# Decreasing the LCoE of Offshore Wind Farms by Improving the Layout Optimisation Process

## A research into the benefits and implications of including foundation costs

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October 30, 2017


TU Delft Delft University of Technology

SIEMENS Gamesa RENEWABLE ENERGY

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## A research into the benefits and implications of including foundation costs

**Master of Science Thesis**

*For obtaining the degree of Master of Science in Sustainable Energy Technology at Delft University of Technology*


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# Summary

As a result of stringent climate policies and increasing interest from investors, the wind-energy industry has been growing rapidly over the last few decades. Especially the popularity of offshore wind farms (OWFs) shows an exponential upsurge. Technological developments, increasing efficiency in the installation processes, and adequate project planning have recently resulted in a significant decrease in the levelised cost of energy (LCoE) of OWFs. This decrease in LCoE has boosted the attractiveness of offshore wind energy; as a result, the sector's competition has skyrocketed. OWF developers are discovering opportunities to further reduce the LCoE so as to compete in the auctions set by the governments and hence to tender the lowest bid, thereby resulting in the privilege to develop the assigned OWF.

In addition to the possibilities mentioned above, offshore wind-farm layout optimisation (OWFLO) is an appropriate way to further reduce the LCoE. Two types of OWFLO can be distinguished: OWFLO which maximizes the annual energy production (AEP), and OWFLO which minimizes the LCoE. OWFLO which maximizes the AEP aims to find the optimal wind-turbine (WT) layout by locating the WTs such that the OWF as a whole can produce the maximum possible amount of electricity. OWFLO which minimizes the LCoE includes the trade-off between AEP and various costs, which depend on the exact or relative position of the WTs. These costs are mainly related to inter-array cables and foundations. Currently, LCoE-based OWFLO - including variations in inter-array cable costs - is being investigated and is occasionally applied in the industry. The presumption exists that foundation costs vary within an OWF and might have potential to further reduce the LCoE on the order of 1 - 3% when included in the OWFLO process. However, despite the expected potential, the possibility of including foundation costs in OWFLO has not yet been investigated in literature.

Therefore, the objective of this thesis is to investigate the benefits of including the foundation costs in the OWFLO process. To achieve this, a method is developed for including foundation costs in OWFLO. Furthermore, site-specific parameters, which are important to consider when including foundation costs in OWFLO, are identified in this thesis. Monopile (MP) foundations are mostly used in the OWF sector. Furthermore, they are reportedly more strongly influenced by their specific location than jacket foundations are. For these reasons, the scope of this study is narrowed to MP foundations.

Reduction in LCoE is used as a measure to assess the benefits of including MP costs in OWFLO. LCoE reduction is calculated by the percentage change in LCoE from OWFLO which excludes MP costs and from OWFLO which includes MP costs.

These MP costs are included as a layer in Openwind® OWFLO software. To exclusively investigate the influence of MP cost variation, all other project costs are considered to be independent of the layout and are scaled with the number of WTs placed in the OWF.

In the feasibility study, a possible LCoE reduction of between 0.2 and 1% was obtained depending on the spread in MP costs. General MP cost variations seen at existing farms have been included and are linearly distributed over the OWF. The sensitivity study shows that the LCoE reduction is slightly insensitive to incorrect estimation of the absolute MP costs. This implies that, despite errors in MP cost estimation, it is worth including MP costs in OWFLO so long as the relative MP cost variation is correctly approximated. However, to allow OWFLO to yield the most optimal layout and precise approximation of the LCoE, the MP cost needs to be estimated as accurately as possible.

After the feasibility study proved that OWFLO which includes MP costs can be beneficial to the LCoE, a method was developed to estimate MP costs at specific locations within an OWF. The method determines the MP costs by using MP mass estimations multiplied with a cost factor in euros per kg of steel. The MP mass was estimated by a support-structure design tool. Water depth and soil type vary considerably within an OWF and are found to contribute significantly to the MP mass. For this reason, water-depth and soil-type variation are the environmental parameters used to determine the MP costs at specific locations within an OWF.

Using this method, OWFLO which includes MP costs is investigated in-depth by means of case studies. These case studies are inspired by geological features seen in real OWF projects, such as glacial channels and sand dunes. Next to this, variations in OWF density - expressed in total number of WTs in the OWF - and dominant wind direction and are applied. Depending the geological feature and the configuration of those parameters, LCoE reductions between 0.2 and 2% were obtained. The main insight from these case studies is that the geometry and location of a geological feature with respect to the OWF dimensions strongly determines the LCoE reduction. This is a result of the trade-off between the MP cost reduction - obtained by placing the WTs in cheaper areas - and the decrease in AEP. Other site-specific parameters found important when including MP costs in OWFLO are wind direction and OWF density. Both aspects exhibit a capacity to double the obtained LCoE reduction in the most favourable situation. Furthermore, it is found that at OWFs where a combination of sand and clay soil occur, it is sometimes better to place WTs in areas with clay soil than in areas with sandy soil. This is more pronounced at greater water depths and depends on the type of clay soil. Finally, OWFLO which includes MP costs has been applied to the Krieger's Flak OWF. A reduction in LCoE of 0.3% was obtained, which results in a total saving in present value of 3 million euros over the total lifetime of the project.

In summary, it has been found that in any case it is beneficial with respect to the LCoE to include MP costs in OWFLO. A method used to include MP cost in OWFLO is successfully developed and implemented in the OWFLO process. The OWFLO process including MP costs is applied to various case studies, with the following result: *'The benefits of including MP costs in OWFLO are investigated, and the site-specific parameters important to consider have been identified.'* Thus, the objective of this thesis is fulfilled.

# Acknowledgements

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Amsterdam,
October 2017,

Tim Damen

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# Nomenclature

**Latin symbols**

| | | |
|---|---|---|
| $a$ | Annuity factor | $-$ |
| $AEP$ | Annual energy production | $MWh$ |
| $C$ | Costs | € |
| $CapEx$ | Capital expenditures | € |
| $C_t$ | Net cashflow in period t | € |
| $C_u$ | Undrained shear strength | $kPa$ |
| $D$ | Diameter | $m$ |
| $EI$ | Bending stiffness | $Pa \cdot m^4$ |
| $F$ | Force | $N$ |
| $F_{cost,MP}$ | Monopile cost factor | $\frac{€}{kg}$ |
| $H$ | Turbine hub height | $m$ |
| $h_w$ | Water depth | $m$ |
| $k$ | Wake-decay constant | $-$ |
| $L$ | Length | $m$ |
| $M$ | Moment | $Nm$ |
| $m$ | mass | $kg$ |
| $OpEx$ | Operational expenditures | € |
| $P_E$ | Energy price | $\frac{€}{MWh}$ |
| $r$ | Discount rate | % |
| $T$ | Time | $years$ |
| $t$ | Period | $years$ |
| $TI$ | Turbulence intensity | % |
| $t$ | Wall thickness | $m$ |
| $V$ | Volume | $m^3$ |
| $z_0$ | Surface roughness | $m$ |

**Greek symbols**

| | | |
|---|---|---|
| $\lambda$ | Wave length | $m$ |
| $\Phi$ | Friction angle | $^\circ$ |
| $\rho_{steel}$ | Density | $\frac{kg}{m^3}$ |

**Abbreviations**

| | |
|---|---|
| AEP | Annual energy production |
| CapEx | Capital expenditures |
| E | East |
| FLS | Fatigue limit state |
| LCoE | Levelised costs of energy |
| MP | Monopile |
| MW | Mega watt |
| MWh | Mega watt hour |
| NE | North-east |
| N | North |
| O&M | Operation & maintenance |
| OpEx | Operational expenditures |
| OWFLO | Offshore wind farm layout optimisation |
| OWF | Offshore wind farm |
| NPV | Net present value |
| PV | Present value |
| TP | Transition piece |
| ULS | Ultimate limit state |
| WT | Wind turbine |

# Chapter 1

# Introduction

This introductory chapter provides an overview of the context wherein this thesis is built upon. Firstly, in Section 1.1 some information is given about the triggers, targets and increasing interest in the renewable energy sector, how offshore wind energy fits into this picture and what their challenges are. Secondly, Section 1.2 provides insight in the principles and developments of offshore wind-farm layout optimisation (OWFLO). Thirdly, the cost components which are dependent on the wind-turbine (WT) layout of the offshore wind farm (OWF) are described in Section 1.3. These three sections provide the background for the problem definition of Section 1.4. This chapter ends with Section 1.5 where a description of the research approach and the thesis outline can be found.

## 1.1 Offshore wind energy in a renewable energy era

The world is struggling with climate change and energy-related air pollution. There is need for a low carbon energy system, as the prevailing situation is the source of at least two-third of greenhouse-gas emissions [29]. Stringent international policies, amongst others triggered by the Paris Agreement in 2015, articulate the need to mitigate climate change and set ambitious targets to reduce these greenhouse-gas emissions and air pollutants in order to meet the goal to stay below a 1.5 degrees Celsius temperature increase [56].

A combination of these policies and year-on-year low oil prices has set a tremendous transformation of the energy sector in motion. Provoked by favourable feed-in tariffs, quotas with tradable green energy certificates, and competitive auctions initiated by the government, renewable energy sources became of major interest to investors [12]. Hence, the wind-energy industry has taken advantage of this and is since growing rapidly. This growth resulted in steady increase in number, size and complexity of OWFs over the past few years [26].

Simultaneous to the upsurge of installed offshore wind energy, the levelised cost of energy (LCoE) is decreasing at a fast pace. To compete in the auctions, to become more attractive than conventional power, and to be able to operate an OWF free from subsidy, companies must further reduce the LCoE of OWFs [26]. To contribute to this purpose, this thesis aims to further reduce the LCoE of offshore wind energy, by improving the OWFLO process.

## 1.2 Offshore wind-farm layout optimisation

Two types of OWFLO are described in this section, maximizing the annual energy production (AEP) and minimizing the LCoE. To describe those, first some background about OWFs and OWFLO in general is provided in the next subsection.

### 1.2.1 Principles of OWFs and OWFLO

An OWF typically consists of 50 - 150 WTs, currently having a total capacity of around 600 megawatt (MW), which implies an average WT rating of about 4 - 8 MW [32]. The definition of OWFLO in this thesis is devoted to the optimisation of the exact and relative position of the WTs within the dimensions of an OWF. The WTs are positioned optimally in order to either maximize the AEP in megawatt hour (MWh) per year or minimize the LCoE in € per MWh.

Depending on the location of the OWF, design restrictions with regard to the layout are imposed, which sometimes forms a hurdle to fully optimise the OWF layout. This study is focussing on OWFs without design restrictions, which implies that the WT are allowed to be placed in every possible layout. The key developments in OWFLO for maximizing the AEP and minimizing the LCoE are described below.

### 1.2.2 OWFLO maximizing the AEP

OWFLO is dating back to when the first OWFs were being commissioned in the 1990s, with its fundamentals of maximizing AEP inspired by the first onshore wind farms originated from 1980 in New Hampshire (USA). Maximizing the AEP can be accomplished within OWFLO by minimizing the wake induced production losses, hereafter named wake losses, of adjacent WTs [33, 26].

The wake losses, which occur due to wake effects from upstream WTs shadowing each other, decreasing the wind speed incident on the WT [18]. This reduction in wind speed can be calculated based upon wake models. One of the most recognized models is based on the theory of N.O. Jensen, who presented the first linearised far wake expansion assumption in the early 1980's [31, 34]. Nowadays, this wake model is still used in most OWFLO projects [65].

Wake losses can account for 5 - 15% of total AEP reduction of an OWF, depending on the compactness of the OWF, which implies this can be even more in the AEP of adjacent turbines placed parallel to the wind direction [6]. Another factor influencing the AEP is the collector system loss, which consist of WT and substation transformer loss and line loss. The collector system loss can account for around 2.5% reduction in AEP [48].

A study, in which the Middelgrunden OWF was optimised with OWFLO maximizing the AEP, found that an AEP increase of 6% was possible compared to its initial layout [25]. Many other studies to OWFLO maximizing the AEP are performed, of which an extensive list can be found in [25, 26].

### 1.2.3 OWFLO minimizing the LCoE

Later on, more comprehensive OWFLOs were performed, including the trade-off between AEP and various cost components. The seeds of modern LCoE-based OWFLO are planted by Mosetti et al. in 1994 [46]. Their research contains a LCoE optimisation procedure by extracting maximum energy at minimum costs, assuming the total cost of an OWF is an exclusive function of the number of WTs [26, 25]. After this publication, no new research about OWFLO by minimising the LCoE was performed for 10 years, and most studies used the cost formula of Mosetti. This implies that these studies did not include the different cost components which varies individually, based on the characteristic of an OWF.

Elkinton changed this in 2007 by developing detailed cost models including turbine, foundation, electrical equipment, operation and maintenance (O&M) and decommissioning costs. Implementing those in the OWFLO process, this research suggests an obtainable reduction in LCoE of 5% [18].

Another study conducted in 2014 envisioned a potential further reduction in LCoE by improvements in OWFLO of 3.1%. Aspects to accomplish this are: greater level of soil-structure surveying (- 0.6%), greater level of optimisation during early project phases (- 0.8%), and introduction of multi-variable OWFLO (- 1.7%) [67]. In contrast to the work of Elkinton, the multi-variable OWFLO of this study only focusses on the cost components which are a function of the WT locations within an OWF layout, which are described in the next section.

## 1.3 Cost components depending on OWF layout

Cost components included in multi-variable OWFLO are dependent on the location of the WTs and facing a trade-off with AEP. These are electrical equipment costs and foundation costs. Below a short description of both can be found and the extent to which research is conducted to the cost component with respect to OWFLO is given.

### 1.3.1 Electrical equipment costs

Electrical equipment costs are calculated by determining the number and location of the offshore substations, the voltage levels of the connection network, and the inter-array cable paths and cable sizes, given the WT positions in the OWF. Nowadays, offshore sub-stations and the grid connection are in some projects, for example the auction projects of OWFs in The Netherlands, out of scope for the OWF developer. The offshore sub-station and grid connection accounts for a large part of the electrical equipment costs, but are not dependent on the layout of the OWF.

Inter-array cables, of which the optimisation lies within the scope of the OWF developer, are a function of the relative position of the WTs. This implies that it is possible to achieve cost reduction by including inter-array cable costs in the OWFLO process [57, 24, 41]. However, studies to OWFLO which includes the trade-off between AEP and electrical equipment cost have already been conducted and the principle is applied in the offshore wind energy sector, by means of optimal choice of cable topologies [26, 25].

### 1.3.2 Foundation costs

The cost of foundations is determined by its design, which is dependent on the WT characteristics and environmental design drivers, such as wind and wave climate, water levels and soil structure. The environmental design drivers vary depending on the location, between OWFs and within the dimension of an OWFs. For this reason, the foundation costs are a function of the exact location of the WTs within an OWF.

A study is conducted to the principle of including foundation costs in OWFLO, using an empirical formula scaling with water depth. It showed a change in WT positions moving towards more shallow areas, which proved that the concept of including foundation costs in OWFLO works. However, no statements are included regarding the potential influence on LCoE [63]. This potential influence is partly included in the work of Elkinton. But he only stated that a 10% decrease in foundation costs can results in a 1.5 to 2% reduction in LCoE [18]. However, this statement is not proved by means of a thorough study which includes foundation costs in OWFLO.

## 1.4 Problem definition

The problem definition consists of three parts. First, a short problem analysis is conducted based on the literature study about OWFLO and cost components. This problem analysis leads to the research objective and corresponding tasks. Thereafter, the scope of this study, with respect to the foundation type, is described.

### 1.4.1 Problem analysis

The previous sections outlined the context of this thesis. In Section 1.3 it is stated that scientific research has been conducted to the trade-off between AEP and electrical equipment costs. This principle is already applied in OWFLO and will not further be investigated in this study.

However, while it is expected that including foundation costs in OWFLO have influence on the OWF layout, and a reduction of foundation costs of 10% induce a LCoE reduction potential up to 2%, the relation between including foundation costs in OWFLO and LCoE is not yet investigated. Besides, no method exists to estimate foundation costs at specific locations within an OWF to include in the OWFLO process. Furthermore, it is not yet known why and how particular site-specific parameters must be considered when including foundation costs in the OWFLO process.

Summarizing, the challenge of this thesis lies in the exclusive focus on the trade-off between AEP and foundation costs within OWFLO, the influence it can have on the LCoE and which parameters are important to consider when including foundation costs in OWFLO. To achieve this a method needs to be developed to include foundation costs in the OWFLO process.

### 1.4.2 Objective and tasks

The problem analysis leads to the following objective:

*'Investigate the benefits and parameters that should be considered when including MP costs in OWFLO, by developing and implementing a method to include the MP costs in the OWFLO process.'*

To pragmatically approach this objective, it is subdivided into the following tasks:

1. Investigate the feasibility of including foundation cost variation in OWFLO with respect to the LCoE.
2. Develop a method for foundation cost estimation at specific locations within an OWF.
3. Implement the method in a location-specific foundation cost estimator, which can be used in the OWFLO process.
4. Identify parameters specific to an OWF which are important to consider when including foundation costs in OWFLO.

By obtaining this objective and fulfilling these tasks, this thesis provides both academic value as well as useful conclusions and recommendations for engineering application.

### 1.4.3 Scope of foundation type

Several foundation types exist with different characteristics and costs. To narrow the scope of this study OWFLOs based on one foundation type are investigated. This specific type is selected and described in this sub-section. Furthermore, only the components of which the costs significantly vary within an OWF are considered and described below.

**Selection of foundation type**
The most common foundation types at this moment are a jacket, gravity based structure and a monopile. The latter accounts for over 80% of total installed foundations and 97% of the newly installed foundations in Europe in 2015 [20, 32]. Because monopile foundations are applied most frequently, the highest value can be created when using monopile foundations in the analysis of this study.

**Description of a monopile foundation**
A monopile foundation consist of a pile, hereafter named the monopile (MP), and a transition piece (TP). The MP is driven into the soil and provides bearing capacity and stability to the tower and the WT. The TP connects the MP with the tower, which is displayed in the centre of Figure 1.1 [14, 55]. The MP and TP consist of a primary structure and a secondary structure. The primary structure contains all load carrying components, which maintains the overall structural integrity [72]. The secondary structure includes additional components attached to the TP, such as platform, boat landings, ladders, anodes and J-tube, showed at the left side of Figure 1.1 [21, 14].

**Mono-pile foundation components which vary in costs within an OWF**
TP's are in general uniform within an OWF. When a differing MP diameter is required, this is corrected by using a conical shaped MP top, which then fits in the TP. Because all secondary structure items are attached to the TP, the cost of the TP as well as the secondary structure are assumed constant within an OWF. For this reason, they are not included in the MP foundation costs [7, 73].

The only MP foundation component of which the costs significantly varies within an OWF, and therefore used in this study, is the primary structure of the MP. This primary structure is called the shell of the MP, which is also the component predominantly determining the costs of the MP foundation. An extra advantage of exclusively considering the shell mass of the MP, is that it makes no difference whether a grouted or bolted connection is used. The picture of a MP shell can be found on the right side of Figure 1.1.

