



# A Tabu Search Heuristic for Chartering Offshore Wind Farm Installation Vessels under Weather Uncertainty

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# Problem description

The purpose of this thesis is to study the chartering of installation vessels used for offshore wind farm installation under weather uncertainty. The charter periods are decided years before the installation starts and the weather is realized. Often extension options are included in the contract to deal with uncertainty in the installation duration.

A two-stage stochastic model is formulated where the objective is to minimize the expected chartering costs. A tabu search heuristic with an integrated simulation procedure is proposed to solve realistically sized test instances. The aim is to provide the offshore wind farm developer with valuable insights that can be used in the planning phase of charter contracts.

# Preface

This masters thesis is written within the field of Managerial Economics and Operations Research (TIØ4905) as the concluding part of our Master of Science degrees in Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU). The thesis is a continuation of our project report, written fall 2019.

The thesis relates to the maritime logistic challenges for the installation of offshore wind farms. The problem studied in this thesis is the optimization of the charter period of installation vessels used for offshore wind farm installation under uncertainty. The objective is to reduce the chartering cost of the vessels. In addition, reasonable lump sum contract prices were assessed.

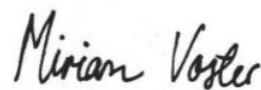
We would like to thank our supervisors Associate Professor in Operations Research Magnus Stålhane at NTNU and Associate Professor in Operations Research Giovanni Pantuso at the University of Copenhagen. Their guidance throughout the semester has been of high value. Additionally, we would like to thank Lars Magne Nonås and Elin Espeland Halvorsen-Weare representing our collaborator SINTEF for giving essential insights about the problem.

Trondheim, June 30, 2020.



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# Summary

The demand for new energy sources will increase in the next decades. Offshore wind farms have the potential to meet a portion of this demand. However, the costs related to offshore wind farms are high and must be reduced to compete with fossil energy sources. One cost reduction opportunity lies within the chartering of installation vessels for the wind farm. This thesis is written in collaboration with SINTEF, and the purpose is to provide a method for wind farm developers to reduce the chartering cost.

The installation vessels chartering problem under weather uncertainty, involves deciding the start date, end date, and the number of extension options for each vessel before the installation starts. When the installation starts, weather windows for installation activities are found. The goal is to minimize the expected cost of chartering installation vessels. What distinguishes this problem from previous research on offshore wind farm installation, is mainly the consideration of weather uncertainty and its effect on the chartering strategy. In addition, the use of extension options and pricing of lump-sum contracts are considered. There exist papers considering weather uncertainty, but these papers assume that the fleet consists of only one vessel or considers only the most weather-sensitive installation activities.

A mathematical two-stage stochastic model is formulated to describe the problem. The first stage relates to the chartering decisions taken years before the installation. The second stage is concerned with scheduling installation activities given the vessels charter periods and the realized weather. A tabu search heuristic is proposed to solve the problem for large instances. A simulator is integrated within the heuristic to estimate the cost for a first-stage solution the heuristic suggests, and simulate the second-stage decisions. Different improvement strategies, tabu list structures, and stopping criteria have been tested to increase the tabu search efficiency and to avoid getting stuck in local optima. A simple neighborhood structure in the heuristic, combined with a simulator to evaluate neighbors, resulted in an efficient search which found the optimal solution or a solution close to optimum for real sized instances within a reasonable time limit. Moreover, testing indicates that extension options constitute a significant part of the charter period, even though options are more expensive than fixed periods. The expected cost is lower with included options, as the number of days to install the wind farm varies with weather scenarios, and options add flexibility in the contract.

# Sammendrag

Etterspørselen etter nye energikilder vil øke de neste tiårene. Offshore vindkraft har potensiale til å dekke deler av denne etterspørselen. Kostnadene knyttet til offshore vindkraft er høye, og må reduseres for at offshore vindkraft kan konkurrere med fossile energikilder. En mulighet for kostnadsreduksjon er å estimere leieperiodene til installasjonsfartøyene med større presisjon. Denne masteroppgaven er skrevet i samarbeid med SINTEF, og formålet er å utvikle en metode for å redusere leiekostnader for installasjonsfartøy.

Beslutninger som må tas for installasjonsfartøy i planleggingsfasen av en offshore vindpark er startdato, sluttdato og antall opsjoner for hvert installasjonsfartøy. Når installasjonen starter, bestemmes værvinduer installasjonsaktiviteter kan utføres i. Målet er å minimere de forventede kostnadene for leie av installasjonsfartøy. Det som skiller dette problemet fra tidligere forskning på installasjon av havvindmøller, er hovedsakelig hensynet til værussikkerhet og dens effekt på strategien for innleie av installasjonsfartøy. I tillegg blir utvidelsesopsjoner og fastsettelse av pris for fastpriskontrakter tatt i betraktning. Det finnes forskning som tar hensyn til værussikkerhet, men disse antar at flåten består av kun ett installasjonsfartøy eller vurderer kun de mest væravhengige installasjonsaktivitetene.

En matematisk to-steps stokastisk modell er formulert for å beskrive problemet. Førstestegsbeslutningen blir tatt før installasjonsfasen starter. Andrestegsbeslutninger dreier seg om planlegging av installasjonsaktivitetene gitt leieperiodene for installasjonsfartøyene og det realiserte været. En tabu-søk heuristikk er foreslått for å løse modellen for store test-instanser. En simulator er integrert i heuristikken for å simulere andrestegsbeslutninger og estimere kostnadene for førstestegsbeslutningene foreslått av heuristikken. Ulike forbedringsstrategier, tabu-listestrukturer og stoppkriterier er testet for å øke effektiviteten til tabu-søket og unngå å stå fast i lokale optimum. En kombinasjon av en enkel nabolagsstruktur i heuristikken og en simulator som evaluerer naboer, resulterte i et effektivt søk som fant løsninger i optimum eller i nærheten av optimum for realistiske instanser innen rimelig tid. Videre indikerer testingen at opsjoner utgjør en betydelig del av installasjonsfartøyenes leieperioder, selv om opsjoner er dyrere enn faste leieperioder. De forventede kostnadene er lavere ved å inkludere opsjoner ettersom antall dager det tar å installere vindparken varierer med værscenarier, og opsjonene gir fleksibilitet i kontrakten.

# Table of contents

1	Introduction . . . . .	1
2	Background . . . . .	6
2.1	Installation activities . . . . .	6
2.1.1	Substructure . . . . .	6
2.1.2	Top structure . . . . .	8
2.1.3	Cables . . . . .	9
2.2	Weather downtime . . . . .	10
2.3	Vessel concepts and capabilities . . . . .	11
2.3.1	Overview of vessel types . . . . .	11
2.3.2	Comparison of installation vessels . . . . .	14
2.4	Contracts and risk . . . . .	15
2.4.1	Day rates and extension options . . . . .	15
2.4.2	Weather risk and lump sum . . . . .	15
3	Problem description . . . . .	17
4	Literature review . . . . .	20
4.1	Literature search strategy . . . . .	20
4.2	Offshore wind farm installation . . . . .	21
4.3	Project scheduling . . . . .	24
4.4	Heuristics for stochastic problems . . . . .	26
4.4.1	Introduction to a simheuristic approach . . . . .	26
4.4.2	Simheuristics within project scheduling . . . . .	27
4.4.3	Project risk . . . . .	28
4.5	Our contribution . . . . .	28
5	Mathematical model . . . . .	30
5.1	Assumptions . . . . .	30
5.2	Notation . . . . .	34
5.3	Mathematical formulation . . . . .	36
5.3.1	First stage problem . . . . .	36
5.3.2	Second stage problem . . . . .	37
5.4	Linearization . . . . .	40
5.5	End effects . . . . .	42
5.6	Symmetry breaking inequalities . . . . .	42
5.7	Discussion of flexibility in the model . . . . .	43
6	Tabu search heuristic . . . . .	44
6.1	Heuristic overview . . . . .	44

6.2	Solution representation . . . . .	46
6.3	Construction heuristic . . . . .	46
6.4	Evaluation of a solution . . . . .	47
6.5	Search space . . . . .	48
6.6	Move restrictions . . . . .	52
6.7	Tabu-lists and use of memory . . . . .	52
6.8	Stopping criterion . . . . .	53
7	Simulator . . . . .	54
7.1	Classification of the simulator . . . . .	54
7.2	The simulator algorithm . . . . .	56
7.2.1	An overview . . . . .	56
7.2.2	Detailed overview . . . . .	57
7.3	Walkthrough example . . . . .	64
8	Risk profile and lump sum . . . . .	67
9	Computational study . . . . .	69
9.1	Input Data . . . . .	69
9.1.1	Offshore wind farm properties . . . . .	69
9.1.2	Time . . . . .	70
9.1.3	Activities . . . . .	70
9.1.4	Vessels . . . . .	72
9.1.5	Extension options . . . . .	74
9.1.6	Scenarios . . . . .	75
9.1.7	Penalty cost for loss of production, $P^f$ . . . . .	76
9.1.8	Fixed penalty cost for not finishing the wind farm within charter period, $P^w$ . . . . .	76
9.1.9	Variable penalty cost for not finishing the wind farm within charter period, $P^Q$ . . . . .	77
9.1.10	Test instances . . . . .	78
9.2	Original model . . . . .	80
9.3	Heuristic tuning . . . . .	81
9.3.1	Search strategies . . . . .	81
9.3.2	Tabu lists and use of memory . . . . .	84
9.3.3	Stopping criterion . . . . .	86
9.3.4	Run time analysis . . . . .	88
9.3.5	Comparison of the original model and the tabu search heuristic . . . . .	89
9.4	Planning of an offshore wind farm . . . . .	89
9.4.1	What-if analysis of vessel configurations . . . . .	91

9.4.2	Dedicated transport vessels . . . . .	95
9.4.3	What-if analysis of extension option configurations . . . . .	96
9.4.4	Lump sum evaluation . . . . .	98
9.4.5	Number of scenarios . . . . .	100
9.5	Summary . . . . .	101
10	Concluding remarks . . . . .	104
11	Future research . . . . .	106
12	References . . . . .	i
	Appendix . . . . .	vii
A	Minutes, Equinor ASA . . . . .	viii
B	Minutes, Fred. Olsen Windcarrier, Part 1 . . . . .	x
C	Minutes, Fred. Olsen Windcarrier, Part 2 . . . . .	xii
D	Minutes, Law firm Hjort DA . . . . .	xiv
E	Mathematical Model . . . . .	xv
E.0.1	Notation . . . . .	xv
E.0.2	First stage problem . . . . .	xvi
E.0.3	Second stage problem . . . . .	xvii



## List of Figures

1	An Ørsted wind farm . . . . .	1
2	Market status 2018 for offshore wind farms. . . . .	2
3	Bottom fixed foundations . . . . .	6
4	Monopiles and transition pieces. . . . .	7
5	Top structure. . . . .	8
6	Illustration of the cable network . . . . .	9
7	Inter-array cable installation. . . . .	9
8	Installation vessels . . . . .	13
9	Cable vessels . . . . .	14
10	Comparison of optimization approaches. . . . .	26
11	Activity-on-the-node network . . . . .	30
12	Overview of the simulator . . . . .	56
13	Structure of the simulator . . . . .	57
14	Scheduling of activities . . . . .	59
15	The last tasks of the simulator . . . . .	62
16	Exercising of options . . . . .	62
17	The $q\%$ tail of the cost distribution. . . . .	67
18	Installation activities for one offshore wind turbine . . . . .	71
19	Performance of search strategies in instance T10V4. . . . .	81
20	Performance of search strategies in instance T10V8. . . . .	82
21	Performance of search strategies in instance T60V4. . . . .	82
22	Performance of search strategies in instance T60V8. . . . .	83
23	Performance of search strategies in instance T120V4. . . . .	83
24	Performance of search strategies in instance T120V8. . . . .	84
25	Cost comparison of vessel configurations . . . . .	92
26	Realized charter cost in different scenarios . . . . .	95
27	Chartering cost distribution for 120 turbines. . . . .	98
28	Objective value as a function of the number of scenarios . . . . .	101

## List of Tables

1	Task durations and operational limits . . . . .	10
2	Overview of vessel types. . . . .	12
3	Search words . . . . .	20
4	Classification of the simulator . . . . .	54
5	First stage solution used in walkthrough example . . . . .	64
6	Activity duration used in walkthrough example . . . . .	64
7	Walkthrough example of the simulator . . . . .	65
8	Wind farm properties . . . . .	70
9	Activity durations, wave and wind limits . . . . .	71
10	Dummy nodes used in the mathematical model . . . . .	71
11	Vessels and their associated installation activities . . . . .	72
12	Vessels and their associated costs and loading sets . . . . .	73
13	Loading and sailing durations . . . . .	73
14	Costs for dedicated transport vessels . . . . .	74
15	Option periods and prices . . . . .	75
16	Option periods and prices for the dedicated transport vessels . . . . .	75
17	Test instances used for testing the original model . . . . .	78
18	Test instances used for tuning the tabu search heuristic . . . . .	78
19	Test instances used for testing vessel configurations . . . . .	78
20	Test instance used for testing of dedicated transport vessels . . . . .	78
21	Test instances used for testing option configurations . . . . .	79
22	Test instance used for testing of lump sum . . . . .	79
23	Test instances testing different numbers of scenarios . . . . .	79
24	Results of testing turbine dimension . . . . .	80
25	Objective value after searches with different tabu lists. . . . .	86
26	Objective value after n iterations without improvements. . . . .	87
27	Tabu search characteristics for different instances. . . . .	88
28	Estimated simulation time for 50 scenarios. . . . .	89
29	Comparison of original model and heuristic . . . . .	89
30	Costs for base case . . . . .	90
31	Contract set up for base case . . . . .	90
32	Comparison of costs for one and two vessels of each vessel type . . . . .	91
33	Comparison of costs for two vessels of one vessel type . . . . .	92
34	Comparison of costs for two vessels of two vessel types . . . . .	93
35	Optimal vessel configuration . . . . .	94

36 Contract set up for the suggested vessel configuration . . . . . 94

37 The effect of using dedicated transport vessels . . . . . 96

38 Expected cost given different option lengths . . . . . 97

39 Contract set up for the suggested option configuration . . . . . 97

40 Expected tail cost. . . . . 99

41 Expected tail cost per vessel. . . . . 99

**List of Algorithms**

1	Tabu search algorithm . . . . .	45
2	Construction heuristic algorithm . . . . .	47
3	Evaluation of solution algorithm . . . . .	48
4	Get neighborhood . . . . .	50
5	Smart improvement . . . . .	52
6	Search for first available weather window . . . . .	61

## Abbreviations

<b>CBV</b>	Cable burial vessel	Pages: 12, 14, 49, 72, 73, 75, 99
<b>CLV</b>	Cable laying vessel	Pages: 12, 14, 49, 72, 73, 75, 99
<b>E[NPV]</b>	Expected net present value	Pages: 25
<b>HLV</b>	Heavy lift vessel	Pages: 12, 14, 48, 49, 72, 73, 75, 99
<b>JUB</b>	Jack-up barge	Pages: 12, 14
<b>O&amp;G</b>	Oil & Gas	Pages: 3, 15, 16
<b>OWF</b>	Offshore wind farm	Pages: 2-4, 10, 11, 14-17, 20, 24, 27, 30-32, 67, 77, 81, 99, 102, 103, 106
<b>OWT</b>	Offshore wind turbine	Pages: 3, 4, 8-10, 17, 18, 31, 42, 43, 67, 68, 71, 87, 88, 102
<b>RCPSP</b>	Resource constrained project scheduling problem	Pages: 24, 25
<b>TIV</b>	Turbine installation vessel	Pages: 11, 12, 14, 49, 72, 73, 75, 99

# 1 Introduction

Offshore wind represents a large area of improvement within renewable energy, with the potential to become an unsubsidized renewable electricity source through the 2020s. The global energy sector is now developing towards a low carbon future. The United Nations have estimated that the global population reaches 9.8 billion people in 2050 and the economy grows 2.0-2.2x compared to 2018 (*Energy Perspectives*, 2019, p. 9). This growth requires new renewable energy sources. The Paris climate conference aims to keep a global temperature rise below two degrees Celsius compared to the pre-industrial levels (European Commission, 2019). As a result, 198 countries agreed to a legally binding climate deal in 2015. Renewable energy is beneficial not only for environmental reasons but also because it is a secure supply and can create new jobs.

Offshore wind energy has a huge unrealized potential as a renewable energy source. By localizing wind turbines offshore, noise pollution can be avoided for humans, there is a larger space available offshore for the construction field, and the wind speed is usually stronger at sea. However, the cost related to offshore wind projects is huge, and several offshore wind projects are depending on direct subsidies. To set the world on a sustainable course of action, renewable energy need to become the preferred choice for consumers, regardless of government targets and subsidies.



Figure 1: An offshore wind farm operated by Ørsted. Photo: Ørsted.

In 2018, China had installed the highest total offshore wind power capacity, but the UK had installed the highest number of offshore wind turbines (OWT) (IEA, 2019). In general, the offshore wind market is more developed in Europe and accounts for 2.6 GW of installed offshore wind in 2018. The EU is taking an assertive role in the energy transition by reviewing legislation to ensure that at least 27 % of all energy consumed in the EU is from renewable energy sources by 2030. Markets for offshore wind in the United States, Chinese Taipei, and Japan are emerging, but are depending on cost reductions and technological improvements (IEA, 2019).

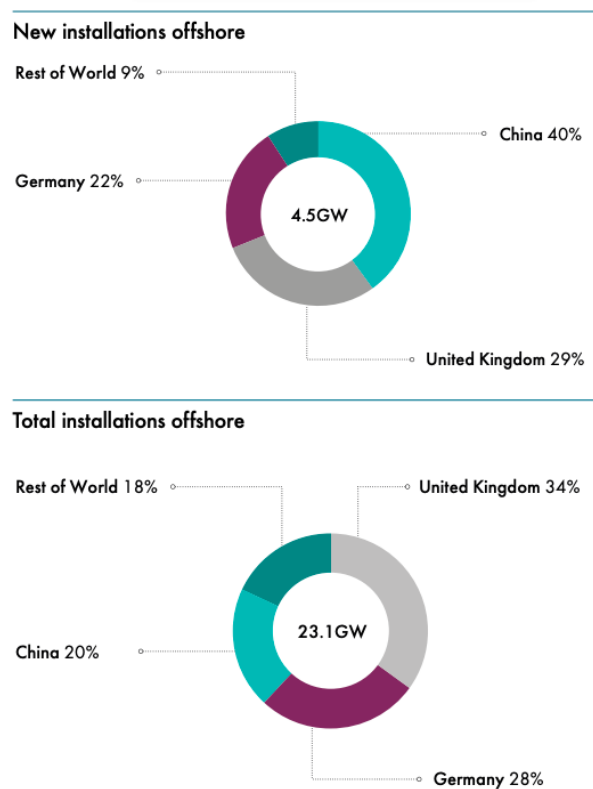


Figure 2: Market status 2018 for offshore wind farms, from GWEC 2018.

The installation phase takes up about 13 % of the total requirements along the value chain for a typical offshore wind farm (OWF) in Scotland (Irena, 2012). However, the costs depend on the project's characteristics such as the distance to shore and water depth. The installation phase show possibilities for cost reductions, and knowledge within optimization can reveal important information about uncertainty in the installation phase (Wind Europe, 2017).

A major cost component is the chartering of installation vessels, as these vessels are highly specialized. The day rates are high, and they cannot operate under harsh weather conditions. The operator’s challenge is to decide the charter period when the weather forecast is unknown. If installation activities are not finished within the charter period, the project can suffer significant cost overrun as the operator has to charter in new vessels. For instance, the two projects in the North Sea, “Bard 1” and “Borkum West”, were both delayed, and weather was a major factor. “Bard 1” was delayed to three years instead of the planned project period of one and a half years. “Borkum West” finished within 367 days, instead of the planned 200 days (Ursavas, 2017).

This thesis is written in collaboration with SINTEF, which has provided insights into the challenges in the offshore wind industry. As SINTEF has identified, the biggest challenge of Norwegian petro-maritime firms is market relatedness, rather than technological relatedness. Market relatedness includes contract setup and processes related to sales and customers. The technological risk is assumed to be lower as offshore wind turbine (OWT) operations are relatively similar to construction projects in Oil & Gas (O&G) (Hanson et al., 2019). Two industry partners of SINTEF have been interviewed in order to gain further insights. An interview with the wind farm operator Equinor can be found in Appendix A, two interviews with wind farm installer Fred. Olsen Windcarrier can be found in Appendix B and C, and an independent interview with the law firm Hjort is presented in Appendix D.

The problem studied in this thesis is the chartering of vessels for the installation of offshore wind farms. The goal is to find the optimal charter periods and number of extension options for each vessel when minimizing the expected cost of chartering vessels. The installation activities considered are the assembly of the OWT components and the laying and burial of the inter-array cable. The weather conditions affect the vessel’s ability to perform installation activities, which causes uncertainty in the total project duration. The vessels’ charter periods are decided about two years before the installation process starts, before weather forecasts are available. When the installation starts, the vessel’s captain uses weather forecast to check when the weather conditions are expected to be suitable to perform installation activities in the coming days. Harsh weather conditions during the installation lead to delays. If the installation activities are not finished within the vessels’ charter periods, the OWF developer has to charter in new vessels, which can take up to two years in waiting time before the installation can continue. In addition, costs re-



lated to loss of energy production associated with installation delays are considered.

This thesis aims to develop methods that can support decisions in the offshore wind industry. The method finds the optimal vessel chartering strategy for the installation of OWTs. Considering the high weather uncertainty, the OWF developers' low ability to bear the risk, and the lack of a standard contract, there is a need for better risk-sharing. Risk sharing is also related to bankability, which can be defined as "the willingness of well established financial institutions to finance a project or proposal at a reasonable interest rate" (Spacey, 2017). Assessing lump sum contracts can lead to a better understanding of cost, more effective risk sharing, and the banks will be more positive to finance a project in which risks are transferred to contractors (Interview with Hjort). The changing market conditions in OWT installation causes uncertainty, and contractors can rely less on experience when evaluating contracts (Interview with Fred. Olsen Windcarrier). In addition to the vessel chartering periods, the pricing of a contract in which the vessel owner bears the weather risk will be studied.

Research on optimization in offshore wind farm installation is scarce. To our knowledge, only two papers (Ursavas (2017), Barlow et al. (2018)) propose a stochastic model to handle weather uncertainty. Ursavas (2017) assumes that only one vessel performs all activities. Barlow et al. (2018) consider uncertain activity durations, but they only consider the most weather-dependent activities. Literature for project scheduling and simheuristics is studied in order to exploit new modeling possibilities for the installation fleet and installation activities.

The thesis is an extension of our earlier work Voster & Kjelby (2019), which is a stochastic fleet size and mix problem. The model performed poorly when the number of OWTs and weather scenarios were increased. The model was not able to solve the model for real-sized test instances. This thesis is built on the assumption that the type and number of vessels used are decided based on practical considerations. The ports used to load the vessels have a limited area, and the material handling in port is complex, especially when many vessels are used, which limits the fleet size (Interview with Fred. Olsen Windcarrier). There are few of these specialized vessels worldwide, and chartering the "optimal fleet" would be challenging. The choice of fleet mix depends on the characteristics of the wind farm site, such as depth and hub height of the turbine. For the largest offshore wind farms, it can be an alternative to charter two installation vessels of the same type to reduce costs,

assuming the practical considerations mentioned are satisfied (Interview with Fred. Olsen Windcarrier). This can be analyzed through a what-if analysis.

This thesis focuses on a stochastic element of offshore wind installation, namely weather uncertainty. As mentioned earlier, weather delays cause huge costs. A method that can reveal the expected cost taking various weather scenarios into account and finds the trade-off between the consequences of not finishing the wind farm, and the cost of including slack in the chartering periods, is highly valuable. Also, a reasonable price for a lump sum contract is hard to decide if weather uncertainty is not considered. Information about contract risk is valuable when dealing with challenges related to market relatedness. To handle the complexity of large test-instances and uncertainty, a tabu search heuristic using a simulator for evaluating the objective value in each scenario is developed.

This thesis is organized as follows: Background information of the problem is provided in Chapter 2. The problem considered is described in Chapter 3. A study of related literature is presented in Chapter 4. Chapter 5 presents a mathematical model of the problem described. Chapter 6 is a description of the tabu search heuristic used to solve the mathematical model presented, and Chapter 7 describes a simulator used within the heuristic. Chapter 8 discusses how to find a reasonable price for a lump sum contract. A computational study is conducted in Chapter 9. Chapter 10 offers concluding remarks on the findings of this report. At last, Chapter 11 discusses future research.

## 2 Background

The purpose of this chapter is to provide information about the installation of offshore wind farms. First, Section 2.1 describes the main installation activities of an offshore wind farm. Further, the effect of weather on the installation is described in Section 2.2. Different vessel concepts used for the installation is described in Section 2.3.1. Lastly, vessel contracts and its features are described in Section 2.4.

### 2.1 Installation activities

In this report, the components discussed are the substructure, the top structure, and the cables. Each of these components has different activities required, depending on the project. In the following section, the components and their corresponding installation activities are explained.

#### 2.1.1 Substructure

The substructure is the first component to be installed. There exist several types of substructures, which can be divided into bottom fixed foundations and floating foundations (Wu et al., 2019). Bottom fixed foundations are used on depths less than 50 meters and include monopiles, gravity based substructures, jackets and tripods.

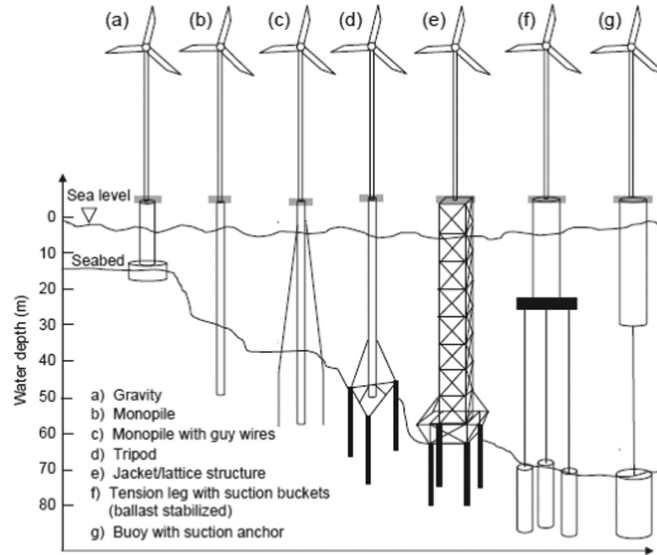


Figure 3: Bottom fixed foundations. Illustration: *Offshore Wind Farms* (p 589).

For depths more than 50 meters, floating foundations are used (Wu et al., 2019). Monopiles accounted in 2016 for about 80 % of the foundations used for offshore wind turbines (Wang et al., 2018), and is thus the most used foundation. However,

floating foundations experience increased interest over the last years due to many countries do not have a coastline with water depths above 50 meters (Wu et al., 2019).

The installation activities required for the substructure depends on the foundation chosen for the project. Monopiles require a vessel that can keep the monopile in place while it uses a hammer to drill it into the seabed (Ng & Ran, 2016). On the other hand, the jacket and tripod foundations are mounted to the seabed by suction buckets. Suction buckets do not require mechanical force such as the monopile, but relies on the pressure difference between the inside and outside of the bucket (Ørsted, 2019). Gravity based foundations are placed directly on the seabed, and may, therefore, require seabed preparations on beforehand. After the placement of the gravity based foundation, they are filled with ballast in order to fix the foundation to the seabed (Asparpour, 2016). In the case of using floating foundations, the offshore wind turbine is normally assembled onshore and towed to the wind farm site (Interview with Equinor ASA).

In order to connect bottom fixed foundations to the top structure, a transition piece is required. In addition, to be a connection between the bottom and top structure, the transition piece possesses features which enable maintenance of the offshore wind turbine such as boat landing, ladder placement, and a work platform (Ng & Ran, 2016). The transition piece is installed by lifting and mounting it to the bottom fixed foundation. The installation of the transition piece takes about 24 hours (Paterson, D'Amico, Thies, Kurt & Harrison, 2018).



Monopiles for Taiwans first offshore wind park are ready for transportation Photo: Recharge. Transition pieces installed offshore Photo: Wilson Walton.

Figure 4: Monopiles and transition pieces.

### 2.1.2 Top structure

The top structure of the OWT consists of a nacelle, a rotor hub, blades and a tower (Ng & Ran, 2016). The nacelle contains the power generation system of the offshore wind turbine and is assembled together with the rotor hub. The rotor hub ensures that the system is able to rotate. The blades are connected to the rotor hub. Wind speed increases with height, and the more wind speed, the more energy can be converted to electricity. The tower provides height to the turbine and connects the substructure to the rotor-nacelle assembly.



Figure 5: Top structure. Photo: Power Gen Advancement.

In order to reduce the number of installation activities offshore, it is common to assemble components of the top structure onshore. The tower is installed by lifting it on top of the transition piece, and then bolt it (Ng & Ran, 2016). Then the rotor-nacelle assembly is installed. The blades can be pre-assembled to the rotor-nacelle assembly onshore. If the blades are not already connected to the rotor, they are mounted to the rotor offshore. It is proven efficient to use a "bunny ear strategy", which means to assemble two blades to the rotor-nacelle assembly onshore, and the last blade offshore (Ng & Ran, 2016). It could also be possible to connect the third blade onshore, but this requires a special deck configuration on the installation vessel.

