, we would like to propose a new vessel strategy in the model for future work. There are projects like WindWorks Jelsa in Norway planning to tow fully assembled wind turbines with the floating spar buoy foundation attached to the turbine. This requires assembly sites with a deep-water quay for this to be possible. The model needs additional decision variables and constraints to make this feasible. The installation process at the offshore farm will only be to attach the mooring lines and power cable. This would probably cause challenges to a 15MW wind turbine due to its height of 150 meters attached to a 170-meters deep spar buoy foundation. We suggest towing smaller wind turbines in the range of 5MW to 10MW with the floating spar buoy foundation attached.

8 Conclusion

The demand for offshore wind energy is increasing worldwide, where Norway has the potential to be a market leader in Europe. As the demand increases, the investments in offshore wind projects need to increase.

We have aimed to optimize the operation from transporting to installation of the floating wind turbines for an offshore wind farm in Sørlige Nordsjø 1. The objective was to minimize total costs consisting of a fixed cost for operating from an assembly site, a mobilization cost for each vessel, and a time charter cost depending on how long the operation would take. This was done by developing a Mixed-Integer Linear Programming (MILP) model in AMPL where we performed different tests within a given time horizon. The data used in our model is a combination of confidential data and realistic estimated data from research papers and new relevant reports.

Based on our main test, it can be concluded that the optimal solution is to operate from only one assembly site on the west coast of Norway. The total cost is lower, and the efficiency is higher. The several assembly site-tests of forcing 3 and 5 assembly sites to be in operation, resulted in a higher total cost compared to Test 3 from the main test where Test 3 was the baseline in the several assembly sites-tests.

In terms of vessel strategies used, the 2-blade formation proves to be too costly for the project size and time horizons of our choice. The Feed is effective in larger projects with its large carrying capabilities and small costs but does seem to be less time efficient in smaller projects. The Unmounted is the in-between option that turns out to be the most effective in smaller, and mid-sized projects. This is due to its short completion time and relative price and carrying capacity advantage compared to the 2-blade formation transit.

From the start of this work, our mathematical MILP model was carefully constructed where parameters and decision variables were specified and defined. Constraints based on the vessel strategies, assembly sites and weather windows were implemented. The objective function was defined at the end. Two additional constraints were developed in the several assembly site-tests so the model could understand that 3 and 5 assembly sites were used. The solver we utilized through all our tests was the CPLEX solver. CPLEX is faster than the Gurobi solver in terms of finding the optimal solution, especially when we were testing the capability of the model with very high numbers of wind turbines and a larger time horizon.

This thesis is relevant to the floating offshore wind industry in Norway. The focus on reducing operational costs is one of the central factors for offshore wind to succeed. This gives great opportunities for investors to invest in projects, which will accelerate the development of more wind farms in the North Sea.

Finally, we recommend Norway and the Government in near future to increase the development of assembly sites on the west coast of Norway. The potential for Norway is enormous due to the knowledge from the oil and gas industry. This knowledge could be transferred to the floating wind turbines. In writing time, the Government has come up with new ambitions for offshore wind; the goal is to install 30GW within 2040, which is almost the same amount as the Norwegian hydropower. (Undheim, 2022). To realize this ambition, one key factor is to reduce the total costs in the operation of a project. Lastly, as we have presented different vessel strategies, we recommend that these will be deployed to achieve better efficiency in the future.