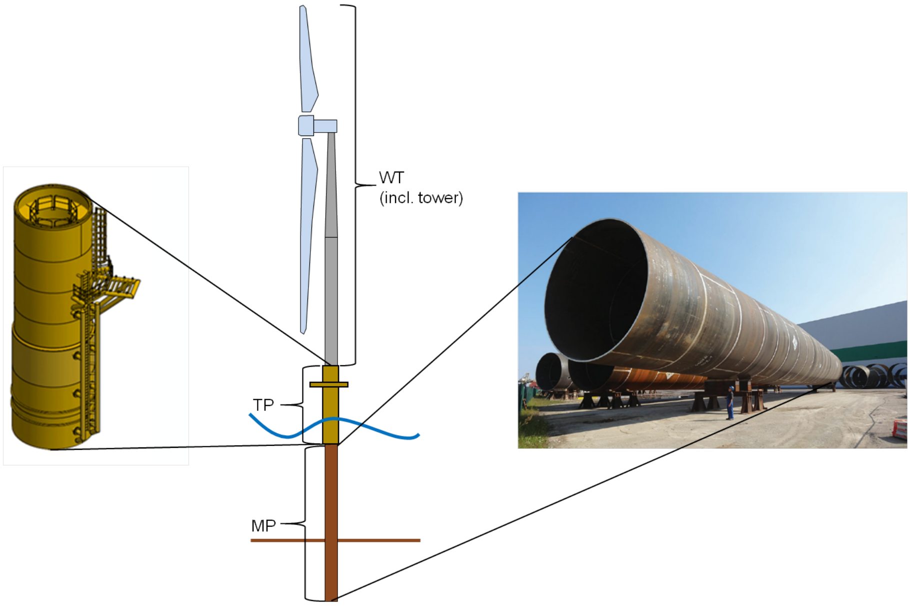



**Figure 1.1:** Impression of a WT attached to a MP foundation containing of a TP and MP [73] (c). Next to this are displayed a zoom-in of a TP including secondary steel items (l) [66] and the shell of a 7.5 m MP for Gode OWF (r) [32].

## 1.5 Research approach and thesis outline

This section describes the approach of this study. It explains how the objective and its tasks are handled in every particular chapter. Additionally, the goal of each chapter and how the chapters are connected is described.

Chapter 2 provides a description of the proposed methodology used in this study. It gives insight in the way how the influence of including MP cost is measured in the OWFLOs by using LCoE compared to AEP based OWFLO. This chapter also provides information about the configuration of the hypothetical OWF, financial data, several assumptions, and the use of software.

In Chapter 3 a feasibility study is performed, complying with Task 1 of the objective. In general, this feasibility study aimed to confirm the hypothesis that including MP-cost variation in OWFLO is beneficial to the LCoE, stated in the problem definition. Furthermore, its goal was to check whether it was worth to continue with Tasks 2, 3 and 4.

Chapter 4 describes the method to estimate MP at specific locations within an OWF, in order to comply with Task 2 of the objective. This method requires the estimation of MP mass, which is explained by describing the MP design process. The explanation of this design process helps to identify environmental design drivers influencing the MP design. The environmental design drivers which also vary within an OWF are used in a 'location-specific MP cost estimator'. The location-specific MP cost estimator makes it possible to include the MP cost estimation in the OWFLOs process.

In Chapter 5 the method developed in Chapter 4 is implemented in a location-specific MP cost estimator, complying with Task 3 of the objective. This location-specific cost estimator consist of two steps. In the first step a selected support structure design tool serves as MP mass estimator. In the second step this MP mass is converted to location-specific MP cost. The output of the location-specific MP cost estimator serves as input for OWFLO which includes MP costs.

Chapter 6 consists of an in-depth investigation of the benefits of including MP costs in OWFLO, by means of several case studies, in order to comply with Task 4 of the objective. The goal of this chapter is to identify OWF-specific parameters important to consider when including MP costs in the OWFLO process. Furthermore, the developed method is applied to a representative OWF, in order to obtain insight in the benefits achievable in a real-life situation.

In the final Chapter 7 the conclusions and recommendations are given. Figure 1.2 visualises the outline of this thesis.

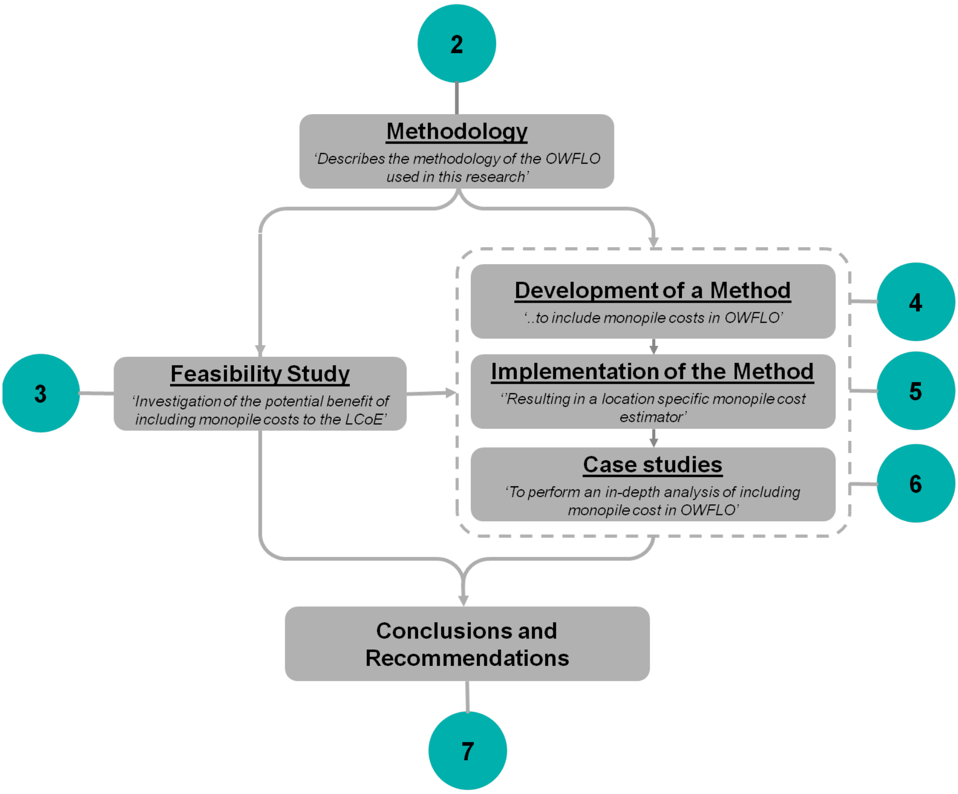



**Figure 1.2:** This thesis outline gives an overview of the location and content of each chapter in this thesis.

# Chapter 2

# Methodology of Investigating OWFLO Including Monopile Costs

In this chapter, the proposed methodology of OWFLO including MP costs is outlined. This mainly applies to the feasibility study and the case studies in Chapter 3 and 6. Firstly, Section 2.1 describes the way how LCoE reduction of OWFLO which includes MP costs compared to OWFLO which excludes MP costs can be measured. In Section 2.2 the configuration of the hypothetical OWF is defined. OWF project costs are required to calculate the LCoE, which is explained in Section 2.3. This chapter ends with an description of the software used to perform the OWFLOs.

## 2.1 Original versus improved OWFLO

First, the concepts of original and improved OWFLO are described. Secondly, the way how LCoE reduction is measured between original and improved OWFLO is explained. Thereafter, the requirements for both the original and the improved OWFLO are mentioned.

### 2.1.1 Concepts of original and improved OWFLO

To enhance the readability of this study, the wordy phases ‘OWFLO which excludes MP costs’ and ‘OWFLO which includes MP costs’ are hereafter mentioned as ‘original OWFLO’ and ‘improved OWFLO’. In the optimisations using original OWFLO AEP is used as objective function and in the optimisations using improved OWFLO LCoE is used as objective function.

### 2.1.2 LCoE comparison between original and improved OWFLO

To investigate the change in LCoE, a comparison is made between the LCoE of the layout which results from an original and an improved OWFLO. Both optimisations start with a random initial layout and no design restrictions are imposed to the optimised layout. Summarizing, this comparison consists of three steps:

**Step 1.** Calculate the LCoE of the layout which results from original OWFLO.
**Step 2.** Calculate the LCoE of layout which results from improved OWFLO.
**Step 3.** Calculate the percentage change in the LCoE of the layouts created by improved compared to original OWFLO.

To perform the original and improved OWFLO and to calculate the LCoE of the resulting layout, data is required. To explain which data is required, both OWFLO types are described individually.

### 2.1.3 Original OWFLO: AEP as objective function

In the original OWFLO the optimisation only requires the calculation of the AEP. This sub-section explains the way AEP is calculated and describes the required data for that calculation.

**AEP calculation**
A distinction is made between gross and net AEP. The gross AEP is the result of multiplying the power curve of the WT with the frequency distribution of the wind at the OWF and the hours in a year [43]. The net AEP can be obtained by extracting all the losses from the gross AEP and multiply that value with the availability of the WT.

The energy loss is the result of wakes losses, electrical system losses, due to resistance and losses in the trafo, and losses in the transformer station and control system [18]. Equation 2.1 expresses this in a formula, where t stands for the specific year at which the energy production and losses occur. To calculate the total energy production over the lifetime of the project, the future AEP is levelised to present values (PVs) which are not included in this equation.

$$AEP_{net,t} = A_F\big((AEP_{gross,t} - E_{Loss,wake,t} - E_{Loss,elec,t}) - E_{Loss,trans,t}\big) \quad (2.1)$$

**Required data**
From the description of the AEP calculation it shows that the most important data is the gross AEP of each individual WT. This requires data about the wind climate, power curve of the WT and the number of WT used in the optimisations, which can be found in Section 2.2. To calculate the wake loss the model of N.O. Jensen is used [34, 31].

Furthermore, data is required concerning the availability of the OWF, the collector system losses, transformer station losses, and - in order to levelise the AEP to PVs - the economical parameters describing the lifetime of the project and the discount rate. All this data is held constant during the project and is displayed in Table 2.2 at the end of this chapter.

### 2.1.4 Improved OWFLO: LCoE as objective function

During the improved OWFLO the LCoE must be calculated. This calculation uses the AEP calculation explained in previous section, but includes costs in order to establish a way to include MP-cost variation in the improved OWFLO. This subsection explains the way LCoE is calculated and describes the required data for the calculation.

**LCoE calculation**

The LCoE is defined by the total life-cycle costs, which is the PV of the total costs to build and operate an OWF, divided by the PV of the total life-time energy production of the project, in € per MWh [71, 26]. The PVs are calculated by using a discount rate (r) which includes the return on capital and inflation [30]. Equation 2.2 expresses this in a formula.

$$LCoE = \frac{CapEx + \sum_{t=1}^{T} \frac{OpEx_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{AEP_t}{(1+r)^t}} \tag{2.2}$$

The LCoE indicates the price of electricity required for a project where revenues would equal costs. In other words, it represents a “break-even” price at which electricity must be sold in order to justify the investment in a project. It allows the comparison of different projects of unequal life-spans, project size, capital costs, risk, return and capacities [13, 44].

**Required data**

Equation 2.2 shows that the LCoE of an OWF is calculated based on project costs, such as capital expenditures (CapEx) and operational expenditures (OpEx), combined with AEP and levelising economical parameters [18].

The CapEx consist of WT (including tower and TP), MP, electrical equipment, installation and other costs. The other costs include, but are not limited to: development, engineering and management costs [44, 18]. The OpEx mainly depends on operation and maintenance (O&M) costs. Recurrent costs related to land use or compensation for noise or visual impact are assumed to be zero for an OWF [44]. A comprehensive overview of these OWF project costs used in this study can be found in Section 2.3.

## 2.2 Configuration of the hypothetical OWF

To perform the OWFLOs a hypothetical OWF has been created. The wind climate, WT type and specifications, and the OWF dimensions are described in this section. An overview of the constants used in this study can be found in Table 2.2 at the end of this chapter.

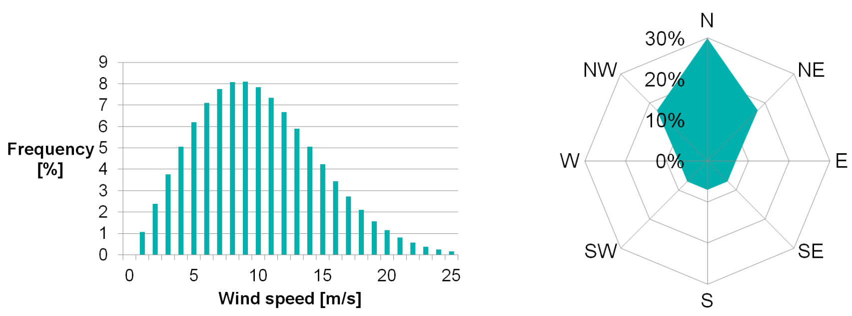
### 2.2.1 Wind climate

The wind climate is mainly characterized by wind direction and frequency distribution. Other parameters contributing to the wind climate are turbulence intensity (TI), surface roughness length ($z_0$) and wake decay constant ($k$).

**Wind direction and frequency distribution**

The wind climate has a dominant wind direction from the north (N), with an average wind speed of 10 $\frac{m}{s}$. The frequency distribution of the wind speed and direction can be found in Figure 2.1. The frequency distribution of the wind speed is constructed based on the Weibull probability function, with 2.2 [-] as shape factor and 11.29 [s] as scale factor [5].

For one specific case study in Chapter 6 the dominant wind direction differs, keeping the distribution of the wind speed constant. For another case study a realistic distribution of the wind speed and direction is used. Both modifications are clearly explained in the description of the particular cases.




(a) (b)

**Figure 2.1:** Distribution of wind speed (a) and direction (b) which are used in the OWFLOs of the hypothetical OWFs.

**TI, surface roughness and wake-decay constant**

For the TI a value 10% is used, which is based on a report expressing metocean data of Hollandse Kust Zuid OWF project [15]. A figure in this report expressed the TI as a function of the main wind speed. The chosen value of 10% corresponds to the main wind speed of 10 $\frac{m}{s}$ used in this study.

The surface roughness influences the behaviour of the wind its surface-boundary layer. The roughness length is defined as the height above the ground in meters at which the wind speed is theoretically equal to zero [59]. The wake-decay constant determines how quick the wind field behind the WT recovers to the free stream. A higher constant result in larger wakes which are damped faster and vice versa [34]. Surface roughness and wake-decay constant are related to each other as expressed in Equation 2.3, where A is a constant equal to 0.5 and H is the hub height [4, 64].

$$k = \frac{A}{ln(\frac{H}{z_0})} \tag{2.3}$$

Various sources mention different values for surface roughness applicable for OWFs. Most frequently cited are a surface roughness of 0.002 m [16, 37] and 0.0002 m [59, 45]. A surface roughness of 0.002 m has been used in the optimisation of this study because this value is considered being the surface roughness describing rough sea, while 0.0002 is related to calm sea [69]. Based on the surface roughness of 0.002, the wake-decay constant used is 0.046. The influence of using 0.0002 m versus 0.002 m roughness length is, for the interested reader, investigated and described in Appendix A.

### 2.2.2 Wind turbine type and specifications

A typical and currently widely applied Siemens Wind Turbine of 8.0 MW rated power and a rotor diameter of 154 m is used. This WT is hereafter named SWT-8.0-154. The SWT-8.0-154 is a direct-drive pitch-regulated WT operating at variable speed. The used hub height is held constant at 100 m.

### 2.2.3 Offshore wind farm dimensions

To determine the dimensions of the hypothetical OWF, the number of WTs is fixed at 16 and they have been arranged in a regular, symmetric grid of 4 by 4 WTs. Assuming an OWF with $\sim 10D_{rotor}$ this results in a squared site of 5000 x 5000 m. Figure 2.2 displays the dimensions of the OWF.

For one case study in Chapter 6 the number of WTs differs, keeping the dimensions of the OWF constant. For another case study a representative OWF is used, having different dimension and number of WTs. Both modifications are clearly explained in the description of the particular cases.

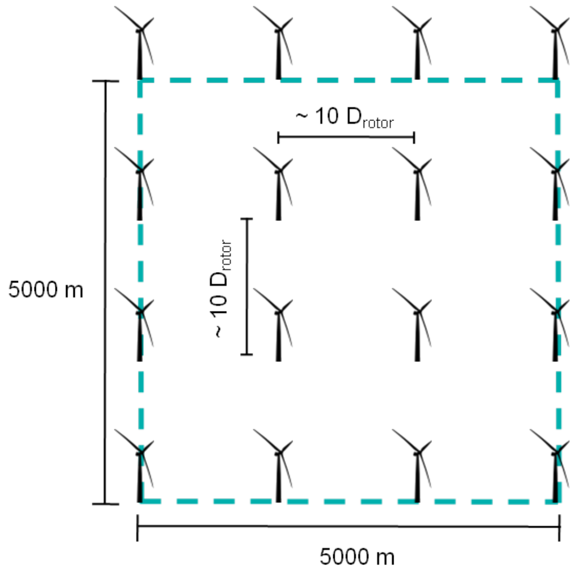



**Figure 2.2:** Dimensions of the hypothetical OWF. The 16 WTs are symmetrically distributed in a square with $\sim 10D_{rotor}$ spacing, resulting in a 5000 x 5000 m site.

## 2.3 Offshore wind-farm project costs

To calculate the LCoE of the layouts resulting from the OWFLOs, the OWF project costs are determined. The next sub-section explains how these costs are estimated using a CapEx breakdown. Subsequently, it is described how the required WT and MP costs are estimated. This section ends with an overview of all OWF project costs.

### 2.3.1 Estimating OWF project costs using CapEx breakdown

To estimate the OWF project costs the CapEx breakdown from Figure 2.3 is used [17]. It is assumed that this CapEx breakdown is valid for an OWF with a water depth of 20 m. This implies that the absolute value of the project costs, except the MP costs which are dependent on the exact location of the WT, will not change.

The electrical equipment, installation and other costs are - in this study - a function of the WT and MP costs. To calculate the electrical equipment, installation and other costs the following steps are taken: First, the values of the WT and MP costs are summed up and divided by their combined share in the CapEx breakdown. Then, this value is multiplied with the percentage share of electrical equipment, installation or other costs individually.

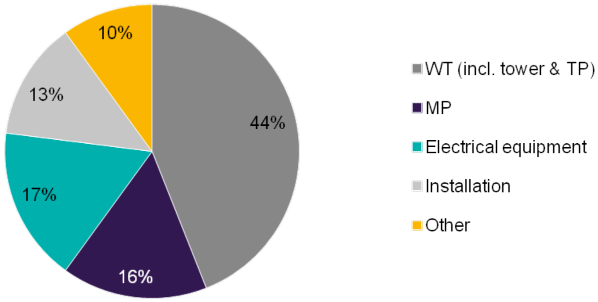



**Figure 2.3:** CapEx breakdown of an OWF project [17]. This CapEx breakdown is used to estimate the electrical equipment, installation and other costs based on the values of the WT and MP costs, and the percentage of their share in the breakdown.

### 2.3.2 Wind-turbine and monopile costs

As explained, to calculate the electrical equipment, installation and other costs, the values of the WT and MP costs are estimated first, which is shown below.

**Wind-turbine costs**

According to reference projects, a multi MW size WT costs approximately 900 $\frac{k€}{MW}$ including the tower and TP however without installation costs [47]. This results in total WT costs of approximately 7,200 $k$€ for the SWT-8.0-154, which can be found in the second row of Table 2.1.

**MP costs**

In the rest of this study the MP costs are variable, depending on the exact location of the WT, while the other CapEx and OpEx are maintained constant. However, to estimate the project costs a rough estimation of the MP cost is made.

To give an indication of the MP costs the MP mass of a sample containing 37 actual design locations is used, which can be found in Appendix B for the interested reader. The actual design locations are design locations within OWFs available in the Siemens Wind Power data base. The mass of these designs is multiplied with a cost factor expressing the costs of an MP in euros per kg of steel, which is assumed $2.25\frac{€}{kg}$ for MPs [74].

The estimated costs of the 37 actual designs are plotted against the water depth resulting in the scatter-plot of Figure 2.4. A least-squares linear trend line is plotted through the data points, which results in the function of Equation 2.4. In this function, the MP costs ($C_{MP}$) are expressed in euros and the water depth ($h_w$) in meters.

$$C_{MP} = 73,675 \cdot h_w - 355,928 \tag{2.4}$$

Equally to the CapEx breakdown, the estimation of the MP costs is based at a water depth of 20 meter. This results in a MP costs of 1,118 $k$€, which can be found in the third row of Table 2.1.