### 2.1.3 Cables

In order to connect the OWT generators to the electricity grid, the following are required; an offshore substation, export cable, and inter-array cables, as shown in Figure 6. The offshore substation is a platform containing transformers that stabilize and maximize the voltage of the OWTs. It is used an inter-array cable between the OWTs and the offshore substation (Ng & Ran). Between the offshore substation and the onshore substation, an export cable is used. Cables are installed using specialized vessels. After installing the cables, the cables are buried due to safety regulations (Paterson et al., 2018).

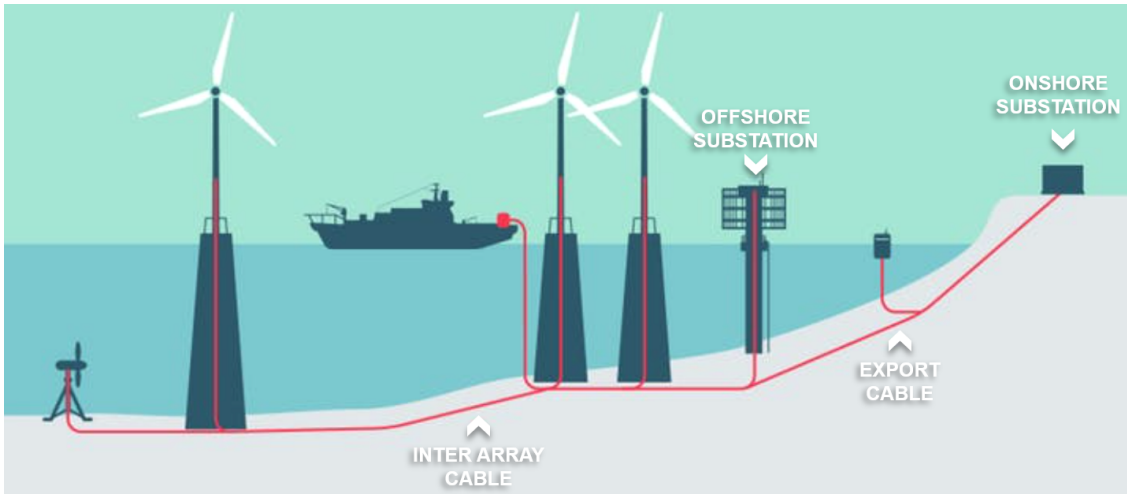


Figure 6: Illustration of the cable network. Photo: CWind Taiwan.

The installation of inter-array cables is done after the installation of the transition piece and before the installation of the top structure. The installation of the substation and the export cable can be done in parallel with installing the foundations and the inter-array cables (Barlow et al., 2018).



Figure 7: Inter-array cable installation at the offshore wind farm SeaMade with the cable installation vessel Living Stone. Photo: Ocean Energy Resources.

## 2.2 Weather downtime

Weather conditions restrict the OWF installation activities. The activities are only performed on days with low wave height and wind speed, to reduce the risk of installation failure or vessel accidents. The duration of the activities and operational limits are varying depending on the vessel type used. However, an approximation is outlined below.

Table 1: Task durations and operational limits. Table from Paterson et al. (2018)

<b>Phase</b>	<b>Reference duration (h/OWT)</b>	<b>Max. Wind Speed (m/s)</b>	<b>Max. Wave Height (m)</b>
<b>Foundation</b>	48	12	2
<b>Transition Piece</b>	24	12	2
<b>Top structure</b>	24.5	8	2
<b>Cable installation</b>	31.7	15	1.5
<b>Cable burial</b>	36	12	3

The number of operational days is often limited, causing a delay in the installation process. As this uncertainty affects the cost of the project, weather stations are placed at OWF sites, to gather weather data. For instance, the wind farm operator Equinor usually analyses fifty years of weather data for a particular site (Interview with Equinor ASA). As the weather conditions are usually better in the summer than during winter, it is most convenient to perform installation activities during summer.

The captain of the installation vessel decides whether to operate or not, on a daily basis. When the short-term weather forecast shows a weather window long enough to complete an activity, the installation vessel starts to operate. A weather window is defined as the time period needed below operational limits for a particular activity. When the weather conditions rise above the operational limits, the vessels wait at the site (Interview with Fred. Olsen Windcarrier).

## 2.3 Vessel concepts and capabilities

The transportation of installation components from port to OWF site can be done by two approaches. The first approach is to use the installation vessels to transport the components. The second approach is to use separate transport vessels to transport the components to the site, and then the components are lifted upon the deck of the installation vessels. The cost of chartering transport vessels is significantly lower than for installation vessels. According to the wind farm operator Equinor, both methods are used (Interview with Equinor ASA). Besides, foreign-built installation vessels cannot dock at ports in the US, and thus the second approach must be used (Interview with Fred. Olsen Windcarrier). When the distance from port to the site is long, and as the transportation vessels are cheaper than installation vessels, it might be beneficial to use the second approach to reduce the chartering cost.

In the last decade, the turbine size has increased, and there is a demand for vessels specialized for OWF installation. For instance, OWF installation requires large deck space, lifting capabilities, dynamic positioning and improved maneuvering in severe weather (Wikborg Rein, 2017). The vessels presented in the next section includes a new vessel concept, namely the wind turbine installation vessel, and traditional offshore installation vessel concepts.

### 2.3.1 Overview of vessel types

In the installation process of OWFs, different vessel types are required for different purposes. An overview of vessel capabilities and prices is given below. The day rates and capabilities for the vessels are taken from BVG Associates (2019) and Ahn, Shin, Kim, & Kharoufi (2016). The day rates for a crane vessel can be assumed to be proportional to its lifting capacities (BVG Associates, 2019). Vessels that perform the activities effectively are more costly than slower vessels. Specialized vessel types such as a Turbine Installation Vessel (TIV), are often chartered years in advance and are difficult to charter instantly as the supply is low for these vessels. To charter a TIV instantly, it needs to be built for the same type of turbine like the one being installed. This is because the vessels need infrastructure on the deck, which takes two years to plan and build (Interview with Fred. Olsen Windcarrier).



Table 2: Overview of vessel types.

Vessel type	Description	Capacities	Day rate (USD)
Heavy lift vessel (HLV)	<ul style="list-style-type: none"> <li>- Can move very large loads</li> <li>- Able to partially submerge</li> <li>- At least one crane on board</li> <li>- Low in supply, more difficult to charter on an urgent order</li> <li>- Not possible to elevate (like a jack-up)</li> <li>- No water depth limitations</li> </ul>	Crane capacity: 1600-5000 ton Loading capacity: 13 000 - 48 000 ton	Approx. 220 000
Wind turbine installation vessel (TIV)	<ul style="list-style-type: none"> <li>- A specialised Jack-up vessel for turbine installation</li> <li>- Self-elevating,</li> <li>- Self-propelled</li> <li>- Dynamic positioning system</li> <li>- High maneuvering capabilities</li> <li>- Water depth limitations</li> </ul>	Crane capacity: 800–1500 tonnes Loading capacity: 1500–8000 ton	150,000– 250,000
Jack-up Barge (JUB)	<ul style="list-style-type: none"> <li>- Self-elevating</li> <li>- Fleet consist of tug boat and cargo barge</li> <li>- Water depth limitations</li> </ul>	Crane capacity 200–1000 ton Loading capacity: approx. 800 ton	100 000 – 180 000
Cargo barge	<ul style="list-style-type: none"> <li>- Cargo only</li> <li>- Large deck area</li> </ul>		30 000 – 50 000
Tugboat	<ul style="list-style-type: none"> <li>- Used to tow crane barge, jack up barge and cargo barge</li> </ul>		1000 – 5000
Cable laying vessel (CLV)	<ul style="list-style-type: none"> <li>- Installing the inter-array cables and the export cable</li> <li>- Contains a remotely operated underwater vehicle (an underwater mobile device)</li> <li>- Cable-handling equipment</li> <li>- Crane</li> </ul>		Approx. 100 000
Cable burial vessel (CBV)	<ul style="list-style-type: none"> <li>- Used in the burial phase of the cable</li> <li>- Crane</li> <li>- Burial tools and equipment</li> </ul>		Approx. 105 000



(a) Heavy lift vessel Alfa Lift owned by Offshore Heavy Transport AS. Photo: Offshore Heavy Transport.



(b) Heavy lift vessel Alfa Lift in Submerged condition (owned by Offshore Heavy Transport AS). Photo: Offshore Heavy Transport.



(c) Wind turbine installation vessel MPI Resolution owned by MPI offshore. Photo: MPI offshore.



(d) Wind turbine installation vessel MPI Resolution in jack-up position. Photo: MPI offshore.



(e) Jack-up barge Sea Worker owned by A2SEA. Photo: Marinelog.



(f) A cargo barge owned by Wagenborg. Photo: Wagenborg.

Figure 8: Installation vessels



(a) Cable laying vessel Skandi Hav owned by DOF group. Photo: DOF .  
 (b) Cable burial (multi purpose) vessel Skandi Vinland owned by DOF group. Photo: DOF.

Figure 9: Cable vessels

### 2.3.2 Comparison of installation vessels

Of the vessels mentioned in Table 2, only TIV and JUB have the abilities to self elevate (jack-up). The not-propelled JUB is towed by tugboats, and cargo barges can be used to supply components to the crane.

For the installation of fundamentals, TIV or JUB are preferred for OWFs close to shore, while HLV is preferred for OWFs with a longer distance from shore (Paterson et al., 2016). OWFs placed a great distance from shore experience worse weather, and the preference for HLV is caused by the need to reduce material handling at the site. HLV have higher loading capacities, and thus the number of loading activities is reduced. When the foundations exceed 1,000 tons, the need for HLV also increases as these vessels have higher lifting capacities (BVG Associates, 2019).

For the installation of transition pieces, TIV is preferred for OWFs close to site, while JUB are preferred for OWFs further from shore (Paterson et al., 2016). The choice for the vessel in this phase also depends on the needed lifting power. For the installation of top structures, TIV and JUB are preferred for OWFs close to shore, while only the TIV is preferred for OWFs further from shore (Paterson et al., 2016). The number of components a vessel can load, depends on the size of the turbines.

The differences between possible CLVs and CBVs are small, and thus a comparison is not necessary.

## **2.4 Contracts and risk**

Vessel chartering contracts for OWF installation lack standards. Contract prices are determined by tendering and negotiations (Interview with Fred. Olsen Windcarrier). In Section 2.4.1 a description of chartering vessel contract terms are given. In Section 2.4.2 the sharing possibilities of risk in a contract are described.

### **2.4.1 Day rates and extension options**

The terms "day rates" and "extension options" are used to describe contracts. Day rates can be understood as the daily market prices when chartering a vessel. An extension option gives the ability to extend the charter period. The extension option is included in the contract for an inclusion price, and if the extension option is exercised, the charterer pays an exercise price. Hence, a contract consists of a fixed number of days and an extension option period. If an extension option is exercised, the whole extension option period is added to the charter period. Further, the charterer often wants sequences of short extension options to gain flexibility, while it is more attractive for the shipowner to have longer option periods to gain predictability. Hence, including short sequences of extension options in the contract is more expensive than including the same number of days in one extension option. The price of exercising an extension option can be assumed to be day rates multiplied with the extension option period (Interview with Fred. Olsen Windcarrier).

### **2.4.2 Weather risk and lump sum**

As previously identified, weather downtime can cause delays and economic loss during OWF installation. The developer of the OWF seeks to transfer the risk to its contractors, to reduce the total project risk and potential economic loss. Often experience from O&G projects is used as a basis for contract setup. Yet, two important factors differentiate OWF installation from O&G projects. Firstly, OWF projects are more sensitive to weather delays, meaning a larger variance in project duration estimation. Secondly, the developer of a OWF project is less capable of bearing risk than an O&G company (Interview with Hjort).

In contract sharing theory, the company with the lowest risk aversion bear the majority of the risk, and low-risk aversion is associated with a large portfolio of projects (Olsen & Osmundsen, 2005). On the other hand, contractors with a low number of projects, are more risk-averse and thus less capable of bearing risk. In

O&G, usually the developer bears the risk, as these have a high economic capacity and a large portfolio of projects. For OWF projects this is less relevant than in O&G projects. This is due to the low margins in OWF, which pushes the OWF developer to transfer risk to its contractors (Interview with Hjort). However, few contractors are accepting to bear the weather risk today and would require a high risk premium to accept it. The lack of standard contracts in OWF installation, and little experience of sharing risk results in an unclear risk profile for the contractors and little willingness to bear the risk (Interview with Fred. Olsen Windcarrier).

There are mainly two contract setups which are used in offshore construction projects: (1) Fixed charter period at day rate price with possibilities of including extension options and (2) Lump Sum contract in which the vessels are chartered until the tasks are finished for a fixed price (Ahlgren & Grudic, 2017). In the first contract, the developer bears the weather risk, while in the lump sum contract, the vessel owner bears the weather risk. For the vessel owner to accept a lump sum contract, a risk premium must be added to the lump sum. For now, the risk premium must be huge, due to the uncertainty and unclear risk profile, which results in contract type one is used instead.

### 3 Problem description

The problem studied in this thesis is to minimize the expected cost of chartering installation vessels for the installation of an offshore wind farm. The goal is to decide the charter lengths, overlapping of operating vessels, and which extension options to include in the contract for each vessel. In addition, an OWF developer seeks to transfer weather risk to its contractors, and therefore the pricing of a lump sum contract is studied. The OWF developer can offer the vessel owner a lump sum contract for a reasonable price, considering the risk level of the OWF developer. If the vessel owners do not accept the price, the OWF developer bears the weather risk.

An offshore wind farm installation process can be divided into a set of activities. An OWT consists of components that are assembled offshore. The assembly process depends on the type of substructure used, as described in Section 2.1.1. In addition to the OWT components, cables are laid and buried between the foundations. For instance, if turbines with monopile substructures are considered, the installation activities are; foundation, transition piece, cable laying, cable burial, and top structure. Some activities must be done before other activities can start (precedence restrictions); the installation of the substructure must be finished before the cable laying and burial, and the cable laying must be finished before the top structure is installed. Activities that do not require precedence can be performed simultaneously; for example, the cable laying can start before all transition pieces are installed, given that there are installed transition pieces that do not already have a cable laid. The installation of the export cable and the substation are only done once for each offshore wind farm, and can be done independently of the other activities. Therefore, these activities are not studied in this thesis.

The activities described above are performed by specialized vessels (Section 2.3.1). A fleet consisting of a mix of specialized vessels is required in order to perform all activities. The essential technical specifications of the vessels are loading capacity and lifting capacity. Other limitations for vessels include the water depth the turbines are installed at and the hub height of the turbine that the vessels are capable of installing. For instance, to install turbines with high hub heights, a vessel that can jack-up is required. On the other hand, jack-up vessels have water depth limitations and can not jack-up on deep waters. Besides the vessels' capacities and capabilities, the vessels differ in day rates and fixed chartering costs. In addition, the duration to perform an installation activity varies from vessel to vessel. Activities are also

performed during the night and weekends because the additional cost of performing at these periods is significantly lower than the charter rates (Energinet DK, 2015)

The OWT installation components are loaded on the installation vessels in loading sets. As mentioned in Section 2.3.1, loading sets can be transported to the site by two approaches: the installation vessels sail round trips from site to port for loading or use dedicated transport vessels to transport loading sets to site. If the last approach is used, the structures must be lifted from the transportation vessel to the installation vessel at the site. In this period, the installation vessel can not be used for other installation activities. When required, the components are available at the installation site, as the operational limits are higher for transporting activities than installation activities. The components in a loading set are predefined, to reduce the challenges related to material handling in port.

The vessels are chartered on contracts which are decided years in advance of the installation. In the contract, the charter length and number of extension options are decided. The installation vessels are subject to weather restrictions. The installation vessels cannot operate safely under conditions with high wind speed and wave height. The vessels start to operate every day when the weather is within limits. The days when the vessel cannot operate, it waits at the site until a new weather window starts. The maximum wind speed and wave height for the activities can be found in Section 2.2. For instance, the installation of the top structure is more sensitive to harsh weather conditions than the installation of the substructure. As long as the weather conditions are below weather restrictions, bad weather does not extend the duration of performing an installation activity. The weather is unpredictable, and it is difficult to estimate the number of days the vessels cannot perform installation activities. The challenge lies in the timing of the charter period decisions and the weather realization. The charter period decisions are usually made about two years before the installation starts, and the weather is realized during the installation. When the weather is realized, the only way to extend the charter period is to exercise extension options.

When the weather is realized, the following decisions must be taken: in which time period are the activities performed, the loading sets each vessel is loaded with, and the time periods the vessels will reload are decided. At last, the necessary extension options must be exercised.

The value of a solution is measured by: the length of time the vessels are chartered and their respective day rates, the total costs of including extension options, the cost of exercising options, the loss of production for each day the wind farm is not finished and a possible penalty for not finishing the wind farm. The loss of production is an important factor in giving incentives to finish the wind farm as fast as reasonably possible.



## 4 Literature review

The purpose of the literature review is to provide an overview of current literature relevant to applying an operation research approach to the installation of OWFs. The literature on this topic is limited, and a wider literature search is thus needed. In Section 4.1, the literature search strategy is described. Literature related to the optimization of offshore wind farm installation is reviewed in Section 4.2. The solution methods applied to these problems are described in Section 4.3. In section 4.4, we investigate the project scheduling literature and its similarities to our problem. Next, a heuristic solution methods for stochastic problems are looked into in Section 4.5. Lastly, Section 4.6 describes how the model presented in this paper relates to existing literature and its contribution to the existing literature.

### 4.1 Literature search strategy

The literature search is divided into three parts. The first part finds relevant literature on applying operation research to the installation phase of offshore wind farms. The search words Table 3 were used to widen the literature search from OWF charter strategy to issues relating to schedule and uncertainty. The second part relates to the project scheduling literature, which is investigated as the OWF installation literature is limited, and because of its similarities with our problem. The literature is extensive in this area, and the search words in Table 3 are used to limit the search. The third part investigates heuristic solution methods in which the focus is simulation integrated into a heuristic framework. In this part, only papers related to projects and a stochastic environment are reviewed, to limit the search.

Table 3: Search words

<b>Offshore wind farm installation</b>	<b>Project scheduling</b>	<b>Heuristics for stochastic problems</b>
Weather Schedule Uncertainty Resources	Resources Uncertainty Heuristics Risk	Weather Two-stage Project makespan Resources

## 4.2 Offshore wind farm installation

In this section, relevant literature regarding operation research within offshore wind farm installation is presented. First, relevant literature considering the objective function is presented, precedence and loading sets is presented. Moreover, literature considering weather, fleet composition, simulation and solution methods is presented.

### Objective function

There exist two main goals when installing an offshore wind farm, minimizing the cost of the installation phase and minimizing the time of the installation phase. These are often conflicting objectives (Interview with Equinor ASA). Scholz-Reiter, Heger, Lütjen & Schweizer (2011) and Barlow et al. (2018) suggest models which minimize the time to build the wind farm. Ursavas (2017) suggests a two-stage stochastic model which minimizes the expected completion time over several weather scenarios. Ait-Alla, Quandt & Lütjen (2013), Sarker & Faiz (2017) and Hansen & Siljan (2017) minimize the cost of installing the wind farm. Hansen & Siljan (2017) suggests to add a penalty in the objective function in order to also minimize the completion period. Irawan, Jones & Ouelhadj (2017) puts forward a bi-objective model which minimizes both total completion period and cost.

### Precedence

Scholz-Reiter et al. (2011) presents a mixed integer linear programming (MILP) model which takes precedence into account. Precedence between the components are modeled by considering the number components which are already installed, as an inventory level. Then it is required that the number of components to be installed is less than or equal the inventory level of the immediate predecessor. For instance, the number of top structures is less than or equal to the number of sub structures already installed. The same approach is later used by Ait-Alla et al. (2013), Ursavas (2017), Hansen and Siljan (2017) and Irawan et al. (2017). Barlow et al. (2018) use precedence relation constraints based on a project scheduling approach. Project scheduling is further discussed in Section 4.3.

## Loading sets

Several of the existing models use predefined loading sets in their modeling (Scholz-Reiter et al., 2011; Ait-Alla et al., 2013; Irawan et al., 2017; Ursavas, 2017; Hansen and Siljan, 2017). A loading set is defined as the number of each type of components which can be loaded to a dedicated vessel. This means that each vessel has several possible loading sets. For example, a possible loading set could be to load four sub structures and two top structures, while another one is to load two sub structures and four top structures. The loading sets are used to specify that a vessel only can install components which belong to its loading set. The feasible loading sets for each vessel must be defined by the user in advance of the run.

## Weather

Scholz-Reiter et al. (2011), Ait-Alla et al. (2013), Irawan et al. (2017) and Hansen & Siljan (2017) propose models which all considers the weather limitations. Weather is modeled by conditions - good, medium and bad weather, and the components loaded on the vessel is dependent upon the condition of the weather. However, these models are deterministic and does not take into account the uncertainty in the weather. In order to take uncertain weather into account, it is suggested to run the model for different weather scenarios (Scholz-Reiter et al., 2011; Irawan et al., 2017; Hansen and Siljan, 2017) or to use the arithmetic mean of historical weather data from the past 50 years (Ait-Alla et al., 2013).

Ursavas (2017) introduce a two-stage stochastic integer program which is based upon the MILP developed by Scholz-Reiter et al. (2011). The first stage decision is the charter period of the vessel. Weather information is realized in the second stage. If the weather realized implies that the planned activities cannot be accomplished, the second stage decisions are whether to delay the installation activity or to chose another installation activity if it is possible given the weather. This model takes the stochastic nature of the weather into account by minimizing the expected value of the completion period over many weather scenarios.

Barlow et al. (2018) suggests to use a mixed-method approach to handle the weather uncertainties. In order to measure the effects different starting times give, a simulation model is developed. The optimization model decides the schedule, and is based on a robust optimization method. At first, the project duration is minimized deterministic. Secondly, it is determined how sensitive the project duration is to changes in the durations of the installation activities. This method implicitly takes

weather into account, as weather may affect the durations. Then it is determined which tasks affects the installation the most, and these tasks are scheduled to optimality.

### **Fleet composition**

Several of the mathematical models proposed are restricted by only considering one vessel in the installation fleet. The models of Scholz-Reiter et al. (2011), Ursavas (2017), Sarker and Faiz (2017) and Barlow et al. (2018) assume that all installation activities are done by one vessel. The model suggested by Ait-Alla et al. (2013) and Irawan et al. (2017) includes the flexibility of including more than one vessel in the model. The vessels are input to the model, which means that the optimal fleet mix is not decided by the models proposed. Hansen & Siljan (2017) proposes a model which decides the optimal fleet size and mix.

### **Simulation**

Tyapin, Hovland & Jorde (2011) use Monte Carlo Simulation to estimate the duration of marine operations. The uncertainty in weather is taken into account when estimating the duration. However, the study only concerns one offshore wind turbine. Lange, Rinne & Haasis (2012) have developed a simulation tool which simulates the total value chain of an offshore wind turbine, which starts at the processing of the components, and ends at the installation of the components offshore. Due to the wide scope of the decision tool, the installation process is quite simplified compared to other models focusing on only the installation process. Barlow et al. (2018) provides a mixed-method framework decision tool. Optimization is used for scheduling the installation of the offshore wind turbines. Simulation is used to simulate the effect on the project duration of changing the start date of the project, where different weather scenarios represents the uncertainty.

### **Solution methods**

Several of the models proposed require a solution method to solve realistically sized test instances within a reasonable time limit. For the deterministic models, there have been proposed different solution methods. Irawan et al. (2017) suggest a Variable Neighbourhood Search and Simulated Annealing to solve the model with realistically sized test instances. Sarker & Faiz (2017) suggest that an exhaustive search method is sufficient due to the limited solution space. Hansen & Siljan (2017) use a solution method by reformulating the mathematical model to a pattern based model and solve the model by pattern generation.

Ursavas (2017) and Barlow et al. (2018) propose stochastic models. Ursavas (2017) propose to use Benders' decomposition to solve realistically sized test instances. Barlow et al. (2018) propose a simulation model for scenario evaluation and an exact optimization model that finds the installation activities' optimal schedule.

### 4.3 Project scheduling

The literature on OWF installation is limited, and a further investigation of solution methods for similar problems is needed. Our problem is closely related to the project scheduling literature in terms of sequencing installation activities and minimizing the project's expected makespan or the expected total cost. Several variants of the project scheduling problem also include stochastic elements, such as stochastic activity duration and stochastic weather.

A variant of project scheduling is the resource constrained project scheduling problem (RCPSP), which involves resource constraints, and the aim is to minimize the project duration, concerning the resources each activity requires. The activities have precedence constraints, meaning that an activity cannot start before a subset of activities are finished. The basic model considers renewable resource constraints, which means the resource capacity is renewed in every period. The constraints of a simple RCPSP model can be described by the following equations (Creemers, 2017):

$$s_i + d_i \geq s_j \quad \forall i, j \in E \quad (4.1)$$

$$\sum_{i \in \mathcal{A}(s,t)} r_{ik} \geq R_k \quad \forall t \geq 0, \quad \forall k \in K \quad (4.2)$$

$$s_i \geq 0 \quad \forall i \in V \quad (4.3)$$

in which  $s_i$  is the start time for activity  $i$ ,  $d_i$  is the duration of activity  $i$ , and there is precedence between activity  $i$  and  $j$ , implying that  $i$  must be performed before  $j$ .  $E$  is the set of precedence relations. Next, constraint 4.2 ensures that the number of resources used for active jobs must be lower than or equal to the available resources.  $r_{ik}$  is the amount of resource  $k$  used for activity  $i$ .  $K$  is the set of resources, and  $R_k$  is the number of renewable resources for  $k$ .  $V$  is the set of activities in the project. At last,  $\mathcal{A}(s, t) = \{i \in V : s_i \leq t \wedge (s_i + d_i) > t\}$  defines the jobs active in  $t$ . This model is nonlinear, and must, therefore, be linearized before implementation in a commercial solver.

Kerkove & Vanhoucke (2016) studies a problem similar to ours; how to optimize the scheduling of weather-sensitive offshore construction projects. It considers the activity durations and weather conditions as stochastic variables. The required resources must be available to start an activity, and its activity predecessors must be finished. In this case, the construction vessels are the required resources. For a resource to be available, the weather must be within operational limits, and the vessels must be chartered. An optimization heuristic is proposed to create schedules for the construction project, which is passed to the simulation procedure to evaluate the expected net present value ( $E[NPV]$ ) of the project schedule. The  $E[NPV]$  is passed back to the optimization heuristic to guide to better schedules. The stochasticity is handled by defining probability distributions of activity duration, and running the evaluation simulator for different activity duration and weather realizations to get an NPV. To estimate the  $E[NPV]$ , several runs of the simulator are needed.

As most RCPSPs focus on minimizing the expected makespan of a project, a variant known as the Resource Renting Problem "aims to minimize the costs associated with renting resources throughout the project. These costs include both fixed (setup) costs and variable costs that are a function of the time a resource is used" (Kerkhove, Vanhoucke & Maenhout, 2017). In our problem, the fastest schedule is not necessarily the cheapest schedule in terms of high chartering cost of vessels and the likelihood of waiting for predecessors to be finished before a vessel can start performing activities. This variant has in similar to our problem a different goal and a has a more complex resource structure as resources are not assumed to be renewed, but are time dependant. Vandenheede, Vanhoucke & Maenhout (2015) and Kerkhove, Vanhoucke & Maenhout (2017) have suggested heuristic methods to solve chartering processes, however only within a deterministic setting.

The papers mentioned apply heuristics to solve the project scheduling problems. This is usually because, as these problems are NP-hard, heuristic methods reduces the computation time for large-scale problems yet can find near-optimal solutions (Mahapatra, Dash & Pradhan, 2017). In Section 4.4.2 a review of heuristic solution methods combined with simulation applied to stochastic project scheduling is given.

## 4.4 Heuristics for stochastic problems

Our experience from earlier work (Voster & Kjelby, 2019), which assumptions are close to this problem, required a lot of computational effort to represent a realistic number of wind turbines. Another feature of our problem is that information about the weather is uncertain when several decisions are made, which increases the complexity of the optimization problem. Heuristics are alternatives to exact algorithms, capable of finding good and sometimes optimal solutions to problem instances of realistic size, in a generally shorter computation time.

### 4.4.1 Introduction to a simheuristic approach

The difficulty of evaluating the objective value for a given solution in a stochastic problem is often greater than in a deterministic problem. As the weather conditions are uncertain in the first stage, an exact evaluation of a candidate solution is impossible. However, sampling can be used to estimate the value of a solution for a stochastic problem, and the number of weather scenario samples used to estimate the solution is a trade-off between precision and computing time (Hvattum & Esbensen, 2011). Commonly, simulations are used to evaluate solutions in heuristics for stochastic problems. Simheuristics is a class of optimization algorithms which "integrates simulation into a metaheuristic-driven framework" and can deal with stochastic combinatorial optimization problems (Juan, Faulin, Grasman, Rabe & Figueira, 2015).