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Appendix

AMPL code for the main tests:

```
set K;
set V;

param costK{K};
param costTC{V};
param costM{V};
param timeL{V};
param timeI{V};
param timeT{V};
param timePJ{V};
param timeK{K,V};
param Y{V};
param U{V} integer;
param R;
param P;

param WWP{v in V};
param WWI{v in V};
param WWT{v in V};
param startI{v in V,1..WWI[v]};
param endI{v in V,1..WWI[v]};
param startP{v in V,1..WWP[v]};
param endP{v in V,1..WWP[v]};
param startT{v in V,1..WWT[v]};
param endT{v in V,1..WWT[v]};

var W{K} binary;
var T{V} binary;
var X{k in K,v in V,1..U[v]} binary;
var Z{v in V,1..U[v],1..Y[v]} binary;

var q{v in V,1..U[v]} >= 0;
var e{v in V,0..U[v]} >= 0;
var s{v in V,1..U[v],1..Y[v]} >= 0;
var f{v in V,1..U[v],1..Y[v]} >= 0;
var g{v in V,1..U[v],1..Y[v]} >= 0;
var h{v in V,1..U[v],1..Y[v]} >= 0;
var E{V} >= 0;

var NI{v in V,1..U[v],1..Y[v],1..WWI[v]} binary;
var NP1{v in V,1..U[v],1..Y[v],1..WWP[v]} binary;
var NP2{v in V,1..U[v],1..Y[v],1..WWP[v]} binary;
```

```
var NT{v in V,1..U[v],1..Y[v]+1,1..WWT[v]} binary;

minimize TotalCost: sum{k in K} costK[k]*W[k] + sum{v in V} (costM[v]*T[v] +
costTC[v]*E[v]);

s.t. TotalTurbineInstallation: sum{v in V,u in 1..U[v],y in 1..Y[v]} Z[v,u,y] >=
R;
s.t. VesselUsedIfMobilized{v in V,u in 1..U[v],y in 1..Y[v]}: Z[v,u,y] <= T[v];
s.t. AsiteUsedIfOpened{k in K,v in V,u in 1..U[v]}: X[k,v,u] <= W[k];
s.t. VesselLeave{v in V,u in 1..U[v]}: sum{k in K} X[k,v,u] <= 1;
s.t. SameAsite{k in K,v in V,u in 2..U[v]}: X[k,v,u] <= X[k,v,u-1];
s.t. LeaveIfTurbineInstalled{v in V,u in 1..U[v]}: Z[v,u,1] <= sum{k in K}
X[k,v,u];
s.t. TurbineInOrder{v in V,u in 1..U[v],y in 2..Y[v]}: Z[v,u,y] <= Z[v,u,y-1];
s.t. CycleInOrder{v in V,u in 2..U[v],y in 1..Y[v]}: Z[v,u,y] <= Z[v,u-1,1];

s.t. StartLoad{v in V,u in 1..U[v]}: e[v,u-1] + sum{y in 1..Y[v]}
timeL[v]*Z[v,u,y] <= q[v,u];
s.t. StartAsite{v in V,u in 1..U[v]}: q[v,u] + sum{k in K} timeK[k,v]*X[k,v,u]
<= s[v,u,1];
s.t. Position{v in V,u in 1..U[v],y in 1..Y[v]}: s[v,u,y] + timePJ[v]*Z[v,u,y]
<= f[v,u,y];
s.t. TimeInstallation{v in V,u in 1..U[v],y in 1..Y[v]}: f[v,u,y] +
timeI[v]*Z[v,u,y] <= g[v,u,y];
s.t. PositionOut{v in V,u in 1..U[v],y in 1..Y[v]}: g[v,u,y] +
timePJ[v]*Z[v,u,y] <= h[v,u,y];
s.t. TransitOfTurbines{v in V,u in 1..U[v],y in 2..Y[v]}: h[v,u,y-1] +
timeT[v]*Z[v,u,y] <= s[v,u,y];
s.t. FinishCycle{v in V,u in 1..U[v]}: h[v,u,Y[v]] + sum{k in K}
timeK[k,v]*X[k,v,u] <= e[v,u];
s.t. CapacityOfTime{v in V,u in 0..U[v]}: e[v,u] <= P;
s.t. TimeVessel{v in V,u in 1..U[v]}: e[v,u] - e[v,0] <= E[v];

s.t. WindowEndPosition1{v in V,u in 1..U[v],y in 1..Y[v]}: s[v,u,y] + timePJ[v]
- P*(1 - Z[v,u,y]) <= sum{n in 1..WWP[v]} NP1[v,u,y,n]*endP[v,n];
s.t. WindowStartPostion1{v in V,u in 1..U[v],y in 1..Y[v]}: sum{n in 1..WWP[v]}
NP1[v,u,y,n]*startP[v,n] <= s[v,u,y];
s.t. WindowIfInstaPostion1{v in V,u in 1..U[v],y in 1..Y[v]}: sum{n in
1..WWP[v]} NP1[v,u,y,n] = Z[v,u,y];

s.t. WindowEndPosition2{v in V,u in 1..U[v],y in 1..Y[v]}: g[v,u,y] + timePJ[v]
- P*(1 - Z[v,u,y]) <= sum{n in 1..WWP[v]} NP2[v,u,y,n]*endP[v,n];
s.t. WindowStartPostion2{v in V,u in 1..U[v],y in 1..Y[v]}: sum{n in 1..WWP[v]}
NP2[v,u,y,n]*startP[v,n] <= g[v,u,y];
s.t. WindowIfInstaPostion2{v in V,u in 1..U[v],y in 1..Y[v]}: sum{n in
1..WWP[v]} NP2[v,u,y,n] = Z[v,u,y];
```

```
s.t. WindowEndInsta{v in V,u in 1..U[v],y in 1..Y[v]}: f[v,u,y] + timeI[v] -
P*(1 - Z[v,u,y]) <= sum{n in 1..WWI[v]} NI[v,u,y,n]*endI[v,n];
s.t. WindowStartInsta{v in V,u in 1..U[v],y in 1..Y[v]}: sum{n in 1..WWI[v]}
NI[v,u,y,n]*startI[v,n] <= f[v,u,y];
s.t. WindowIfInsta{v in V,u in 1..U[v],y in 1..Y[v]}: sum{n in 1..WWI[v]}
NI[v,u,y,n] = Z[v,u,y];

s.t. WindowEndAsiteTransit1{v in V,u in 1..U[v]}: q[v,u] + sum{k in K}
timeK[k,v]*X[k,v,u] - P*(1 - Z[v,u,1]) <= sum{n in 1..WWT[v]}
NT[v,u,1,n]*endT[v,n];
s.t. WindowStartAsiteTransit1{v in V,u in 1..U[v]}: sum{n in 1..WWT[v]}
NT[v,u,1,n]*startT[v,n] <= q[v,u];
s.t. WindowEndTurbTransit{v in V,u in 1..U[v],y in 2..Y[v]}: h[v,u,y-1] +
timeT[v] - P*(1 - Z[v,u,y]) <= sum{n in 1..WWT[v]} NT[v,u,y,n]*endT[v,n];
s.t. WindowStartTurbTransit{v in V,u in 1..U[v],y in 2..Y[v]+1}: sum{n in
1..WWT[v]} NT[v,u,y,n]*startT[v,n] <= h[v,u,y-1];
s.t. WindowEndAsiteTrans2Last{v in V,u in 1..U[v]}: h[v,u,Y[v]] + sum{k in K}
timeK[k,v]*X[k,v,u] - P*(1 - Z[v,u,1]) <= sum{n in 1..WWT[v]}
NT[v,u,Y[v]+1,n]*endT[v,n];
s.t. WindowIfTransit{v in V,u in 1..U[v],y in 1..Y[v]}: sum{n in 1..WWT[v]}
NT[v,u,y,n] = Z[v,u,y];
s.t. WindowIfTransitLast{v in V,u in 1..U[v]}: sum{n in 1..WWT[v]}
NT[v,u,Y[v]+1,n] = Z[v,u,1];
```