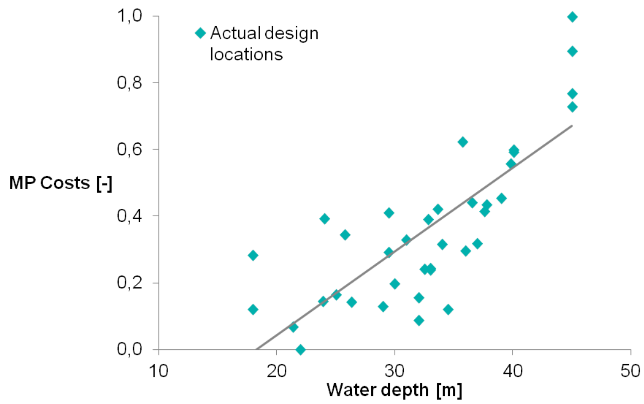



**Figure 2.4:** Scatter-plot displaying the MP costs of available designs within OWFs, plotted against the water depth. The MP costs are normalized between 0 and 1 for confidentiality reasons, with 0 not corresponding to absolute zero, but to the lowest available MP cost.

### 2.3.3 Overview of OWF project costs

In this sub-section, the CapEx and OpEx representing the input of the project costs required to determine the LCoE of the OWFLO are given.

**CapEx**
Table 2.1 shows a complete overview of the different CapEx. The values of the WT and MP are known. Based on those values the electrical equipment, installation, and other costs are calculated as explained in Section 2.3.1. Because the hypothetical OWF, described in Section 2.2 contains 16 WTs, the values in the right column are used as input for the LCoE calculation. For the case studies with a different number of WTs the cost per WT is used to calculate the correct project-cost input for that particular case.

**OpEx**
The total OpEx is calculated by assuming that its value is 2% of the total CapEx [30]. This results in a yearly OpEx of 277 $k$€ per WT and 4,436 $k$€ for 16 WTs.

**Table 2.1:** Cost calculation using CapEx breakdown, with predefined WT and MP costs.

| Aspect | CapEx breakdown | Cost per WT [$k$€] | 16 WTs [$k$€] |
|---|---|---|---|
| WT [a] | 44% | 7,200 | 115,200 |
| MP | 16% | 1,118 | 17,888 |
| Electrical equipment | 17% | 2,357 | 37,712 |
| Installation | 13% | 1,802 | 28,832 |
| Other | 10% | 1,386 | 22,176 |
| Total CapEx | 100% | 13,863 | 221,808 |

[a] Including TP and tower.

## 2.4 Software use

Two software programs are used: AWS Truepower OpenWind® Enterprise, hereafter named Openwind®, to perform the OWFLOs and MathWork®'s program MATLAB to construct the location-specific MP cost estimator.

### 2.4.1 Openwind®

Openwind® is the software program on which the analyses this study are based. For this reason, a comprehensive description including its basics, objective functions for OWFLOs, the specifications of its LCoE module, and optimisation algorithm and settings are given.

**Basics**
Openwind® combines wind resource assessment, with OWFLO, including wakes and turbulence. The program uses a graphical information system approach to the layout problem, meaning that the use of maps, digital terrain models and layering techniques are the core of the program [4].

**Objective functions**
The program has two options for running the OWFLOs. First, energy-based optimisation with maximizing the AEP as objective. Secondly, cost based optimisation with minimizing the LCoE as objective. Furthermore, the program can calculate the LCoE of a particular layout, apart from running an optimisation.

**LCoE module**
Openwind® uses the net present value (NPV) to calculate the LCoE. This formula is given in Equation 2.5.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - CapEx = 0 \tag{2.5}$$

$$C_t = (AEP_t \cdot P_E) - OpEx_t \tag{2.6}$$

The CapEx and discount rate are predefined input parameters. The net cash inflow during period t ($C_t$), expressed in Equation 2.6, consist of the energy revenues, which is the AEP multiplied with the energy price ($P_E$), minus the OpEx, of which the latter is also a predefined input parameter.

The energy price is the only unknown parameter in the formula and this value is minimized by the optimiser for a NPV equal to zero. Hence, for a NPV equal to zero, the LCoE is equal to the energy price. This means that in this way the LCoE formula from Equation 2.2 and the NPV formula from Equation 2.5 give the same result.

**Optimisation algorithm and settings**
Openwind® uses a greedy heuristic algorithm as optimiser. An explanation of this algorithm can be found in Section 5.3.1 of the work of Elkinton [18].

To generate reliable results, every optimisation run consist of 1000 iterations. With this number of iterations, the optimisation converges to the results with an error on the order of 0.2%.

The LCoE optimiser is more prone to the problem of local minima and cannot guarantee that it always finds the global optimum. To avoid this problem every individual optimisation is repeated 3 times.

And because the optimiser tends to bunch WTs closer to each other to reduce costs, it is important to set a minimum WT spacing to avoid layouts which result in unacceptable fatigue loading. Therefore, a minimum WT spacing of 3 $D_{rotor}$ is assumed.

### 2.4.2 MATLAB

The location-specific MP cost estimator used for the OWFLO is constructed in MATLAB. This script is able to converts location-specific environmental design drivers into MP costs at specific locations within the OWF. The output of this MATLAB script is a MP-cost layer, to be included in Openwind® in order to perform the improved OWFLOs. Further explanation of the design of this MP cost estimator can be found in Section 5.4. MATLAB is used to create the cost layers used for the assessment of the general MP-cost variation in the feasibility study.

**Table 2.2:** Constants used in the OWFLO analysis

| Parameter | Value |
|---|---|
| WT | |
| Rated power | 8 MW |
| Rotor diameter | 154 m |
| Hub height | 100 m |
| OWF specifications | |
| Dimensions | 5000 x 5000 m |
| Overall farm availability | 100% |
| Wind climate at the OWF | |
| Mean wind speed | 10 $\frac{m}{s}$ |
| Turbulence intensity | 10% |
| Surface roughness [6, 69, 22] | 0.002 m |
| Wake decay [6, 69] | 0.042 |
| Electrical interconnection | |
| Collector system loss | 0% |
| Transformer station loss | 0% |
| Economic parameters [47] | |
| Economic lifetime of OWF | 25 years |
| Discount rate | 6% |

# Chapter 3

# Feasibility Study of Including Monopile-Cost Variation in OWFLO

In this chapter, a feasibility study is conducted in order to comply with Task 1 of the objective: Investigate the feasibility of including MP cost variation in OWFLO with respect to the LCoE. In Section 3.1 the approach of this feasibility study is explained. Section 3.2 describes the results, followed by the main insights of this chapter in Section 3.3.

## 3.1 Approach

For simplicity of the feasibility study, only general MP-cost variation typical for an OWF is applied, instead of including the MP costs estimated at each specific location within the OWF, which is done later in this study. The next two subsections give an explanation of the way this general MP-cost variation is determined and how the sensitivity study is performed.

### 3.1.1 General monopile cost variation

In order to estimate general MP-cost variation the data of actual MP designs from 13 OWFs is used. These 13 OWFs and their MP-cost variations are based on the MP mass of actual MP design locations of OWFs within the Siemens Wind Power data-base, which can be found in Table B.1 of the Appendix. The MP costs of these designs are estimated by multiplying the MP mass with a cost factor describing the price of the MP in € per kg of steel, having a value of 2.25 $\frac{€}{kg}$ [74].

Figure 3.1 shows 13 of the 15 OWFs, indicated on the x-axis, and their upper and lower boundary of MP costs of the design locations. The costs are normalized for confidentiality reasons. F13 and F14 are not incorporated in Figure 3.1, because there is no MP-mass range available for those OWFs. From the non-normalized data, it transpired that small ($\sim$ 250 $k$€) to large ($\sim$ 1000 $k$€) variation in MP cost exist at different magnitudes, starting at $\sim$ 1000 $k$€ up to 4000 $k$€.

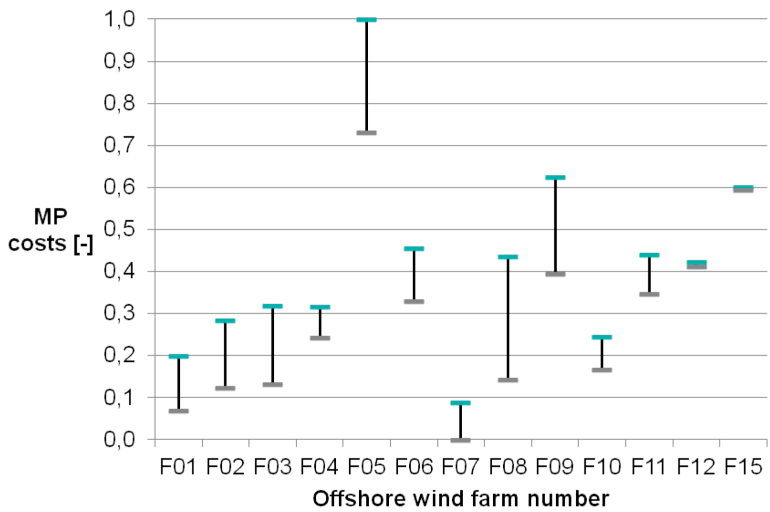



**Figure 3.1:** MP-cost variation of MP designs within several OWFs. Indicated are the upper and lower boundaries of MP costs within the OWFs. For confidentiality reasons the costs are normalized between 0 and 1, with 0 being the lowest MP cost available.

Based on this MP-cost range and magnitude variation seen in the non-normalized data from Figure 3.1 a classification is made, which is displayed in Table 3.1. Eight cases are identified having low variation (250 $k$€), to high variation (1000 $k$€) for MP costs starting at 1000 $k$€ (Cases A), and MP costs of maximum 4000 $k$€ (Cases B). The ranges are linear distributed over the hypothetical site, with the highest MP cost at the Northern side, and the lowest MP cost at the Southern side.

A larger range is anticipated to have stronger influence on the WT positions, because of the MP-cost variation increases. The question is how the OWFLO deals with the trade-off between placing the WTs in less expensive areas - to save MP costs - with respect to the obtained loss in AEP due to wake loss.

Furthermore, it is expected that for the same absolute difference between upper and lower boundary of the MP costs, the cases A shows stronger influence in LCoE then cases B. The reason therefore is that the percentage difference between the lower and upper bound is larger for cases A then for case B.

**Table 3.1:** Cases with different MP-cost ranges, for both low (A) and high (B) magnitude of MP costs.

| Case number | Range [$k$€] |
|---|---|
| A1 | 1000 - 1250 |
| A2 | 1000 - 1500 |
| A3 | 1000 - 1750 |
| A4 | 1000 - 2000 |
| B1 | 3750 - 4000 |
| B2 | 3500 - 4000 |
| B3 | 3250 - 4000 |
| B4 | 3000 - 4000 |

### 3.1.2 Sensitivity study

The sensitivity study is conducted to examine the sensitivity of errors in the MP cost estimation to the reduction in LCoE. The layouts are optimised using improved OWFLO with an error in the MP cost estimation. The LCoE of the resulting layout is calculated with the reference MP cost estimation. This error is expressed by means of a percentage with respect to the extent to which the MP costs are included, compared to the reference value. For example, if MP costs are included 50% or 150% of the reference value (100%), this corresponds to an error of 50%. The reference values are the MP costs of the case with the highest reduction in LCoE. This is shown in the results of the general MP-cost variation of Section 3.2.1.

## 3.2 Results

In this section the results of the general MP-cost variation and sensitivity study can be found.

### 3.2.1 General monopile cost variation

The results of the optimisations, expressed in Figure 3.2, show a reduction in LCoE between 0.2% and 1%, when using improved OWFLO and hence the MP-cost variation is included. For both cases A and B the reduction in LCoE is larger when the range in MP-cost variation is larger. This is in line with what was expected. Besides, the reduction in LCoe for cases A versus cases B overall is slightly larger. This is also in line with what was expected.

Figure 3.3 shows the change in layouts for the case with the largest reduction in LCoE (A4). Figure 3.3a is based on original OWFLO and Figure 3.3b is based on improved OWFLO. It can be seen that when improved OWFLO is applied, the WTs tend to move towards areas with lower MP costs. Furthermore, the site becomes slightly denser which resulted in lower AEP due to wake loss. The reduction in LCoE is the result of the fact that the lower MP costs outweighs the decreased AEP.

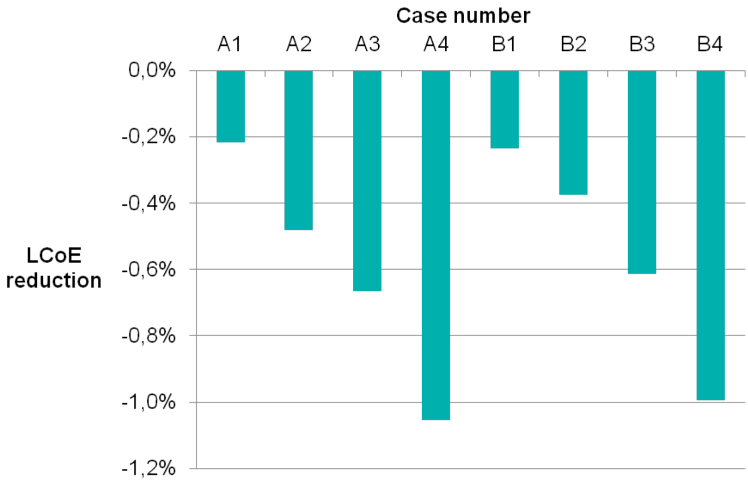
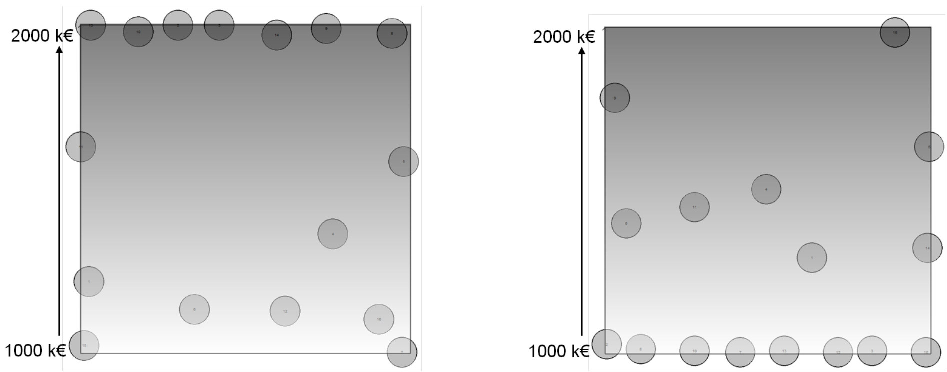



**Figure 3.2:** Percentage reduction in LCoE when MP-costs variation is included in the OWFLO process (improved OWFLO) for various MP-cost ranges and magnitudes. The case numbers are explained in Table 3.1.




**(a)** **(b)**

**Figure 3.3:** Impression of WT layout resulting from original OWFLO (a) and improved OWFLO (b). Site configuration is as explained in Section 2.2, having Northerly dominated wind direction. Linear MP-cost variation is applied, ranging from 1 M€ to 2 M€.

### 3.2.2 Sensitivity study

The results of the sensitivity study are shown in Figure 3.4. The percentage of the included MP cost is plotted at a logarithmic scale on the x-axis. The 0% is fictional, because in reality this value does not exist on a logarithmic scale. The figure shows that taking MP-cost variation for 0% into account, meaning a 100% decrease, the deviation in LCoE reduction is indeed also 100%. The vertical line indicates the reference point, where 100% of the MP-costs is included.

The graph shows that the reduction in LCoE is slightly insensitive for an error in the MP cost estimation. This is confirmed by the coloured marks. A ±50% error the included MP costs decreases the reduction in LCoE with 20 - 24%, as indicated with the green mark. The yellow mark indicates that a doubling of the included MP costs results in a decrease in the LCoE reduction of 38%. A tenfold of the MP costs, results in a decrease of LCoE reduction of 126%, indicated with the purple mark.

This insensitivity can be explained by the fact that MP costs account for a small percentage of the total project costs. This justifies the insensitivity, because a percentage change in MP costs results in a relatively much smaller percentage change of the complete OWF project costs.

Though the insensitivity of the LCoE when MPs are included in the OWFLO with error in the MP costs, an exact value of the MP costs is desirable to calculate the achievable savings in total project costs and to determine the optimal layout of the OWF.

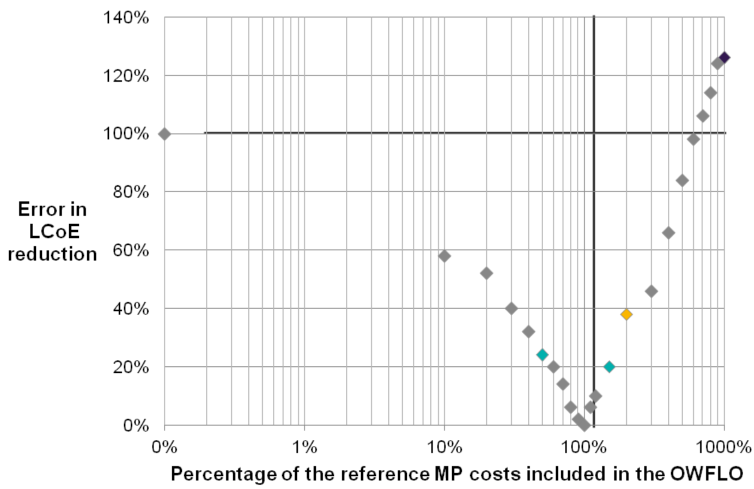



**Figure 3.4:** Results of the sensitivity study. On the x-as the percentage of the reference MP costs included in the OWFLOs, this expresses the error in MP cost estimation. The y-axis expresses the resulting deviation in LCoE reduction.

## 3.3 Insights from the feasibility study

In this chapter Task 1 of the objective is fulfilled: Investigate the feasibility of including MP cost variation in OWFLO with respect to the LCoE. While taking all the assumptions into account, the following main conclusions can be drawn from the performed OWFLOs in this feasibility study:

- Including MP-costs variation in OWFLO is beneficial to the LCoE. LCoE reductions are obtained in the range of 0.2 to 1%.
- An increase in the range of MP-cost variation significantly increased the degree of LCoE reduction.
- The magnitude of the MP-cost variation did not have significant influence on the reduction in LCoE.

The obtainable reduction between 0.2 and 1% is line with the expectations mentioned in the introduction, stating an anticipated LCoE reduction with improvements in OWFLO of several percent. Furthermore, a sensitivity study is performed to check the influence of an error in the MP cost estimation to the deviation in the LCoE reduction. The most important conclusions of the sensitivity study are as follows:

- The sensitivity of the reduction in LCoE with respect to errors in the MP costs is moderate. An error of $\pm$ 50% in the MP-costs estimation resulted in a deviation of the LCoE reduction of 20 - 24%.
- Including incorrect MP costs in OWFLO still improved the layout of the OWF resulting in reduced LCoE. Reason for this is that the relative variation in MP costs in governing.
- For obtaining the most optimal layout and precise approximation of the LCoE, the MP cost estimation must be as accurate as possible.

Based on these conclusions, the feasibility of including MP costs in OWFLO is proved and it is decided to be worth to develop a method to estimate MP cost at specific locations within an OWF include in the OWFLO process.

# Chapter 4

# The Development of a Method to Estimate Monopile Costs

This chapter complies with Task 2 of the objective: Develop a method for MP cost estimation at specific locations within an OWF. In order to achieve this, in Section 4.1 the method used to estimate the MP costs is selected. This method requires the calculation of the MP mass, which is explained in Section 4.2. Section 4.3 elaborates on the MP design, needed to determine the parameters serving as input for the MP mass calculations. The MP design is influenced by environmental design drivers. Based on these the environmental design drivers which vary within an OWF are identified in Section 4.4. This chapter ends with the insights obtained during the development of this method in Section 4.5.

## 4.1 The methods to estimate monopile costs

In this section two methods are compared, one using empirical data and another using mass estimations. At the end of this section a choice is made of the method which best suited the purpose of this study.