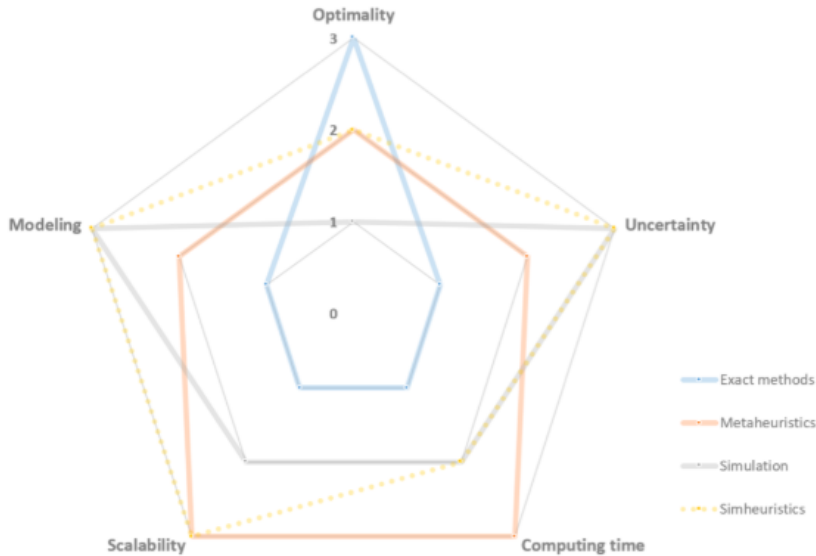


Figure 10: Comparison of optimization approaches based on their performance with respect to different dimensions. From Chica, Juan, Cordon & Kelton (2017).

Chica, Juan, Cordón & Kelton (2017) distinguish the methodologies; Exact methods, Metaheuristics, Simulation and Simheuristics into five dimensions; optimality (capability to find the optimal solution), scalability (ability to handle large-scale problems), modeling (capability to model real-life problems, without simplifications), uncertainty (ability to handle uncertain parameters), and computing time (how fast large-scale problems are solved). Figure 10 shows a comparison of how the methodologies scores on the dimensions, where the outer core is a high score. It shows that simheuristics are applicable for large-scale problems dealing with uncertainty when the problem investigated is complex to model and when an exact solution is not required. Metaheuristics require less computing time than simheuristics. However, simheuristics perform better at dealing with uncertainty and complex modeling, which are important features of our problem.

#### **4.4.2 Simheuristics within project scheduling**

A simheuristic approach is often proposed to project scheduling problems with stochastic processing times (Herroelen & Leus, 2005). Vonder, Demeulemeester, Herroelen & Leus (2007) aims at finding the trade-off between stability and makespan in project baseline schedules by inserting time buffers. Several scheduling heuristics are proposed with different priorities. For each schedule, they measure the stability performance (the difference between the planned and realized start times) and makespan performance (expected project duration) by means of simulation.

Baker & Altheimer (2012) and Juan, Barrios, Vallada, Riera & Jorba (2014) use heuristic procedures to schedule the project and simulation to estimate the expected makespan for a project scheduling problem with stochastic processing times. Whereas Baker & Altheimer (2012) assumed normal or exponential probability to model processing times, Juan et al. (2014) uses historical data to model stochastic processing time. It states that the assumption of processing times following a normal distribution is unrealistic and restrictive.

Moreover, Gonzalez-Neira, Ferone, Hatami & Juan (2017) uses biased randomization and simulation to schedule project activities with stochastic processing times, and a GRASP heuristic calculates the expected makespan. This method provides other statistics such as makespan variance, and the simulation component can also perform a risk analysis. This is further discussed in the next section (4.4.3).



In conclusion, a wide range of heuristic frameworks have been published and applied to optimization problems. Papers that have successfully applied heuristics to a problem similar to ours do to our best knowledge not exist. We consider stochastic weather, which leads to a stochastic makespan, but problems in the literature with stochastic processing times focus on finding the optimal schedule, not the optimal rental period of resources. The resource renting literature, on the other hand, has so far only studied deterministic problems. The heuristics applied to these problems seek to find time-slots to perform activities to minimize the expected cost, which has a different optimal solution for each weather scenario we apply in our problem. Our choice of heuristic is discussed in Chapter 6.

#### **4.4.3 Project risk**

Simheuristics can enable risk analysis to stochastic optimization problems, and this is useful as a risk-averse decision-maker want a solution with a lower variability than a more risky solution with a better expected value (Juan et al., 2015). The risk analysis is performed by evaluating different solutions by simulation to make a probability distribution to model the project makespan (Chica et al, 2017).

Although the objective of Gonzalez-Neira et al., (2017) is to minimize the expected makespan of a project scheduling problem, solutions with reduced variability or risk and slightly longer expected makespan, are also identified. When a solution is evaluated in the GRASP framework, both the makespan performance and the associated variance are estimated. Good solutions with low variance are stored.

### **4.5 Our contribution**

Our contribution to this area of research is threefold. First, the problem studied in this thesis has to our knowledge never been studied before. Second, a simheuristic for the two-stage stochastic resource renting problem have been developed. Third, a method for assessing lump sum prices for a different risk profiles in a OWF installation charter contract has been developed.

The problem studied has several differences from the existing literature. Our focus is the optimal charter strategy of expensive resources under weather uncertainty. The problem is modeled as a two-stage stochastic problem, in which the charter period is decided in the first stage, and scheduling in the second. To our knowledge,

this is only modeled for the installation problem by Ursavas (2017). Nonetheless, it does only consider one installation vessel and two types of installation activities. In addition, Barlow et al. (2018) considers uncertain activity durations, but it does only consider the most weather dependant activities. At last, none of the papers reviewed have included extension options in the modeling.

The literature on simheuristics brings important insights on how to deal with uncertainty in our problem. The simheuristic approach is advantageous as our problem will be applied to large-scale problems, is complex to model, and is subject to uncertainty. Further, this methodology allows us to use samples to estimate the value of a solution. As Juan et al. (2014) points out, the most realistic way to model uncertainty is to use historical data. Our modeling is inspired by (Vonder et al., (2007), Baker & Altheimer (2012), Juan et al., (2014) and Gonzalez-Neira et al., (2017)) which develop heuristics which suggest activity schedules, and the expected performance is estimated by simulation. In our case, a heuristic is developed to suggest charter periods, and the expected cost of the vessels is estimated by simulation. The simulation procedure creates schedules for the vessels and activities, with regard to the charter periods the heuristic suggests and returns the cost associated with the solution suggested. The expected cost is estimated by running the simulator for different weather scenarios with defined probabilities, inspired by Kerkove & Vanhoucke (2016).

At last, a need for risk analysis to assess lump sum prices in our problem, has been identified. Chica et al. (2017) suggest to simulate different samples to make a probability distribution, to measure risk. In our case, the risk profile of the decision-maker is represented by a loss distribution function. An objective of Juan et al. (2015) and Gonzalez-Neira et al. (2017) was to identify solutions with lower associated risk, but with slightly higher expected cost and expected makespan. In our case, the goal is to find a reasonable lump sum contract price, which is associated with lower risk and a higher expected cost.

## 5 Mathematical model

This chapter presents a mathematical formulation of the OWF installation described in Chapter 3. Section 5.1 presents the modeling assumptions. Section 5.2 describes the notation used in the model. The mathematical formulation with explanations follows in Section 5.3. Section 5.4 offers linearizations of non-linear constraints and the handling of end effects in 5.5. Section 5.6 introduces symmetry breaking inequalities for the model. Section 5.7 is a discussion of flexibility in the model.

### 5.1 Assumptions

#### Project activities

The installation process is divided into activities, which cannot be paused when started. These activities are modeled as an activity-on-the-node network with nodes as the activities and the arcs as the precedence relations. Precedence relations represent the installation order of components. For instance, the foundation for each wind turbine must be installed before the transition piece. Next, all turbines have to be installed before the project can end.  $i=1$  and  $i=N$  are dummy nodes that represent the start time and end time of the project, respectively. An example of an activity network for a monopile turbine is presented below:

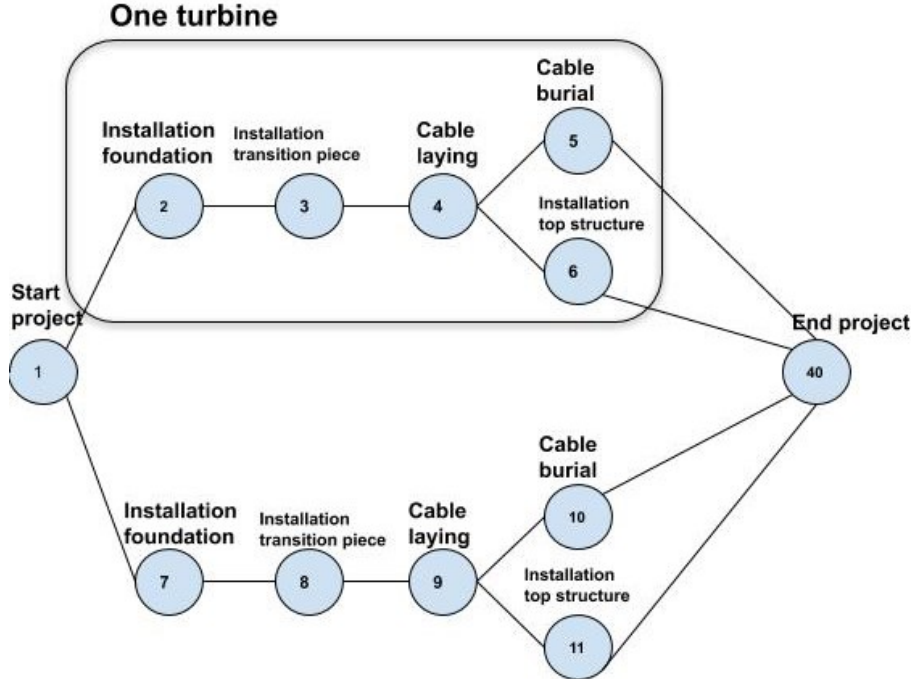


Figure 11: An activity-on-the-node network for bottom fixed monopiles.

The arcs in figure 11 represent the order of the activities. The installation order of the turbines is not specified, except the order of the components for each OWT. Here the transition piece can start if the foundation is installed. The inter-array cables must be laid before both the cable burial and top structure can start. The cable laying and installation of top structure can be done simultaneously. In addition to this example, other activities and precedence relations can be included in the activity set  $N$  or precedence sets  $P_i$ .

### **Two-stage stochastic model**

The OWF installation problem can be divided into two stages. In the first stage, the chartering contract for the installation vessels must be decided; how many fixed days and how many extension options are included. The first stage occurs about two years before the installation starts, and the weather conditions for the installation are uncertain. The second stage of this problem is the actual installation. Although the weather conditions are realized from day to day during a project, it can be assumed that the weather for the entire period is realized at the start point of the installation. This does not affect the solution as all activities start as long as there is an available weather window. Short-term weather forecasts are assumed to be accurate enough to find the duration of the weather window. Further, if the fixed number of days in the contract is over before the wind farm is finished, an extension option must be exercised. The model considers a set of weather condition samples, and the second stage evaluates each weather scenario, given the first stage decision. Each weather scenario has the same probability.

### **Time discretization**

The model assumes time periods can be divided into discrete time periods. Each activity duration is rounded up to the closest multiplier of the discretization. This involves that each activity must start at the beginning of a time period and last the entire period for each period the activity is performed.

### **Extension options**

Extension options for each vessel can be exercised in stage two if the option is bought in stage one. Each vessel can buy several options and only exercise some of them in stage two. This can be understood as a sequence of options extending the charter period.

## Transport

The transportation from port to OWF site is not modelled, if dedicated vessels are used. As described in the problem description (Chapter 3), these vessels are significantly cheaper to charter, and the transportation operation is less weather restrictive than installation. If the installation vessels are used to transport components from port, the sailing time is added to the duration loading time  $D_v^L$

## Components and loading sets

Which components to be loaded on the vessels depend on the immediate planned activities and available deck space onboard the installation vessel. Thus, the model must track how much space each component takes and when the vessels need to load a new loading set. Each vessel has a set of available loading sets, and the model finds the components the loading sets are filled with. Not all loading sets of the available loading sets need to be used. Moreover, loading sets can be predefined. Set  $F_i$  defines activities which must be performed by the same vessel and loading set as activity  $i$ .

## Capabilities and available vessels

Vessels have different loading capacity available denoted  $Q_v$ . The link between the required capability for each activity and the chartered-in vessels are modeled by a set of resource constraints. In addition to loading capacities, an activity might require other capabilities, for instance, lifting capacity over 1600 tons or ability to jack up. If a vessel  $v$  has the required capabilities to perform activity  $i$ , then  $A_{iv} = 1$ .

## Forbidden periods

There are time periods in which vessels cannot perform activities. Firstly, the time periods when the vessel is loading a new loading set, are forbidden. Hence, the resource for the capabilities this vessel has becomes unavailable in these periods. Secondly, activities cannot be performed when the weather conditions are above operational weather limits. This is handled by checking if the consecutive time periods are not forbidden, with regard to the required activity duration.

## Project start time and end time

For convenient reasons, at least one vessel is fixed to start in the first time period. As the weather is uncertain in stage one, and if a sufficient number of weather scenarios are included, the solution will not be affected by the start day. Further, the possible charter start period and end periods for each vessel are predefined. It is

often required to charter vessels from Monday morning to Sunday evening, as the vessel owners require to charter out their vessels a whole number of weeks.

**Risk level**

The model assumes a risk-neutral decision-maker, which implies that the decision-maker chooses the solution with the lowest expected cost, ignoring the risk features relative to the other solutions.

## 5.2 Notation

### Sets

$\mathbf{N}$  Set of activities  $i$

$\mathbf{P}_i$  Set of immediate predecessors of activity  $i$

$\mathbf{T}$  Set of time periods  $t$

$\mathbf{B}$  Set of time periods  $t$  in which charter periods can start (Mondays 00:00).

$\mathbf{E}$  Set of time periods  $t$  in which charter periods can end (Sundays 23:59).

$\mathbf{U}$  Set of extension options  $u$

$\mathbf{V}$  Set of vessels  $v$

$\mathbf{L}$  Set of possible loading sets  $l$

$\mathbf{F}_i$  Set of activities requiring to be performed by the same vessel and loading set as activity  $i$ .

$\mathbf{S}$  Set of scenarios  $s$

### Parameters

$\mathbf{C}_V^F$  Fixed cost of chartering vessel  $v$

$\mathbf{C}_V^V$  Variable cost of chartering vessel  $v$

$\mathbf{P}_{vu}$  Price of including extension option  $u$  for vessel  $v$  in the contract

$\mathbf{E}_{vu}$  Exercise price of extension option  $u$  for vessel  $v$

$\mathbf{L}_u$  Length of period of extension option  $u$

$\mathbf{P}^f$  Penalty representing the loss of production per time period

$\mathbf{P}^w$  Fixed penalty for not finishing the wind farm

$\mathbf{P}^Q$  Variable penalty for not finishing the wind farm

$\mathbf{D}_{iv}^A$  Duration of performing activity  $i$  by vessel  $v$

$\mathbf{D}_v^L$  Duration of loading of vessel  $v$

$\mathbf{N}^A$  Number of activities in set  $\mathbf{N}$

$\mathbf{A}_{iv}$  1 if vessel  $v$  can perform activity  $i$ , 0 otherwise

$\mathbf{Q}_i$  Loading capacity required for activity  $i$

$\mathbf{Q}_v$  Total loading capacity on vessel  $v$

$\mathbf{W}_i^{BMAX}$  Operational wave limit for activity  $i$

$\mathbf{W}_i^{VMAX}$  Operational wind limit for activity  $i$

$\mathbf{M}^P$  Big M used to check if all activities are performed

- $\mathbf{M}_v^F$  Big M used to forbid periods when loading new loading sets
- $\mathbf{M}_{its}^B$  Big M used for wave restrictions
- $\mathbf{M}_{its}^V$  Big M used for wind restrictions
- $\mathbf{p}_s$  Probability of realization of scenario s
- $\xi_s = (W_{ts}^B, W_{ts}^V)$  Realization of random parameters in scenario s, containing wave height realization and wind speed realization in time period t in scenario s

## Variables

- $\beta_{vu}$  1 if extension option u is included in the contract for vessel v, 0 otherwise
- $\mathbf{s}_{vt}$  1 if vessel v starts operating in time period t, 0 otherwise
- $\mathbf{e}_{vt}$  1 if vessel v last period is t for the fixed days in the contract, 0 otherwise
- $\lambda_{vus}$  1 if vessel v exercises extension option u in scenario s, 0 otherwise
- $\mathbf{e}_{vts}^f$  1 if vessel v last operating period is t in scenario s, 0 otherwise
- $\mathbf{p}_{vts}$  1 if vessel v is chartered in period t in scenario s, 0 otherwise
- $\mathbf{z}_{ivlts}$  1 if activity i is performed by vessel v and loading set l starting in period t in scenario s, 0 otherwise
- $\mathbf{x}_{ivts}$  1 if activity i is performed by vessel v in period t in scenario s, 0 otherwise
- $\mathbf{w}_s$  1 if not all activities are performed, 0 if all activities are finished within charter period
- $\delta_{vts}$  1 if vessel v is chartered and not loading a new loading set in period t in scenario s, 0 if vessel v is loading or not chartered
- $\sigma_{vls}$  The first period loading set l is used for vessel v in scenario s
- $\mathbf{f}_{vlt}$  1 if the t is the first period vessel v uses loading set l in scenario s, 0 otherwise
- $\mathbf{e}_s^{Tot}$  The last period of installation in scenario s



### 5.3 Mathematical formulation

A two-stage stochastic model is presented in the following section. Some simplifications are made to make the model more readable. Linearizations of non-linear constraints can be found in Section 5.4 and the handling of end effects in Section 5.5. Symmetry breaking constraints are presented in Section 5.6.

#### 5.3.1 First stage problem

##### Objective function

The objective function (5.1) minimizes the total expected cost of chartering the installation fleet. The first term contains the variable cost of chartering the vessels expressed by day rates, while the second term contains the fixed cost of chartering the vessels. The third term includes the cost of buying extension options. The fourth term includes the expected cost of exercising options, the expected penalty of not finishing the wind farm, and the expected loss of production.

$$\begin{aligned} \min z = & \sum_{v \in V} \sum_{t \in T} C_V^V (te_{vt} - ts_{vt}) + \sum_{v \in V} C_V^F + \sum_{v \in V} \sum_{u \in U} P_{vu} \beta_{vu} \\ & + \sum_{s \in S} p_s Q(e_{vt}, \beta_{vu}, s_{vt}, \xi_s) \end{aligned} \quad (5.1)$$

##### Charter constraints

Constraints (5.2) secure that the start period of each vessel does not exceed its end period. Constraints (5.3) and (5.4) make sure that each vessel chartered, has one start and one end date. Constraints (5.5) ensure that at least one vessel is chartered for the project start. Constraints (5.6) decide that charter periods only can start Monday morning and (5.7) that a charter period can only end at the end of a week.

$$\sum_{t \in T} te_{vt} - \sum_{t \in T} ts_{vt} \geq 0 \quad v \in V \quad (5.2)$$

$$\sum_{t \in T} s_{vt} = 1 \quad v \in V \quad (5.3)$$

$$\sum_{t \in T} e_{vt} = 1 \quad v \in V \quad (5.4)$$

$$\sum_{v \in V} s_{vt} \geq 1 \quad t = 1 \quad (5.5)$$

$$s_{vt} = 0 \quad v \in V \quad t \in T \setminus \{B\} \quad (5.6)$$

$$e_{vt} = 0 \quad v \in V \quad t \in T \setminus \{E\} \quad (5.7)$$

### Binary constraints

All decision variables in stage one are binary variables.

$$\beta_{vu} \in \{0, 1\} \quad v \in V \quad u \in U \quad (5.8)$$

$$s_{vt} \in \{0, 1\} \quad v \in V \quad t \in T \quad (5.9)$$

$$e_{vt} \in \{0, 1\} \quad v \in V \quad t \in T \quad (5.10)$$

### 5.3.2 Second stage problem

In stage two, the weather is realized, the schedules are made, and the necessary extension options are exercised.

### Objective function

The first term of the objective function is the cost of exercising the options. The second term is the loss of production for each day the wind farm is not completed. The third term is the fixed penalty if the wind farm is not finished. The fourth term is the variable penalty of not finishing the wind farm, depending on the number of activities that are not completed.

$$Q(e_{vt}, \beta_{vu}, s_{vt}, \xi_s) = \min \left[ \sum_{v \in V} \sum_{u \in U} E_{vu} \lambda_{vus} + P^f e_s^{Tot} + P^w w_s + P^Q (N^A - \sum_{i \in N} \sum_{v \in V} \sum_{l \in L} \sum_{t \in T} z_{ivlts}) \right] \quad (5.11)$$

### Extension option constraints

Constraints (5.12) ensure an extension option is exercised if the charter period for a vessel exceeds the fixed days in the contract. Constraints (5.13) set  $p_{vts}$  to 1 for every period a vessel is chartered depending on the exercise of options. Constraints (5.15) find the last operating period in each scenario for all vessels. Constraints (5.12) are non-linear and must be linearized before implementation in a commercial solver. The linearization can be found in Section 5.4

$$\sum_{t \in T} t e_{vts}^f - \sum_{t \in T} t e_{vt} = \sum_{u \in U} L_u \beta_{vu} \lambda_{vus} \quad v \in V \quad s \in S \quad (5.12)$$

$$p_{vts} = \sum_{t'=1}^t s_{vt'} - \sum_{t'=1}^t e_{vt's}^f \quad v \in V \quad t \in T \quad s \in S \quad (5.13)$$

$$\sum_{t \in T} t e_{vts}^f \leq e_s^{Tot} \quad v \in V \quad s \in S \quad (5.14)$$

### Scheduling constraints

Constraints (5.15) model the precedence relations between the installation activities: an activity cannot start before its predecessors are finished. Constraints (5.16) model a penalty if not all installation activities are performed. Constraints (5.17) model activities requiring to be performed by the same installation vessel and loading set. These constraints are relevant when the loading sets are predefined. Constraints (5.18) ensure that an activity can only start if the consecutive time periods equal to the activity duration, are below operational weather limits. Constraints (5.18) are not restricting when  $t > |T| - D_{iv}^A + 1$ , which involves that activities can start after this period. This end effect is handled in Section 5.5.

$$\sum_{v \in V} \sum_{l \in L} \sum_{t \in T} (t + D_{i'v}^A) z_{i'vlt s} \leq \sum_{v \in V} \sum_{l \in L} \sum_{t \in T} t z_{ivlt s} \quad i \in N \quad i' \in P_i \quad s \in S \quad (5.15)$$

$$\sum_{i \in N} \sum_{v \in V} \sum_{l \in L} \sum_{t \in T} z_{ivlt s} + M^P w_s \geq N^A \quad s \in S \quad (5.16)$$

$$\sum_{t \in T} z_{ivlt s} - \sum_{t \in T} z_{i'vlt s} = 0 \quad i \in N \quad i' \in F_i \quad v \in V \quad l \in L \quad s \in S \quad (5.17)$$

$$\sum_{t'=t}^{t+D_{iv}^A-1} x_{ivt's} \geq \sum_{l \in L} D_{iv}^A z_{ivlt s} \quad i \in N \quad v \in V \quad t = 1, \dots, |T| - D_{iv}^A + 1 \quad s \in S \quad (5.18)$$

### Resource constraints

Constraints (5.19) ensure that an activity is performed by a vessel with sufficient capabilities. Constraints (5.20) ensure that a vessel only can perform an activity if it is chartered and is not loading a new loading set. Constraints (5.21) guarantee that a loading set's total load does not exceed the vessel's loading capacity.

$$\sum_{l \in L} \sum_{t \in T} z_{ivlt s} \leq A_{iv} \quad i \in N \quad v \in V \quad s \in S \quad (5.19)$$

$$\delta_{vts} \geq \sum_{i \in N} x_{ivts} \quad v \in V \quad t \in T \quad s \in S \quad (5.20)$$

$$\sum_{i \in N} \sum_{t \in T} Q_i z_{ivlt s} \leq Q_v \quad v \in V \quad l \in L \quad s \in S \quad (5.21)$$

### Loading sets constraints

Constraints (5.22) are used to find the first period a vessel is loaded with a new loading set. Constraints (5.23) ensure that all activities performed by a loading set must be started, and indirectly finished before a new loading set starts. A consequence of modeling the loading sets this way is that the first indexes of possible loading sets are not used if the set  $L$  exceeds the number of loading sets needed. Constraints (5.24) find  $f_{vlt s}$ , which is used in the forbidden periods constraints. Constraints (5.22) are non-linear and must be linearized before implementation in a commercial solver. The linearization can be found in Section 5.4.

$$\sigma_{vls} = \min_{i \in N} \left\{ \sum_{t \in T} t z_{ivlt s} \right\} \quad v \in V \quad l \in L \quad s \in S \quad (5.22)$$

$$\sigma_{v(l+1)s} \geq \sum_{t \in T} t z_{ivlt s} \quad i \in N \quad v \in V \quad l = 1, \dots, |L| - 1 \quad s \in S \quad (5.23)$$

$$\sigma_{vls} = \sum_{t \in T} t f_{vlt s} \quad v \in V \quad l \in L \quad s \in S \quad (5.24)$$

### Forbidden periods constraints

Constraints (5.25) enforce the vessel to be loading  $D_v^L$  periods before it can perform any activities with the loading set. It should be noted that constraints (5.25) are not restricting in the first  $D_v^L$  periods, but it can be assumed that it is not called for a new loading within these first periods. The vessels are assumed to be loaded with the first loading set in the start project node. Constraints (5.26) force the vessel to be unavailable resources and cannot perform any activities in these periods. Constraints (5.27) and (5.28) handle the weather restrictions for wave height and wind speed, respectively.  $x_{its}$  is forced to be zero in the time periods, when the weather realization exceeds operational limits for activity  $i$ . These last two constraints are preprocessed in the implementation.

$$\sum_{t'=t-D_v^L}^{t-1} \delta_{vt's} \leq M_v^F (1 - f_{vlt s}) \quad v \in V \quad l \in L \quad t = D_v^L + 1, \dots, |T| \quad s \in S \quad (5.25)$$

$$\delta_{vts} \leq p_{vts} \quad v \in V \quad t \in T \quad s \in S \quad (5.26)$$

$$M_{its}^B (1 - x_{ivts}) \geq W_{ts}^B - W_i^{BMAX} \quad i \in N \quad v \in V \quad t \in T \quad s \in S \quad (5.27)$$

$$M_{its}^V (1 - x_{ivts}) \geq W_{ts}^V - W_i^{VMAX} \quad i \in N \quad v \in V \quad t \in T \quad s \in S \quad (5.28)$$

### Binary constraints

$$z_{ivlts} \in \{0, 1\} \quad i \in N \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (5.29)$$

$$e_{vts}^f \in \{0, 1\} \quad v \in V \quad t \in T \quad s \in S \quad (5.30)$$

$$x_{ivts} \in \{0, 1\} \quad i \in N \quad v \in V \quad t \in T \quad s \in S \quad (5.31)$$

$$p_{vts} \in \{0, 1\} \quad v \in V \quad t \in T \quad s \in S \quad (5.32)$$

$$\lambda_{vus} \in \{0, 1\} \quad v \in V \quad u \in U \quad s \in S \quad (5.33)$$

$$\delta_{vts} \in \{0, 1\} \quad v \in V \quad t \in T \quad s \in S \quad (5.34)$$

$$f_{vltts} \in \{0, 1\} \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (5.35)$$

$$w_s \in \{0, 1\} \quad s \in S \quad (5.36)$$

### Non-negativity constraints

$$e_s^{TOT} \geq 0, integer \quad s \in S \quad (5.37)$$

$$\sigma_{vls} \geq 0, integer \quad v \in V \quad l \in L \quad s \in S \quad (5.38)$$

## 5.4 Linearization

Non-linear constraints need to be linearized before implementation in Xpress Mosel.

### Extension option constraints

Constraints (5.12) must be linearized as  $\beta_{vu}$  and  $\lambda_{vus}$  both are variables in the implementation. The constraints are shown below:

$$\sum_{t \in T} te_{vts}^f - \sum_{t \in T} te_{vt} = \sum_{u \in U} L_u \beta_{vu} \lambda_{vus} \quad v \in V \quad s \in S \quad (5.39)$$

This is solved by replacing the constraints with the two constraints below:

$$\beta_{vu} \geq \lambda_{vus} \quad v \in V \quad u \in U \quad s \in S \quad (5.40)$$

$$\sum_{t \in T} te_{vts}^f - \sum_{t \in T} te_{vt} = \sum_{u \in U} L_u \lambda_{vus} \quad v \in V \quad s \in S \quad (5.41)$$

Constraints (5.40) express that an extension option can only be exercised if the given option is bought in the first stage. Constraints (5.41) extend the chartering period for vessels when options are exercised.