Additional constraints for the 3 assembly sites used:

```
s.t. ThreeFixedSites: sum{k in K} W[k] = 3;
s.t. VesselMustBeUsed{k in K}: W[k] <= sum{v in V, u in 1..U[v]} X[k,v,u];
```

Data used for all tests: (15 turbines and 30 days in this example, “param R” is changed when testing 5 and 9 turbines)

```
set K:= bergen stord eigersund jelsa stvg;
set V:= feed 2blade unmounted;


param costK:=
bergen          1000
stord           2000
eigersund       3000
jelsa           1500
stvg            1800;

param:                 costTC          costM:=
feed                   184                    1305
2blade                 356                    1190
unmounted              215                    1190;
```

```
param:                  timeL         timeI         timeT         timePJ:=
feed                    0.83          1.00          0.011         0.125
2blade                  0.5           0.67          0.005         0.083
unmounted               0.83          1.00          0.005         0.083;

param:          Y       U:=
feed            8       2
2blade          3       5
unmounted       6       3;

param timeK:                   feed    2blade  unmounted:=
bergen                         1.8     0.72    0.72
stord                          1.52    0.61    0.61
eigersund                      0.84    0.34    0.34
jelsa                          1.28    0.56    0.56
stvg                           1.11    0.45    0.45;

param R:= 15;

param P:= 30;

param WWP:=
feed            3
2blade          5
unmounted       4;

param WWI:=
feed            5
2blade          3
unmounted       5;

param WWT:=
feed            3
2blade          4
unmounted       5;

param startP:           1       2       3       4       5       :=
feed                            0       14      22      .       .
2blade                          0       6       12      18      24
unmounted                       0       6       16      22      .;

param endP:             1       2       3       4       5       :=
feed                    6       20      28      .       .
2blade                  6       12      18      24      30
unmounted               6       12      20      28      .;

param startI:           1       2       3       4       5       :=
feed                            0       6       12      18      24
2blade                          0       10      18      .       .
unmounted                       0       6       12      18      24;

param endI:             1       2       3       4       5       :=
feed                    6       12      18      24      30
2blade                  6       14      26      .       .
unmounted               6       12      18      24      30      ;

param startT:           1       2       3       4       5       :=
feed                            0       14      22      .       .
2blade                          0       6       16      22      .
unmounted                       0       6       12      18      24;

param endT:             1       2       3       4       5       :=
feed                    6       20      28      .       .
2blade                  6       12      20      28      .
unmounted               6       12      18      24      30;
```