### 4.1.1 Empirical data

The first method to estimate MP costs is based on empirical data from actual projects. Some studies use a constant value for MP costs [42]. More often, scaling formulas are used, including turbine capacity or water depth as dependent input variable [21, 19]. Other, more extensive formulas, also include hub height, rotor diameter or WT costs [53, 61].

The advantage of this method is that it is easy to use and it gives an estimation of the MP costs based on a limited number of variables. However, this method has some significant limitations. A limitation of this method is that it does not consider the costs of the MP dependent on site specific environmental design drivers, while this is important because every OWF has different design drivers influencing the costs of the MP. Furthermore, this method excludes fluctuations in material and manufacturing costs.

### 4.1.2 Mass estimations

This method estimates the MP costs by multiplying the MP mass ($m_{MP}$) with a cost factor ($F_{costs,MP}$) in € per kg of steel. Equation 4.1 shows how the MP costs are calculated. An estimation of the MP mass is obtained by making the MP design.

The MP-cost factor used is 2.25 $\frac{€}{kg}$, consisting of material and manufacturing costs [74]. It is assumed that the latter include costs for corrosion control, which consist of coating and linings [28, 23].

$$C_{MP} = F_{costs,MP} * m_{MP} \tag{4.1}$$

The advantage of this method is that it is able to estimate the MP-costs location specific, based on environmental design drivers and WT characteristics applied to the specific OWF. Furthermore, this method is able to adapt cost factors to current material and manufacturing costs. The limitations of this method are the time it takes to perform MP designs for each specific location and the insufficiency in input data.

### 4.1.3 Selection of the method

This study aims to develop a method able to estimate MP costs at specific locations within an OWF and incorporate that in the OWFLO. Furthermore, the influence of several environmental design drivers on the MP costs and the effect they have in the OWFLO process will be investigated. The method to estimate MP costs suited for this purpose is based on making mass estimations.

## 4.2 Calculation of monopile mass

This section describes how MP mass is calculated. The MP its shell mass is estimated by multiplying the steel volume of the shell with the density of steel, expressed in Equation 4.2. This volume ($V_{MP}$) is determined by the dimensions of the MP, defined by the length ($L_{MP}$), diameter ($D_{MP}$) and wall thickness ($t_{MP}$) per section, using the formula expressed in Equation 4.3.

$$m_{MP} = \rho_{steel} * V_{MP} \tag{4.2}$$

$$V_{MP} = \sum_{n=1}^{N} L_{MP} * \left( \pi \left( \frac{D_{MP}}{2} \right)^2 - \pi \left( \frac{D_{MP} - t_{MP}}{2} \right)^2 \right) \tag{4.3}$$

A MP design is required to determine the diameter, length and wall thickness, which is explained in the next section.

## 4.3 Monopile design

In this section, the MP design process is explained and every design step is described individually. The goal of the explanation of the design process is twofold: on the one hand the MP design provides insight in how the MP mass is determined, on the other hand it provides insight in the environmental design drivers, which makes it possible to identify the location-specific MP design drivers used in the location-specific MP cost estimator of the next chapter.

To determine the dimensions of the MP a complete support structure must be designed. A support structure consists of the MP, TP and tower. The reason for this is that the MP, TP and tower are influencing each other's designs. The loads - induced by environmental design drivers - combined with the WT specifications and the initial support-structure geometry, determines the dimensions of MP, TP and tower of which the design is optimised in an iterative process. These iterations result in different designs and hence different loads, and vice versa. The simplified steps in this iterative process are as follows:

1. Define **Initial geometry**
2. Determine diameter based on **natural frequency**
3. Identification of **loads**
4. Determine length based on **foundation stability**
5. Determine wall thickness based on **strength** checks

Step 2 to 5 are iterated until an optimised support structure is designed, minimizing the mass, while meeting all design requirements. In the next sub-section a brief description of the five steps is given, based on a combination of comprehensive descriptions from several sources [11, 69, 40, 68]. A visual expression of the design steps can be found in Figure 4.1.

### 4.3.1 Step 1: Initial geometry

The first step towards a complete support-structure design is the indication of the initial geometry, which consist of design elevations, diameter, pile length and wall thickness. The initial geometry has its characteristic mass (m) and bending stiffness (EI), as indicated in the figure.

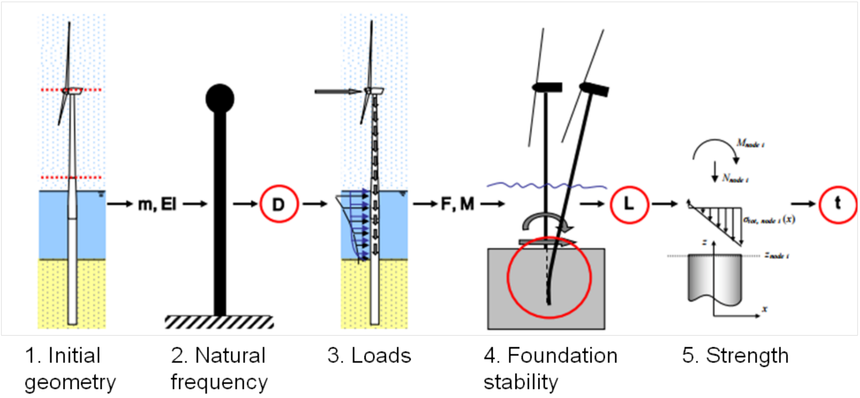



**Figure 4.1:** Visualisation of the design steps. Indicated is at which steps the adjustments of the diameter, length and wall thickness take place [68].

**Design elevations**
The interface level, which is the elevation of the bottom tower flange above sea level, is determined based on water levels and waves. Subsequently, the hub height, being the elevation of the hub above sea level, is set. Both are indicated with the red dotted line.

**Diameter, pile length and wall thickness**
Together with the design elevations, water depth, the predefined diameter of the MP and the penetration depth, the preliminary pile length and wall thickness are determined, both using rules of thumb.

### 4.3.2 Step 2: Natural frequency

Subsequently, using the initial geometry, a natural frequency analysis must be performed. The natural frequency should be within the soft-stiff region, which implies that it is not allowed to coincide with the wave excitation frequency, the rotational frequency of the rotor and the blade passing frequency.

**Adjust diameter**
The natural frequency can be tuned, until it is within the soft-stiff region, by adjusting the diameter of the initial geometry.

### 4.3.3 Step 3: Loads

To determine the length and the wall thickness of the structure, respectively a foundation stability check and strength checks must be performed. This can be done by applying load cases on the structure. Environmental loads consist of aerodynamic and hydrodynamic loads, which are later called the environmental design drivers. The loads are applying force (F) and overturning moment (M) to the support structure.

A load case combines an external condition with an operational situation, both with reasonable probability of occurrence. The external conditions are the result of environmental design drivers, which include, amongst others, 5 or 50 years maximum water levels, wind, waves and currents. Dependent on the load case, it tests the ultimate limit state (ULS) or fatigue limit state (FLS). In an ULS analysis the loading on the structure, resulting in highest loads, is tested. In a FLS analysis the total damage incurred over the lifetime of the structure is assessed.

### 4.3.4 Step 4: Foundation stability

In the assessment of the foundation stability the lateral and axial stability is tested. Because axial stability is not governing for MPs this is not further explained. The lateral bearing capacity of the soil must withstand the bending moment of the structure, which determines the required penetration depth of the MP. In the design process the deflection at the pile toe and mud-line, and the rotation at mud-line are not allowed to exceed certain constraints. The soil structure is the geological design driver influencing the bearing capacity of the soil.

**Adjust pile length**
To stay within the maximum deflection and rotations the initial length of the pile is adjusted. This new length changes the natural frequency which must be checked again, to avoid coinciding with the frequency of the waves and the blade passing excitations.

### 4.3.5 Step 5: Strength

With the length and the diameter established in respectively step 2 and 4, the final wall thickness can be determined, using stress and fatigue checks. The stress checks consist of yield and buckling checks. These are performed in order to determine whether the structure is able to withstand the loads of the ULS load cases. If the structure is able to resist the stress checks, the final step is to perform the fatigue check based on the FLS loading.

**Adjust wall thickness**
In order to meet the strength checks, the wall thickness of the structure can be adjusted.

## 4.4 Identification of location-specific environmental design drivers

As explained in the previous section the design of a support structure is induced by environmental design drivers, and with this the environmental design drivers determine the MP mass. Figure 4.2 provides a visualisation of all environmental design drivers included in this study, which are effecting the diameter, length and wall thickness of the MP.

The aerodynamic and hydrodynamic design drivers and the geological design driver, which only consists of the soil structure, are described separately in the next sub-sections. Of each environmental design driver three conditions are discussed. First, the aspect of the MP design the design driver has effect to. Secondly, the magnitude of the effect on the MP design. Lastly, whether the design driver is assumed location specific within an OWF. This section ends with a selection of which design drivers are considered for use in the location-specific MP cost estimator.

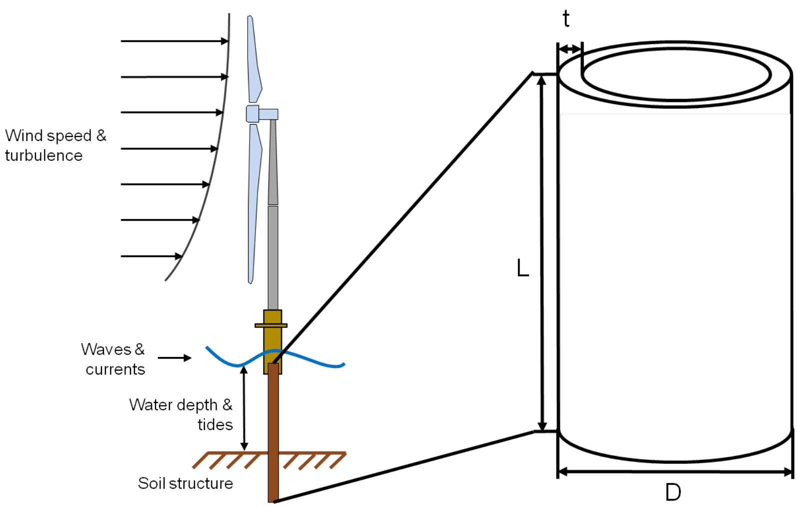



**Figure 4.2:** A visualisation of the environmental design drivers determining the geometry of the MP and therewith its mass. The drawing of the WT attached to a MP foundation is inspired by [73].

### 4.4.1 Aerodynamic design drivers

The aerodynamic design drivers consist of wind speed and turbulence.

**Wind speed**

The wind speed is inducing aerodynamic loads on the WT and tower. Wind-turbine loads are operational loads, predominantly resulting in bending moments due to the thrust force at the rotor [62]. The loads on the tower are induced by drag force, which must be calculated for every segment of the tower, due to the effect of wind shear [70]. The magnitude of the effect on MP design aerodynamic loads has compared to hydrodynamic loads is moderate.

On global scale, wind speed is driven by the sun its energy, inducing circulation. This global circulation pattern is disturbed by land masses and oceans, resulting in continental scale variation. Hills and mountains trigger increased wind speeds in local regions. However, far offshore where the earth surface is uniform and the distance to the coast has no effect, the mean wind speeds are assumed uniform. Besides, the mean wind speed on local scale mainly varies within time [8]. Those two statements together result in the assumption of constant wind speed within an OWF, which means that wind speed does not influence MP-cost variations within an OWF.

One can advocate that wakes, resulting from adjacent WT, induce local wind speed variations. Furthermore, the wakes can influence each other as a result of the blockage effect, which can cause local wind speed variations. With the blockage effect the presence of parallel adjacent wakes are influencing each other by increasing the velocity of the wake-flow due to funnelling in an area with a decreased cross-section [27]. Both statements might be true, however, these local wind speed variations are the result of the relative position of the WTs within an OWF, instead of the wind climate, and are for this reason not an environmental design driver. These wakes are included in the calculation of the AEP, but are not considered as design driver determining the MP-cost variation within an OWF.

**Turbulence**

While mean wind speed is assumed to be constant, in reality local disturbances in the airflow called eddies exist. These eddies cause instantaneous wind speed fluctuations, which is known as turbulence. Turbulence is measured with TI in percentage, which is defined as a function of the standard deviation and the mean wind speed. This turbulence causes aerodynamic loading, triggering increased fatigue loading on the structure [8]. The effect TI on MP design is moderate, because MP design is not fatigue driven. Besides, hydrodynamic loads are governing over aerodynamic loads in the MP design.

Two types of turbulence exist: general turbulence and wake induced turbulence. General turbulence is the average turbulence occurring within a certain wind climate. Offshore, this turbulence is much lower than onshore [70]. Wake induced turbulence is turbulence as a result of the wakes of adjacent WTs. Both are included in the calculation of the AEP in the OWFLO performed in Openwind. However, they are not considered as location-specific environmental design parameter determining the MP-cost variation within an OWF.

### 4.4.2 Hydrodynamic design drivers

In the category of hydrodynamic design drivers are considered: the tides, waves, currents and water depth.

**Tides**
Tides result in variation of water levels, leading to lowest astronomical tide and highest astronomical tide, which are co-determining the interface level of the initial geometry of the support structure [11]. This effect to the MP design is moderate, since the interface level is mainly influencing the length of the TP.

At a large scale, tides are influenced by the relative positions of the sun, moon and earth. At a smaller scale, the magnitude of the tides can be influenced by the shape of the shoreline and bays. All the parameters influencing the tides do not vary at local scale for far OWFs, for this reason tides are considered constant within an OWF[8].

**Waves**
A wave is characterised by a certain wave length, period, amplitude and direction, induced by the wind climate [36]. Other parameters influencing wave behaviour are water depth, which shows correlation with maximum wave height, and sea bed slope [10]. Waves are co-determining the design elevations of the initial geometry and are inducing hydrodynamic loads on the structure. In particular the hydrodynamic loads induced by waves have a high magnitude of the effect on MP design.

For deep water areas waves are predominantly the result of the wind climate. At shallow waters, water depth and seabed shape becomes more important in determining the shape of the waves and also triggers breaking waves. Breaking waves contains the highest amount of energy and hence are important to consider in MP design [10]. Waves are considered constant within an OWF, because this study is not focussing on shallow water depths and the wind climate is already assumed constant in this study.

**Currents**
Currents are contributing to the hydrodynamic loads on the MP and scour of the soil. The effect to the hydrodynamic loads is small, and has for this reason low effect on MP design [11, 35]. The scour effect can result in a hole of 1.5 times the diameter of the MP especially in sandy soils. This hole can reduce the supporting function of the seabed. The effects of scour can be mitigated with scour protection [75]. Because this study only focusses on the costs of the MP shell, the costs for scour protection are out of the scope.

The type of current that applies to hydrodynamic loads and scour are currents induced by surface circulation. Surface currents are predominantly generated by wind and tides, and are for this reason also considered constant within an OWF.

**Water depth**
Water depth is co-determining the design elevation of the initial geometry. Furthermore, the water depth is highly affecting the magnitude of the effect of waves and currents on MP design, by increasing the hydrodynamic loads and overturning moment in twofold. On the one hand the loads induced by waves and currents significantly increase with greater water depths, because the surface area of the MP on which the loads are applied increase. On the other, the bending moment of the complete structure increases at greater water depths, which - in principle - result in heavier and more expensive MPs, as a consequence of the required increase in diameter, wall thickness and penetration depth [11].

Within an OWF water depth varies several meters (Hohe See: 39 - 40 m [2]) up to more than 20 meters (Borssele 16 - 38 m [52]). However, the latter situation is more common. For this reason, water depth is assumed location specific within an OWF.

### 4.4.3 Geological design driver: soil structure

The magnitude of the effect of soil structure on the MP design is high. The stiffness of the soil is determining the required penetration depth and therewith the length of the MP. This length is influencing the natural frequency, which can coincide with the wave spectrum or the 1P region, indirectly inducing higher hydrodynamic loads [9, 3]. Soil structure strongly varies within an OWF, as can be seen in Figure 4.3 and is therefore considered location specific within an OWF[57, 32].

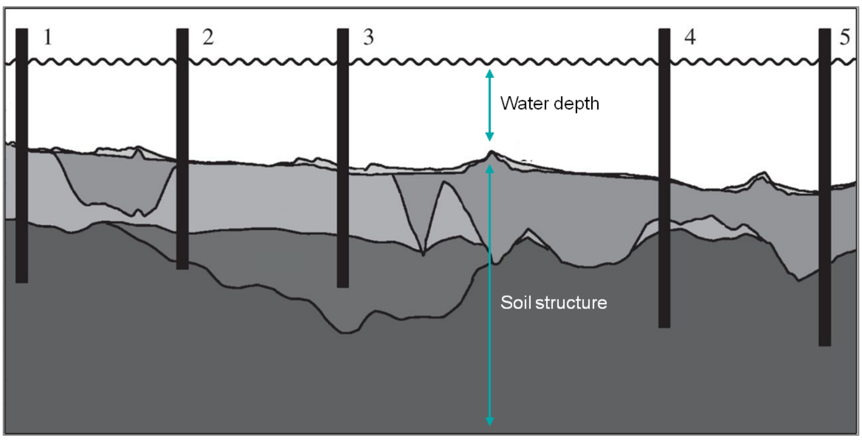



**Figure 4.3:** Cross section of soil structure and water-depth variation at Westermost Rough OWF. Indicated are MP positions (1 - 5), of which the mass reportedly varies with a maximum of 40%. The different grey colours are indicating the variation in soil structure [32].

### 4.4.4 Selection of location-specific environmental design drivers

In Table 4.1 an overview can be found of the environmental design drivers discussed in this section. Displayed are the magnitude of the effect on the MP design and whether the design driver is considered location specific within the dimensions of an OWF. As explained the MP design directly relates to the MP mass and hence the cost.

The environmental design drivers which are both highly affecting the MP design and are at the same time assumed location specific within an OWF are considered most important to include in the location-specific MP cost estimator, required to include MP costs in OWFLO. Based on the overview of Table 4.1 it transpires that water depth and soil-structure variation both meet these criteria.

The presumption that water depth and soil structure significantly vary within the dimensions of an OWF and highly affecting the MP mass is confirmed by a study to the Westermost Rough OWF. The combination of variation in both water depth and soil structure results in a MP-mass difference of 40%. This is visualised in Figure 4.3.

As can be seen in the Figure the soil structure normally consists of several layers. However, for the sense of simplicity, soil structure is assumed uniform in this study, and for this reason hereafter named soil type. This implies that the soil is described with a certain parameter expressing whether the soil type is sand or clay, equalising the dominating soil type considered at a particular location. In Section 5.4 a further elaboration regarding the classification of the uniform soil type can be found.

**Table 4.1:** Overview of the environmental design drivers. Displayed are their effect on the MP design resulting in its mass and hence determining the costs, and whether the design driver is assumed location specific within the dimensions of an OWF. Water depth and soil type are selected as input parameters for the location-specific MP cost estimator.

| Environmental design driver | Magnitude of the effect on MP design | Assumed location specific within an OWF |
|---|---|---|
| Wind | Moderate | No |
| Turbulence | Moderate | No |
| Tides | Moderate | No |
| Waves | High | No |
| Currents | Low | No |
| Water depth | High | Yes |
| Soil type | High | Yes |

## 4.5 Insights obtained during the development of the method

In this chapter Task 2 - Develop a method for MP cost estimation at specific locations within an OWF - is successfully fulfilled. Two conclusions can be drawn with respect to this task which are summarized as follows:

- The method to estimate MP costs considered appropriate for this study is based on MP mass estimations multiplied with cost factors in € per kg of steel.
- Water depth and soil-type variation are location specific within an OWF and at the same time key design drivers determining MP costs.

Figure 4.4 shows a process diagram visualizing how the method described in this chapter is included in a location-specific MP cost estimator. The fixed site data contains the environmental design drivers which are assumed constant within an OWF. The location-specific site data includes the water depth and soil type, which are identified as varying within the dimensions of an OWF. Turbine data consists of WT characteristics, such as turbine mass and rotor speed.