### Loading sets constraints

A few of the loading set constraints are replaced to linearize the model.

$$\sigma_{vls} = \min_{i \in N, t \in T} \{tz_{ivlts}\} \quad v \in V \quad l \in L \quad s \in S \quad (5.42)$$

$$\sigma_{v(l+1)s} \geq \sum_{t \in T} tz_{ivlts} \quad i \in N \quad v \in V \quad l = 1, \dots, |L| - 1 \quad s \in S \quad (5.43)$$

$$\sigma_{vls} = \sum_{t \in T} tf_{vltts} \quad v \in V \quad l \in L \quad s \in S \quad (5.44)$$

Constraints (5.42) are non-linear. New variables and parameters are needed.

$\theta_{vltts}$  is forced to be 0 for every period  $t$  before loading set  $l$  is first used for vessel  $v$  in scenario  $s$

$\gamma_{vltts}$  is forced to be 0 for every period  $t$  after loading set  $l$  is first used for vessel  $v$  in scenario  $s$

$M_{vts}^L$  Big M used to restrict new loading sets

The linearization is done by replacing constraints (5.42-44) with constraints (5.45-52).

$$\sum_{i \in N} \sum_{t'=1}^t z_{ivlt's} \geq \theta_{vltts} \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (5.45)$$

$$\sum_{i \in N} \sum_{t'=1}^t z_{ivlt's} \leq M_{vts}^L (1 - \gamma_{vl(t+1)s}) \quad v \in V \quad l \in L \quad t = 1, \dots, |T| - 1 \quad s \in S \quad (5.46)$$

$$f_{vltts} \leq \theta_{vltts} \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (5.47)$$

$$f_{vltts} \leq \gamma_{vltts} \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (5.48)$$

$$\sum_{t \in T} f_{vltts} = \sum_{t \in T} \theta_{vltts} \quad v \in V \quad l \in L \quad s \in S \quad (5.49)$$

$$\sum_{t \in T} tf_{v(l+1)ts} \geq \sum_{t \in T} tz_{ivlts} \quad i \in N \quad v \in V \quad l = 1, \dots, |L| - 1 \quad s \in S \quad (5.50)$$

$$\theta_{vltts} \in \{0, 1\} \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (5.51)$$

$$\gamma_{vltts} \in \{0, 1\} \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (5.52)$$

Constraints (5.45-48) are used to find the first period a vessel is loaded with a new loading set. Constraints (5.49) ensure that every loading set used to perform an activity is assigned a start point. Constraints (5.50) ensure that all activities

performed by a loading set are started, and indirectly finished before a new loading set starts. It should be noted that the loading activity of the first loading set used for a vessel is not modeled. It can be assumed that the vessels are loaded in the start node for each vessel. As mentioned earlier, a consequence of modeling the loading sets this way, is that the first indexes of possible loading sets are not used, if the set  $L$  exceeds the number of loading sets needed.

## 5.5 End effects

Constraints (5.18) are not restricting when  $t > |T| - D_{iv}^A + 1$ , which involves that activities can start after this period.

$$\sum_{t'=t}^{t+D_{iv}^A-1} x_{ivt's} \geq \sum_{l \in L} D_{iv}^A z_{ivlts} \quad i \in N \quad v \in V \quad t = 1, \dots, |T| - D_{iv}^A + 1 \quad s \in S \quad (5.53)$$

The end effect is solved by replacing constraints (5.18) with constraints (5.53).

$$\sum_{t'=t}^{|T|} x_{ivt's} \geq \sum_{l \in L} D_{iv}^A z_{ivlts} \quad i \in N \quad v \in V \quad t = |T| - D_{iv}^A + 1, \dots, |T| \quad s \in S \quad (5.54)$$

Now activities can only start in the last periods if the sum of consecutive time periods is equal to the activity duration.

## 5.6 Symmetry breaking inequalities

Each OWT includes the same activities, which leads to symmetric solutions. When the number of turbines increases, the symmetry may cause problems when solving the model. In order to reduce the symmetry in the model, symmetry breaking inequalities for the turbines are introduced. The symmetry can be broken without affecting the problem by requiring that the foundation of turbine one must be installed before the foundation of turbine two and so on. The additional notation and inequalities are described below. However, these constraints are not valid if the loading sets are predefined by constraints 5.17.

$G_i$  Set of predecessors for activity  $i$

$$\sum_{v \in V} \sum_{l \in L} \sum_{t \in T} t z_{i'vlt s} \leq \sum_{v \in V} \sum_{l \in L} \sum_{t \in T} t z_{ivlt s} \quad i \in N \quad i' \in G_i \quad s \in S \quad (5.55)$$

## 5.7 Discussion of flexibility in the model

As mentioned in the model assumptions (Section 5.1), the activity input can be arranged to solve problems with other phases included or OWT types. In this section, a discussion of the application of the model is given.

Firstly, the activity set  $N$  and precedence relations set  $F_i$  can be adjusted to fit several problems. This chapter has focused on the monopile consisting of: assembled by a foundation, transition piece and top-structure. On the other hand, if the bunny ear assembly strategy is chosen, an activity is to install the preassembled nacelle, hub and two blades, and at last, the third blade. In essence, all types of assembled wind turbines can be solved as long as the installation can be divided into activities with the corresponding duration for the vessel installed by, and the resources required. This also applies to different types of sub-structures. Moreover, projects have different phases; cable burial is not done in all projects, and some also prepare the sea bed in advance of the installation. Project phases can be included or excluded from the activity set  $N$ .

Secondly, the input for loading duration can be arranged to capture more than the actual loading. For now, the logistic system consists of dedicated installation vessels at the site and dedicated transport vessels of components. Several projects use installation vessels to transport the components from port to site (Interview with Equinor ASA). If  $D_v^L$  consists of both the time to sail back and forth from the port and the loading at the port, a logistic system where the installation vessels also perform the transport of the components is obtained. Thus, the dedicated transport vessels are not needed.

Thirdly, the model can handle both problems in which the loading sets are predefined and problems in which the model finds the optimal loading sets (which components included). To predefine loading sets,  $F_i$  defines the activities which must be included in the same loading set as activity  $i$ . Constraints 5.17 ensure that these activities are performed by the same vessel and loading set.



## 6 Tabu search heuristic

In order to solve realistic sized test instances, a tabu search heuristic is developed. In Section 6.1, a brief introduction of the tabu search heuristic is given. In 6.2, the solution representation is described. Section 6.3 shows how a solution is evaluated. Next, a description of the search space of the heuristic is given in Section 6.4. Some comments on move restriction are given in Section 6.5, and comments on tabu list lengths are given in 6.6. At last, an overview of the stopping criterion is given in Section 6.7.

### 6.1 Heuristic overview

Tabu Search is an acknowledged and widely used heuristic. It is a single-solution-based and local search heuristic, which means that the search addresses one solution at each iteration and moves across the solution space by applying local changes. It is characterized by some concepts: Tabu lists, a neighborhood structure, a defined search space, aspiration criteria and stopping criteria. The search space of the tabu search is all solutions within reach. Moreover, the neighborhood structure consists of operators that are applied to a solution in order to move to new solutions and across the solution space. A number of different neighborhood operators are possible depending on the problem studies. The advantage of the tabu search is the ability to avoid getting stuck in a local optimum. Tabus are forbidden solutions, and local optima or properties of local optima are stored in a tabu list, in order to avoid cycling back to previously visited solutions. An aspiration criterion permits solutions that are tabu and is relevant when tabus are forbidding promising solutions that have not been visited. At last, the stopping criterion decides at what point the search stops (Gendreau, 2002).

This heuristic framework is chosen concerning two factors: an easy neighborhood structure and the problem of cycling. The search space in our problem is described in Section 6.5, and is easy to build up as a neighborhood structure. There are almost none infeasible solutions (Section 6.6), and its easy to move across the search space with a few neighborhood operators. A challenge could be that the search cycles back to previous solutions as when non-improving moves must be made to find good solutions. The tabu list handles this problem. The implementation of the tabu search heuristic is flexible in terms of; search- and improvement strategies, the configuration of tabu lists, and stopping criterion. During preliminary testing, the

concepts of tabu search can be adjusted to make the search more effective.

---

**Algorithm 1** Tabu search algorithm

---

**Input:** Vessels - number of vessels types chartered, max - maximal length of short term tabu list

```

1: function Tabusearch
2:    $x_0, x_1, x_2 \leftarrow \text{construction}()$  (Algorithm nr 2)
3:    $s\_tabuList.push, l\_tabuList.push \leftarrow []$ 
4:   for ( $v$ ) in Vessels do
5:     while (not stoppingCondition()) do
6:        $N(x_1) \leftarrow \text{getNeighbors}(x_1, v)$  (Algorithm nr 4)
7:        $f(x_n) \leftarrow \text{evaluate}(x_n \text{ in } N)$  (Algorithm nr 3)
8:        $x_0 \leftarrow \arg \min\{f(x_n) : x_n \in N \wedge x_n \notin \text{tabuList}\}$ 
9:        $s\_tabuList.push(x_0)$ 
10:      if ( $f(x_0) < f(x_1)$ ) do
11:         $i \leftarrow N.index(x_0)$ 
12:         $x_0 \leftarrow \text{smartImprovement}(x_0, i)$  (Algorithm nr 5)
13:         $x_1 \leftarrow x_0$ 
14:        if ( $x_1 < f(x_2)$ ) do
15:           $x_2 \leftarrow x_1$ 
16:        else
17:           $l\_tabuList.push(x_1)$ 
18:           $x_1 \leftarrow x_0$ 
19:        if ( $s\_tabuList.size > \text{max}$ ) do
20:           $s\_tabuList.removeFirst()$ 
21:      end while
22:    end for
23:    return  $x_2, f(x_2)$ 
24: end function

```

---

Algorithm 1 represents the structure of the tabu search applied to our problem. In the search  $x_0, x_1$  and  $x_2$  represent the current solution, but at different levels.  $x_0$  is the best solution in the neighborhood,  $x_1$  is the best-known solution after the last non-improving move, and  $x_2$  is the best-known solution during the entire search.  $x_n$  represent neighboring solutions. The search iterates for vessel types, optimizing the charter periods separately (line 6). Each vessel iteration runs until a stopping criterion is met (line 7). A function is called upon to find the neighborhood of the current solution (line 8). Next, a function is called upon to evaluate each of these neighbors (line 9). The solution with the lowest associated cost is chosen as the new current solution (line 10). When the search moves to a new solution, the solution is added to the short-term tabu list, consisting of recently visited solutions

(line 11). If this solution is an improvement compared to the last solution, the smart improvement heuristic is called upon (lines 12-15). The smart improvement function repeats the same improving move until it is not improving the solution. If the solution is better than the best know solution, will this also be updated (lines 16-17). If the solution in line 10, is non-improving, the move is made, but the last move is added to a long-term tabu list to avoid moving right back at it (lines 19-20). The short-term tabu list is shortened down if it exceeds the maximum size (lines 21-22). The purpose of different tabu lists is explained in Section 6.7.

## 6.2 Solution representation

A solution is represented as a two-dimensional array containing the first-stage decision in the mathematical model presented in Section 5.3. The decisions are: start day and end day of the fixed charter period and the number of included extension options, for each vessel type. The solution is represented per vessel type as it is assumed that the same vessel types must be chartered in the same periods, as these vessels are required to collaborate. The size of the array is thus  $3 \times V$ , where  $V$  is the number of vessels type chartered in a given project. The order of the vessels in the array follows the order of operation start for the vessels.

$$[[Start_v], [End_v], [Options_v]] \quad v \in V.$$

The overlapping of charter periods of the vessels is an important feature of the solution and is indirectly represented.

## 6.3 Construction heuristic

A contrition heuristic is a search that finds a promising initial solution, which the local search later improves. An important part of the local search's preliminary testing was to test different variations of initial solutions to study if the same best solution was found. All tests found the same best solution, but initial solutions in which the wind farm was finished in many scenarios, lead to fewer problems with cycling. Local optimums can arise as the cost of adding a week can be higher than the reward of finishing a few activities, especially when the weather conditions are harsh. Thus, a construction heuristic that finds an initial solution that finishes the wind farm in all scenarios is applied, as this finds the best solution the fastest.

---

**Algorithm 2** Construction heuristic algorithm

---

```
1: function construction()
2:    $x_0 = [apr_0, des_0, 0]_v$ 
3:   add_year  $\leftarrow 1$ 
4:   while add_year==1 do
5:      $penalty \leftarrow \text{evaluate}(x_0)$  (Algorithm nr 3)
6:     If penalty > 0 do
7:       add a year to  $End_v$ 
8:        $penalty \leftarrow \text{evaluate}(x_0)$  (Algorithm nr 3)
9:     Else
10:      add_year=0
11:   end while
12:    $x_1 \leftarrow x_0$ 
13:    $x_2 \leftarrow x_0$ 
14:   return  $[x_0, x_1, x_2]$ 
15: end function
```

---

For this case, it is assumed that the start day of the project is fixed, and in this case it is fixed to April 1st. The construction heuristic starts with the charter period from April to December (nine months), and adds one year to the charter period for each vessel until the wind farm is finished for every weather scenario.

The heuristic is simple and could be advanced to find a even more promising initial solution. However, the local search stops to improve within a reasonable time limit (Section 9.3.3), and the search finds the best charter length relatively fast. A majority of the computational effort in the local search is now used to find the best ratio between fixed periods and extension options and overlapping of vessels.

## 6.4 Evaluation of a solution

Each candidate solution the heuristic proposes, is evaluated by simulation. Further details of the simulation model are described in Section 7. The candidate solution must be evaluated for a sufficient number of scenarios. The simulation model returns a fitness value for each weather scenario for a given solution. If all activities are completed within the charter period, the returned fitness is the cost of the number of chartered days, included options, exercised options and a penalty for the loss of production for each additional day the installation takes. If not all activities are completed within the charter period, the returned fitness is the chartering costs as just mentioned and a major penalty cost for not completing the wind farm. The estimated value of a solution is the average fitness of the different weather

realizations, as all weather scenarios have the same probability.

---

**Algorithm 3** Evaluation of solution algorithm

---

**Input:**  $nScenarios$  - number of weather scenarios,  $weatherScen$  - array of weather data for each scenario

```

1: function evaluate( $x_n \in N, tabuList, storedList$ )
2:   for ( $x_n$ ) in  $N$  do
3:     If ( $x_n \notin tabuList \wedge \notin storedList$ ) do
4:       [ $f(x_n), penalty$ ] =  $\sum_{s=1}^{nScenarios} simulation(x_n, weatherScen[s]) / nScenarios$ 
5:        $storedList.push([f(x_n), penalty])$ 
6:     Elseif  $x_n \in storedList$  do
7:       return [ $f(x_n), penalty$ ] from  $storedList$ 
8:   end for
9:   return [ $f(x_n), penalty$ ]
10: end function

```

---

Algorithm 3 shows how a solution is evaluated. The solution is evaluated by simulations for different weather scenarios if not evaluated before (line 4). Also, the value for the penalty of not finishing the wind farm is returned (0 if finished). If the solution has already been visited, is the objective value returned from a list of previously evaluated solutions (line 7). In this way, the computational effort is reduced.

## 6.5 Search space

The tabu search procedure seeks to find the charter period and number of extension options for each vessel type, with the lowest estimated cost. The neighborhood of a solution consists of solutions that have added or removed weeks from the charter period or number of extension options, for a given vessel type. It is assumed that the charter periods must start and end Monday 00:00 (Assumptions Section 5.1). The procedure starts with optimizing the charter period and extension options for vessel type one, which correspond to the first operation (e.g., vessels for installation of foundations). Each project has a fixed start day, and thus it is not possible to change the start date for vessel type one. For instance, if two HLV are used for foundation installation, these are chartered from day zero of the project and have the same contract length and number of extension options.

The tabu search procedure optimizes the solution for each vessel type, separately. As previously described, the heuristic iterates for each vessel type, and the order of

the iterations follow the order of the installation process. For instance, vessels for foundation installation before cables laying vessels. This iteration is based on the assumption of one-way dependency; the optimal charter period for a vessel depends on when the charter period of the previous vessel type, and not the succeeding vessels. A vessel waits at the site until the predecessors of the activities it performs are finished, and to minimize slack, the optimal overlapping is searched for. However, the vessels must not wait at the site until the succeeding vessels arrive. The optimal overlapping of vessels is a trade-off between minimization of slack and loss of production when extending the project duration. For example, a HLV vessel is chartered in from day zero, and the heuristic searches for the optimal charter length and number of extension options. Next, a CLV is chartered in, and the heuristic searches for an optimal start period based on when the HLV is expected to finish foundations. Moreover, the optimal charter period for a CBV depends on when the CLV is expected to finish enough cables laying for the cable burial to start. At last, the optimal charter period for a TIV also depends on when the CLV is expected to finish enough cables.

The neighborhood of a solution is described with neighborhood operators, which perform operations on a solution such as adding an element, removing an element or exchange of elements. The choice of neighborhood operators is based on the attributes of the solution and how the search is structured. The add/remove operators with regard to the solution representation are:

1. *Add operator*: By adding a week to  $Start_v$ , the vessel starts a week later.
2. *Add operator*: By adding a week to  $End_v$ , the vessel has a week longer fixed charter period.
3. *Add operator*: Adding an extension option to  $Options_v$ .
4. *Remove operator*: By removing a week from  $Start_v$ , the vessel starts a week earlier.
5. *Remove operator*: By removing a week from  $End_v$ , the vessel has a week shorter fixed charter period.
6. *Remove operator*: Removing an extension option from  $Options_v$ .

As previously discussed, the search optimizes the solution for each vessel type iteratively and separately, and thus, neighborhood operators that change solution

elements across vessel types are not relevant. In addition to the add/remove operators listed, it is relevant to consider exchange operators that exchange elements of a solution to find good solutions more effectively. The exchange operators considered related to options versus a fixed period are:

7. *Exchange operator*: Exchanging fixed weeks with an extension option. This is done by removing the equal period of weeks compared to an option from  $End_v$ , and adding an option to  $Options_v$ .
8. *Exchange operator*: Exchanging an extension option with a number of fixed weeks. This is done by removing an option from  $Options_v$ , and adding the equal period of weeks compared to an option to  $End_v$ .

The exchange operators considered related to overlapping of vessels are:

9. *Exchange operator*: Changing the fixed charter period for a vessel one week forward. This is done by adding a week to  $start_v$  and adding a week to  $End_v$ .
10. *Exchange operator*: Changing the fixed charter period for a vessel one week backward. This is done by removing a week from  $start_v$  and removing a week from  $end_v$ .

Preliminary testing shows that the exchange operators listed are attractive moves in a search and help find good solutions faster than add/remove operators.

---

**Algorithm 4** Get neighborhood

---

**Input:** weeksO - length of an option, T - available time periods

---

```

1: function getNeighbors( $x_0, v$ )
2:   N  $\leftarrow$  []
3:   if  $v > 1$ 
4:     N  $\leftarrow$  apply operators 1,4,9,10
5:   N  $\leftarrow$  apply the remaining operators

6:   for  $x_n$  in N do
7:     if  $Start_v < 0$  or  $Options_v < 0$  or  $(End_v + weeksO * Options_v) > T$ 
8:       or  $Start_v > End_v$ 
9:       N  $\leftarrow$  remove  $x_n$ 
10:  end for
11:  return N
12: end function

```

---

Algorithm 4 shows how to get the neighborhood of a solution. Some of the operators are not applied to vessel type one, as this vessel type must start at day zero (line 3-5). Next, unfeasible solutions, such as periods where the end day is before start day, are removed from the neighborhood (line 6-9).

Evaluating a neighboring solution requires much computational effort, considering the number of samples needed to estimate the value of a solution. Thus, an investigation of effective improvement and move strategies is needed. The best improvement heuristic and the first improvement heuristic, are the most common neighborhood move strategies. The best improvement heuristic evaluates every neighbor before moving to the best neighbor, while the first improvement heuristic evaluates neighbors until it finds an improving solution, and then makes a move. In the next section, a search strategy is presented based upon preliminary testing. A comparison of the performance of this strategy compared to the performance of different neighborhood structures and improvement strategies is presented in the computational study (Section 9.3.1).

All neighborhood operators are included in the neighborhood of a solution. The number of neighborhood operators is relatively small, and a part of the search consists of repeating the same neighborhood operator. There is an advantage behind repeating the same operator (compared to a best-improvement search), which lies in moving in the direction of the global optimum as fast as possible. Preliminary testing indicates that good solutions lie close to each other, so moving towards a local optimum leads us close to the global optimum. As the neighborhood operators suggested are relatively small steps towards an optimal solution, the same operator improves the solution for several iterations. Instead of checking which is the best operator for each iteration, we check if the current operator leads to an improved solution. If not improving, the search for a new operator starts. The argument for including all neighborhood operators in the neighborhood of a solution is this: we want to move as fast as possible towards the optimum, and the effort of evaluating a complete neighborhood to find the most improving operator to repeat, is less than the effort of repeating a less effective operator (if we used a reduced neighborhood).



---

**Algorithm 5** Smart improvement

---

```
1: function smartImprovement( $x_0$ ,  $i$ , tabuList)
2:    $m \leftarrow \text{true}$ 
3:   while  $m$  is true do
4:      $N(x_0) \leftarrow \text{getNeighbors}(x_0, v)$ 
5:     If  $N(x_0)[i] \notin \text{tabuList}$  do
6:        $f(N(x_0)[i]) \leftarrow \text{evaluate}(N(x_0)[i])$ 
7:       if  $f(N(x_0)[i]) < x_0$ 
8:          $x_0 \leftarrow f(N(x_0)[i])$ 
9:          $s\_tabuList.push(x_0)$ 
10:      else
11:         $m \leftarrow \text{false}$ 
12:      else
13:         $m \leftarrow \text{false}$ 
14:      return  $x_0$ 
15:   end while
16: end function
```

---

Algorithm 5 shows how a strategic move is repeated until its not improving the solution. The  $i$ -th neighbor of the current solution corresponds to the same move, which leads to this solution, and is evaluated if not in the tabu list (line 6). The procedure repeats as long as this strategic move is improving (lines 7-11). Recently visited solutions are stored in a short-term tabu list (line 9). If the smart improvement search suggests a solution that is tabu, the smart improvement loop stops.

## 6.6 Move restrictions

The tabu search procedure applied to this problem allows "infeasible solutions". A significant penalty is given for solutions in which the wind farm is not finished. Allowing infeasible solutions can enhance the performance of the local search (Gendreau, 2002). However, some infeasible solutions must be forbidden as they do not enhance the search. These solutions are: when the start charter day is negative, when the fixed charter end is before the start charter date for a vessel type, and when the charter period exceeds beyond the available time periods. These infeasible solutions are removed in Algorithm nr 4.

## 6.7 Tabu-lists and use of memory

The purpose of tabu-lists is to escape local optimums and avoid cycling of the same solutions in a search. In our problem, we can get stuck with a certain overlapping

of vessel charter periods in a search, and need a tabu list to force the search to try new start and end dates. The size of a tabu-list decides whether the tabu search has an intermediate or long-term memory. A general principle is that longer tabu list diversifies more than a shorter list (Gendreau, 2002). The most effective tabu-lists and use of memory depend on the problem studied, and different strategies are tested in Section 9.3.2.

In Algorithm 1, two types of tabu lists are applied: a short-term and a long-term. The short-term list stores recently visited solutions, and elements are removed from the list when the list exceeds a predefined length. In addition, a long-term memory structure is tested to diversify the search further. This tabu list stores all local optimums (before making non-improving moves) and has no length limit. We assume that good solutions lie close to each other, considering the exchange neighbors implemented. Storing all local optimums in a tabu list will not restrict the search area around it, but avoid moving in a large cycle through a local optimum, which can be the case for a short-term list based on recently visited solutions. Overlapping of both methods is also tested.

## 6.8 Stopping criterion

As the optimal value is not known in advance of the search, the algorithm could run endlessly. Thus, a stopping criterion is needed. Gendreau (2002) outlines three commonly used stopping criteria:

- after a fixed number of iterations (or a fixed amount of running time)
- after a fixed number of iterations without an improvement in the objective value
- when the search finds a pre-specified objective value

Preliminary testing of the tabu search applied to our problem shows that the objective function value stops improving within a reasonable time limit, and thus stopping criterion number two is most relevant. However, if the size of the test instance is increased significantly, by more turbines and weather scenarios, stopping criteria one and three should be considered. The use of the stopping criterion is further discussed in Section 9.3.

## 7 Simulator

A simulator has been created to evaluate the cost of the contract in each weather scenario. The simulator finds a schedule for each vessel's installation activities based on the first stage decisions suggested by the heuristic. Based on the simulated schedule, the simulator finds whether extension options are exercised and assigns a penalty to activities not done, and vessels that cannot perform all assigned activities. These correspond to the second stage decision. After finding the schedule, the number of exercised extension options, and penalties, the simulator evaluates the contract configuration's objective value for the given scenario.

First, a classification of the simulator is presented. Second, the simulator algorithm is illustrated by an overview and afterward, a detailed explanation. Finally, a walkthrough example of the simulator simulating the installation of two offshore wind turbines is presented.

### 7.1 Classification of the simulator

The simulator can be characterized by the following characteristics; dynamic or static, deterministic or stochastic, and by how the simulation clock is updated; fixed-increment time progression or next-event time progression.

Table 4: Classification of the simulator

Alternative 1	Alternative 2
Dynamic ✓	Static
Deterministic	Stochastic ✓
Fixed-increment time progression	Next-event time progression ✓

A static simulator simulates the system in a given time period, while a dynamic simulator shows a system while it varies over time. The simulator updates the system when the time progresses, and is therefore classified as a dynamic simulator. The simulator can be either deterministic or stochastic, depending on if the simulator has any stochastic variables as input. The weather realization is a stochastic input, and the simulator is therefore characterized as stochastic.

The simulation clock can be updated by fixed-increment time progression or by next-event time progression. Fixed-increment time progression updates the simulation clock by a small fixed time increment for each iteration and updates the system

for each fixed time increment. Next-event time progression updates the simulation clock to the time of when the next event occurs. Afterwards, the system is updated. Fixed-increment time would require an update of the system for a high number of time periods, especially for large wind farms, and cause the simulator to run significantly slower than when using next-event time progression. Because of this, next-event time progression is chosen instead of fixed-increment time progression.

## 7.2 The simulator algorithm

### 7.2.1 An overview

Figure 12 presents an overview of the simulator. The different parts of the simulator will be described in detail in the next section.

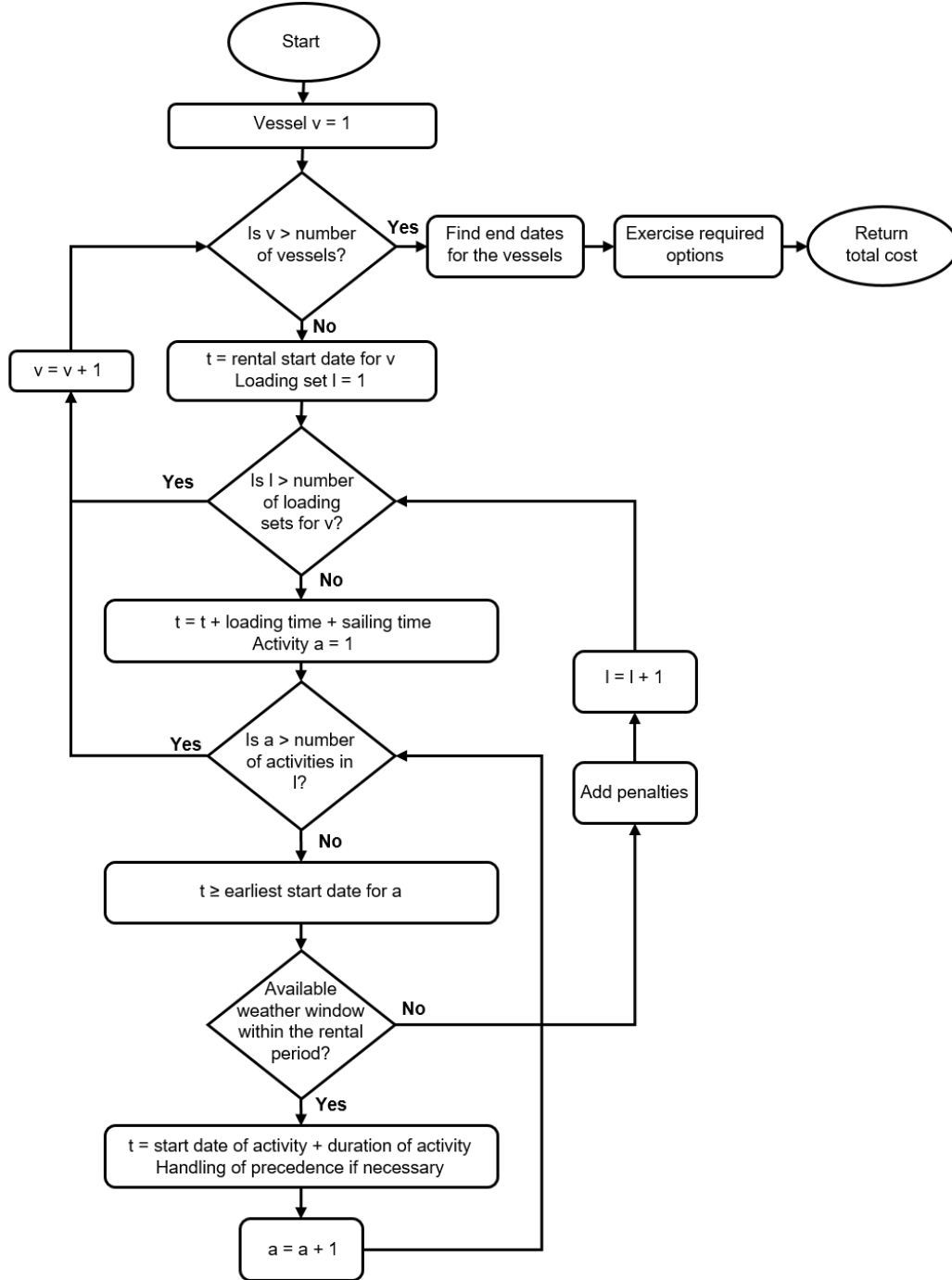


Figure 12: An overview of the simulator.

### 7.2.2 Detailed overview

This section will give a detailed description of the simulator flow diagram presented in the previous section.

#### Simulator structure

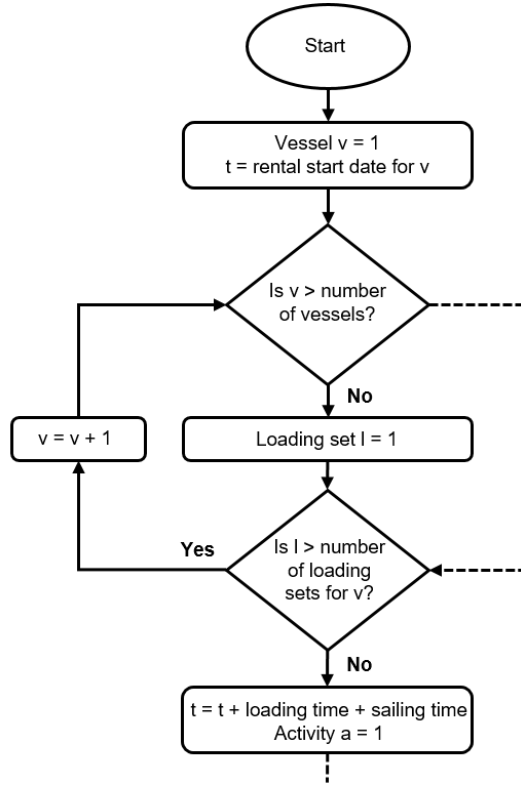


Figure 13: Structure of the simulator.

Figure 13 shows the structure of the simulator. The simulator iterates over each vessel, and for each vessel, it iterates over the vessels corresponding loading sets and then for the activities which belong to the loading set. The simulator first schedules the activities for vessel one, secondly for vessel two, and so on. This structure is chosen due to the following properties of the problem:

1. The vessels have predefined precedence. For example, the vessel installing the foundation will always operate before the vessel installing cables or the top structure.
2. The types of activities each vessel performs are predefined
3. There is a predefined precedence of the activities in a loading set. For example, foundations and transition pieces are typically loaded on the same loading set.

The foundation is installed first, then the transition piece, before moving on to the next wind turbine.

4. The structure simplifies making vessels unavailable for performing an activity, as this is automatically given by updating the simulation clock when the vessel is loading or installing an activity.

The simulation clock is updated for each new vessel and each new loading set. For each new vessel, the simulation clock starts for the vessel's charter start date, as this is the earliest possible time period when the vessel can perform an installation activity. For each new loading set, the vessel must load the components. If it is not used dedicated transport vessels for transporting the components to the offshore site, the vessel must sail to shore and back to the wind farm. Therefore, for each new loading set, the simulation clock is updated by the loading time and the necessary sailing time.

## Scheduling of activities

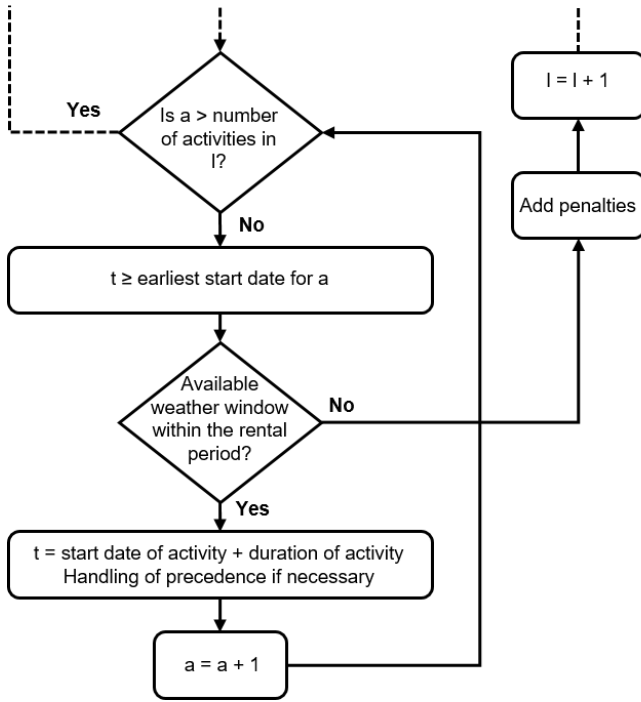


Figure 14: Scheduling of activities.

Figure 14 presents the handling of the installation activities. In order to perform the installation activity, two criteria must be met. First, precedence must be assured. Secondly, the first possible weather window must be found within the total charter period of the vessel. The two criteria are described in detail below.

### *Assuring precedence*

Most of the installation activities have precedence restrictions. For example, the installation of a transition piece requires an installed foundation, the installation of a cable requires an installed transition piece, the burial of a cable requires an installed cable, and so on. The only component that does not have any precedence restriction is the foundation, which is the first component installed. The simulator handles precedence in two ways, depending on the case. The two different cases are explained below:

1. If the loading set consists of more than one activity with precedence restrictions. For example, the foundation and transition piece are components that normally are loaded on the same loading set. For each turbine, the foundation is installed first, and then the transition piece is mounted upon the foundation.



2. If components loaded on different vessels have precedence restrictions. For example, the installation of a cable (cable laying) depends on a transition piece installed and available (which means that not a cable is installed already on the transition piece). The burial of a cable depends on an installed and available cable (which means that the cable is not already buried).

In the first case, where the activities with precedence restrictions are loaded on the same loading set, precedence is handled by the activity list. The activity list is sorted in the precedence needed, which does that precedence automatically occur when iterating over the activities in the loading set.

In the second case, the precedence is handled by defining the earliest start period for each activity. This is done by storing the time period when an required activity is done in a vector. For example, it must be installed a transition piece for the cable laying to proceed. Therefore, each time a transition piece is installed, the time period when the transition piece is fully installed is stored. For the cable laying, a counter is initialized. It can then be checked whether there is a transition piece installed and available (which means that it is not already installed a cable on the transition piece) in the current period. If there is no installed and available transition piece in the current time period, the simulation clock is updated to where it is an installed and available transition piece. The precedence concept is also illustrated in the walkthrough example in Section 7.3. If two equal vessels perform the same activities, and there are not enough required components available, they will perform the activities every other time.

#### *Find an available weather window*

If precedence can be assured, it must be found an available weather window for the installation activity. In order to find a weather window, it must be found consecutive days with wave and wind realizations lower than the wave and wind limits for the activity corresponding with the duration of the activity. Algorithm 6 describes how the search for an available weather window is done.

---

**Algorithm 6** Search for first available weather window

---

**Input:** Vessel  $v$ , loading set  $l$ , activity  $a$

```
1: counter = 0
2: activityDone = 0
3: while  $t \leq$  time periods do
4:   if activityDone == 1
5:     break
6:   if  $t + \text{duration of activity } a \geq$  last charter date of vessel  $v$  then
7:     assign penalties
8:     break
9:   if weather realization in  $t \geq$  weather limit for activity  $a$  then
10:     $t = t + 1$ 
11:   else if weather realization in  $t \leq$  weather limit for activity  $a$  then
12:     while  $t \leq t + \text{duration of activity } a$ 
13:       if weather realization  $\geq$  weather limit for activity  $a$  then
14:          $t = t + 1$ 
15:         break
16:       if counter  $\leq$  duration of activity  $a$  then
17:          $t = t + 1$ 
18:         counter = counter + 1
19:       else if counter == duration of activity  $a$  then
20:         start date of activity  $a = t - \text{duration of activity } a$ 
21:         activityDone = 1
22:         break
```

---

First, a counter is initialized to zero (line 1). The counter is used to check if there are found consecutive time periods with weather realizations corresponding to the duration of the installation activity. In line number 2, activityDone is initialized. ActivityDone will be changed to one if the installation activity can be performed, and the search for the weather window will thereby be stopped. In line number 3 the search for the first available weather window for the installation activity starts. Lines 6-8 assures that if the simulation clock exceeds the last possible charter date of the vessel, the installed activity can not be performed by the vessel. In this case, penalties will be assigned as explained in the next section. If the weather realization is worse than the vessel's weather limits, the simulation clock is incremented (lines 9-10). Else, the search for consecutive time periods with good enough weather realizations starts (lines 12-18). If there are found as many consecutive days with good enough weather as the duration of the installation activity, the activity is scheduled and considered performed by the vessel (lines 19-22).

### Assigning penalties

If it is not possible to either find an available weather window or the precedence restriction is violated, penalties are assigned. A penalty is assigned to the vessel not able to perform its predefined activities. There will also be assigned penalties to the activity not done. If the vessel is unable to perform the activity, it means that it cannot perform the next activities of the same type or activities with the same precedence restrictions as the assigned activity. These activities will also be canceled and assigned penalties.

### After scheduling

Figure 15 illustrates what is done in the last part of the simulator. After all activities are either scheduled or given a penalty, the simulator finds the end date for each vessel. Afterwards, it is found how many extension options each vessel must exercise to perform the activities scheduled before the simulator returns the total cost.

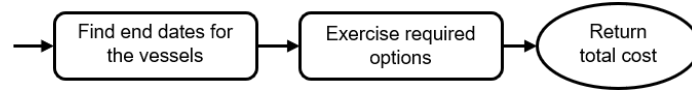


Figure 15: After the scheduling is done, the simulator finds the end dates for each vessel, finds which options that are exercised and returns the total cost.

The end period of each vessel is found after the scheduling is done for all vessels. By finding the start date of the last activity of the last loading set for each vessel and adding the duration of this activity, the end period of the vessel is found.

The simulator also finds if the extension options included in the contract must be exercised or not. Figure 16 shows the fixed rental period of a vessel as 70 time periods, and one included extension option of 30 time periods. The time required to perform all activities is 100. Comparing the vessel's fixed rental period to the time required to perform all activities for the vessel gives that the extension option is exercised.

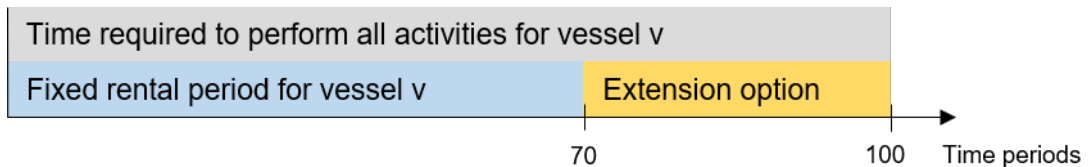


Figure 16: The exercising of the extension option is required, as the fixed rental period for the vessel is not long enough.

At last, the simulator returns the total cost of the simulated solution. The total cost is the sum of the cost of the first stage decision suggested by the heuristic and cost of the second stage decisions simulated by the simulator. The cost of the first stage decisions is the cost of the number of chartered days and included options. The cost of the second stage is the cost of the exercised options, the penalty costs assigned for not completing installation activities and the penalty for the loss of production for each additional day the installation takes.

### 7.3 Walkthrough example

This section describes a walkthrough example of how the simulator operates. Table 5 describes the vessel used in the example and their corresponding charter periods. It also gives information about how many extension options bought for each vessel and the option length. Table 6 shows which vessel that performs the installation activities and the associated performing duration.

Table 5: Charter periods and extension options for each vessel used in the walkthrough example

Vessel	Charter start period	Charter end period	Option length	Included options
HLV	1	21	14	3
CLV	1	21	14	3
CBV	1	21	14	3
TIV	1	21	14	3

Table 6: The performing duration (in time periods) of each activity for each vessel used in the walkthrough example of the simulator

	Foundation	Transition piece	Cable laying	Cable burial	Offshore wind turbine
HLV	2	1			
CLV			2		
CBV				2	
TIV					3

Table 7 presents a walkthrough example of the simulator for the installation of two offshore wind turbines. The structure of the simulator is illustrated through vessel  $v$ , loading set  $l$ , and activity  $a$ . The event illustrates what causes the incrementing of the simulation clock. The performing periods indicates in which time periods the installation activities are performed. The updating of the simulation clock, precedence restrictions, and the scheduling of installation activities are illustrated and commented in the walkthrough example. A summary is included for each vessel, illustrating the earliest start date for components depending on the components installed by the vessel, the vessel's end date, penalties assigned, and the number of exercised options for the vessel.

Table 7: Walkthrough example of the simulator

Vessel: Heavy-lift vessel (HLV)						
v	l	a	Event	Performing periods	Update of simulation clock	Comment
1	-	-	Charter start date	-	1	The simulation clock is updated to the charter start date of the vessel
1	1	-	Loading and sailing	1-2	3	The simulation clock is updated by the loading and sailing time of the vessel
1	1	1	Foundation	3-4	5	A weather window is found directly after transportation to the offshore site, and the foundation is installed. The simulation clock is updated to the time when the vessel is available for installing a new component.
1	1	2	Transition piece	5-5	6	A weather window is found directly after installation of the foundation. The transition piece require an installed foundation and can be installed on top of the already installed foundation. The simulation clock is updated to the time when the vessel is available for installing a new component.
1	1	3	Foundation	11-12	13	A weather window is first found in time periods 11-12.
1	1	4	Transition piece	15-15	16	A weather window is first found in time periods 15-15.
Summary for HLV						
<p>Earliest start dates for components depending on the foundation: Only the transition piece is dependent on the installation of foundations. The transition piece and the foundation are loaded on the same loading set, and the precedence in this case is therefore taken care of by the activity list.</p> <p>Earliest start dates for components depending on the transition piece: [6, 16]</p> <p>End date: 16</p> <p>Penalties assigned: 0</p> <p>Number of exercised options: 0</p>						
Vessel: Cable laying vessel (CLV)						
v	l	a	Event	Performing periods	Update of simulation clock	Comment
2	-	-	Charter start date	-	1	The simulation clock is updated to the charter start date of the vessel.
2	1	-	Loading and sailing	1 - 2	3	The simulation clock is updated by the loading and sailing time of the vessel.
2	1	1	Precedence restriction	-	6	Installation of a cable requires an installed transition piece, and the simulation clock is therefore updated to 6, which is the time period when the first transition piece is installed.
2	1	1	Cable laying	6 - 7	8	A weather window is found for the cable laying.
2	1	2	Precedence restriction	-	16	Installation of a cable requires an installed transition piece that does not already have an installed cable. The second transition piece is installed in time period 16, and the simulation clock is therefore updated to 16.
2	1	2	Cable laying	16 - 17	18	A weather window is found for the cable laying.
Summary for CLV						
<p>Earliest start dates for components depending on cable laying: [8, 18]</p> <p>End date: 18</p> <p>Penalties assigned: 0</p> <p>Number of exercised options: 0</p>						

Vessel: Cable burial vessel (CBV)						
v	l	a	Event	Performing periods	Update of simulation clock	Comment
3	-	-	Charter start date	-	1	Simulation clock is updated to the charter start date of the vessel.
3	1	-	Loading and sailing	1 - 2	3	The simulation clock is incremented by the loading and sailing time of the vessel.
3	1	1	Precedence restriction	-	8	Cable burial requires installation of a cable. The first cable is fully installed in time period 8, and the simulation clock is therefore incremented to this time period.
3	1	1	Cable burial	8 - 9	10	A weather window is found for the cable burial.
3	1	2	Precedence restriction	-	18	The second cable is first installed in time period 18. As the burial of a cable requires an installed and available cable, the simulation clock is incremented to time period 18.
3	1	2	Cable burial	18 - 19	20	A weather window is found for the cable burial.
Summary for CBV						
Earliest start dates for components depending on cable burial: No activity is dependent on the cable burial. End date: 16 Penalties assigned: 0 Number of exercised options: 0						
Vessel: Turbine installation vessel (TIV)						
v	l	a	Event	Performing periods	Update of simulation clock	Comment
4	-	-	Charter start date	-	1	The simulation clock is incremented to the charter start date of the vessel.
4	1	-	Loading and sailing	1 - 2	3	The simulation clock is incremented by the loading and sailing time of the vessel.
4	1	1	Precedence restriction	-	8	Installation of the offshore wind turbine requires an installed cable. The first installed cable is fully installed in time period 8, and the simulation clock is therefore updated to time period 8.
4	1	1	Offshore wind turbine	18 - 20	21	A weather window is found for the cable installation.
4	1	2	Precedence restriction	-	21	The precedence restriction is fulfilled in the current time period. Due to this, the simulation clock is not incremented.
4	1	2	Offshore wind turbine	29 - 31	32	A weather window is found for the installation of the offshore wind turbine in the time periods 29-31.
Summary for TIV						
Earliest start dates for components depending on installation of the offshore wind turbine: No activity is dependent on the installation of the offshore wind turbine. End date: 32 Penalties assigned: 0 Number of exercised options: 1						
Returning total cost						
At this point, the scheduling of the activities for all vessels is completed. The simulator can thereby evaluate the total cost. The total cost is found by summing the cost of chartering the vessels, the included options, the cost of the exercised options, the cost of the penalties assigned for not completing activities, and the penalty related to loss of production. In this walkthrough example, only the TIV needed to exercise an option. All activities are completed within the possible charter periods of the vessels, and therefore no penalties are assigned for activities not done. The penalty cost for loss of production is calculated by multiplying the loss of production rate with the projects end date. In this walkthrough example, the projects end date corresponds to the TIV end date, as this vessel completes its activities last.						

## 8 Risk profile and lump sum

This chapter describes a method to assess the price of a lump sum contract. The method is based on the information given in Section 2.4.2. The difference between the expected return on a portfolio and a riskless asset is often termed its risk premium. (Sharpe, 2020). For the weather risk, the expected chartering cost is the expected return, and the lump sum is a riskless asset.

The lump sum can be expressed as:

$$Lump\ sum = Expected\ cost + Risk\ premium$$

Where the expected cost is the expected cost for OWT installation vessels when a risk-neutral OWF developer bears the weather risk. The risk premium is the additional cost he pays due to his risk aversion, for the contractor to bear the risk.

The chartering cost distribution provides useful information to decide a reasonable lump sum price. In our two-stage stochastic model, the cost distribution depends on the first stage decision. To estimate the cost distribution, the simulation model evaluates a number of weather scenarios and calculates the cost in each scenario, given the first stage decisions. In general, a risk-averse decision-maker is willing to pay an additional cost to avoid the consequences of the  $q\%$  tail.

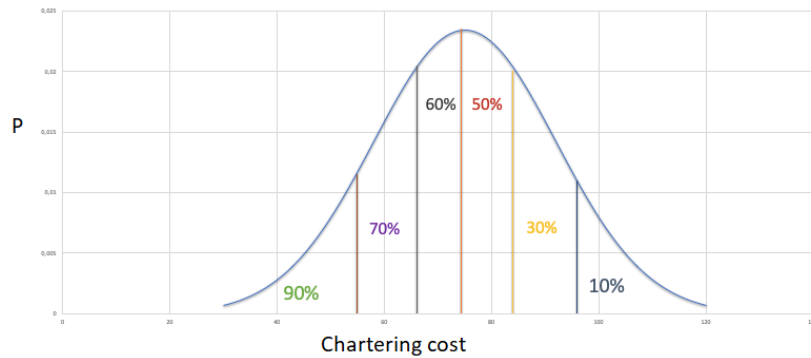


Figure 17: The  $q\%$  tail of the cost distribution, where the chartering cost is drawn on the x-axis and the probability on the y-axis.

A risk-neutral decision-maker "makes decisions on the average return on an investment and is not interested in the standard deviation of returns" (Oxford Reference,



2020). Therefore, the risk-neutral OWF developer considers all scenarios and the expected cost, when deciding the lump sum. A risk-averse OWF developer is willing to offer a higher lump sum price to avoid uncertainty and the possibility of losing money in the worst scenarios. The degree of risk aversion depends on several factors: the number of projects the developer is involved in, economic capacity and the variance in the scenarios studied. The risk-averse decision-maker decides how much he is willing to pay to avoid uncertainty based on the factors mentioned.

As mentioned in the problem description, our goal is to assess a lump sum price for the installation fleet. The decision-maker needs information to assess the contract and decide how much he is willing to offer in a lump sum to the vessel owners. As a starting point the cost distribution is estimated for a risk-neutral first-stage decision, as our assumption is that the decision maker has little information about how much loss he can bear with different confidence levels. If the cost distribution shows some extremely negative cases, a risk-averse decision maker can adjust the first-stage decision to better represent his situation. A risk-averse OWF developer could add more extension options in the contract to hedge himself from not finishing the OWF in the worst cases. However, this first-stage decision has a higher expected cost than the risk-neutral first-stage decision.

The expected tail cost is calculated by sorting all weather scenarios considered, according to increasing objective value. The expected cost in the 20% tail is the same as the average cost of the 20% scenarios with the highest cost, for a fixed first-stage decision.

The method described in this chapter gives the OWT developer elements to assess the lump sum price. However, the exact price he is willing to offer depends on the risk level. Our method suggests reasonable values for the minimum lump sum (the expected cost in 100% tail) and maximum (the expected cost in the 5-20 % tail).

## 9 Computational study

The purpose of the computational study is to test the mathematical model presented in Section 5.3, the tabu search heuristic presented in Section 6 and to perform an analysis of the contract configuration of an offshore wind farm. First, the input data is presented in Section 9.1. A brief testing of the original model is presented in Section 9.2. The tabu search heuristic is tuned and tested in Section 9.3. Section 9.4 shows how the method can be used to give valuable insights when planning the chartering contracts of an offshore wind farm of 120 turbines. Finally, a summary of the computational study is presented in Section ??.

The mathematical model is implemented in the commercial optimization software FICO Xpress IVE 8.6. It applies branch and bound with depth first strategy. The maximum run time is set to 3 hours (10 800 seconds) for practical purposes. The heuristic is implemented in PyCharm 2020.1.2 with Python 2.7 as the interpreter. All the test instances are run on a Hewlett Packard 64-bit Windows 10 Enterprise PC with Intel(R) Core(TM) i7-8700, 3.20 GHz processor and 32,0 GB (31,8 GB usable) RAM.

### 9.1 Input Data

This section describes the input data used in the test instances given in Section 9.1.10. For the sake of generating realistic test instances, the input data is based on information given in Chapter 2, in addition to information given in interviews with Equinor ASA and Fred. Olsen Windcarrier (Appendix A, B and C). The input data is described for the offshore wind farms properties, time, installation activities, vessels, extension options, weather scenarios, and penalty cost. At last, the test instances used to test the model are presented.

#### 9.1.1 Offshore wind farm properties

Two properties characterize the offshore wind farm; the distance from shore and the number of turbines. The distance from shore will affect the sailing time for the vessels when picking up new loading sets. The largest offshore wind farm tested in this thesis has 120 offshore wind turbines and is located 130 km from shore. This choice is inspired by the current largest offshore wind farm project, Dogger Bank, which consists of three projects of offshore wind farms of 110-120 offshore wind turbines each, which are located about 130 km from shore (Dogger Bank, 2020).

The tabu search heuristic is tuned and tested for the wind farms presented in Table 8 in Section 9.3. To illustrate how the model can be used in the planning phase of an offshore wind farm, it is performed an analysis on Offshore wind farm 3 in Section 9.4.

The three wind farms are also characterized by distance from shore, and typically larger farms are further from shore (Paterson et al., 2018). Different distances from shore for a wind farm size is not tested, as preliminary testing showed that the effect on the running time is very small.

Table 8: Wind farm properties

Wind farm	Turbines	Distance from shore
Offshore wind farm 1	10	6 km
Offshore wind farm 2	60	20 km
Offshore wind farm 3	120	130 km

### 9.1.2 Time

The test instances use a time discretization of 12 hours. The time discretization is based on the installation times of the activities, which are described in Section 9.1.3. The start time of installation is set to the 1st of April. The planning horizon of the problem is dependent on the size of the wind farm. For the smaller offshore wind farms tested in FICO Xpress with the number of turbines less than ten turbines, the planning horizon is six months (April-September). For larger instances solved by the heuristic, the planning horizon is set to five years. Preliminary testing showed that the largest offshore wind farm of 120 turbines required a planning horizon of this length, but this is not required for the smaller offshore wind farms of 10 and 60 OWTs. In the following sections durations are given in periods with discretization of 12 hours.

### 9.1.3 Activities

As mentioned in Section 2.1.1, the monopile is by far the most used foundation. The testing is therefore applied to the installation of an offshore wind farm that uses monopiles as foundations. The activities included in the testing are; installation of foundation, transition piece, cable laying, cable burial, and installation of the top structure.

Figure 18 shows the precedence of the activities for one offshore wind turbine. The foundation is installed before the transition piece. The cable laying requires a crew entering the transition piece, and the transition piece must, therefore, be completely installed before the cable laying can start. When the cable laying is completed, the top structure of the wind turbine can be installed on top of the transition piece. In addition, the cable is buried after cable laying. The installation of the top structure and the cable burial can be done in parallel.

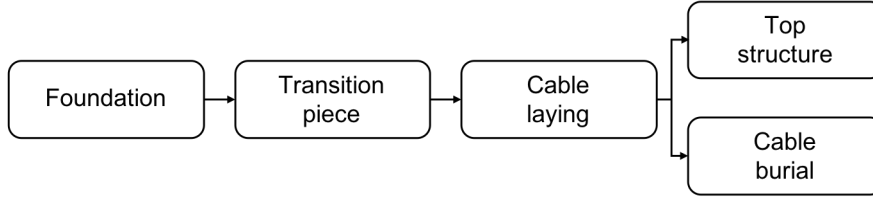


Figure 18: Installation activities for one offshore wind turbine

The activities for installing one wind turbine and the activity duration, operational wind and wave limits are based on the values given in Table 1 in Section 2.2 and are presented in Table 9. The top structure's installation duration includes the time needed jacking up and down the turbine installation vessel (TIV).

Table 9: Activities and their properties for one OWT

Activity	Duration (periods)	Wave limit (m)	Wind limit (m/s)
Installation of foundation	2	2	12
Installation of transition piece	1	2	12
Cable laying	2	1.5	15
Cable burying	2	3	12
Installation of top structure	3	2	11

For the mathematical model, dummy nodes that represent the start and end node are needed. These will have a duration of one and wave and wind limit of infinity, as presented in Table 10.

Table 10: Dummy nodes used in the mathematical model

Activity	Duration (periods)	Wave limit (m)	Wind limit (m/s)
Start project (dummy node)	1	$\infty$	$\infty$
End project (dummy node)	1	$\infty$	$\infty$

#### 9.1.4 Vessels

For the purpose of the testing, the following vessels are included; heavy lift vessel (HLV), cable-laying vessel (CLV), cable burial vessel (CBV) and turbine installation vessel (TIV). Table 11 shows which installation activities each vessel perform. The HLV is required to install the monopile foundation and the transition piece. The CLV is chartered to install the cables, and the CBV is required to bury the cables. Lastly, the TIV is required to install the top structure. The vessels used in testing are decided on the basis of the comparison in Section 2.3.1. HLV are preferred for wind farms with a longer distance from shore for the installation of foundations and transition pieces, and TIV for top structures. Furthermore, it is assumed that the charter start date of a vessel can only be every seventh day.

Table 11: Vessels and their associated installation activities

	Foundation	Transition piece	Cable laying	Cable burial	Wind turbine
HLV	✓	✓			
CLV			✓		
CBV				✓	
TIV					✓

The fixed costs and the day rates for the vessels are presented in Table 12. The chartering costs are subject to high variations in supply and demand, and are therefore kept strictly confidential (Interview with Fred. Olsen Windcarrier). The day rates are therefore based on numbers from BVG Associates (2019) and Ahn et al. (2016), as shown in Table 2. For the purpose of the testing, the day rates are assumed to be proportional to the capacity assumed for the vessels. The loading capacity of the vessel is based on numbers from the same table. The magnitude of the fixed costs are based on numbers from Hansen and Siljan (2017).

The loading sets used in testing are presented in Table 12. The loading capacity of the HLV and the TIV are inspired by the loading sets used for the HLV and the TIV chartered for the Dogger Bank project and the information given in 2. The HLV chartered for this project loads 10 foundations and 10 transition pieces on each loading set (Kalvseth, 2019), while the TIV is assumed to load 9 top structures in each loading set. It is assumed that the CLV and the CBV have enough capacity for the activities they perform; installation of cables and burial of cables. Their loading set is therefore assumed to be the number of turbines in the offshore wind farm and loading for these vessels are therefore only performed once.