The location-specific MP cost estimator consists of two steps: a MP mass estimator (1) and a MP mass to location-specific MP-costs converter (2). The output of the location-specific MP cost estimator is used to include MP costs in OWFLO. In order to do this, a further elaboration of both steps can be found in the next chapter.

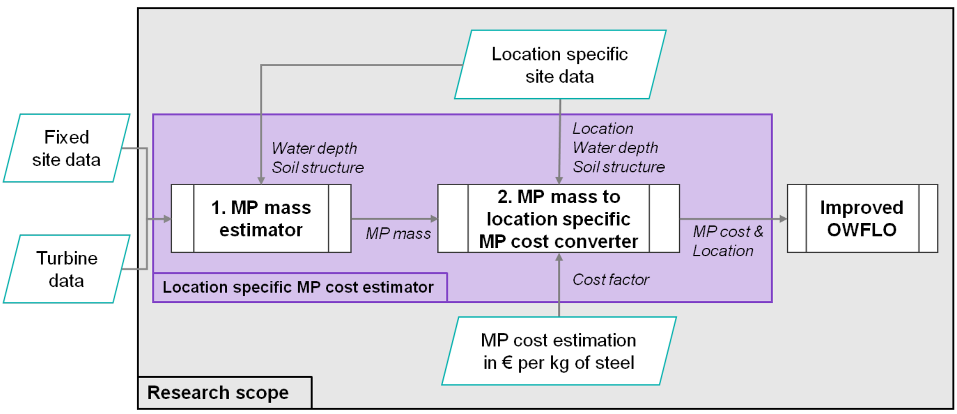



**Figure 4.4:** Process-flow diagram of the method incorporated in a model able to estimate MP costs at specific locations within an OWF.

# Chapter 5

# The Location-Specific Monopile Cost Estimator

This chapter complies with Task 3 of the objective: Implement the method in a location-specific MP cost estimator, which can be used in the OWFLO process. As can be seen in visualisation of the process in Figure 4.4 this location-specific MP cost estimator consists of two steps.

The first part of this chapter describes Step 1: the MP mass estimator. This part compares three support-structure design tools able to estimate MP mass and select the tool which is most appropriate for the purpose of this study. Section 5.1 explains the criteria for the design tool. Section 5.2 provides a description of the compared tools and in Section 5.3 the selection takes place.

The second part of this chapter works towards Step 2: The MP mass to location-specific MP-cost converter. In Section 5.4 the MP mass estimations are performed using the selected tool and are incorporated in the MP mass to location-specific MP-cost converter. This step completes the location-specific MP cost estimator. In Section 5.5 this chapter ends with some main insights.

## 5.1 Identification and description of the criteria for the MP mass estimator

The compared tools are all able to estimate MP mass based on the design of a complete support structure. The criteria to which the tool must comply are based on the findings of the sensitivity study in the feasibility study of Chapter 3.1.2, the identification of location-specific environmental design drivers of Section 4.4, and ease of - future - use. The criteria are displayed in Figure 5.1. A detailed explanation can be found in the following sub-sections.

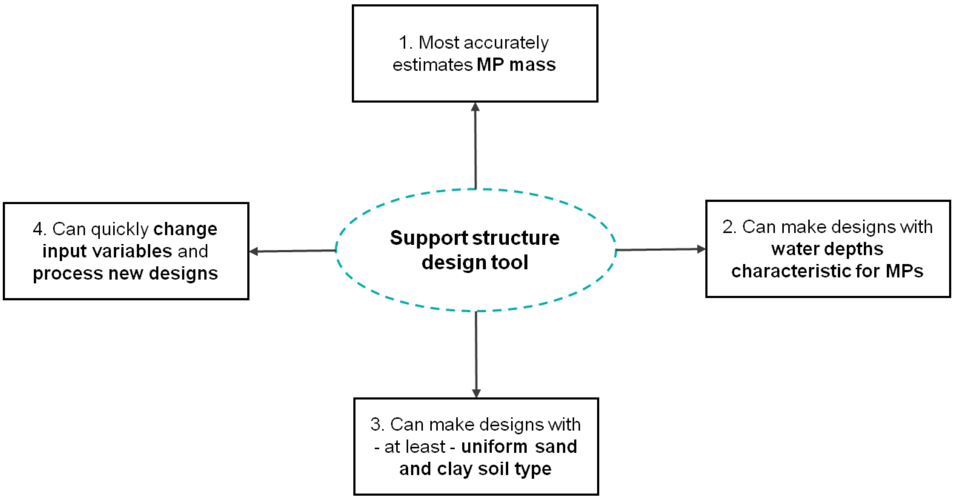



**Figure 5.1:** The identified criteria to which the support-structure design tool must comply. The support-structure design tool has the function of a MP mass estimator in this study.

### 5.1.1 Most accurately estimates MP mass

In order to ensure that the benefits of the improved OWFLO are not annulled by errors in the MP mass estimation, the most important criterion is that the MP mass is accurately estimated by the tool. The MP mass is directly related to the MP costs, which means that an accurate estimation of the MP mass is important in order to let the OWFLOs result in the most optimal layout and precise approximation of the LCoE. The tool which estimates the MP mass most accurately, scores the best at this criterion.

To measure this accuracy, the MP mass estimation resulting from the designs made by the tools is compared with actual MP mass obtained from available designs made at locations within several OWFs. The difference between those determines the accuracy in percentage. Only the OWFs of which an approximation of the soil type is available are used, these are the design locations within OWFs F01, F03, F04, F05, F15 and F16 of Table B.1 of the Appendix.

A difference in MP mass estimated by the tools and the mass from the actual designs is expected. One reason for this is difference in the assumptions for the design process and the assumption of a uniform soil type used in the designs made with the tools, while the actual designs are based on comprehensive non-uniform soil data. Furthermore, the classification from non-uniform to uniform soil type is performed by a geo-technical expert based on experience rather than physical fundamentals.

### 5.1.2 Can make designs with water-depths characteristic for MPs

Water depth is a key variable contributing to MP mass, as described in Section 4.4.2. Currently, MPs are suited for water depths from 0 to 50 m [1, 54]. In order to estimate MP mass for the whole spectrum of MPs used at this moment the tool should be able to create design with water depths ranging from 0 - 50 m. If this criterion is not met, the tool is considered as inappropriate for the use in the location-specific MP cost estimator.

### 5.1.3 Can make designs with - at least - uniform sand and clay soil type

From Section 4.4.3 it transpired that another variable, influencing the MP mass and which is location-specific within an OWF, is the soil type. To obtain insight in the relation between uniform soil type and MP mass, the tool should be able to establish designs with variations of sand and clay soil type. It is sufficient if the tool is able to process designs based on uniform sand and clay type soil.

Both sand and clay type soil are defined by one parameter describing the soil stability in terms of bearing and lateral capacity. The parameter describing soil type sand is the internal angle of friction ($\Phi$) in degrees ($^{\circ}$). The internal angle of friction is the angle on the graph of the shear stress and normal effective stresses at which shear failure occurs. Clay type soil is described by the undrained shear strength ($C_u$) in kilopascal (kPa). The shear strength is the internal resistance per unit area that the soil mass can offer to resist replacement of the MP in the soil.

This criterion is also classified as being a requisite to assign a tool as appropriate for the use in the location-specific MP cost estimator. Furthermore, the words ‘at least’ in this criterion suggests that it is an advantage for later use of the tool if it is able to produce designs based on non-uniform soil data. This will become useful if comprehensive soil data becomes available in projects before a decision is made regarding the final layout. An interpolated MP-cost model can then be constructed of the complete OWF, without the need for uniform soil type assumptions.

### 5.1.4 Can quickly change input variables and process new designs

In this study designs are made based on variations in water depth and uniform soil type. In reality, also designs must be made in varying situations of wind and wave climate and different WT types. The input variables for the tools determining the way these variations are applied. Therefore, it is an advantage if the tool can quickly change input variables and process new designs. However, this criterion is not decisive, it will increase the usability and time efficiency of the tool.

## 5.2 Description of the supports-structure design tools

In the next three subsections a short description of each tool is provided. A more comprehensive explanation of the tool that is eventually selected, is given in Section 5.4.

### 5.2.1 Tool 1

Tool 1 is developed by ir. W.E. de Vries, as part of 'Project UpWind' completed in 2011. It is a parametric tool developed in Excel able to quickly create a support-structure design by changing a limited number of WT and site design drivers. In order to assess the mass it makes a distinction between MP, TP and tower mass.

The design drivers in Tool 1, expressing the environment, are water depth, maximum wave height, and uniform soil type. Wind-turbine parameters included are rotor diameter, rotor speed, and WT mass. A detailed description of Tool 1 can be found in Chapter 6 of 'Final report WP 4.2' [11].

### 5.2.2 Tool 2

Tool 2 is developed by Dr.ir. M.B. Zaaijer, as part of his PhD thesis which he finished in 2013. It is a parametric tool developed in Python and is initially designed to assess the influence of various parameters to the LCoE within the OWFLO process. For this current study the part of Tool 2 is used which designs the support-structure and gives an estimation of, amongst other things, the MP mass.

Additional to the design drivers Tool 2 used, this parametric tool requires more specific data about wind climate, tides and storm surge, and thrust and power curves of the WTs. A detailed description of Tool 2 can be found in Section 4.5.2 of the dissertation 'Great Expectations for Offshore Wind Turbines' [74].

### 5.2.3 Tool 3

Tool 3 is the in-house design tool used at Siemens Wind Power. The support-structure designs made by Tool 3 are used for the production for most of the projects within Siemens Wind Power. Tool 3 requires detailed input data compiled in input files. The input files are comprehensively describing the WT, environmental and geophysical specifications. However, using the full extension of Tool 3 is time consuming. Therefore, a few short cuts are taken in the design process. These short cuts consist of the assumptions of using constant wind and wave loading.

The manual processes which must be taken to perform the designs with Tool 3 were subsequently: processing of wind loads (1 hour), processing of met-ocean data (2 hour); interpretation of soil data (2 hour); set-up of initial geometry (1 hour); running of the design optimisation tool (30 minutes). Except the step of the interpretation of the soil data are all steps performed by Siemens Wind Power.

## 5.3 Choice of the tool to estimate MP mass

The next subsections work towards the choice of the tool. First, the 'fit to the criteria' is discussed for every criterion individually. Subsequently, the selection of the tool is performed, containing an overview of the criteria and the score of each tool.

### 5.3.1 Fit to the criteria

In this sub-section the fit to each criterion is discussed for all three tools.

**Most accurately estimates MP mass (1)**
Support-structure designs are created with all three tools to estimate MP mass for variations in the water depth and soil type, keeping the other environmental design drivers constant. The resulting MP mass is compared with the MP mass of the available MP designs at the different locations within existing OWFs.

Table 5.1 shows the actual design location, the water depth, soil type and its describing parameter, the MP mass of the actual design, and the MP mass of the designs created by the tool and the difference in MP mass with the actual designs. Tool 2 is only able to process sand based soil, for this reason the comparison for this tool is incomplete.

Tool 1 showed an average estimation error of 22%. The mass of the MPs was mainly underestimated. Tool 2 mainly gave an overestimation, with an average error of 21%. Tool 3 is most accurate, with an average error of 16%, and is more frequently overestimating than underestimating the MP mass.

**Table 5.1:** Results of MP mass estimation accuracy of the three tools. MP mass is normalized for confidentiality reasons.

| **Existing design** | | | | | **Tool 1** | | **Tool 2** | | **Tool 3** | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Location* | $h_w$ *[m]* | Soil type | $\Phi$ *or* $C_u$ | $m_{MP}$ *[-]* | $m_{MP}$ *[-]* | *Error* | $m_{MP}$ *[-]* | *Error* | $m_{MP}$ *[-]* | *Error* |
| F01DL1 | 30 | Clay | 150 kPa | 0.20 | 0.19 | 1% | | | 0.36 | 31% |
| F01DL2 | 21 | Clay | 100 kPa | 0.06 | 0.08 | 4% | | | 0.18 | 29% |
| F03DL1 | 32 | Sand | 42° | 0.15 | 0.11 | 9% | 0.37 | 44% | 0.31 | 32% |
| F03DL2 | 36 | Sand | 42° | 0.29 | 0.16 | 21% | 0.43 | 21% | 0.43 | 21% |
| F04DL1 | 33 | Sand | 39° | 0.24 | 0.13 | 18% | 0.41 | 29% | 0.36 | 22% |
| F04DL2 | 34 | Clay | 100 kPa | 0.31 | 0.25 | 9% | | | 0.49 | 27% |
| F05DL1 | 45 | Clay | 50 kPa | 1.00 | 0.45 | 41% | | | 0.98 | 1% |
| F05DL2 | 45 | Clay | 50 kPa | 0.77 | 0.45 | 28% | | | 0.98 | 19% |
| F05DL3 | 45 | Clay | 50 kPa | 0.90 | 0.45 | 36% | | | 0.98 | 7% |
| F15DL1 | 40 | Sand | 42° | 0.49 | 0.21 | 34% | 0.48 | 1% | 0.41 | 9% |
| F15DL2 | 40 | Sand | 42° | 0.48 | 0.21 | 33% | 0.48 | 0% | 0.41 | 8% |
| F16DL1 | 26 | Sand | 39° | 0.19 | 0.05 | 26% | 0.32 | 25% | 0.19 | 0% |
| F16DL2 | 23 | Sand | 39° | 0.14 | 0.00 | 28% | 0.28 | 30% | 0.13 | 1% |
| | | | | **Average error** | | **22%** | | **21%** | | **16%** |

**Can make designs with water depths characteristic for MPs (2)**
Tool 1 can generate designs for water depths ranging from 1 to 50 meters. The same holds for Tool 3, which proved itself in practise by creating appropriate designs for all actual projects it is used for.

Tool 2 is not trusted to make designs for water depths below 7 meters. Furthermore, Tool 2 generates designs with inconsequently high MP mass at water depths below 10 m, which is a known shortcoming of Tool 2. For the interested reader: This shortcoming is visualised in Figure C.1 of the Appendix showing the MP mass of support- structure designs created by Tool 1 & 2, based on sandy soil with a friction angle of 37.5°.

**Can make designs with - at least - uniform sand and clay soil type (3)**
With Tool 2 it is possible to make designs for sandy soil only. With Tool 1 and 3 this is possible with both sand and clay. Additionally, Tool 3 provides the opportunity to make designs with non-uniform soil. This can be a benefit for later use of the tool.

**Can quickly change input variables and process new designs (4)**
It transpired that all tools are - beside changes in water depth and uniform soil type - able to make design for varying situations of wind and wave climate and different WT types. The input variables determining the way these variations are made. The ease of changing these parameters is key to the usability and time efficiency of the tool.

Because Tool 1 and 2 are parametric models, it is possible to quickly change input variables and process new designs. With Tool 3 this takes more time, as discussed in the manual process of Section 5.2.3.

### 5.3.2 Tool selection

An overview of the three tools and their outcomes considering the criteria can be found in Table 5.2. Based on the information in the table Tool 3 is considered most appropriate for the use in this study and is selected for making the support-structure designs and estimate the MP mass to be used as input in the location-specific MP cost estimator. Tool 3 most accurately estimated the MP mass and despite this tool did not met criterion 4, it is able to make designs with non-uniform soil as well. As discussed, the latter might be an additional advantage for future use of the tool.

Though Tool 1 and Tool 2 are useful tools for other purposes, they are considered inappropriate for use in this study. Tool 1 met criteria 2, 3 and 4. However, it did not estimate the MP mass most accurately. The latter was also the case for Tool 2, which only met criterion 4. With Tool 2 it was also not possible to perform realistic designs in shallow waters and only sandy soil type can serve as soil input.

**Table 5.2:** Overview of the tools and their outcome considering the criteria.

| Criteria | Assessed parameter | Tool 1 | Tool 2 | Tool 3 |
|---|---|---|---|---|
| 1. Most accurately estimates MP mass | Average error with respect to actual designs | 22% | 21% | 16% |
| 2. Can make designs with water depths characteristic for MPs | Water depth | 1 - 50 m | 10 - 50 m | 1 - 50 m |
| 3. Can make designs with - at least - uniform sand and clay soil type | Sand, Clay or Both (Non)-Uniform | Both Uniform | Sand Uniform | Both (Non)-Uniform |
| 4. Can quickly process changes in input variables | Yes or No | Yes | Yes | No |

## 5.4 The MP mass to location-specific MP-cost converter

In this section, it is explained how the selected tool is used in the MP mass to location-specific MP-cost converter in order to comply with Step 2 of the location-specific MP costs estimator from process diagram of Figure 4.4. The principles of Step 2 are described first, followed by the MP mass estimations required for the use of the estimator.

### 5.4.1 The principles of the converter

The location-specific MP cost estimator is designed to convert the water depth and uniform soil type at particular coordinates within an OWF to a description of the OWF containing the MP costs linked to the coordinates. This description can be used as a cost layer in the OWFLOs, as explained in Section 2.4.1.

For the estimation of MP costs at a certain water depth and uniform soil type the MP mass estimations are made based on support-structure designs with Tool 3. The mass is then multiplied with the cost factor, which is explained in Section 4.1.2.

### 5.4.2 MP mass estimation based on support-structure designs made with Tool 3

In this sub-section, the design conditions and the resulting MP mass are described. The design process and the underlying assumptions are explained in Appendix D. Because a constant cost factor in euros per kg of steel is used to calculate the MP cost, the behaviour of the MP costs is equal to the MP mass. The MP-costs values of this graph are used in the location-specific MP cost estimator. This cost estimator is used in the case studies to estimate MP costs for variations in water depth and soil type.

**Design conditions**
The support-structure designs are created and MP mass is estimated for 18 combinations of water depth and soil type variation. These 18 designs consist of the three types of uniform sand and clay classified soil type at water depths of 20, 30 and 40 m. The classification of the variation in soil type is expressed in Table 5.3.

**Table 5.3:** Description of the variations in uniform soil types. Indicated are the friction angle (sand) and the undrained shear strength (clay), the assumption regarding the density (sand) and stiffness (clay) of the classification and the abbreviation.

| Soil type | $\Phi$ or $C_u$ | Assumption | Abbreviation |
|---|---|---|---|
| Sand | 35° | medium dense to dense | S35 |
| | 37.5° | dense | S37.5 |
| | 40° | dense to very dense | S40 |
| Clay | 50 kPa | soft to medium stiff | C50 |
| | 100 kPa | medium to stiff | C100 |
| | 200 kPa | stiff to very stiff | C200 |

**Results**
In Figure 5.2 the result of the MP costs against the water depth for the different soil types is displayed. The plotted line is based on a spline interpolation trough the data points based on the performed support-structure designs. Two observations can be done from the MP-costs behaviour shown in the graph. First, different behaviour in MP costs between the types of clay and sandy soil occur. Next to this, dissimilar behaviour of clay and sandy soil at increasing water depth is shown. The latter implies that sand shows a higher sensitivity at greater water depths, while for clay this occurs at shallow depth. A combination of the variation in MP costs for the different soil types and water depths, leads to the fact that at greater water depths some types of clay appears to result in cheaper MPs than sandy soils do.

One reason for the larger MP-costs deviation between types of clay soil than for types of sandy soil is that the steps taken in the classification are relatively larger for the undrained shear strength than for the friction angle. Another reason might be that clay is more sensitive for variations in the undrained shear strength than sand is for the friction angle.

An explanation for the different behaviour for MP costs between sand and clay soil at increasing water depth is expected to be related to the expressions of the p-y curves. These p-y curves express the lateral stiffness of the soil, which determines the required penetration depth and hence the mass and costs of the MP. These curves are different for clay and sandy soil. However, further explanation of this phenomenon is beyond the scope of this study, but can be found in Sections 5.9.10 to 5.9.12 of the book ‘Offshore geotechnical engineering’ [60].

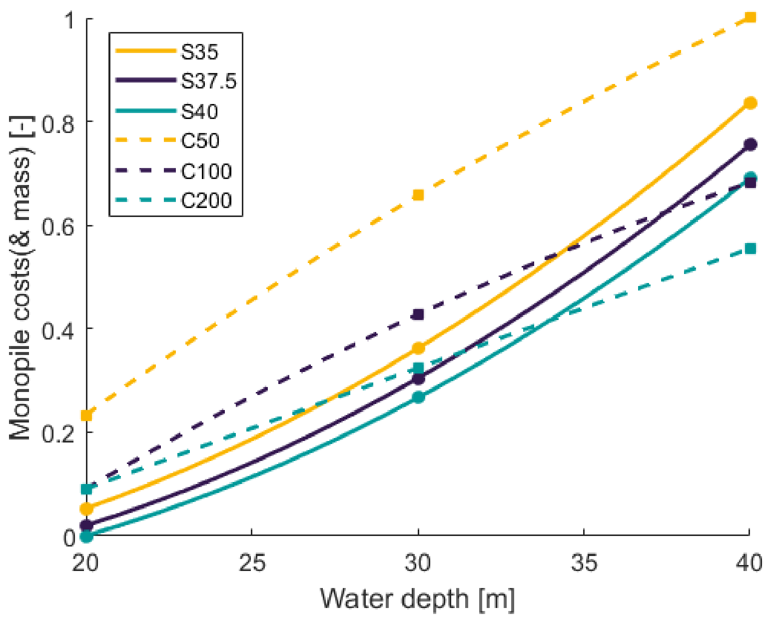



**Figure 5.2:** MP costs (& mass) against the water depth for variations in uniform soil types. The estimations are normalized for confidentiality reasons between 0 and 1, with 0 not reflecting an absolute zero in real values. The indicators display the points for which designs are created. The plotted line is based on spline interpolation.

## 5.5 Main insights obtained from this chapter

In this chapter Task 3 of the objective is brought to completion: Implement the method in a location-specific MP cost estimator, which can be used in the OWFLO process. The following conclusions can be drawn with respect to the criteria for the support-structure design tool and the selection of the tool which is used in remainder of this study.

- The criteria for support-structure design tool appropriate for use in OWFLO which includes MP costs, are the ability to accurately give MP mass estimations based on variations in water depth and different types of uniform sand and clay soil type.
- Tool 3 is considered most appropriate with respect to the criteria and is used in the remainder of this study.

In order to use this tool in the location-specific MP cost estimator, MP mass estimations are made in this chapter for different water depths and variations in uniform soil types. Because a constant costs factor is used, the MP costs are linear related to the MP mass estimations. The results of these MP costs estimations, displayed in Figure 5.2, provided some interesting additional insights:

- The MP costs obtained from designs with variations in uniform sand and clay soil type shows different behaviour for sand soil type compared to clay soil type, at increasing water depths. The MP costs at increasing water depths for uniform sand soil type shows a rising slope, while for uniform clay type soil this slope follows a decreasing rate.
- Variation in uniform clay soil type shows a wider spread in MP costs than variations in uniform sandy soil type, especially at greater water depths.
- At greater water depths a stiff type of uniform clay soil type can results in MPs having a lower cost than uniform sand soil type.

# Chapter 6

# In-depth Investigation of Including Monopile Cost in OWFLO

In this chapter, an in-depth investigation of including MP costs in OWFLO is performed in order to comply with Task 4 of the objective: Identify parameters specific to an OWF which are important to consider when including MP costs in OWFLO. This is conducted by means of case studies. The first two case studies are devoted to geological features seen at OWFs. The last case study applies to an representative OWF.

In Section 6.1 the cases are identified, followed by a description of the selected cases in Section 6.2. Section 6.3 provides the results of the case studies on which the obtained insights of Section 6.4 are based.

## 6.1 Identification of cases

This case study consists of three cases. The first two cases are used to identify the site-specific parameters which are important to consider when including MP costs in OWFLO. These two cases are based on geological features occurring within OWFs. In this section four geological features are described of which the two most suitable features are selected to form the basis of the case studies. The third case is used to show the effect of including MP costs within a representative OWF. This case is further described in the case descriptions.

### 6.1.1 Criteria for the selection of the case studies

The aim of case studies 1 and 2 is to identify site specific environmental parameters which are important to consider when including MP cost in OWFLO. Included in the site specific environmental parameters are water depth and soil type, which were initially used as location-specific design drivers. Therefore, it is important that cases are selected which one of these parameters can be studied on individually. Furthermore, it is important to select cases with the water depth and soil conditions being constant over the operational lifetime of an OWF project, otherwise including MP costs in OWFLO makes no sense.

### 6.1.2 Description of geological features within OWF projects

Geological features which are encountered during OWF projects are, amongst others dredging holes, glacial channels, sand dunes and sand waves. Below a short description of these geological features is given.

**Dredging holes**
Dredging holes are characterised by soft clay and a decrease of water depth of around 5 m, stretching at a diameter between 250 and 500 m. Examples of dredging holes can be found at the proposed Wind Park Fryslan in the Dutch IJsselmeer [51].

**Glacial channels**
Large areas of the North Sea contain glacial channels, formed during the Quaternary period triggered by fluvial processes. These channels vary from 0.5 to 3 km width, with depth ranging from 50 to 400 m deep. During centuries, they are filled with soft sediments as clay. Figure 6.1 shows a cross section of a glacial channel in the North Sea [39]. An example of an OWF with glacial channels is the Offshore Windpark Innogy Nordsee 1 in Germany [51].

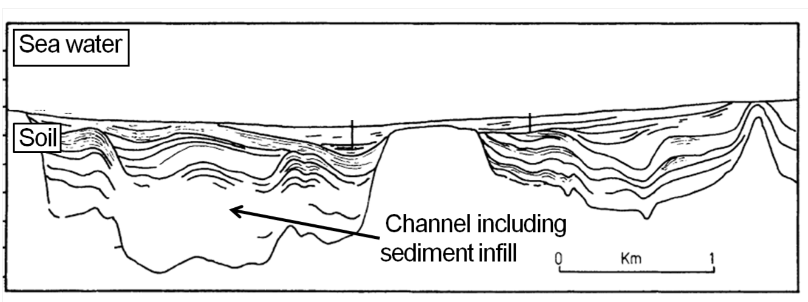



**Figure 6.1:** A cross section of a glacial channel in the North Sea [39].

**Sand dunes**

Sand dunes mainly occur at sand banks. They reach between 4 and 11 m measured from peak to trough, having a peak to peak distance (wave length) of around 2 - 4 km [38]. Furthermore, they show static behaviour, which imply that they do not move in time [51]. Examples of sand dunes are found along the coast of Belgium and the Netherlands. The sand dunes in Belgium are concentrated in the regions of Flemish Banks and Hinder Banks. At the Borssele Wind Farm Zone near the Dutch coast sand dunes exist which reach a height up to 15 m with a wave length of around 4 km. A visualisation of this sand dune can be found on the left side in Figure 6.2 [52].

**Sand waves**

Sand waves are in geometry similar to sand dunes, but smaller in size. They are characterised by a peak to trough distance of several meters and a wave length on the order of several ten to hundred meters. In contrast to sand dunes, they show dynamic behaviour, which means they move in time. Water depths in an area with sand waves can change several meters per year at a particular location [51, 50, 49]. Examples of sand waves are found at Hollandse Kust Wind Farm Zone along the Dutch coast, visualised on the right side in Figure 6.2 [58].

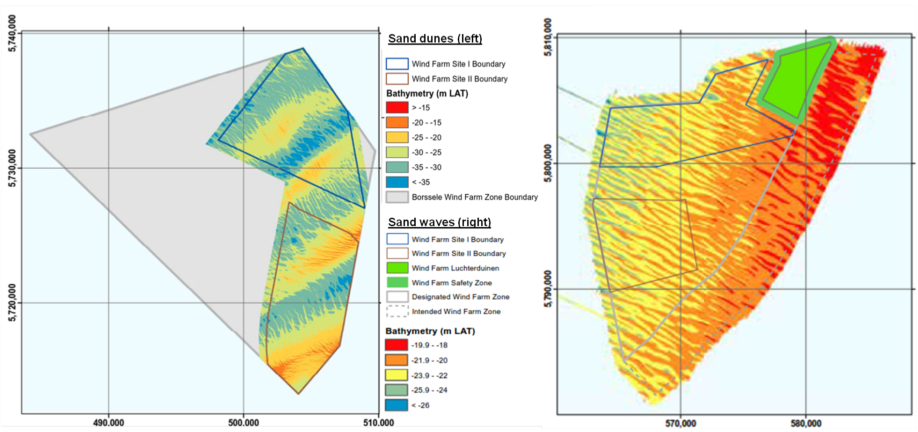



**Figure 6.2:** Sand dunes at Borssele Wind Farm Zone (left) [52]. Sand waves at Hollandse Kust Zuid Wind Farm Zone (right) [58].

## 6.1.3 Selection

The geological features dredging holes and sand waves do not have the best fit to the criteria and therefore are not used in the case study. Dredging holes vary in water depth and soil type at the same time. Sand waves behave dynamically within the time span of the operational life time of an OWF.

Glacial channels and sand dunes are best suited for case studies. With variations in glacial channels the soil-type variation can be investigated individually. The same holds for sand dunes with which the water-depth variation can be investigated individually, while the depth variation is not changing over the operational life time of an OWF.

## 6.2 Case descriptions

In this section, a description of the cases can be found. First, general information is given about the configuration of the OWFs site used in the OWFLOs of the case studies. Thereafter Case 1, the glacial channels, and Case 2, the sand dunes are described. As mentioned in the beginning of the previous section a third case study is included inspired by a representative OWF, explained at the end of this section.

### 6.2.1 The configuration of the OWF

The configuration of the OWF, explained in Section 2.2, forms the basis of this case study. The resolution for the water depth and soil type is 10 x 10, which equals one-hundred - 500 x 500 m - grid-points, each containing a particular water depth and a parameter describing the soil type. The resolution for the WT positions is 25 x 25 m. The configuration of case study 3 is different and is explained in Section 6.2.4.

### 6.2.2 Case 1: Glacial channels

Figure 6.3 shows a visualisation of how a glacial channel is modelled. In Table 6.1 the basic parameters can be found, describing the configuration of the OWFs of Case 1 in specific. The soil outside the glacial channel is kept constant at S40 for every sub-case. Reason for this is the small variation in MP costs for different types of sand dominated soil, which is concluded in Chapter 5 based on Figure 5.2.

As explained previously the main purpose of Case 1 is to investigate the influence of soil variation. MP costs behave dissimilar for variations in soil type at different water depths, therefore the influence of soil variation is studied at different water depths. Besides, the influence of variations in the channel width, wind direction and density of the site are investigated. As a result, Case 1 consist of the following four sub-cases:

- Sub-case 1a: Variation in soil inside the channel at different water depths.
- Sub-case 1b: Variation in the width of the channel.
- Sub-case 1c: Variation in the dominant wind direction.
- Sub-case 1d: Variation in the density of the site.

In Table 6.2 an overview of the parameters which vary for every sub-case can be found. The sub-cases are described further below.

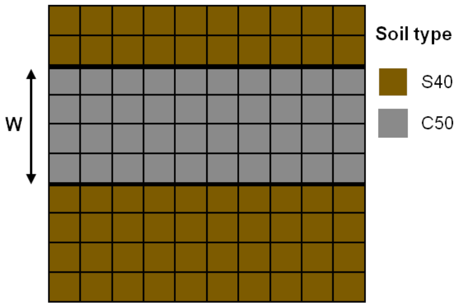



**Figure 6.3:** Visual expression of how a glacial channel having a width (W) of 2000 m is simulated.

**Table 6.1:** Overview of the basic configurations of Case 1. Indicated are the aspects and their corresponding values.

| Aspect | Value |
|---|---|
| Soil type outside channel | S40 |
| Soil type inside channel | C50 |
| Water depth | 30 m |
| Channel width | 2000 m |
| Dominant wind direction | North |
| Number of WTs | 16 |

**Table 6.2:** Overview of the specific configuration of the sub-cases within Case 1: glacial channel. Indicated are the aspect of variation and the corresponding values.

| Sub-case | Aspect of variation | Values |
|---|---|---|
| 1a. | Soil in channel at varying water depth | C50, C100 & C200<br>20, 30 & 40 m |
| 1b. | Channel width | 500 - 4000 m |
| 1c. | Wind direction | N, NE, E & Uniform |
| 1d. | Site density expressed in number of turbines | 16, 25, 36, 49 & 64 |

**Sub-case 1a: Variation in the soil in the channel at different water depths**
In Sub-case 1a the influence of variation in the soil inside the channel is investigated at different water depths. The clay soil type inside the channel is varied from C50 to C100 and C200. This is done for water depths of 20, 30 and 40 m which results in 9 variations of Sub-case 1a.

Figure 5.2 shows in particular large MP-costs variation between the three types of clay soil, and the magnitude of this variation changes for different water depths. Furthermore, the relative difference between the MP costs for S40 type soil compared to the types of clay soil type vary over the water depth.

Based on the behaviour of the MP costs in Figure 5.2 it is expected that the more sand and clay soil type show similar MP costs, the less reduction in LCoE will occur. In all situations, except for C100 and C200 soil type at 40 m water depth, it is anticipated that the LCoE reduction is the result of WTs placed outside the channel. At 40 m water depth, no LCoE reduction is expected for C100 soil type and the LCoE reduction for C200 soil type is expected to be the result of WTs placed inside the glacial channel, because MP costs for C100 and C200 soil type at 40 m water depth are respectively equal or lower than for S40 soil type.

**Sub-case 1b: Variation in width of the channel**
In Sub-case 1b the influence of variation in the width of the glacial channel is studied. The width is varied from 500 to 4000 m. It is expected that an increased width of the glacial channel leads to a further relative reduction in LCoE. Reason for this is that the difference between the number of WTs placed outside instead of inside the channel will increase at larger channel width. Furthermore, it is expected that at a certain channel width a turning point exist were the difference in WT placed outside instead of inside the channel will stagnate. Reason for this is the decrease in AEP, due to the increasing wake loss triggered by the WTs which are placed closer to each other. This will outweigh the reduction in MP costs by avoiding placement of WTs in the channel.

**Sub-case 1c: Variation in the dominant wind direction**
In Sub-case 1c the influence of the dominant wind direction towards the orientation of the glacial channel is examined. The variation in wind direction includes: north (N), north-east (NE), east (E) dominated and uniform wind direction. For the interested reader see Figure E.1 of the Appendix for the distribution of these variations in dominant wind directions.

It is expected that the dominant wind direction has influence on the magnitude of the reduction in LCoE. Reason for this is the change in direction of the wakes for different dominant wind directions. This counteracts with the orientation of the glacial channel with respect to the available WT locations and their resulting AEP.

**Sub-case 1d: Variation in the density of the site**
In Sub-case 1d the influence of variation in the density of the site is investigated. The density of the OWF is increased by adding more WTs to the OWF. The number of WTs is increased by subsequently adding one extra WT in each row and column, this results in a number of WTs within the site of 16 ($4^2$) to 25 ($5^2$), 36 ($6^2$), 49 ($7^2$) and 64 ($8^2$) WTs. It is expected that a decrease in AEP, due to wake losses triggered by the increasing density of the site, will - at a certain number of WTs - outweigh the cost savings obtained by placing the WTs outside the channel.

### 6.2.3 Case 2: Sand dunes

As explained previously the purpose of Case 2 is to investigate the influence of water-depth variations. This is done by means of two sub-cases:

- Sub-case 2a: Variation in peak to trough range at different water depths.
- Sub-case 2b: Variation in wave length of the sand dune.

Figure 6.4 shows a visualisation of how a sand dune is modelled, indicating the peak, trough and wave length ($\lambda$). In Table 6.3 an overview of the parameters which vary in the two sub-cases can be found. Soil type, dominant wind direction and number of WTs are kept constant at respectively S40, North and 16 WTs. The two sub-cases are further described below.

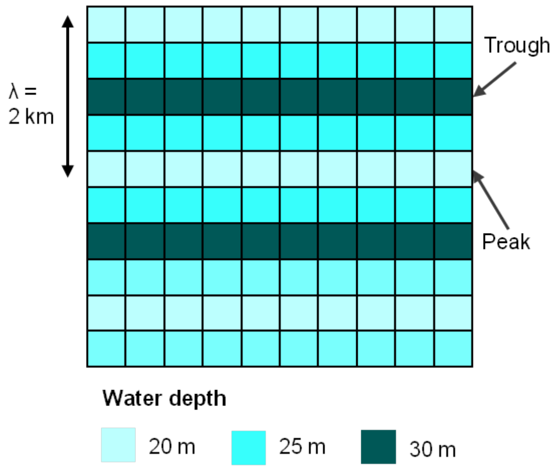



**Figure 6.4:** Visual expression of how a sand dune having a wave length of 2 km is simulated. This example has a peak to trough range of 10 m, with the trough at 20 m water depth.

**Table 6.3:** Overview of the specific configuration of the sub-cases within Case 2: sand dunes. Indicated are the aspect of variation and the corresponding values.

| Sub-case | Aspect of variation | Values |
|---|---|---|
| | Peak to trough range | 5, 10 & 15 m |
| 2a. | .. at small water depths | 20 - 25, 20 - 30 & 20 - 35 m |
| | .. at great water depths | 35 - 40, 30 - 40 & 25 - 40 m |
| 2b. | Wave length | 2, 3 & 4 km |

**Sub-case 2a: Variation in peak to trough range at different water depths**
In Sub-case 2a the influence of varying peak to trough ranges at different water depths is studied. In order to do this the peak to trough range is varied from 5, 10 to 15 m for deep and shallow waters, resulting in ranges of 20 - 25, 20 - 30 and 20

- 35 m for small water depths and ranges 35 - 40, 30 - 40 and 25 - 40 m for great water depths.

It is anticipated that peak to trough range at a greater water depths has a stronger effect on LCoE reduction than small water depths. Reason for this is the higher share of MP costs in the overall project costs. Another expectation is that a larger peak to trough range triggers stronger effect on LCoE reduction. A reason for this is the increase in difference in MP costs between the troughs and peaks of the sand dunes.

**Sub-case 2b: Variation in wave length**

In Sub-case 2b the influence of variations in the wave length is investigated. In each case the peak is oriented perpendicular the dominant wind direction and for each wave length located in the outermost upwind area of the OWF, as can be seen in Figure 6.5. It is expected that with an increased wave length a certain threshold will be reached where the AEP outweighs the benefits of placing the WTs at shallow waters.

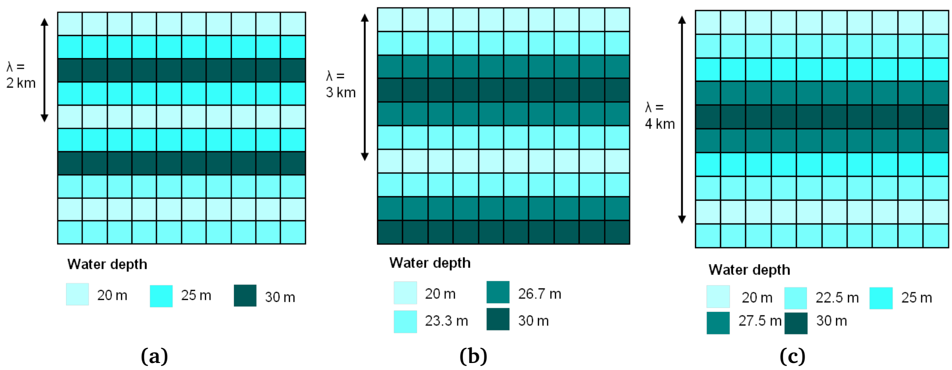



**Figure 6.5:** Visual expression of the simulation of a sand dunes with a wave length of 2 km (a) 3 km (b) and 4 km (c).