Table 12: Vessels and their associated costs and loading sets

<b>Vessel</b>	<b>Fixed Cost (kUSD)</b>	<b>Day rate (kUSD/12h)</b>	<b>Loading set</b>
HLV	5500	110	10 foundations and 10 transition pieces
TIV	5000	100	9 top structures
CLV	2500	50	Number of turbines
CBV	2650	53	Number of turbines

The loading duration and the sailing duration for a round trip from the offshore wind farm site to the port and back to the offshore wind farm site is presented in Table 13. The loading time is assumed to be 12 hours, inspired by the loading time used by Scholz-Reiter et al. (2011). According to Livanidou et al. (2015) the average vessel sailing speed is 4-8 knot for the HLV and the TIV. Based on this, an average sailing time of 6 knot is assumed for all vessels chartered to find the sailing duration described in Table 13.

Table 13: Loading and sailing duration (in periods)

<b>Distance from shore (km)</b>	<b>Loading duration (periods)</b>	<b>Sailing duration round trip (periods)</b>
10	1	1
60	1	1
120	1	2

The standard of the testing is transporting the components from the port to the offshore wind farm with the installation vessels. However, it is also tested whether it can be cost-effective to charter dedicated transport vessels to transport the components instead of using the expensive installation vessels for transporting. In this case, the sailing duration for the installation vessels are avoided. In order to use dedicated transport vessels, a cargo barge that loads the components and a tugboat used to tow the cargo barge are needed. The weather requirements for sailing are lower than the weather requirements for installation (Interview with Equinor). Therefore, it is assumed that the dedicated transport vessels always have components available for the installation vessels.

The dedicated transport vessels must be available for the installation vessel for the entire charter period for the installation vessel. Because of this, it is assumed that the dedicated transport vessels must be chartered in the same time periods and with the same number of extension options as the installation vessel for which the dedicated transportation vessels transport the components. The dedicated transport vessels are only chartered for the HLV and the TIV, assuming that the CLV and the

CBV have the cables and equipment loaded for the total installation period. It is assumed that one cargo barge and one tugboat is needed for each installation vessel requiring the dedicated transport vessels. The costs of the dedicated transportation vessels are as explained in Table 2, and are presented in Table 14. The testing is done by adding the fixed costs and the day rates of the dedicated transport vessels to the fixed costs and the day rates of each HLV and TIV. In other words, the dedicated transport vessels are indirectly taken account of, by increasing the cost of chartering HLV and TIV. However, the sailing time to port and back to site for HLV and TIV is removed, which involves cost reductions.

Table 14: Costs for dedicated transport vessels

Vessel	Fixed cost (kUSD)	Day rate (kUSD)
Cargo barge	200	40
Tugboat	6	3

### 9.1.5 Extension options

As described in Section 2.4, extension options can be added to the contract by buying one or several options. For the purpose of testing, extension option periods of four weeks (56 time periods) have been used as the standard extension option period.

For the same reason as day rates and fixed costs are kept confidential, option prices are also kept confidential. To our knowledge, it does not exist literature which addresses the specific option prices and exercise prices for specific vessels, neither how to assume these. However, it will not apply any extra engineering work for exercising the option (Interview with Fred. Olsen Windcarrier). It is therefore reasonable to assume that the exercise price of the extension option can be calculated as described in equation 9.1.

$$\text{Exercise price} = \text{Day rate} \times \text{Extension option period} \quad (9.1)$$

The price of including an option in the contract, is calculated by multiplying the exercise price by a factor  $\beta < 1$ , as shown in equation 9.2. The  $\beta$  is assumed to 0.5 for extension options of the standard length of four weeks.

$$\text{Option price} = \text{Exercise price} \times \beta \quad (9.2)$$

It is also tested whether extension options of longer periods can give a lower expected cost for the wind farm operator. As described in Section 2.4.1, longer options are of higher interest for the ship owner and the price of extension options with longer

periods than the standard period of 4 weeks will therefore have a lower relative price, and therefore a lower  $\beta$ . The option periods given a 12-hour discretization and the corresponding option prices and exercise prices are shown in Table 15.

Table 15: Option periods and prices

Vessel	Option period	Exercise price (kUSD)	$\beta$	Option price (kUSD)
HLV	1 month	6600	0.50	3300
CLV	1 month	3000	0.50	1500
CBV	1 month	3180	0.50	1590
TIV	1 month	6000	0.50	3000
HLV	3 months	18480	0.45	8316
CLV	3 months	8400	0.45	3780
CBV	3 months	8904	0.45	4007
TIV	3 months	16800	0.45	7560
HLV	6 months	36960	0.40	14784
CLV	6 months	16800	0.40	6720
CBV	6 months	17808	0.40	7123
TIV	6 months	33600	0.40	13440

The options for the testing of dedicated transport vessels are described in Table 16. The dedicated transportation vessels are only tested for the standard option length of four weeks. For the purpose of testing, the exercise prices and option prices of the dedicated transport vessels are added to the exercise price and option price of the associated installation vessel (HLV or TIV).

Table 16: Option periods and prices for the dedicated transport vessels

Vessel	Option period	Exercise price (kUSD)	$\beta$	Option price (kUSD)
Cargo barge	1 month	2240	0.50	1120
Tugboat	1 month	168	0.50	84

### 9.1.6 Scenarios

The weather data used in the testing is given by Equinor. The data is retrieved from a site on the northern hemisphere characterized by harsh weather conditions. This data contains wave height and wind speed, and is collected every three hours from 1973-1993. As it is not possible to operate through the 12-hour period if the weather conditions at some point exceed the operational limits within the 12-hour period, the maximum wave height and wind speed for each 12-hour period in the data set have been used.

It is assumed that the weather scenarios are uniformly distributed. This means that the probability of each weather scenario is the same, and calculated by  $1/|S|$ .



The first weather scenario corresponds to the weather realized from year 1973 to 1977, the second weather scenario corresponds to the weather from year 1974 to 1978, and so on. The start date of the project is fixed to the 1st of April in the first year of the scenario. This gives a total of 15 scenarios for the purpose of testing.

The number of scenarios used in the testing will affect the results of the model. The use of 15 scenarios in the testing assumes that the 20 years of weather data provide an exact picture of the entire history. In Appendix A Equinor explained that they have access to more than 50 years of weather data, so it is assumed that the decision maker can use a higher level of precision if needed.

#### **9.1.7 Penalty cost for loss of production, $P^f$**

The earlier the wind farm is able to operate, the earlier the operator can start earning money by selling electricity. Therefore, it is desirable to finish the installation of the wind farm as soon as possible, and it is applied a penalty for each day the wind farm is not finished. This penalty is decided by calculating revenues of selling the generated electricity, as shown in equation 9.3.

$$\text{Lost revenues} = \text{Electricity price} \times \text{Rating of turbine} \times \# \text{Turbines} \times \text{Time} \quad (9.3)$$

The average rating of newly installed turbines in 2018 was 6,8 MW (Wind Europe, 2019, p. 9). The average electricity price in the US in 2018 was 133.1 USD/MWh (Electric Choice, 2019). The calculation of the penalty is based on these numbers.

#### **9.1.8 Fixed penalty cost for not finishing the wind farm within charter period, $P^w$**

Two major cost drivers are addressed when estimating a penalty cost for not finishing the wind farm within the charter period: the cost of chartering in new vessels, and the loss of production while waiting for new vessels. Quantifying these cost components is difficult, as the waiting time for a new vessel can vary between three months to two years (Interview with Fred. Olsen Windcarrier). The cost of chartering new vessels is also uncertain, as it depends on how much work is already done on the wind farm. Assuming one year loss of production is a reasonable assumption (average waiting time), in addition to the fixed cost of chartering in new vessels.

$$\begin{aligned} \text{Penalty} = & \text{Loss of production rate} \times 1 \text{ year} \times \text{Turbines} \\ & + \text{Fixed cost of all vessels} \end{aligned} \quad (9.4)$$

### 9.1.9 Variable penalty cost for not finishing the wind farm within charter period, $P^Q$

As mentioned above, the penalty cost depends on how much work is already done on the wind farm. To avoid making a new optimization problem to find the time needed for each vessel needed again, a conservative assumption is made; each activity takes two weeks each, including weather delays, and day rates for the most expensive vessel are used. Two weeks installation time is reasonable because the OWF developer might have to charter in vessels during winter, as the supply for installation vessels is higher during winter.

$$\begin{aligned} \text{Penalty} = & \text{Day rate of the most expensive vessel} \times 2 \text{ weeks} \\ & \times \text{Decision variable for number of not finished activities} \end{aligned} \tag{9.5}$$

### 9.1.10 Test instances

Table 17: Test instances used for testing the original model in FICO Xpress

Instance	Turbines	Scenarios	Vessels	Planning horizon
T1	1	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336
T2	2	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336
T3	3	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336
T4	4	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336
T5	5	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336
T6	6	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336
T7	7	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336
T8	8	1	1×HLV, 1×CLV, 1×CBV, 1×TIV	336

Table 18: Test instances used for tuning the tabu search heuristic

Instance	Turbines	Scenarios	Vessels	Planning horizon
T10V4	10	15	1×HLV, 1×CLV, 1×CBV, 1×TIV	4200
T10V8	10	15	2×HLV, 2×CLV, 2×CBV, 2×TIV	4200
T60V4	60	15	1×HLV, 1×CLV, 1×CBV, 1×TIV	4200
T60V8	60	15	2×HLV, 2×CLV, 2×CBV, 2×TIV	4200
T120V4	120	15	1×HLV, 1×CLV, 1×CBV, 1×TIV	4200
T120V8	120	15	2×HLV, 2×CLV, 2×CBV, 2×TIV	4200

Table 19: Test instances used for testing vessel configurations

Instance	Turbines	Scenarios	Vessels	Planning horizon
T120V4	120	15	1×HLV, 1×CLV, 1×CBV, 1×TIV	4200
T120V5HLV2	120	15	2×HLV, 1×CLV, 1×CBV, 1×TIV	4200
T120V5CLV2	120	15	1×HLV, 2×CLV, 1×CBV, 1×TIV	4200
T120V5CBV2	120	15	1×HLV, 1×CLV, 2×CBV, 1×TIV	4200
T120V5TIV2	120	15	1×HLV, 1×CLV, 1×CBV, 2×TIV	4200
T120V6HLV2CLV2	120	15	2×HLV, 2×CLV, 1×CBV, 1×TIV	4200
T120V6HLV2TIV2	120	15	2×HLV, 1×CLV, 1×CBV, 2×TIV	4200
T120V6CLV2TIV2	120	15	2×HLV, 1×CLV, 1×CBV, 2×TIV	4200
T120V7	120	15	2×HLV, 2×CLV, 1×CBV, 2×TIV	4200
T120V8	120	15	2×HLV, 2×CLV, 2×CBV, 2×TIV	4200

Table 20: Test instance used for testing of dedicated transport vessels

Instance	Turbines	Scenarios	Vessels	Planning horizon
T120V7D	120	15	2×HLV, 2×CLV, 1×CBV, 2×TIV, 4× cargo barge, 4× tugboat	4200

Table 21: Test instances used for testing option configurations

<b>Instance</b>	<b>Turbines</b>	<b>Scenarios</b>	<b>Vessels</b>	<b>Option length</b>	<b>Planning horizon</b>
T120V7O1	120	15	2×HLV, 2×CLV, 1×CBV, 2×TIV	1 month	4200
T120V7O3	120	15	2×HLV, 2×CLV, 1×CBV, 2×TIV	3 months	4200
T120V7O6	120	15	2×HLV, 2×CLV, 1×CBV, 2×TIV	6 months	4200

Table 22: Test instance used for testing of lump sum

<b>Instance</b>	<b>Turbines</b>	<b>Scenarios</b>	<b>Vessels</b>	<b>Planning horizon</b>
T120V7	120	15	2×HLV, 2×CLV, 1×CBV, 2×TIV	4200

Table 23: Test instances used for solving the model with different numbers of scenarios

<b>Instance</b>	<b>Turbines</b>	<b>Scenarios</b>	<b>Vessels</b>	<b>Planning horizon</b>
T120V7	120	1	2×HLV, 2×CLV, 1×CBV, 2×TIV	4200
T120V7	120	2	2×HLV, 2×CLV, 1×CBV, 2×TIV	4200
T120V7	120	4	2×HLV, 2×CLV, 1×CBV, 2×TIV	4200
T120V7	120	7	2×HLV, 2×CLV, 1×CBV, 2×TIV	4200
T120V7	120	15	2×HLV, 2×CLV, 1×CBV, 2×TIV	4200

## 9.2 Original model

The mathematical model presented in Section 5 is tested in order to find which test instances the model can solve within the predetermined CPU time of 3 hours. Table 24 presents the results of running the mathematical model. The CPU time increases with the number of turbines. For a wind farm with seven turbines or more, it is not possible to find a feasible solution within three hours. Increasing the number of turbines from six to seven turbines leads to that a feasible solution can not be found within three hours.

The testing shown in Table 24 is done with only one scenario and with a planning horizon of 6 months. Voster & Kjølby (2019) showed that the CPU time increased significantly by increasing the number of scenarios. Preliminary testing also showed that the complexity of the model increased when increasing the planning horizon.

In summary, the complexity of the model increases with the number of turbines, the number of scenarios and the number of time periods. It is not possible to solve realistic test instances within a reasonable time limit.

Table 24: Results of testing turbine dimension

<b>Instance</b>	<b>CPU Time</b>	<b>Gap</b>	<b>Primal bound</b>
T1	151	0	10619
T2	460	0	20570
T3	725	0	28477
T4	1463	0	33136
T5	1850	0	40035
T6	9688	0	47802
T7	10800	100 %	-
T8	10800	100 %	-

### 9.3 Heuristic tuning

Six OWF instances are used to test and adjust the tabu search, and are presented in Table 18. The instances are combinations of three types of wind farms and two different fleets. As presented in Section 9.1.1, three offshore wind farms are tested. The three wind farms represent a small, medium, and large wind farm. The two fleet alternatives represent two extremes: using one of each vessel is the minimum in a OWF project, and using more than two of each vessel is not practically feasible for a single project due to material handling (Interview with Fred. Olsen Windcarrier).

#### 9.3.1 Search strategies

In this section, the results of testing different search strategies within the tabu search are presented. The search strategies are best improvement, first improvement, and a combination of both (hybrid search). These strategies are described in Section 6.5. As improvements are made at different points in time, and as the objective value eventually stops improving in every search strategy, it is valuable to study how the objective value changes as a function of time. In addition, the process of finding good solutions depends on the instance tested, meaning that it is valuable to test the search strategies for different instances. The comparison of the search strategies is based on computation time as a comparison of improvements per iteration is misleading. The computation time per iteration differs, especially for first improvement and best improvement.

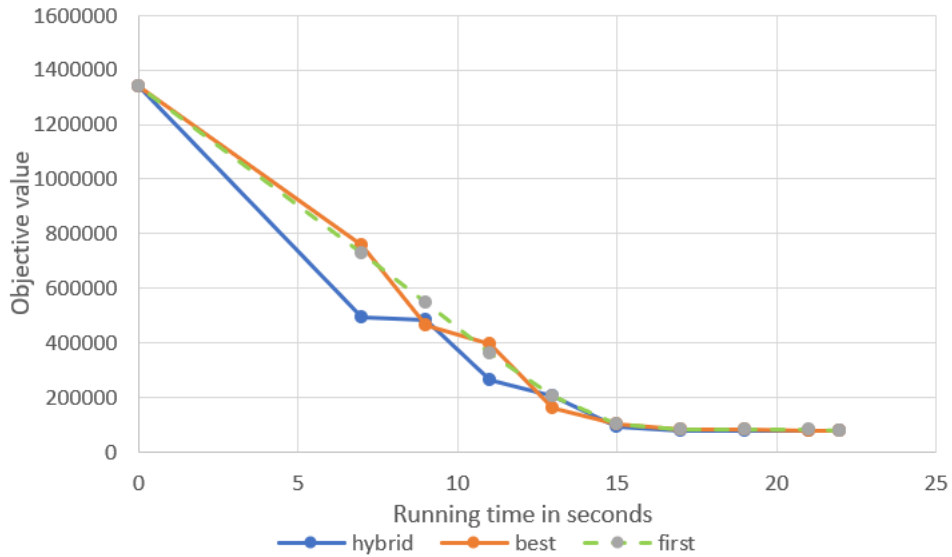


Figure 19: Performance of search strategies in instance T10V4 (expected cost in thousand dollars).

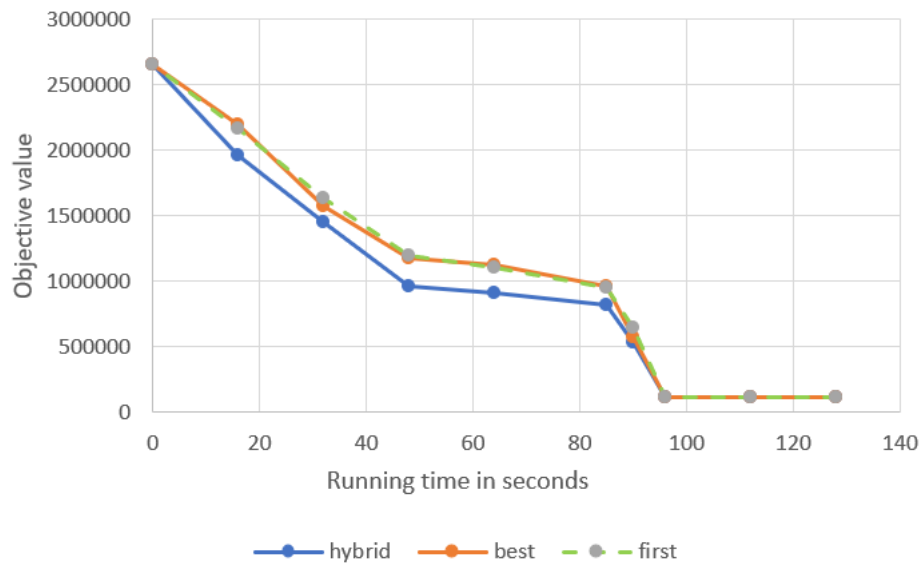


Figure 20: Performance of search strategies in instance T10V8 (expected cost in thousand dollars).

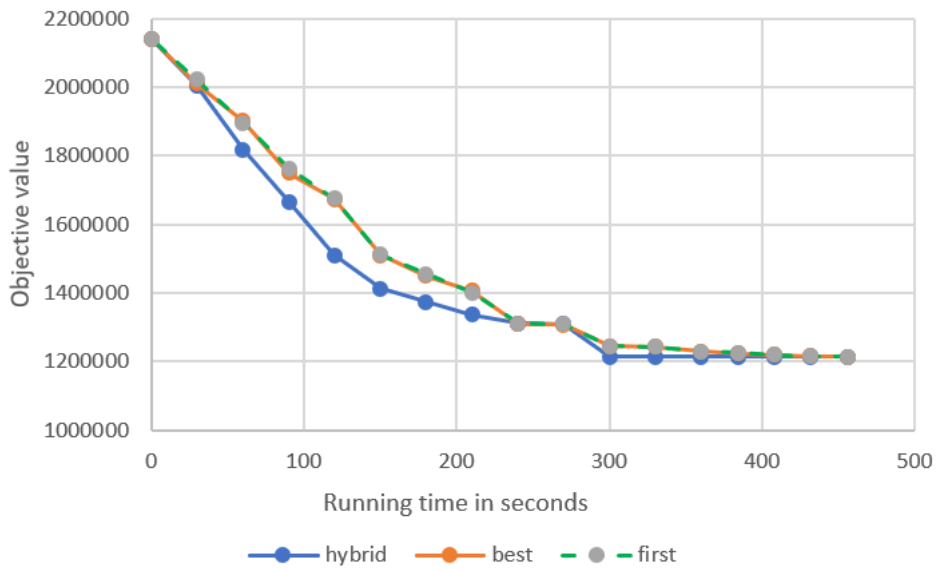


Figure 21: Performance of search strategies in instance T60V4 (expected cost in thousand dollars).

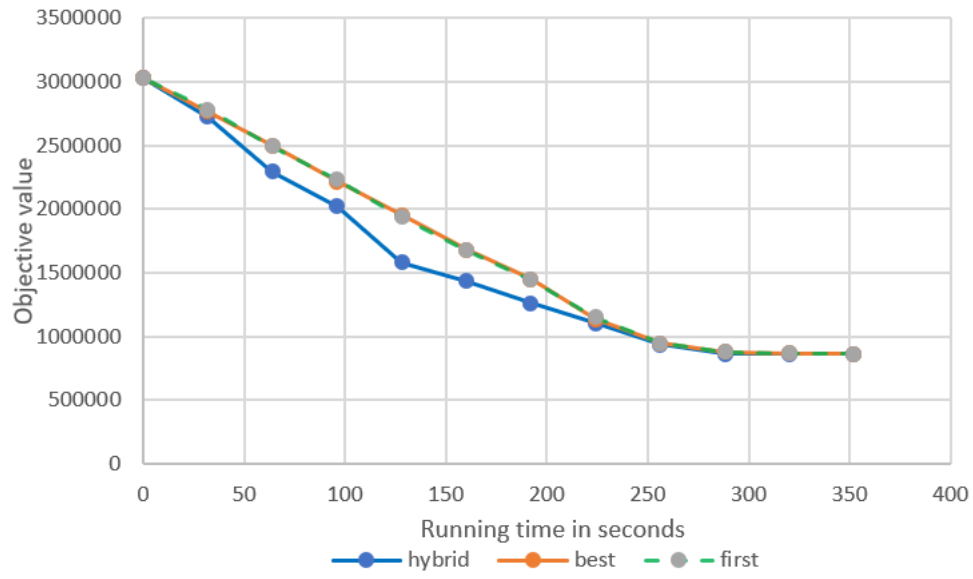


Figure 22: Performance of search strategies in instance T60V8 (expected cost in thousand dollars).

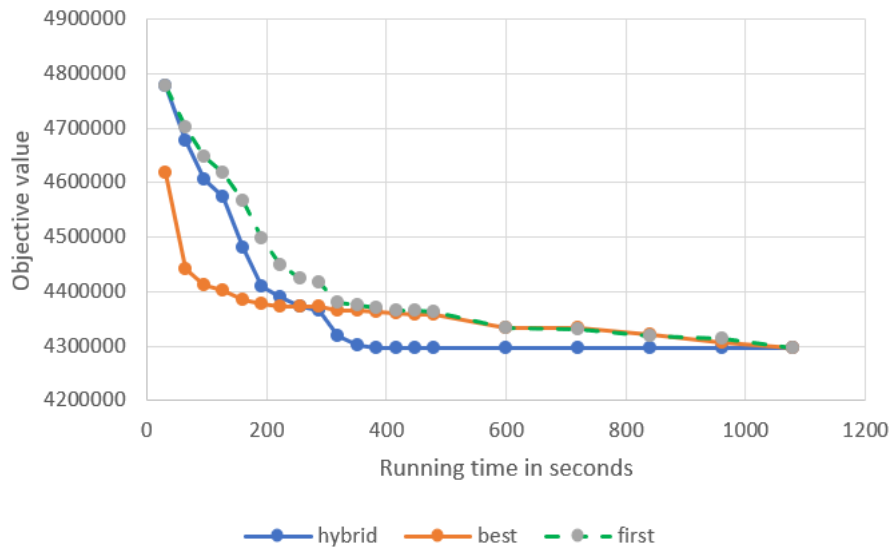


Figure 23: Performance of search strategies in instance T120V4 (expected cost in thousand dollars).



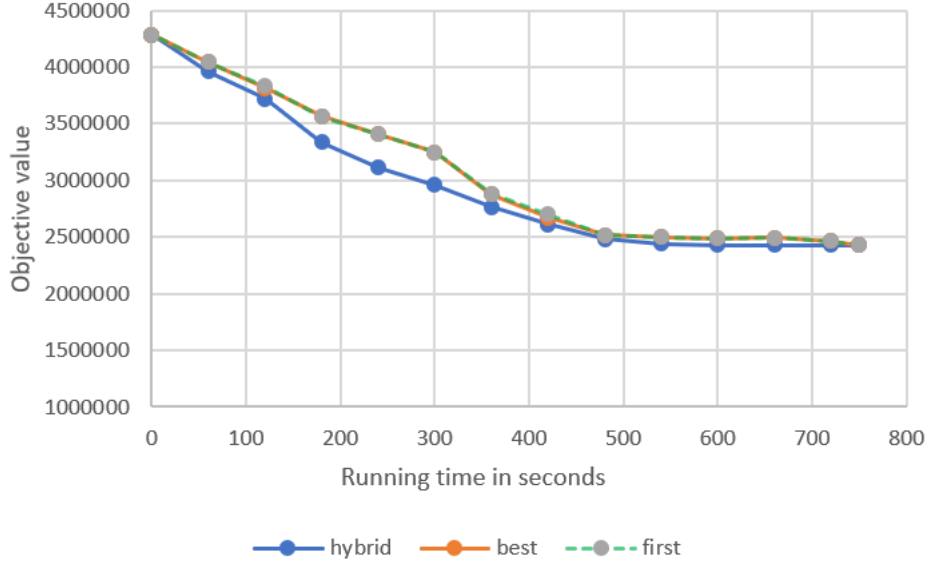


Figure 24: Performance of search strategies in instance T120V8 (expected cost in thousand dollars).

Instance T120V4 showed the largest difference when testing different improvement strategies, as the hybrid search stopped improving at the best solution found, approximately 600 seconds before the first improvement and best improvement search. In instance T60V4 and T120V8, the hybrid search found the best solution 100 and 200 seconds before the other searches. In the remaining instances, the hybrid search made improvements faster than the other searches, but all search methods used the same amount of computation time to find the best solution. The hybrid search will be applied in the following sections as this was either as fast or faster than the two other search strategies in all instances tested.

### 9.3.2 Tabu lists and use of memory

In this section, different tabu list sizes and strategies are tested. As the size of a tabu list can be in the range  $[0, \infty]$ , we limit the testing to the following sizes: 0, 5, 10, 20, 30, 40, 50, 100. The goal of a tabu list is to prevent the search from cycling around local optimums. Hence, the stopping criterion is: the vessel type iteration stops when the best solution has not been improved for 15 minutes. Test runs have shown that the vessel type iterations differ in time used before the search stops to improve. Hence this stopping criterion is more effective than considering the total computation time per vessel iteration. Long-running times are required to check if the search finds a better solution, and to compare tabu list results. However, a reasonable time limit is set as the search can continue forever. Considering that the

hybrid improvement in Section 9.3.1 only uses 9 minutes before the best solution is found, a total running time of 15min x 4 (four vessel type iterations) without improvements is a reasonable time to stop and evaluate the tabu lists. Although time is used as a stopping criterion, the number of iterations without improvements is studied in Section 9.3.3.

Two types of tabu list memory structures are tested: short-term and long-term. The two tabu lists are described in Section 6.7. A short-term tabu lists with different lengths of the tabu lists is tested. In addition, a long-term memory structure is tested to diversify the search further. Overlapping of both methods is also tested.

Tabu lists longer than 100 neighbors are not tested as the search quickly get stuck in dead-ends of tabu moves, after already searching into non-promising areas. An option could be to implement an aspiration criteria to diversify further; however, an examination of the search procedure shows that the diversification already tested drive the search into non-promising areas, which are unrealistic.

In Table 25, different tabu lists are tested for the six instances presented in Table 18. For each instance, the first row shows test results for the short-term memory, where  $l$  denotes the length of the tabu list. A search without tabu lists is represented by  $l = 0$ . The second row shows a long-term tabu list without a length limitation. Row two, column one ( $l$ -term,  $l = 0$ ) shows a search with only the long-term tabu list and not a short-term list. The remaining columns show the overlapping of both methods. For instance, ( $l$ -term,  $l = 5$ ) is a search with a short-term tabu list with a maximum length of five solutions and a long-term list without a length limitation. The results in Table 25 is presented with five significant digits to show that the searches find the same solution with different tabu lists.

Table 25: Objective value after searches with different tabu lists (in million dollars).

Instance	Length	l = 0	l = 5	l = 10	l = 20	l = 30	l = 40	l = 50	l = 100
T10V4	s-term	79.751	79.751	79.751	79.751	79.751	79.751	79.751	79.751
	l-term	79.751	79.751	79.751	79.751	79.751	79.751	79.751	79.751
T10V8	s-term	114.74	107.32	107.32	107.32	107.32	107.32	107.32	107.32
	l-term	107.32	107.32	107.32	107.32	107.32	107.32	107.32	107.32
T60V4	s-term	1214.2	1214.2	1214.2	1214.2	1214.2	1214.2	1214.2	1214.2
	l-term	1214.2	1214.2	1214.2	1214.2	1214.2	1214.2	1214.2	1214.2
T60V8	s-term	862.78	862.78	862.78	862.78	862.78	862.78	862.78	862.78
	l-term	862.78	862.78	862.78	862.78	862.78	862.78	862.78	862.78
T120V4	s-term	4297.0	4297.0	4297.0	4297.0	4297.0	4297.0	4297.0	4297.0
	l-term	4297.0	4297.0	4297.0	4297.0	4297.0	4297.0	4297.0	4297.0
T120V8	s-term	2428.4	2428.4	2428.4	2428.4	2428.4	2428.4	2428.4	2428.4
	l-term	2428.4	2428.4	2428.4	2428.4	2428.4	2428.4	2428.4	2428.4

For the test instances T10V4, T60V4, T60V8, T120V4 and T120V8, all searches find the same best solution, which indicates that cycling is not an issue. In instance T10V8, all searches find the same best solution, with the exception of the search without any tabu lists. This indicates that cycling is an issue, but is handled by both the short-term and long-term tabu list structures.