### 6.2.4 Case 3: Representative OWF

Krieger's Flak, an OWF development area in the Baltic Sea off the coast of Denmark, is chosen for the simulation of a representative OWF. Seventy SWT-8.0-154 WTs, having a total capacity of 560 MW, are placed in the OWF. The OWF is divided into two separate areas, with 46 WTs placed in the eastern part and 24 WTs placed in the western part. The soil type is remained constant for simplicity reasons at S40 soil type. The water-depth variation within the site boundaries is between ∼ 15 and ∼ 31 meters. For this reason the MP-costs graph of Figure 5.2, which is constrained by water depths between 20 and 40 meters, is extended with an extrapolation to 15 meter water depth in Figure 6.6. The project costs are displayed in Table F.1 of the Appendix. Figure 6.7 gives an impression of the Krieger's Flak OWF, containing the site boundaries, frequency distribution of the wind direction and the bathymetry.

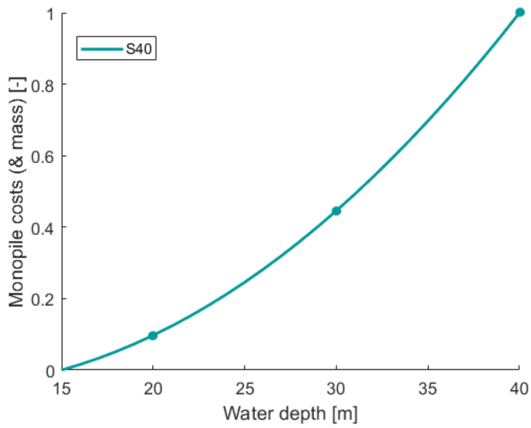



**Figure 6.6:** MP costs (& mass) against the water depth for S40 soil type. The estimations are normalized for confidentiality reasons between 0 and 1, with 0 not reflecting an absolute zero in real values. The indicators display the points for which designs are created. The plotted line is based on spline inter and extrapolation.

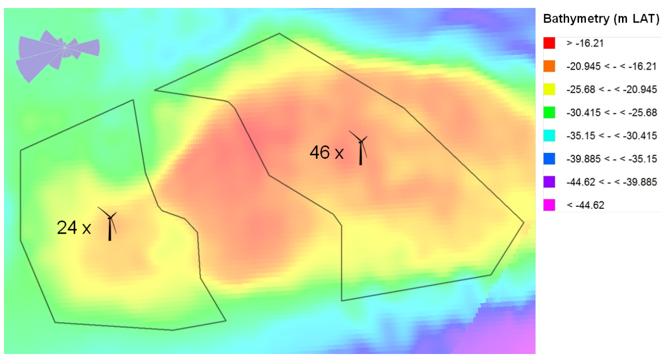



**Figure 6.7:** Impression of the Krieger's Flak offshore wind farm. Indicated are the site boundaries, bathymetry, and the frequency distribution of the wind direction.

## 6.3 Results

In this section, the results of the three case studies can be found. For all the results, the LCoE is the parameter indicating the financial benefits of using improved OWFLO. Every time that LCoE reduction is mentioned this relates to the relative LCoE reduction obtained by using improved OWFLO (which includes MP costs) compared to original OWFLO (which excludes MP costs) for that particular (sub-)case.

### 6.3.1 Case 1: Glacial channel

This sub-section provides the results and interpretation of the sub-cases belonging to Case 1, the glacial channel. Each sub-case is treated individually.

**Sub-case 1a: Variation in the soil inside the channel at different water depths**
Figure 6.8 shows the reduction in LCoE at variations in soil type at different water depths. Figure 6.9 shows, for the same variations, the number of WTs placed in the channel for original and improved OWFLO. The results are in line with the expectations described in the case descriptions.

From the figures, it can be deduced that in general the reduction in LCoE is larger at 30 m water depth than at 20 m water depth. Furthermore, for both 20 and 30 m water depth the reduction in LCoE is smaller when the soil inside the channel is dominated by stiffer clay. All LCoE reductions at 20 and 30 meters water depth are the result of the placement of the WTs outside the glacial channel, because at these water depths clay soil types result in higher MP costs than sandy soil types.

The results of the LCoE reduction at 40 m water depth shows a different behaviour for C100 and C200 soil type. In the case of C100 soil type no LCoE reduction occurs and for C200 soil type the LCoE is reduced because WTs are placed inside the channel, instead of outside the channel. This is visualised in Figure 6.10 where the layout of the WTs for soil-type variations at 40 m water depth is shown.

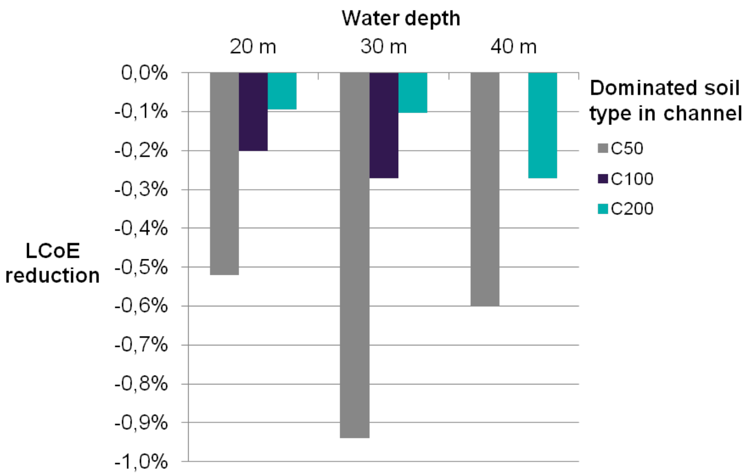



**Figure 6.8:** LCoE reduction against variations in clay soil type inside the channel at different water depths.

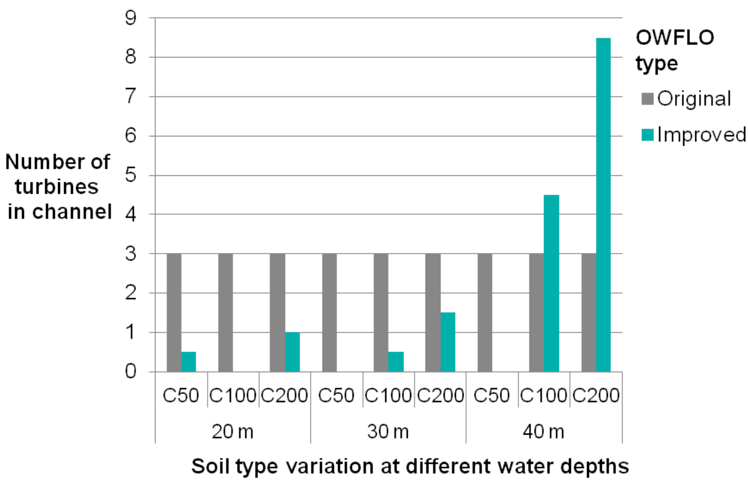



**Figure 6.9:** Comparison of the number of WTs placed inside the channel between original and improved OWFLO. This is indicated for three types of clay soil at different water depths.

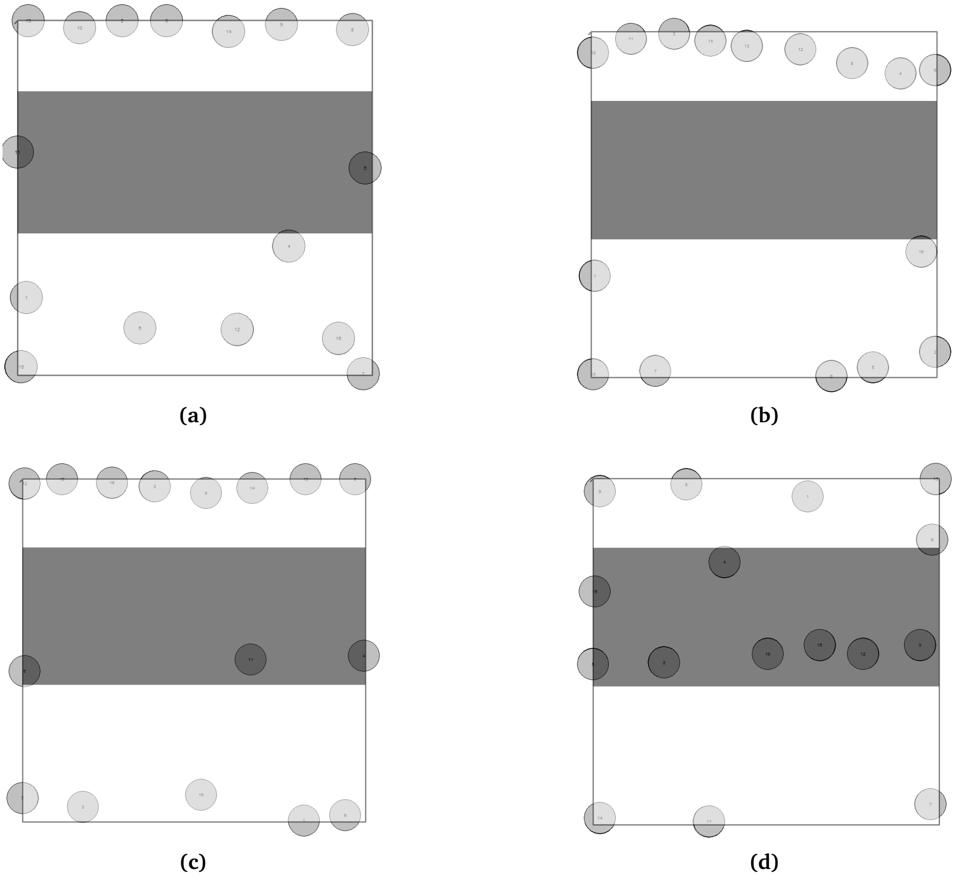



**Figure 6.10:** Wind-turbine layout for a channel width of 2000 m at 40 m water depth. Original OWFLO (a) and improved OWFLO for C50 (b), C100 (c) and C200 (d) soil type inside the glacial channel.

**Sub-case 1b: Variation in width of the channel**

Figure 6.11 shows the reduction in LCoE at different widths of the glacial channel, which confirmed that an increased width of the channel leads to a further reduction in LCoE. Additionally, Figure 6.12 shows an increased number of WTs placed in the glacial channel at larger channel width with original OWFLO. With improved OWFLO no WTs are placed in the channel for all channel widths.

An explanation for the reduction in LCoE for improved OWFLO is that the WTs avoid placement in the glacial channels. This is due to the fact that the higher MP costs outweigh the loss in AEP due to increased wake loss as a results of a higher site density. This is visualised in Figures 6.13 and 6.14 where the OWF layout for original and improved OWFLO for a glacial channel of 2000 and 4000 m are shown. Sub-case 1c and 1d will reveal whether wind direction or site density play a role in the amount of LCoE reduction.

Having a closer look at Figures 6.11 and 6.12 it can be seen that the reduction in LCoE goes in steps, synchronous to the number of WTs placed in the channel when original OWFLO is performed. Faster reductions in LCoE took place when the number of WTs placed in the channel for original OWFLO increased at certain channel widths. This can be seen for channel widths of 500 to 1000 m, 2000 to 2500 m, 3000 to 3500 m and 3500 to 4000 m. Especially for the latter the effect is clearly present.

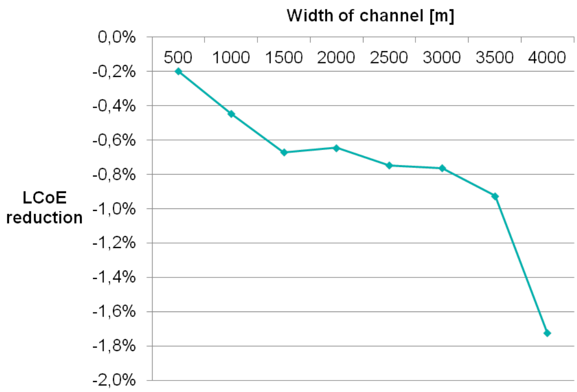



**Figure 6.11:** Reduction in LCoE against variation of the glacial channel width.

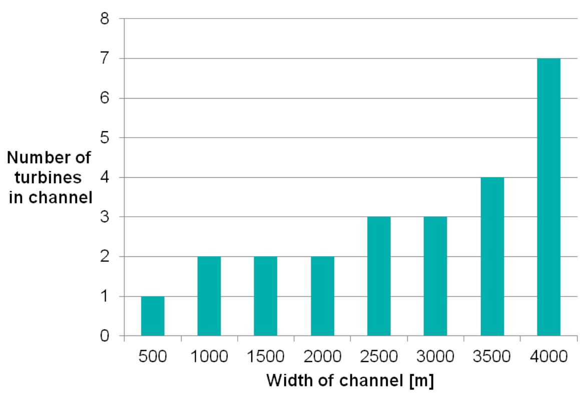
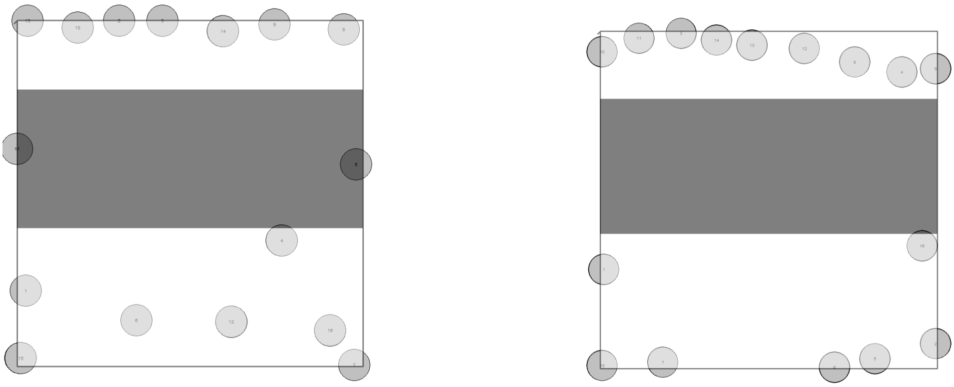
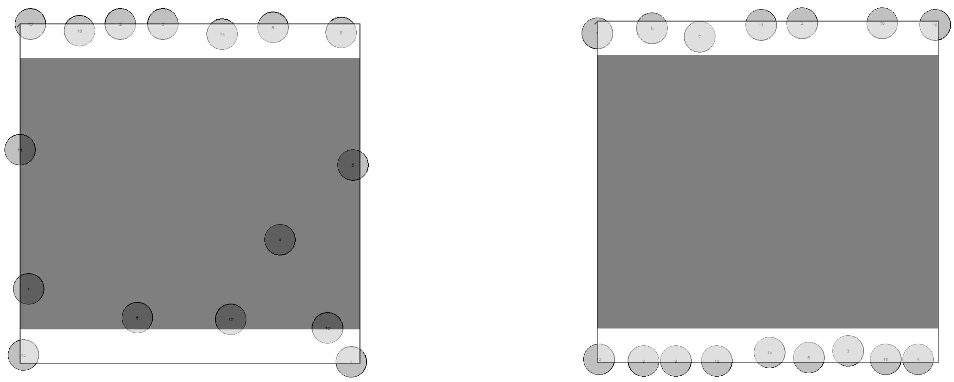



**Figure 6.12:** Number of WTs placed in channel with original OWFLO.



(a) (b)

**Figure 6.13:** Wind-turbine layout with a channel width of 2000 m. Layouts are created with original (a) and improved (b) OWFLO.



(a) (b)

**Figure 6.14:** Wind-turbine layout with a channel width of 4000 m. Layouts are created with original (a) and improved (b) OWFLO.

**Sub-case 1c: Variation in the dominant wind direction**

Figure 6.15 shows the results of the LCoE reduction against the dominant wind directions. The number of WTs placed in the channel for original and improved OWFLO for the different dominant wind direction can be found in Figure 6.16.

The results show difference in the magnitude of LCoE reduction if the orientation of the dominant wind direction towards the channel has changed. NE and E dominated wind direction show significantly larger LCoE reduction than N dominated and uniform wind direction.

This can, on the one hand, be explained by the fact that the difference in number of WTs placed in the channel between original and improved OWFLO, is larger for NE or E dominated wind (∼ 3.5) than for N or uniform dominated wind (∼ 2.5). This implies that larger savings in MP costs are achieved for NE or E dominated wind direction. On the other, the AEP is larger for NE and E dominated wind direction, because of the WTs are placed in more favourable areas with respect to wakes.

Both statements are confirmed in Figures 6.17 and 6.18 showing the layouts with original and improved OWFLO for sites with N and E dominated wind. It can be seen that for E dominated wind direction the difference in number of WTs placed inside the channel between original and improved OWFLO is higher than for N dominated wind direction. Furthermore, the WTs are positioned more spacious in the layout as a result of the improved OWFLO for E dominated wind versus N dominated wind direction.

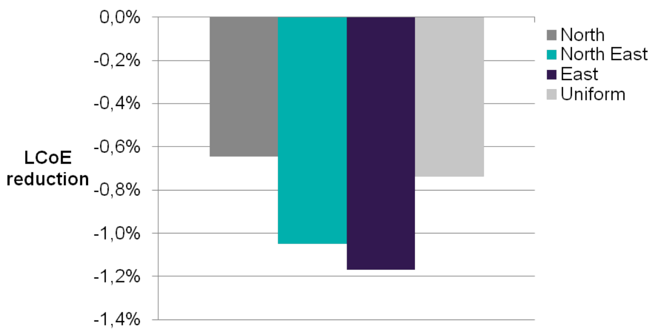



**Figure 6.15:** LCoE reduction against dominant wind direction.

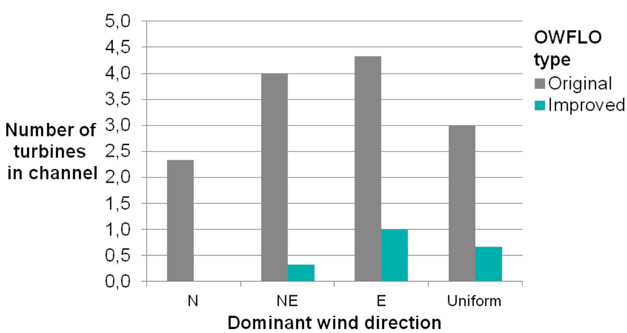
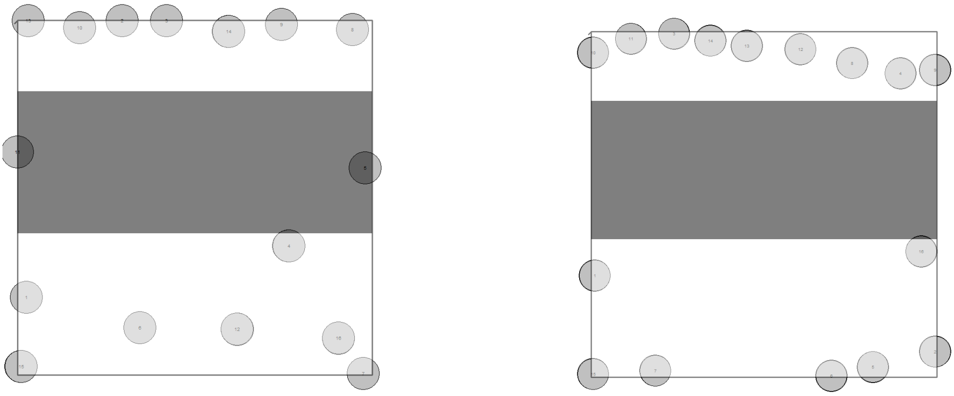
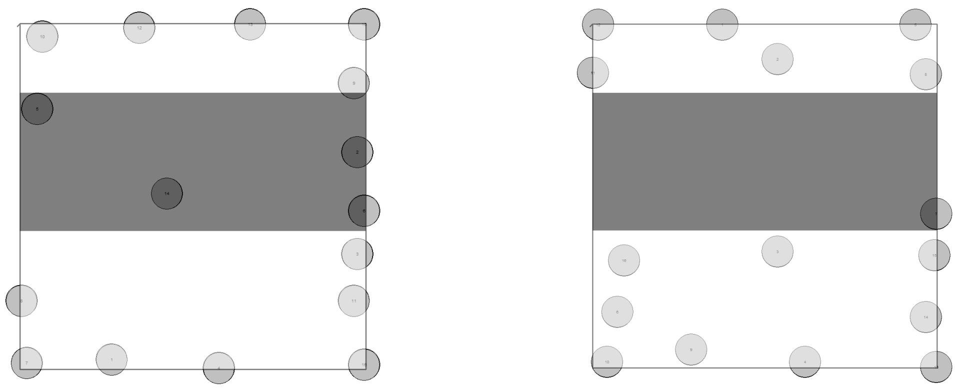



**Figure 6.16:** Number of WTs placed inside the channel for original and improved OWFLO against dominant wind direction.