These results strengthen our assumption that the good solutions lie close to each other in the search space (few local optima) and that very restrictive diversification rules are unnecessary. However, in instance T10V8 cycling was an issue handled by tabu lists. This suggests that other instances can have issues with cycling. Thus, having a tabu list structure in the heuristic is useful. For the testing in the following sections, a long-term tabu without a length limitation and a short-term tabu list with ten solutions as a length limitation, are applied to handle cycling. This tabu list structure handles cycling in instance T10V8, do not get stuck in dead-ends of tabu moves. As mentioned earlier, the long-term tabu list has no length limitations as it only stores local optimums.

### 9.3.3 Stopping criterion

As mentioned in Section 6.8, stopping after some number of iterations without an improvement in the objective function value is the most relevant stopping criterion, as the searches stop to improve after a reasonable time period. In our case, the search stops improving at different time periods for each vessel type iteration. Hence, the search moves to the next vessel type iteration after n iterations without improvements in the current vessel type iteration. To find a reasonable value for n, different n's are tested for six instances (presented in Table 18). Table 26 shows

the total running time for each instance and the objective value after  $n$  iterations without improvements. The results in Table 26 is presented with five significant digits to show that the searches find the same solution for several of the stopping criteria.

Table 26: Objective value after  $n$  iterations without improvements (in million dollars).

Instance	$n = 1$	$n = 10$	$n = 100$	$n = 1000$	$n = 10000$
T10V4	81.607 (4.44sec)	79.751 (4.83sec)	79.751 (11.9sec)	79.751 (53.8sec)	79.751 (15min,29sec)
T10V8	116.82 (4.98sec)	107.32 (6.35sec)	107.32 (15.9sec)	107.32 (6min,4sec)	107.32 (12min,45sec)
T60V4	1 214.2 (18.5sec)	1 214.2 (27.3sec)	1 214.2 (1min,22sec)	1 214.2 (9min,42sec)	1 214.2 (1hour,29min)
T60V8	862.78 (16.7sec)	862.78 (26.5sec)	862.78 (3min,8sec)	862.78 (8min,12min)	862.78 (1hour,10min)
T120V4	4 297.0 (45.1sec )	4 297.0 (64.6 sec)	4 297.0 (3min)	4 297.0 (21min,28sec)	4 297.0 (2hours,16min)
T120V8	2 428.4 (38.4 sec)	2 428.4 (59.9 sec)	2 428.4 (5min,9sec)	2 428.4 (21 min)	2 428.4 (2hours,36min)

For instance T10V4 and T10V8, the search must make non-improving moves to find the best solution as the best solution is not found at  $n = 1$ . For the remaining instances, the best solution is found without any non-improving moves. A simple neighborhood structure with effective neighbors could be why the search finds the best solution without non-improving moves and without tabu list in several instances. In instance T10V8 cycling was an issue, and the search made non-improving moves to find the best solution, but in instance T10V4 the search finds the "right track" after making non-improving moves and cycling is not a problem.

In all instances the search finds the same solution for all  $n \geq 10$ , which implies that the search will not find a better solution for additional iterations. The instance with the longest running time before no improvements found, is instance T120V4. Instance T120V4 runs for under 45.1 seconds before it stops to improve and represent the maximum number of OWTs, which are useful to test. Although the best solution is found for  $n=10$  in Table 26, there is no evidence that the optimal solution is found. Of course, the more iterations we apply, the better. The number of iterations is a trade-off between time and precision. For economic testing in the following sections, the stopping criterion is  $n = 100$ , as this finds the best solution in all instances tested in Table 26, and the running time is considered as reasonable for further testing.

### 9.3.4 Run time analysis

The running time before the search stops to improve increases when the number of OWTs increases. Table 27 outlines some characteristics which may explain why the running time increases. The table is based on stopping criterion  $n = 10$ .

Table 27: Tabu search characteristics for different instances.

Instance	Average simulation time per neighbor	Simulations	Iterations
T10V4	0.0114 sec	398	177
T10V8	0.0136 sec	464	204
T60V4	0.0559 sec	487	203
T60V8	0.0567 sec	444	183
T120V4	0.113 sec	560	267
T120V8	0.118 sec	506	211

The running time increases significantly when the number of OWTs increases. The number of OWTs has the highest effect on the simulation time for a neighbor. When the number of OWTs increases, the number of activities to schedule also increases. Further, the instances with two of each vessel have slightly longer simulation time. Most likely, the additional computational effort required is caused by the effort of coordinating the vessels. By multiplying the simulation time with the number of simulations, we observe that most of the heuristic running time lies in the simulations of neighbors. The number of iterations shows little variations between the instances tested.

As mentioned in Section 9.1.6, a decision-maker might increase the number of scenarios to increase the accuracy of the expected cost estimate. Table 28 shows that the time to evaluate a neighbor (simulation time) will be reasonable when the number of scenarios increases. Fifty weather scenarios are used as an example, as this is what Equinor uses (Interview with Equinor ASA). The simulation time increases linearly as the simulation algorithm runs for each weather scenario, and the expected cost is the average cost of the simulations. The total simulation time is estimated by linear regression of simulation time per neighbor( $t*50/15$ ). The estimated total simulation time is calculated by multiplying the simulation time per neighbor with simulations in Table 27. The estimated total simulation time is assumed to be close to the total running time, as the simulation time for 15 scenarios is at its least 94% of the total running time.

Table 28: Estimated simulation time for 50 scenarios (in seconds).

<b>Instance</b>	<b>Simulation time per neighbor, 15 scenarios</b>	<b>Estimated simulation time per neighbor, 50 scenarios</b>	<b>Estimated total simulation time, 50 scenarios</b>
T10V4	0.0114	0.0380	15.1
T10V8	0.0136	0.0453	21.0
T60V4	0.0559	0.182	90.7
T60V8	0.0567	0.189	83.9
T120V4	0.113	0.377	211
T120V8	0.118	0.393	199

### 9.3.5 Comparison of the original model and the tabu search heuristic

As shown in Section 9.2, the model implemented in Fico XPress can only solve instances in a deterministic setting up to six offshore wind turbines within a reasonable time limit. The heuristic is run for six offshore wind turbines with one scenario to compare the two methods. Table 29 presents the results of using the two methods. The heuristic solves the model to optimality within 41 seconds compared to almost three hours for the exact model. For the original model, it is impossible to find a feasible solution within three hours for offshore wind farms of more than six offshore wind turbines. Therefore, it is not possible to compare the original model and the heuristic of greater instances. The comparison shows that the heuristic finds optimal solutions for small instances with one scenario.

Table 29: Comparison of solving the original model by branch and bound in Fico Xpress and solving the model with the heuristic

<b>Instance</b>	<b>Solution method</b>	<b>CPU time (s)</b>	<b>Objective value</b>
T6	Original model	9688	47 802
T6	Heuristic	41	47 802

## 9.4 Planning of an offshore wind farm

This section will illustrate how the method can be used to support decisions in the planning phase of an offshore wind farm of 120 turbines and a distance from shore of 130 km. The starting point of the analysis uses one vessel of the following vessel types; HLV, CLV, CBV, and TIV.

Solving the model for this vessel configuration and extension options of one-month lengths gives the costs shown in Table 30. Table 30 presents the total cost, the average penalty cost for loss of production, charter costs and the average end period

for the project. The total cost is the objective value returned by the model. The total cost consists of penalty costs and charter costs. For this offshore wind farm, the optimal solution in all cases tested were to finish the offshore wind farm in all scenarios. Thus, both the fixed penalty cost (Section 9.1.8) and variable penalty cost (Section 9.1.9), equal zero. The penalty cost for loss of production (Section 9.1.7) is therefore the only penalty cost presented in this analysis.

Table 30: Costs for one HLV, CLV, CBV and TIV

<b>Vessels</b>	<b>Total cost (M)</b>	<b>Avg. penalty cost for loss of production (M)</b>	<b>Charter costs (M)</b>	<b>Avg. end period for the project</b>
HLV×1, CLV×1, CBV×1, TIV×1	\$ 4 297	\$ 3 470	\$ 827	2703

The contract set up suggested by the model is presented in Table 31. Table 31 presents the charter start period, fixed charter end period, number of bought extension options with one-month lengths, and the last possible charter date for the vessel if it chooses to exercise all extension options bought. The fixed part of the contract is the days between charter start period and fixed charter end period. After this period, the OWF developer can choose to exercise the bought options.

Table 31: Contract set up for one HLV, CLV, CBV and TIV

<b>Vessel</b>	<b>HLV</b>	<b>CLV</b>	<b>CBV</b>	<b>TIV</b>
<b>Charter start period</b>	0	14	1554	14
<b>Fixed charter end period</b>	1736	2422	2422	2618
<b>Included options</b>	11	13	13	21
<b>Last possible charter date</b>	2352	3150	3150	3794

In the following, a what-if analysis is performed to understand the effect of including two vessels of the same vessel type in the fleet. It is also tested whether chartering dedicated transportation vessels is cost-effective for the optimal vessel configuration found. In order to find the effect of different option lengths and prices on the contract, what-if analysis of different extension option configurations is performed. Moreover, the lump sum is evaluated. Finally, the number of scenarios used in the testing is commented.

#### 9.4.1 What-if analysis of vessel configurations

In the planning phase of an offshore wind farm, it must be decided how many vessels one should use. For larger offshore wind farms, an alternative for decreasing the installation time is charter two equal installation vessels instead of one (Interview with Fred. Olsen Windcarrier) for one or more of the required installation vessels.

The testing is initialized by testing the two boundary cases; either install the offshore wind farm by one vessel of each required vessel or by two vessels of each required vessel. Table 32 presents the costs of the boundary cases and suggests use of two vessels of each type cuts total costs with 43 %.

Table 32: Comparison of costs for one and two vessels of each vessel type

Vessels	Total cost (M)	Avg. penalty cost for loss of production (M)	Charter costs (M)	Avg. end period for the project
HLV×1, CLV×1, CBV×1, TIV×1	\$ 4 297	\$ 3 470	\$ 827	2703
HLV×2, CLV×2, CBV×2, TIV×2	\$ 2 428	\$ 1 644	\$ 785	1277

Figure 25 illustrates the cost components; the charter costs and the average loss of production for each vessel configuration. Both charter costs and the average loss of production are lower in the case of chartering two vessels of each type.

The cost of chartering the vessels are slightly lower using two vessels of each type. This indicates that the vessels are able to benefit from using weather windows earlier in the project period. This reduces the installation period, which in turn will reduce the variable cost of renting the vessels. Lower total charter costs indicates that the saved variable costs exceeds the fixed costs accrued by chartering additional vessels.

The average loss of production constitutes the greatest part of the cost saving potential of using two vessels instead of one vessel of each type. This is due to that the expected end date of the project is significantly earlier in the case of using two vessels of each type. An earlier start date enables the offshore wind farm to start producing electricity earlier and will therefore give revenues for the wind farm operator in an earlier time period. From a present value perspective this will have a value for the offshore wind farm operator, but the exact value of this is not quantified further in this report.



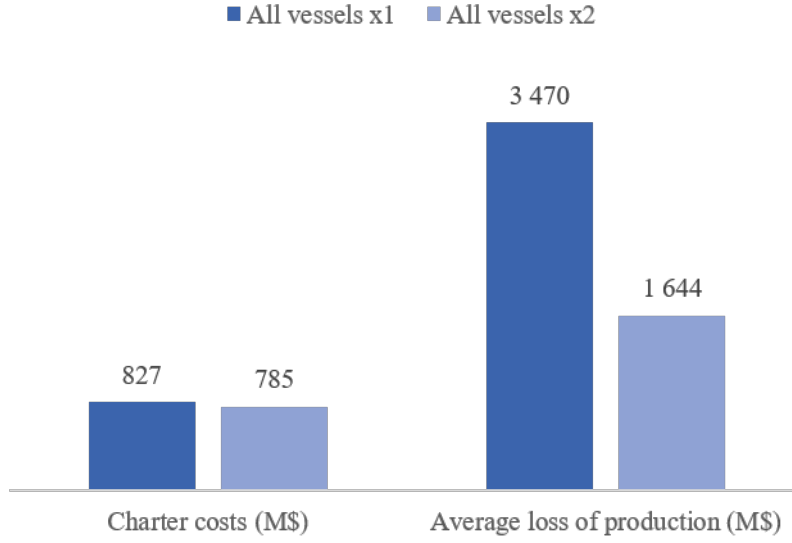


Figure 25: Comparison of chartering one vessel of each vessel type and two vessels of vessel each type

Another possible vessel configuration could be to use two vessel of one vessel type and one vessel of the other vessel types as presented in Table 33.

Table 33: Comparison of costs for two vessels of one vessel type

Vessels	Total cost (M)	Avg. penalty cost for loss of production (M)	Charter costs (M)	Avg. end period for the project
HLV×2, CLV×1, CBV×1, TIV×1	\$ 4 342	\$ 3 442	\$ 899	2681
HLV×1, CLV×2, CBV×1, TIV×1	\$ 4 062	\$ 3 203	\$ 859	2495
HLV×1, CLV×1, CBV×2, TIV×1	\$ 4 358	\$ 3 470	\$ 888	2703
HLV×1, CLV×1, CBV×1, TIV×2	\$ 4 144	\$ 3 235	\$ 909	2519

Table 33 suggests that chartering of two CLV's is the most cost-effective alternative of this type. This indicates that for this offshore wind farm, with project starting date and the weather scenarios given, the CLV presents the bottleneck of the installation time, as using two of this type decreases the installation time the most. At last, it must be noted that although using two CLV's is the most cost-effective case in Table 33, it is still more cost effective to use two CLV's of each type.

Using two CBV's is the least cost-effective vessel configuration and is more expensive than the boundary cases presented in Table 32. It can be noted that the average

end date when using one vessel of each type compared to using an additional CBV, is the same in both cases. As explained in Section 5.1, the burial of cables can be done in parallel with the installation of the wind turbines done by the TIV. The fact that the end date of the project is the same using one or two CBV's indicates that the use of an additional CBV will not affect the project end date and will therefore only lead to an additional fixed cost of chartering the additional CBV. In summary, it shows that the use of two CBV's is not cost-effective in this particular offshore wind farm, and the testing of two CBV's will not be tested further.

The third possible vessel configuration is to use two of each type of two vessel types, and one of the two last vessel types, as shown in Table 34 below. Testing of two CBV's is left out of the testing as this previously was proven to be less cost effective for this offshore wind farm.

Table 34: Comparison of costs for two vessels of two vessel types

Vessels	Total cost (M)	Avg. penalty cost for loss of production (M)	Charter costs (M)	Avg. end period for the project
HLV×2, CLV×2, CBV×1, TIV×1	\$ 3 877	\$ 3 116	\$ 761	2427
HLV×2, CLV×1, CBV×1, TIV×2	\$ 4 176	\$ 3 182	\$ 994	2478
HLV×1, CLV×2, CBV×1, TIV×2	\$ 3 312	\$ 2 440	\$ 872	1899

Testing shows that using two CLV's and two TIV's is the most cost effective vessel configuration, but that this vessel configuration is less cost effective than using two of each vessel type. The vessel configuration consisting of two HLV's and two TIV's is the least cost effective. This indicates that the positive effects of using two HLV's will not propagate to the TIV's when only using one CLV. The use of two HLV's and two CLV's is not as cost effective as using two CLV's and two TIV's. This indicates that the use of two TIV's will affect the end date the most (in a positive way), which will affect the average end period for the project and also the loss of production, which constitutes a large part of the cost.

The last possible vessel configuration given that using two CBV's is not cost-effective is using two HLV's, two CLV's and two TIV's. Table 35 presents the results of this vessel configuration, and reveals that this is the most cost effective vessel configuration of all configurations tested. This vessel configuration both lead to a reduced average penalty cost and a reduced charter cost of the vessels as fixed cost for the

CBV only accrues once.

It can be noted that the lowest total charter cost is given by chartering two HLV's, two CLV's and one CBV and one TIV. Even though this gives a slightly lower charter cost than two of all vessels but the CBV, the total cost is much higher due to the high end period.

Table 35: Optimal vessel configuration

Vessels	Total cost (M)	Avg. penalty cost for loss of production (M)	Charter costs (M)	Avg. end period for the project
HLV×2, CLV×2, CBV×1, TIV×2	\$ 2 414	\$ 1 639	\$ 775	1277
HLV×2, CLV×2, CBV×2, TIV×2	\$ 2 428	\$ 1 644	\$ 785	1277

In summary, the suggested optimal vessel configuration is the following; two HLV's, two CLV's, one CBV and two TIV's. This vessel configuration leads to reduced installation time and reduced chartering costs. The suggested contract set up for this vessel configuration is summarized in Table 36.

Table 36: Contract set up for the suggested vessel configuration

Vessel	HLV 1	HLV 2	CLV 1	CLV 2	CBV	TIV 1	TIV 2
<b>Rental start period</b>	0	0	0	0	238	14	14
<b>Fixed contract end period</b>	882	882	1050	1050	1064	1400	1400
<b>Included options</b>	2	2	10	10	10	4	4
<b>Last possible charter date</b>	994	994	1610	1610	1624	1624	1624

Figure 26 presents how the charter cost will be realized in the 15 different scenarios for this vessel configuration. The expected charter cost is also marked. This illustrates how the actual cost is realized, depending on the scenario realized. In some scenarios, a higher cost than the expected cost will be realized as extension options are exercised. Exercising options lead to an additional exercise price, and the realized cost will be higher than only using the fixed period and including the options in the contract. In other scenarios, a lower cost than the expected cost is realized as none or few extension options are exercised.

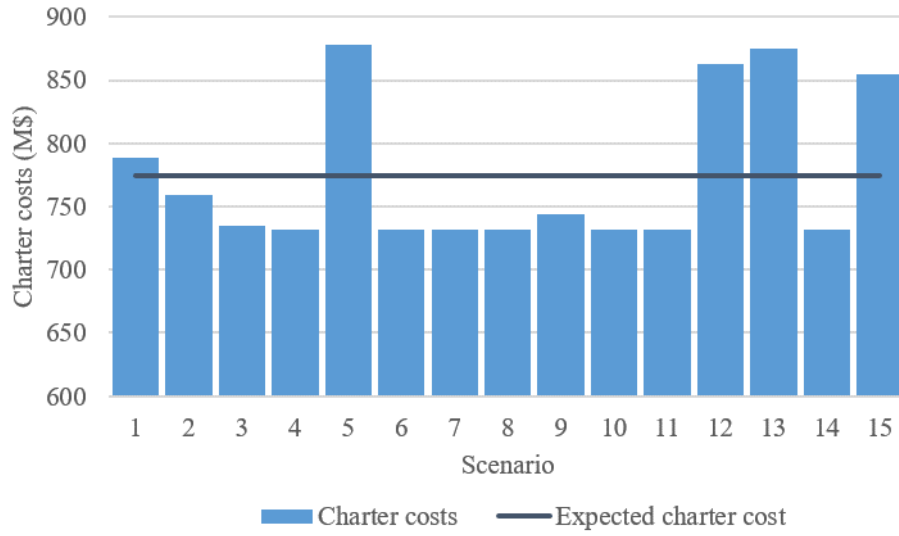


Figure 26: The realized charter cost will vary for each scenario, depending on the number of options exercised. The realization of the charter costs in each scenario is presented.

Although this is the suggested optimal vessel configuration by the model, it must be noted that this assumes that the required vessels are available at the market at the given price. At times, it is impossible to charter two specialized vessels due to high demand in the market, as explained in Section 2.3.1. If it is not possible to charter two of any of the vessels, it can be interesting to explore the vessel configurations presented in Table 32, 33 and 34 depending on the vessels available. Besides, the suggested solution assumes that the wind farm operator utilizes the vessels efficiently. A risk of chartering two vessels of the same type is that the vessels cannot be used efficiently due to, for example, insufficient capacity in the port or lack of logistics planning. If the vessels are not used efficiently, and one of the vessels cannot be used, the cost increases quickly. The wind farm operator must ensure that the additional vessel chartered of one type can be used efficiently to benefit from the advantages of chartering two vessels of the same vessel types.

#### 9.4.2 Dedicated transport vessels

As described in Section 2.3.1, an alternative to transporting the components with the specialized installation vessels is to use dedicated transport vessels, which have significantly lower costs. This leads to a shorter duration between installing the components of consecutive loading sets, as the sailing time between the offshore wind farm and the shore is saved. Table 37 presents the costs of using dedicated

transport vessels and suggests that for this offshore wind farm, the cost is slightly higher in the case using dedicated transport vessels.

Table 37: The effect of using dedicated transport vessels

<b>Dedicated transport vessels?</b>	<b>Total cost (M)</b>
No	\$ 2 414
Yes	\$ 2 493

As explained in Section 2.3.1, foreign-built installation vessels cannot dock at ports in the U.S. In these cases, dedicated transport vessels must be chartered. If this where the case for this particular OWF, the cost would be as described in Table 37.

In summary, for this offshore wind farm, it is suggested to use the installation vessels for both transportation and installation of the components as the cost for this case is slightly lower than for using dedicated transport vessels.

### 9.4.3 What-if analysis of extension option configurations

The testing of vessel configurations in Section 9.4.1 is done with an option length of one month. The wind farm operator and the shipowner negotiate the length and the price of the options, as explained in Section 2.4.1. Longer option periods give predictability for the shipowner and less flexibility for the wind farm operator. Therefore, the price relative to the length of the extension option is lower for longer extension options. The testing assumes that a three month long option's price can be negotiated to 45 % of the exercise price ( $\beta = 0.45$ ), and a six month long option's price can be negotiated to 40 % of the exercise price ( $\beta = 0.40$ ). The options are also tested with different levels of the  $\beta$  to find which  $\beta$ -level the offshore wind farm developer must negotiate to give the equivalent expected cost of the contract.

Table 38 presents the expected total cost of each contract configuration. With the given  $\beta$ -level, the expected cost is equivalent for both one and three month options. The expected cost is slightly higher for six month long options, even if the option price relative to the option length is lower than for the other options.

Table 38: The expected cost solving the model for different option lengths and  $\beta$ -values

Option length	$\beta$	Total cost (M)
1 month	0.50	\$ 2 414
3 months	0.45	\$ 2 414
6 months	0.40	\$ 2 421

Table 39 presents the contract set up of the option lengths tested. In general, it can be noted that extending the option length results in a larger part of the contract being fixed. Longer extension option periods give less flexibility for the OFW operator than shorter extension options. When exercising an extension option, the total exercise price accrues, even if the installation only requires an additional week to complete the installation. Therefore, the expected cost of choosing a longer fixed contract period can be more cost-effective than to include an additional extension option, especially with increasing option lengths if the  $\beta$ -value is not sufficiently low.

Table 39: Contract set up for the suggested option configuration

Extension option length: 1 month							
Vessel	HLV 1	HLV 2	CLV 1	CLV 2	CBV	TIV 1	TIV 2
Rental start period	0	0	0	0	238	14	14
Fixed contract end period	882	882	1050	1050	1064	1400	1400
Included options	2	2	10	10	10	4	4
Last possible charter date	994	994	1610	1610	1624	1624	1624
Extension option length: 3 months							
Vessel	HLV 1	HLV 2	CLV 1	CLV 2	CBV	TIV 1	TIV 2
Rental start period	0	0	0	0	238	14	14
Fixed contract end period	994	994	1106	1106	1120	1288	1288
Included options	0	0	3	3	3	2	2
Last possible charter date	994	994	1610	1610	1624	1624	1624
Extension option length: 6 months							
Vessel	HLV 1	HLV 2	CLV 1	CLV 2	CBV	TIV 1	TIV 2
Rental start period	0	0	0	0	238	14	14
Fixed contract end period	994	994	1274	1274	1288	1288	1288
Included options	0	0	1	1	1	1	1
Last possible charter date	994	994	1610	1610	1624	1624	1624

To find which  $\beta$ -value that gives equal total cost for the six month long option as the one and three month long options, the model is solved for different  $\beta$ -values. Testing reveals that a  $\beta$ -value corresponding to 0.35 will give the same expected cost for using six month long option than as the corresponding one month option and three month long options. This means that the OFW operator must negotiate the option price to 35 % of the exercise price for the six month long options for this contract to be as cost effective as the one-month and three-month-long option.

In summary, using options of three and six months will give an equivalent expected cost to one month options if the offshore wind farm operator can negotiate the cost of the option to respectively 45 % and 35 % of the option price, from 50 % of the option price for one month options. Finding the  $\beta$ -value that gives the equivalent total cost, gives an upper limit of how much the offshore wind farm operator can be willing to pay for the options when negotiating prices. Negotiating lower prices than the upper limit will lead to cost reductions for the offshore wind farm operator.

#### 9.4.4 Lump sum evaluation

As mentioned in Chapter 8, estimating the cost distribution is valuable to find the expected cost in the  $q\%$  worst scenarios to assess lump sum prices. The cost distribution is estimated for the risk-neutral first stage decision. Figure 27 shows the cost distribution for the instance in Table 22. The loss of production is subtracted from the cost.

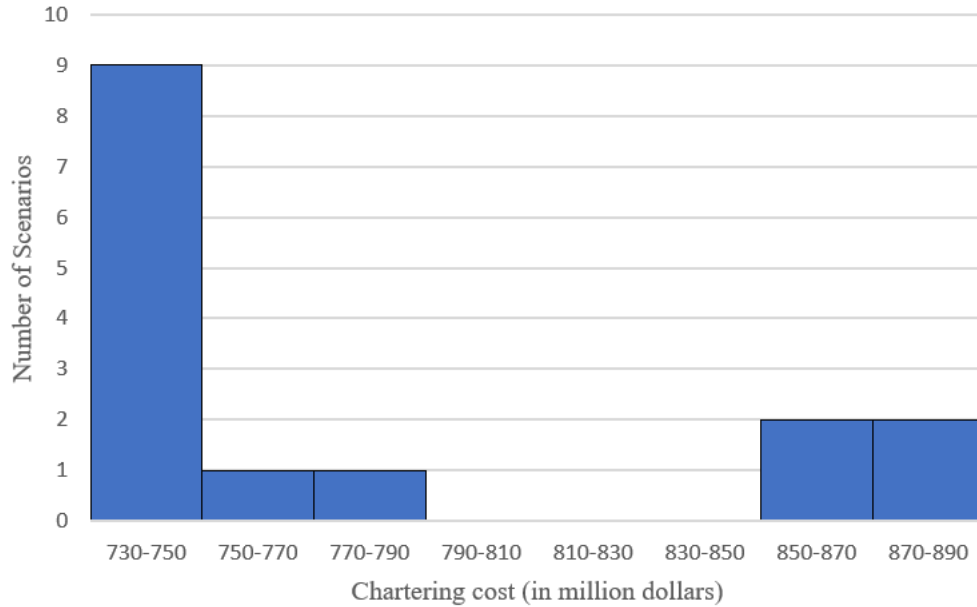


Figure 27: Chartering cost distribution for 120 turbines. The cost distribution is estimated for a given fixed first-stage decision, and shows how many scenarios that have objective values within the cost ranges on the x-axis.

The cost distribution is skewed towards the left of the scale, meaning that few extension options are exercised in many weather scenarios. The wind farm is finished in all scenarios, as a sufficient number of extension options are included. In the first

block to the left, none or few extension options are exercised. In the second and third blocks, a few more extension options are exercised. In the last two blocks, all or almost all extension options are exercised. The results are used to find the expected cost in the  $q$  tail of the distribution.

Table 40: Expected tail cost (in million dollars). The cost is estimated for a risk-neutral first-stage decision. The expected tail cost is what you can expect to lose in the  $q\%$  worst scenarios.

<b>q</b>	<b>Expected tail cost</b>	<b>Expected tail cost - loss of production subtracted</b>
20%	2 941	872
40%	2 833	836
60%	2 685	803
80%	2 532	785
100%	2 414	775

As the value of the scenarios considered in each tail is calculated for the same first-stage decision, the expected tail cost is equal to the average cost of the  $q\%$  worst scenarios. The objective values of the scenarios are sorted to find the tail cost. The results show that the expected cost for all 15 scenarios is 775 million dollars. This entails that a risk-neutral vessel owner will never accept a lump sum contract below this value. As mentioned in Chapter 8, how high lump sum the OWF developer is willing to offer, depends on his risk aversion. However, a total of 872 million dollars for the whole fleet should be a maximum for any OWF developer as the likelihood of losing money, compared to bearing the risk himself, is significant.

Until this point, only the total lump sum is studied. Different companies usually own the different vessel types, and hence the total lump sum is distributed to the different owners. It is assumed that the same vessel types are chartered from the same owner, as these vessels are required to collaborate to a higher degree than across vessel types. Also, the vessel owners are responsible for starting installing at the optimal overlapping period or before to reduce the loss of production.

Table 41: Expected tail cost per vessel (in million dollars)

<b>q</b>	<b>Expected cost HLTV</b>	<b>tail</b>	<b>Expected cost CLV</b>	<b>tail</b>	<b>Expected cost CBV</b>	<b>tail</b>	<b>Expected cost TIV</b>	<b>tail</b>
20%	239		194		91		356	
40%	235		175		82		347	
60%	229		164		76		335	
80%	226		158		72		329	
100%	225		154		70		325	



### **Risk averse first stage decision**

Studying the cost distribution is valuable to find the expected cost in the  $q\%$  worst scenarios to find a reasonable lump sum. The cost distribution depends on the first stage decision and is estimated for the risk-neutral model. A risk-averse decision-maker would add more extension options in the contract to hedge himself from not finishing the wind farm.

In this case, there are no extremely negative cases as the penalty of not finishing the wind farm in one scenario is higher than the cost of including enough extension options. Thus even the risk-neutral decision-maker decides to include enough extension options. The risk-neutral first decision is assumed to represent the situation (cost distribution) of the risk-averse decision-maker, in this case, as there are no extremely negative cases.

#### **9.4.5 Number of scenarios**

Figure 28 presents the result of solving the model with an increased number of scenarios. First, the model is solved 15 times with one scenario, which corresponds to solve the model deterministic. Moreover, the model is solved for an increasing number of scenarios. The scenarios are drawn from the 15 scenarios available, and each scenario is used once. This means that the model is run 15 times using one scenario, seven times using two scenarios, three times using five scenarios and one time using 15 scenarios.

Figure 28 indicates that the objective value is highly dependent on the scenario used. The spread of the objective values of the deterministic runs is significant. Figure 28 indicates that the spread of the objective value decreases when increasing the number of scenarios used in the model. The high spread of the objective value using different scenarios emphasizes the importance of using a model that takes the weather's uncertainty into account.

The results presented in Section 9.4 are based on 15 scenarios. As we do not have access to more than 15 weather scenarios, it is impossible to say anything about the spread of using 15 weather scenarios. Nevertheless, Figure 28 indicates that the spread decreases when increasing the number of scenarios and therefore, we assume that results given for 15 scenarios is reasonable.

The decision maker can improve the precision of the decision support by increasing the number of scenarios used in the model. Equinor explained that they use about 50 scenarios (Interview with Equinor ASA). As described in Section 9.3.4, the model can solve instances with 50 scenarios and still solve the model within a reasonable time limit. Due to this, the decision maker can achieve the required level of precision using the model.

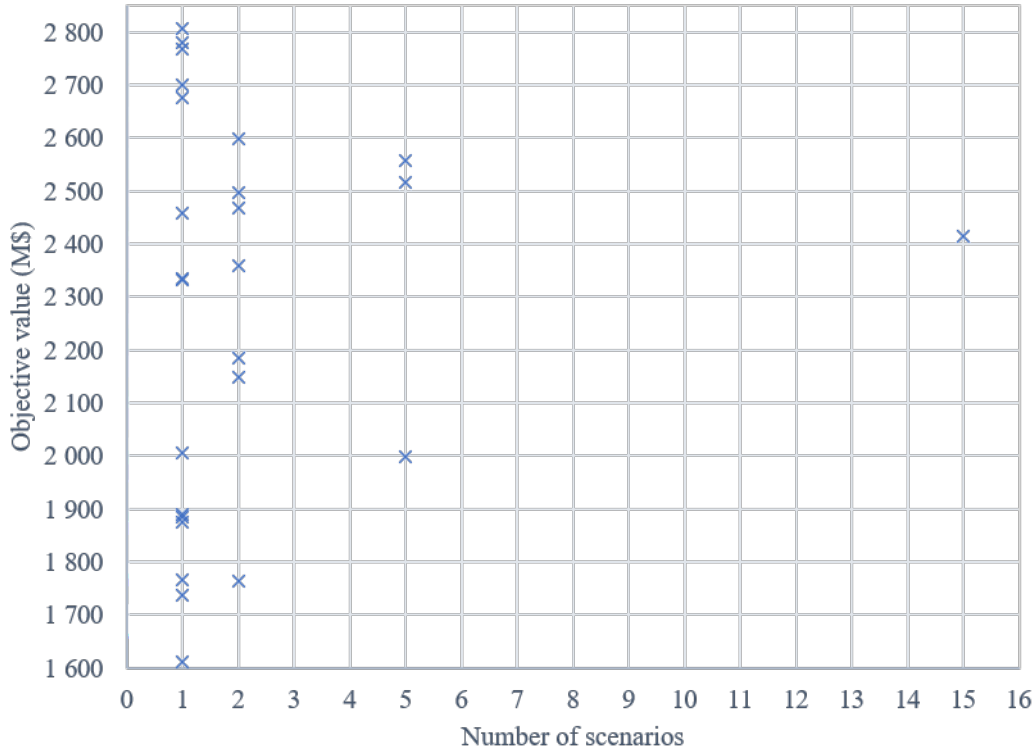


Figure 28: The objective value given by solving the model for a different number of scenarios

## 9.5 Summary

Tuning of the heuristic was performed to make the search more effective and prevent cycling around local optimums. The results showed that the hybrid search was the fastest improvement strategy. Different tabu list types and lengths were tested to investigate if better solutions were found than a search without tabu lists. Only in one of the instances tested did the search without a tabu list find another solution than the searches with tabu lists. All tabu list types and lengths found the same and a better solution in this instance. Testing showed that the search stopped improving within a reasonable time, and hence a stopping criterion based

on a number of iterations without improvements were suggested. For all instances tested, no improvements were made after ten iterations without improvements (after ten non-improving iterations). For further testing, the hybrid search, a long-term tabu list without a maximum length, a short-term tabu list with maximum length of ten solutions, and 100 iterations without improvements as a stopping criterion were used.

A run time analysis showed that the simulation time per neighbor increased when the number of OWTs increased. The majority of the total running time was simulations. The total simulation time for fifty scenarios was estimated, which resulted in a reasonable running time.

Trough the analysis performed on vessel configurations, dedicated transport vessels, option configurations, and lump sum evaluation, a contract setup can be suggested. The model suggested that the most cost-effective vessel configuration is chartering two HLVs, two CLVs, one CBV and two TIVs. Chartering additional vessels gave a significant reduction of the end date of the project and reduced charter costs compared to only chartering one vessel of each vessel type. This assumes that there are two vessels available of the suggested vessels and that the chartered vessels can be used efficiently. If this is not possible, the model also presents other alternatives that can be further investigated. Moreover, the model suggested that it is slightly more cost-effective to use the installation vessels as transportation vessels.

It was shown that the option price must be negotiated to 45 % of the exercise price for an option length of three months. For an option length of six months, the price must be negotiated to 35 % of the exercise price to give an equivalent total cost as the one month option with an option price of 50 % of the exercise price. Negotiating option prices lower than this will be advantageous for the OFW developer. The fixed charter part of the contract tended to increase when increasing the length of the option.

The lump-sum assessment showed that there were no extremely negative cases in the cost distribution. Thus, the risk-neutral first-stage decision was assumed to represent the situation of risk-averse OWF developers. The expected tail cost provided values for the expected cost in the  $q\%$  worst scenarios. It is suggested to offer the vessel owners a lump sum in the range between the expected cost in 100% and 20% worst scenarios, depending on the risk-level. If the vessels owners reject the

offer, it is better for the OWF developers to bear the risk.

The suggested contract setup is based on using 15 weather scenarios. Solving the model in a deterministic setting for each of these scenarios gave a significant spread of the objective values. This emphasizes the importance of using a stochastic model. The precision level given on the suggested contract setup is dependent on the number of scenarios. The testing done in this section is based on 15 scenarios. If the decision maker requires a higher precision level, the heuristic can be solved with a higher number of scenarios within a reasonable time limit.

## 10 Concluding remarks

The installation vessels chartered in the installation phase of an offshore wind farm constitutes a significant part of the installation cost. The time it takes to install an offshore wind farm is highly dependent on the weather realization. Besides, the installation vessels are specialized, and there are few of them on the market. Chartering the vessels for longer periods than needed is expensive as the day rates are high. Chartering the vessels shorter than needed leads to high additional costs related to delays of the wind farm. This thesis aims to develop a method to find the charter start date, charter lengths, number of extension options, and to provide an assessment of lump sum prices. Based on interviews with an offshore wind farm developer, a shipowner, and a law firm, a two-stage stochastic model is developed.

The mathematical model provided to describe the problem, is unable to solve real-sized test instances within a reasonable time frame with an exact solution method. Therefore, a tabu search heuristic and a simulator are developed. The heuristic makes it possible to optimize the vessel contracts, while the simulator enables efficient estimation of solutions. The computational study reveals that the heuristic and simulator can solve real-sized test instances within a reasonable time. The efficiency of the heuristic may be due a well-defined neighborhood. It seems that good solutions lie close to each other in the solution space. The testing showed that the best solution was found without any non-improving moves in several instances, which strengthens the assumption of a well-defined neighborhood. The testing showed that cycling is an issue in few of the instances tested, which is probably a consequence of few local optima in the solution space.

Solving the model deterministic for all scenarios shows a significant spread of the objective values for the scenarios tested. This emphasizes the need for a model that addresses the stochastic nature of the weather and installation duration. Based on testing done on 15 scenarios, we observed that extension options were included in most of the contracts, as this gives a lower expected cost. The inclusion of extension options supports the choice of a stochastic model, as the total cost of including and exercising an extension option is higher than buying fixed periods.

The number of extension options included for each vessel is dependent on the option length and price. For shorter options that provide flexibility for the OWF developer, extension options is included for all vessels. For longer options, extension options

are still included in the contract for most vessels, but the total extension option period is reduced and the fixed charter period is increased. Further, the testing indicated that chartering two vessels of some vessel types, assuming the vessels were available in the market and could be used efficiently, could lead to both a reduction in total chartering costs and in the completion date of the project.

The thesis has identified a need for more use of lump sum contracts, and assessment of reasonable prices for these contracts. It is likely that estimating the expected cost in the  $q$  % worst scenarios, can help a risk-averse decision-maker decide lump sum prices. The method has been provided to find a range of reasonable lump sum prices, which the decision-maker can decide between given his level of risk-aversion.

## 11 Future research

A possible improvement is implementing a bi-objective function that minimizes the cost and maximizes the project's net present value. Reducing the offshore wind farm's installation time leads to the offshore wind farm producing electricity and thereby getting revenues at an earlier time period. Earning revenues at an earlier time period leads to a higher net present value for the project as the offshore wind farm developer can invest the revenues at an earlier time period, but will not necessarily lead to a lower expected cost as the vessels might be chartered for shorter periods that lead to a longer project date, but lower charter costs.

In this thesis, a method to assess lump sum prices is provided. A risk-neutral first-stage decision, or assessing variations of a risk-neutral first-stage decision, is assumed to represent the situation of both a risk-neutral and risk-averse OWF developer. Our study of this problem can provide insights into future research, as no literature on risk-sharing for OWF installation within operational research, does to our knowledge exist. In cost distributions with some very negative cases, an idea could be to minimize the problem with different CVaRs as the objective value, to represent the situation of the risk-averse decision-maker better.

Uncertainty related to logistics at ports could also be considered. In this thesis, the installation components were assumed to be ready at the port and the installation site when needed. In reality, components can be delayed from the supplier or take longer than expected to transport components through the port to the loading point for the transport vessels. Delays in port can lead to delays in the installation process.

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# A Minutes, Equinor ASA

*Skype interview with project engineer Gudmund Kleiven at Equinor, October 11, 2019.*

## **Weather**

In practice, the weather is accounted for by analysis on observed weather series or numerical generated weather scenarios from observed models. This is often done over several years, often up to 50 years, such that they get an overview over what happens in the best case scenario, worst case scenario and on the average.

## **Vessels**

It is reasonable to assume that the components are available on the offshore site when the installation vessel will install the components. This means that components are transported and installed by different vessels. The weather criteria for transportation of the components will be less restrictive than the weather criteria for installation of components. One could add a cost component for transportation if one want to take the transportation in account. Still, there are projects where the installation vessels also transport the components to site.

## **Installation**

The jack-up vessel can either install the monopile and the transition piece for all the offshore wind turbines in the wind park before it installs the rest of the components, or it can install the offshore wind turbines one by one. These are two strategies being used when installing offshore wind turbines.

## **Cost**

Choice of vessel depends on the weather criteria. The extra costs of renting a specialized and more expensive vessel can pay off if one would have to wait for the weather to be better when using a less expensive vessel.

## **Floating offshore wind turbines**

Hywind Scotland, an offshore wind farm using floating foundations, was towed fully assembled from shore in Stord. As floating wind turbines are fully assembled onshore, the installation of offshore wind turbines with floating foundations differs significantly from installing offshore wind turbines with bottom fixed foundations.

**Objective**

Completion time and cost are outputs of interest for Equinor. It will end up like a pareto function, instead of one optimal solution. If one could value the price of delay or the benefits of finish early, it could be a one parameter function.



## B Minutes, Fred. Olsen Windcarrier, Part 1

*Skype interview with project engineer Hege Eskild at Fred. Olsen Windcarrier, October 22, 2019.*

### **Chartering of vessels**

Chartering of vessels is done about two years in advance of the installation phase. The vessels need infrastructure depending on for example type of turbine used in the project and to secure the components.

If the contract between the operator and the shipowner expires, but the operator still need the vessel in order to finalize the offshore wind farm, it should be possible to charter a new vessel within 2-3 months. This time period is given that it exist a vessel with existing infrastructure for the components. It is reasonable to assume that the operator will be more risk averse and charter the vessels for longer periods when going into periods with many projects going on in offshore wind than in periods with few projects. Foreign-built installation vessels cannot dock at ports in the US, and U.S built transport vessels must be used to transport components to installation site.

### **Contracts and options**

If one choose to exercise an option, one must exercise the total period. That is, if you have an option for 6 months, you have to pay the day rates for the total period of 6 months. However, it is possible to buy options in packages, for instance 2 x 3 months instead of one option of 6 months. It is also possible to write options for only one week, but this is of less interest for the shipowner.

Normally contracts are written for project to project. This means that the shipowner is not hired for several years to do all the projects of the operator.

Most probably, the day rate is the same independent of including an option or not, and also after exercising the option. Surely, it does not apply additional project costs like adding infrastructure to the vessel and engineering as this is done in advance. These costs make it expensive to charter another vessel if the charter period ends before all offshore wind turbines are installed.

Day rates for vessels are kept confidential, as contract prices are determined by tendering and negotiations, so it is necessary to assume these prices. One possibility could be to assume that one vessel is better than another, and multiply the assumed price with a parameter.

**Weather**

When the shipowner writes an offer, they do a weather downtime analysis for the project. This analysis is based on a percentage that they will be done in time. The operator asks for this analysis, and wants to commit to typically a 50 % chance that they will be finish on time. The vessels wait at site when the weather conditions rise above weather limits.

When choosing to perform activities or not, weather forecasts are used, both week to week forecasts and day to day forecasts. If there are weather windows for at least one day, one can sail to the offshore site. If the weather gets bad, one can jack-up and be offshore and wait for better weather. The decision is taken by the captain, and is done on a daily basis.

## C Minutes, Fred. Olsen Windcarrier, Part 2

*Skype interview with project engineer Hege Eskild at Fred. Olsen Windcarrier, 10.03.2020*

### **Sharing of risk**

Fred. Olsen Windcarrier does not usually bear weather risk, but they are capable of doing so if the terms are good. However, bearing risk involves great consequences if delays happens, as they lose the opportunity to start on new contracts.

### **Project duration estimation**

Fred. Olsen Windcarrier use P50(50% confidence level to not exceed the estimate) as a base case, but estimations based on P90 are also possible if the customer prefer it. The estimations are based on site specific weather data, and the contract specifies the maximum wave height and wind speed the vessel can operate in. If delays occur, and weather conditions are below operational limits, then Fred. Olsen Windcarrier pays a penalty for the delay. A representative from the customer is onboard the vessel, and clarifies together with Fred. Olsen Windcarrier if the delay is caused by technicalities (Fred. Olsen Windcarrier pays a penalty) or by weather (not Fred. Olsen Windcarrier's responsibility). If the wind farm is not finished within the charter period, Fred. Olsen Windcarrier can leave if it is not a lump sum contract.

### **Need for risk measures**

Fred. Olsen Windcarrier describes the marked conditions as changing; the customer wants to transfer more risk, and larger wind farms are planned. Dogger Bank is mentioned as a large project with high weather risk, which will be installed in the North Sea with rough weather conditions. The risk picture is changing when the marked conditions are changing. Fred. Olsen Windcarrier have little experience with bearing weather risk, and base decisions on experience when accepting to bear risk. They would benefit from knowing how much extra should they be paid to accept to bear risk.

### **Installation of larger wind farms**

For offshore wind farms smaller than 50 turbines, the installation is normally done during the months April-September. For the larger offshore wind farms the installation can be done through the year. The winter months where the weather down time can be up to 60 %, can be used for installation and trying and failing in the start of a project. For larger wind farms it is also possible to rent two vessels for doing the same installation activities in a shorter period than for renting one vessel for a longer period.

### **Challenges related to logistics at port**

Managing large turbine components and loading of vessels at the port is a complicated

procedure. Poor planning can lead to delays in the installation. The complexity of logistics planning both in port and at the installation site increases with the number of vessels used. Usually, one vessel for one installation phase is used, but two vessels are possible. More than two vessels of each type are not practically feasible.

## D Minutes, Law firm Hjort DA

*Skype interview with lawyer Ola Hermansen at Advokatfirmaet Hjort DA (law firm), Energy department, 13.05.2020*

There are established standards and contracts for similar industries to the offshore wind industry, such as contracts from shipping, offshore, and petroleum. The new element in contracts for offshore wind is that significant parts of the industry today is international and will also be international in the future. Except for offshore wind turbines used for testing, it has not been any projects in Norway. Due to this, the Norwegian industry has not developed standard contracts.

Contract risk related to weather is handled in different ways. It is often subject to negotiation between the contractors and the constructor of the wind farm. For instance, when buying a turbine, one can choose between having the responsibility of the delivery, giving away the responsibility of the delivery and the installation for a risk premium or giving away the responsibility of the delivery and keeping the responsibility of the installation. The parts will agree on how far the responsibility extends.

In the petroleum industry, the operating companies often take a larger part of the risk as they have more projects in their portfolio and a higher economic capacity, and is therefore, able to bear a more significant part of the risk. The suppliers are more sensitive because they do not have as many projects and are therefore not willing to bear the same level of risk as the operator companies. Lower earning potential in offshore wind projects compared to petroleum means that the operator is not willing to bear the same level of risk in offshore wind projects as in petroleum projects. Experience shows that the operators in offshore wind projects bear less of the risk than in petroleum projects.

Transferring risk to its contractors, helps the wind farm constructor or developer to finance their projects (often termed bankability).

# E Mathematical Model

## E.0.1 Notation

### Sets

**N** Set of activities  $i$

**P<sub>i</sub>** Set of immediate predecessors of activity  $i$

**T** Set of time periods  $t$

**B** Set of time periods  $t$  in which charter periods can start (Mondays 00:00).

**E** Set of time periods  $t$  in which charter periods can end (Sundays 23:59).

**U** Set of extension options  $u$

**V** Set of vessels  $v$

**L** Set of possible loading sets  $l$

**F<sub>i</sub>** Set of activities requiring to be performed by the same vessel and loading set as activity  $i$ .

**S** Set of scenarios  $s$

### Parameters

**C<sub>V</sub><sup>F</sup>** Fixed cost of chartering vessel  $v$

**C<sub>V</sub><sup>V</sup>** Variable cost of chartering vessel  $v$

**P<sub>vu</sub>** Price of including extension option  $u$  for vessel  $v$  in the contract

**E<sub>vu</sub>** Exercise price of extension option  $u$  for vessel  $v$

**L<sub>u</sub>** Length of period of extension option  $u$

**P<sup>f</sup>** Penalty representing the loss of production per time period

**P<sup>w</sup>** Fixed penalty for not finishing the wind farm

**P<sup>Q</sup>** Variable penalty for not finishing the wind farm

**D<sub>iv</sub><sup>A</sup>** Duration of performing activity  $i$  by vessel  $v$

**D<sub>v</sub><sup>L</sup>** Duration of loading of vessel  $v$

**N<sup>A</sup>** Number of activities in set  $N$

**A<sub>iv</sub>** 1 if vessel  $v$  can perform activity  $i$ , 0 otherwise

**Q<sub>i</sub>** Loading capacity required for activity  $i$

**Q<sub>v</sub>** Total loading capacity on vessel  $v$

**W<sub>i</sub><sup>BMAX</sup>** Operational wave limit for activity  $i$

**W<sub>i</sub><sup>VMAX</sup>** Operational wind limit for activity  $i$

**M<sup>P</sup>** Big M used to check if all activities are performed

$\mathbf{M}_v^F$  Big M used to forbid periods when loading new loading sets

$\mathbf{M}_{its}^B$  Big M used for wave restrictions

$\mathbf{M}_{its}^V$  Big M used for wind restrictions

$\mathbf{p}_s$  Probability of realization of scenario  $s$

$\xi_s = (W_{ts}^B, W_{ts}^V)$  Realization of random parameters in scenario  $s$ , containing wave height realization and wind speed realization in time period  $t$  in scenario  $s$

### Variables

$\beta_{vu}$  1 if extension option  $u$  is included in the contract for vessel  $v$ , 0 otherwise

$s_{vt}$  1 if vessel  $v$  starts operating in time period  $t$ , 0 otherwise

$e_{vt}$  1 if vessel  $v$  last period is  $t$  for the fixed days in the contract, 0 otherwise

$\lambda_{vus}$  1 if vessel  $v$  exercises extension option  $u$  in scenario  $s$ , 0 otherwise

$e_{vts}^f$  1 if vessel  $v$  last operating period is  $t$  in scenario  $s$ , 0 otherwise

$\mathbf{p}_{vts}$  1 if vessel  $v$  is chartered in period  $t$  in scenario  $s$ , 0 otherwise

$\mathbf{z}_{ivlts}$  1 if activity  $i$  is performed by vessel  $v$  and loading set  $l$  starting in period  $t$  in scenario  $s$ , 0 otherwise

$\mathbf{x}_{ivts}$  1 if activity  $i$  is performed by vessel  $v$  in period  $t$  in scenario  $s$ , 0 otherwise

$\mathbf{w}_s$  1 if not all activities are performed, 0 if all activities are finished within charter period

$\delta_{vts}$  1 if vessel  $v$  is chartered and not loading a new loading set in period  $t$  in scenario  $s$ , 0 if vessel  $v$  is loading or not chartered

$\sigma_{vls}$  The first period loading set  $l$  is used for vessel  $v$  in scenario  $s$

$\mathbf{f}_{vlt}$  1 if the  $t$  is the first period vessel  $v$  uses loading set  $l$  in scenario  $s$ , 0 otherwise

$\mathbf{e}_s^{Tot}$  The last period of installation in scenario  $s$

### E.0.2 First stage problem

$$\begin{aligned} \min z = & \sum_{v \in V} \sum_{t \in T} C_V^V (te_{vt} - ts_{vt}) + \sum_{v \in V} C_V^F + \sum_{v \in V} \sum_{u \in U} P_{vu} \beta_{vu} \\ & + \sum_{s \in S} p_s Q(e_{vt}, \beta_{vu}, s_{vt}, \xi_s) \end{aligned} \quad (\text{E.1})$$

$$\sum_{t \in T} te_{vt} - \sum_{t \in T} ts_{vt} \geq 0 \quad v \in V \quad (\text{E.2})$$

$$\sum_{t \in T} s_{vt} = 1 \quad v \in V \quad (\text{E.3})$$

$$\sum_{t \in T} e_{vt} = 1 \quad v \in V \quad (\text{E.4})$$

$$\sum_{v \in V} s_{vt} \geq 1 \quad t = 1 \quad (\text{E.5})$$

$$s_{vt} = 0 \quad v \in V \quad t \in T \setminus \{B\} \quad (\text{E.6})$$

$$e_{vt} = 0 \quad v \in V \quad t \in T \setminus \{E\} \quad (\text{E.7})$$

$$\beta_{vu} \in \{0, 1\} \quad v \in V \quad u \in U \quad (\text{E.8})$$

$$s_{vt} \in \{0, 1\} \quad v \in V \quad t \in T \quad (\text{E.9})$$

$$e_{vt} \in \{0, 1\} \quad v \in V \quad t \in T \quad (\text{E.10})$$

### E.0.3 Second stage problem

$$Q(e_{vt}, \beta_{vu}, s_{vt}, \xi_s) = \min \left[ \sum_{v \in V} \sum_{u \in U} E_{vu} \lambda_{vus} + P^f e_s^{Tot} + P^w w_s + P^Q (N^A - \sum_{i \in N} \sum_{v \in V} \sum_{l \in L} \sum_{t \in T} z_{ivlts}) \right] \quad (\text{E.11})$$

$$\sum_{t \in T} t e_{vts}^f - \sum_{t \in T} t e_{vt} = \sum_{u \in U} L_u \beta_{vu} \lambda_{vus} \quad v \in V \quad s \in S \quad (\text{E.12})$$

$$p_{vts} = \sum_{t'=1}^t s_{vt'} - \sum_{t'=1}^t e_{vt's}^f \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.13})$$

$$\sum_{t \in T} t e_{vts}^f \leq e_s^{Tot} \quad v \in V \quad s \in S \quad (\text{E.14})$$

$$\sum_{v \in V} \sum_{l \in L} \sum_{t \in T} (t + D_{i'v}^A) z_{i'vlt} \leq \sum_{v \in V} \sum_{l \in L} \sum_{t \in T} t z_{ivlts} \quad i \in N \quad i' \in P_i \quad s \in S \quad (\text{E.15})$$

$$\sum_{i \in N} \sum_{v \in V} \sum_{l \in L} \sum_{t \in T} z_{ivlts} + M^P w_s \geq N^A \quad s \in S \quad (\text{E.16})$$

$$\sum_{t \in T} z_{ivlts} - \sum_{t \in T} z_{i'vlt} = 0 \quad i \in N \quad i' \in F_i \quad v \in V \quad l \in L \quad s \in S \quad (\text{E.17})$$

$$\sum_{t'=t}^{t+D_{iv}^A-1} x_{ivt's} \geq \sum_{l \in L} D_{iv}^A z_{ivlts} \quad i \in N \quad v \in V \quad t = 1, \dots, |T| - D_{iv}^A + 1 \quad s \in S \quad (\text{E.18})$$

$$\sum_{l \in L} \sum_{t \in T} z_{ivlts} \leq A_{iv} \quad i \in N \quad v \in V \quad s \in S \quad (\text{E.19})$$

$$\delta_{vts} \geq \sum_{i \in N} x_{ivts} \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.20})$$

$$\sum_{i \in N} \sum_{t \in T} Q_i z_{ivlts} \leq Q_v \quad v \in V \quad l \in L \quad s \in S \quad (\text{E.21})$$



$$\sigma_{vls} = \min_{i \in N} \left\{ \sum_{t \in T} t z_{ivlts} \right\} \quad v \in V \quad l \in L \quad s \in S \quad (\text{E.22})$$

$$\sigma_{v(l+1)s} \geq \sum_{t \in T} t z_{ivlts} \quad i \in N \quad v \in V \quad l = 1, \dots, |L| - 1 \quad s \in S \quad (\text{E.23})$$

$$\sigma_{vls} = \sum_{t \in T} t f_{vlt s} \quad v \in V \quad l \in L \quad s \in S \quad (\text{E.24})$$

$$\sum_{t'=t-D_V^L}^{t-1} \delta_{vt's} \leq M_v^F (1 - f_{vlt s}) \quad v \in V \quad l \in L \quad t = D_V^L + 1, \dots, |T| \quad s \in S \quad (\text{E.25})$$

$$\delta_{vts} \leq p_{vts} \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.26})$$

$$M_{its}^B (1 - x_{ivts}) \geq W_{ts}^B - W_i^{BMAX} \quad i \in N \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.27})$$

$$M_{its}^V (1 - x_{ivts}) \geq W_{ts}^V - W_i^{VMAX} \quad i \in N \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.28})$$

$$z_{ivlts} \in \{0, 1\} \quad i \in N \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (\text{E.29})$$

$$e_{vts}^f \in \{0, 1\} \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.30})$$

$$x_{ivts} \in \{0, 1\} \quad i \in N \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.31})$$

$$p_{vts} \in \{0, 1\} \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.32})$$

$$\lambda_{vus} \in \{0, 1\} \quad v \in V \quad u \in U \quad s \in S \quad (\text{E.33})$$

$$\delta_{vts} \in \{0, 1\} \quad v \in V \quad t \in T \quad s \in S \quad (\text{E.34})$$

$$f_{vlt s} \in \{0, 1\} \quad v \in V \quad l \in L \quad t \in T \quad s \in S \quad (\text{E.35})$$

$$w_s \in \{0, 1\} \quad s \in S \quad (\text{E.36})$$

$$e_s^{TOT} \geq 0, \text{integer} \quad s \in S \quad (\text{E.37})$$

$$\sigma_{vls} \geq 0, \text{integer} \quad v \in V \quad l \in L \quad s \in S \quad (\text{E.38})$$