(a) (b)

**Figure 6.17:** Wind-turbine layout for N dominated wind direction. Layouts are created with original (a) and improved (b) OWFLO.



(a) (b)

**Figure 6.18:** Wind-turbine layout for E dominated wind direction. Layouts are created with original (a) and improved (b) OWFLO.

**Sub-case 1d: Variation in the density of the site**
Figure 6.19 shows the results of the LCoE reduction achieved for variations in density of the site by increasing the number of WTs. Figure 6.20 shows the number of WTs placed inside the channel for original and improved OWFLO against the total number of WTs placed within the OWF.

From the results, it can be deduced that the LCoE reduction has its optimum around 25 WTs. Reasons for the increased magnitude in LCoE reduction from OWFs with 16 to 25 WTs is, beside the moderate AEP reduction, the difference between the number of WTs placed inside the channel for original versus improved OWFLO. With the improved OWFLO this increases from $\sim 2$ for the site with 16 WTs to $\sim 5$ for the site with 25 WTs.

The LCoE reduction gradually decreases when more WTs are added to the OWF. Reason for the gradual decrease is twofold. On the one hand, the relative difference in the number of WTs placed inside the glacial channel between original and improved OWFLO becomes smaller at increasing site density. This is indicated with the percentages in Figure 6.20. On the other, a relative decrease in AEP emerges due to increased wake loss triggered by higher site density. Figure 6.21 shows that more WTs are placed within the channel with large site density, when compared with low site density from Figure 6.17. Those two reasons implies that at a certain turning point exists, which is around 25 WTs, at where the relative decrease in AEP outweighs the cost reduction that can be obtained by placing WTs outside the glacial channel. However, in all situations a minimum LCoE decrease of 0.6% is achieved.

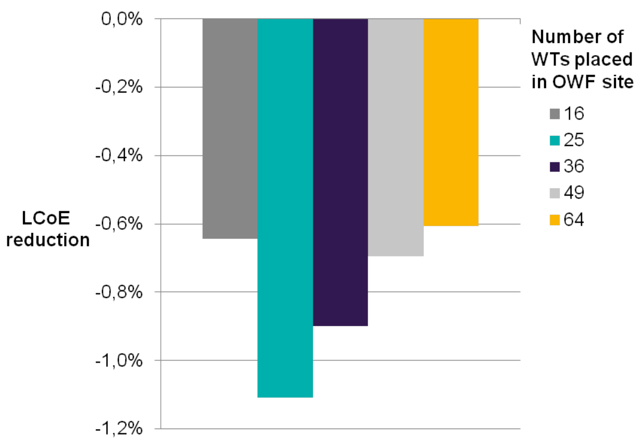



**Figure 6.19:** Reduction in LCoE against the number of WTs placed within the OWF.

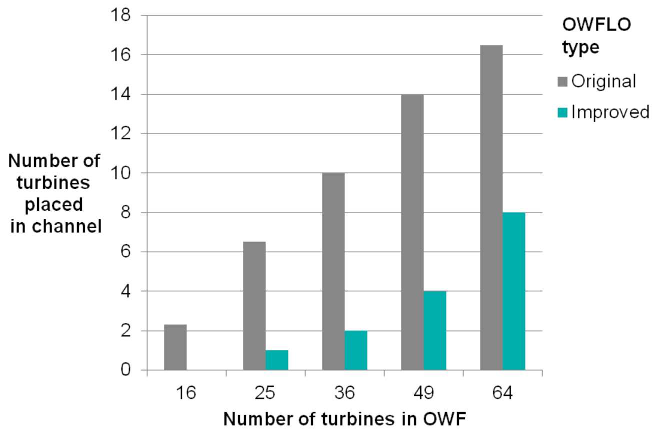
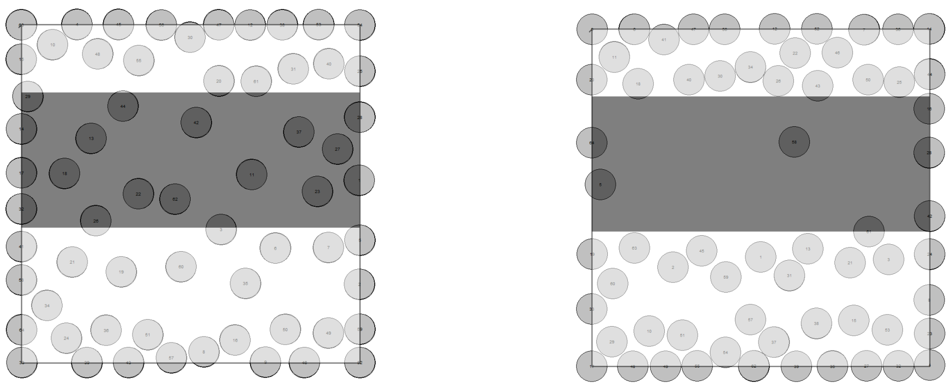



**Figure 6.20:** Number of WTs placed in the glacial channel for original and improved OWFLO against the number of wind turbines placed inside the OWF.



(a) (b)

**Figure 6.21:** Dense OWF containing 64 WTs having a glacial channel width of 2000 m. Wind-turbine layouts are created with original (a) and improved (b) OWFLO.

### 6.3.2 Case 2: Sand dunes

The results of Case 2 are plotted in one bar chart which can be found in Figure 6.22. The interpretation of the results can be found below, where the influence of the variation in wave length and peak to trough range at different water depths is explained.

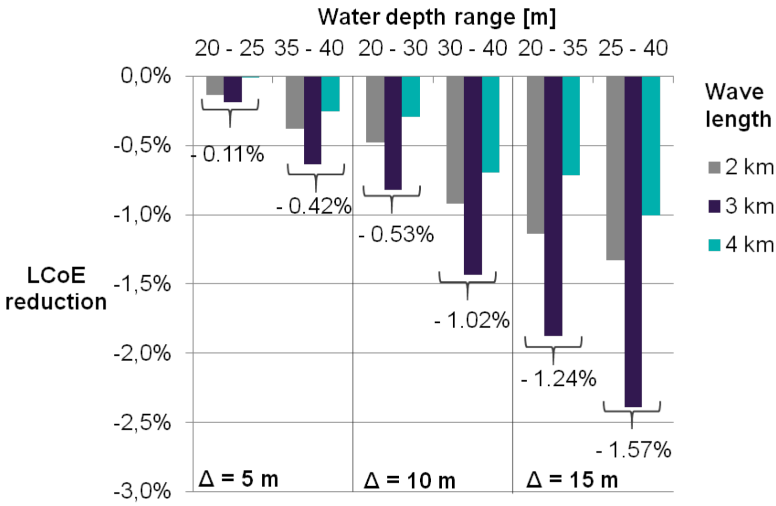



**Figure 6.22:** LCoE reduction for different variations of sand dunes. Variations include wave length indicated with the legend and water depth range indicated at the x-axis. The peak-to-trough range is indicated with Δ. Furthermore, for every particular water depth range the average LCoE reduction is indicated.

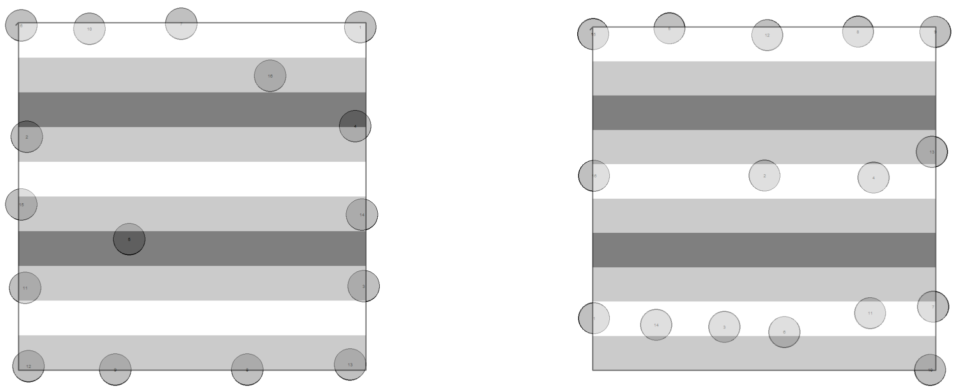
**Sub-case 2a: Variation in peak to trough range at different water depths**
From Figure 6.22 it can be deduced that the degree of LCoE reduction increases at greater water depths and larger peak to trough ranges. This is in line with the expectation. The average magnitude of LCoE reduction for every water depth range, indicated in the figure, is $\sim$ 0.4 percent point higher at larger water depths for the same peak to trough range. Reason for this is the increased slope at greater water depths for S40 soil, derived from the graph describing MP costs against water depth in Figure 5.2.

**Sub-case 2b: Variation in wave length**
From Figure 6.22 it can be deduced that the LCoE reduction is sensitive for different wave lengths, with the highest reduction in LCoE for a wave length of 3 km, followed by a wave length of 2 and 4 km. Figures 6.23, 6.24 and 6.25 shows the layouts of original (left) versus improved (right) OWFLO, for a water depth range of 20-35 m for varying wave lengths. In general, it can be deduced from these figures that in the layouts with improved OWFLO the WTs tend to be placed in the shallower areas of the OWF in order to save MP costs.

The explanation of the difference in magnitude of LCoE reduction between the variations in wave length is as follows. The number of WTs placed in the troughs of the layouts resulting from original OWFLO are 2, 5 and 0 for wave lengths of respectively 2, 3 and 4 km. The troughs are, indicated by the darkest grey areas in the figure, are the most expensive areas to place an MP. In the improved OWFLO these areas are avoided for every wave length. This implies that the MP costs savings between original and improved OWFLO are much higher for a wave length of 3 km than for 2 or 4 km.

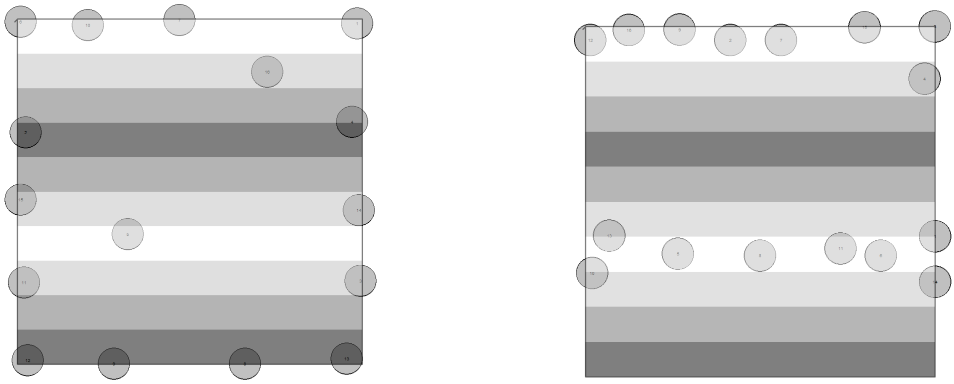
The underlying reasons for the placement of the large number of WTs in the most expensive areas of the OWF with a wave length of 3 km is as follows. The site configuration used in this study forced the WTs during the original OWFLO to place themselves in a row at the boundaries of the OWF both upwind and downwind in order to maximize the AEP. This resulted in a large number of WTs placed in the trough of the sand dune with a wave length of 3 km for original OWFLO. This is not the case for wave lengths of 2 and 4 km.

Furthermore, savings on MP costs by placing WTs towards the peaks of the sand dunes outweighs the effects of reduced AEP. This is based on the fact that almost all WTs are placed on the lowest or second lowest water depth, as can be seen on Figures 6.23, 6.24 and 6.25. The ideal orientation of the N dominated wind direction with respect to the wakes is the explanation of the fact that the AEP loss is subordinate in this case. However, this effect is already treated in Sub-case 2c.



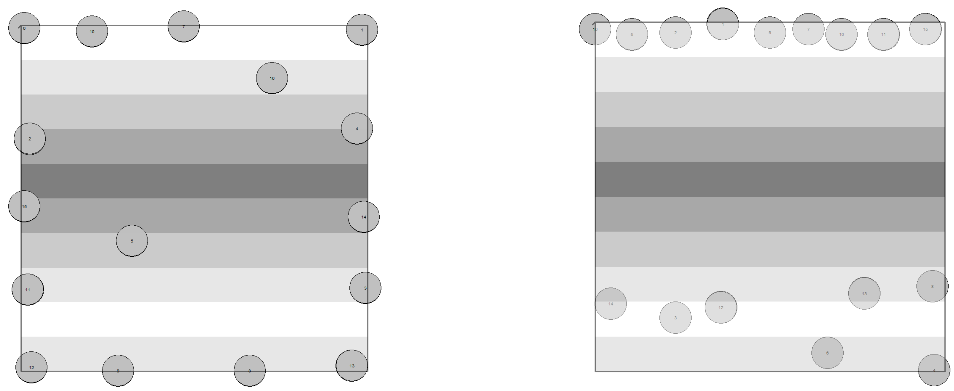
**(a)** $\lambda$ = 2 km **(b)** $\lambda$ = 2 km

**Figure 6.23:** Wind-turbine layouts with original (left) and improved (right) OWFLO for a water depth range of 20 - 35 m, and varying wave lengths.



**(a)** $\lambda$ = 3 km **(b)** $\lambda$ = 3 km

**Figure 6.24:** Wind-turbine layouts with original (left) and improved (right) OWFLO for a water depth range of 20 - 35 m, and varying wave lengths.



**(a)** $\lambda$ = 4 km **(b)** $\lambda$ = 4 km

**Figure 6.25:** Wind-turbine layouts with original (left) and improved (right) OWFLO for a water depth range of 20 - 35 m, and varying wave lengths.

### 6.3.3 Case 3: Representative OWF

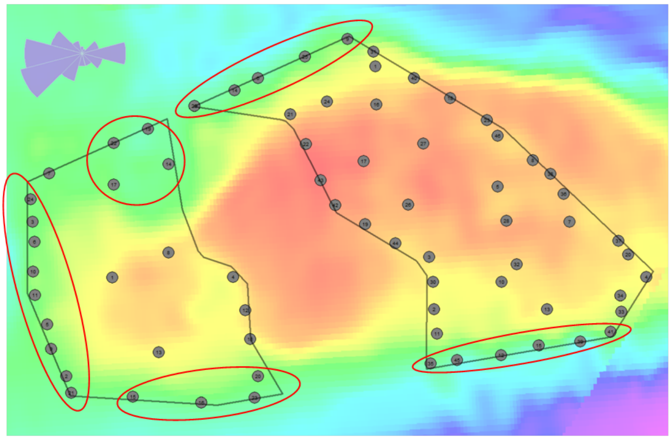
Figure 6.26 shows the layout as a result of original OWFLO (a) and improved OWFLO (b) of the Krieger's Flak OWF. It can be seen that the number of WTs in areas with large water depths, indicated with the red circles, is significantly lower for the layout which results from improved OWFLO than for original OWFLO. As a result, a LCoE reduction of 0.3% is obtained. This LCoE reduction is achieved by a decrease in MP costs of -7.6%, combined with a 0.4% lower AEP due to increased wake losses.

With this LCoE reduction, a saving in PV of $\sim$ 3 million Euro is obtained. This is calculated taking the assumptions with respect to project costs, mass estimations, cost factor and financial parameters into account. Furthermore, it is assumed that the energy price is equal to the calculated LCoE in a break-even situation (NPV = 0) for the original OWFLO, and is constant over the project lifetime. How this calculation is performed is displayed in Table 6.4.

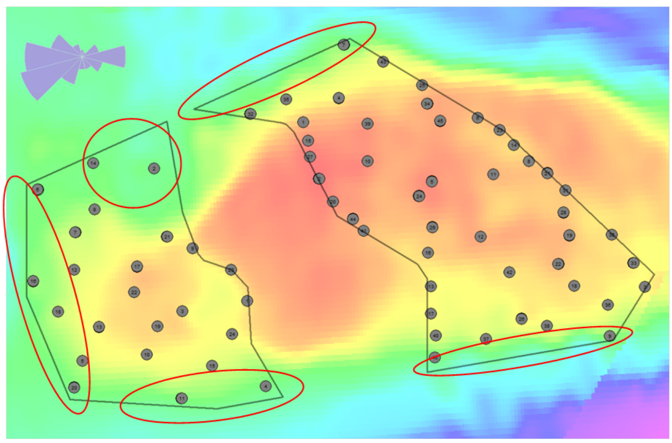
**Table 6.4:** Description of the calculation of the total savings in PV for the Krieger's Flak OWF.

| Parameter | Unit | Original OWFLO | Improved OWFLO |
|---|---|---|---|
| CapEx [a] | $k€$ | 892,153 | |
| MP costs | $k€$ | 100.430 | 92.782 |
| Total CapEx | $k€$ | 992.583 | 984.935 |
| PV of total OpEx [b] | $k€$ | 248.095 | |
| **PV of total project costs [b]** | $k€$ | **1,240,678** | **1,233,030** |
| PV of total AEP [b] | $MWh$ | 33,714,076 | 33,595,231 |
| Energy price | $\frac{€}{MWh}$ | 36.80 | |
| **PV of total revenues [b]** | $k€$ | **1,240,678** | **1,236,305** |
| **Total savings in PV** | $k€$ | **-** | **3,275** |

[a] Excluding MP.
[b] Over project lifetime.



**(a)**



**(b)**

**Figure 6.26:** Resulting layouts of Krieger's Flak OWF using original OWFLO (a) and improved OWFLO (b).

## 6.4 Insights obtained from the case studies

This chapter aimed to fulfil Task 4 of the objective: Identify parameters specific to an OWF which are important to consider when including MP costs in OWFLO. This is achieved by means of performing case studies, of which the insights obtained are given in this section. Two cases are performed to get insights in the environmental parameters which are important to consider when including MP costs in OWFLO. Another case is conducted with the aim to simulate a representative OWF.

Case 1, the glacial channels, investigated the influence of soil-type variation at different water depths. Besides, understanding is obtained regarding the influence of the size of the area having bad soil, resulting in expensive MPs, and variations in dominant wind direction and site density. The main insights are summarized as follows:

- **General insights about including MP costs in OWFLO.**
  From the results, it can be obtained that in all situations it is beneficial to include MP costs in the OWFLO process. The results are in line with what was expected from the behaviour of the MP-costs estimation with respect to variation in the uniform soil type for different water depths. According to this it can be concluded that the improved OWFLO showed to be able to find the improved optimal layout when MP costs included.

- **Soil-type variation at different water depths.**
  The type of soil transpired to be an important parameter to consider when including MP costs in OWFLO for several reasons. Firstly, if sand and clay soil types simultaneously occurred at an OWF, the LCoE reduction depended on the difference in MP costs between the sand and clay soil type. Secondly, variations in clay soil types showed large differences in LCoE reduction. Lastly, the difference in MP costs for variations in sand or clay soil type, differed depending on water depth. At some water depths clay soil showed to be better suited for WT placement than sand soil.

- **Influence of the size of the area showing variations in MP costs.**
  From the variation in glacial channel width it can be concluded that a certain area having a particular soil type influenced the magnitude of LCoE reduction. This is the result of the trade-off between savings on MP costs by placing them in cheaper areas, determined by the dominant soil type, and decreased AEP by putting the WTs at less favourable spots with respect to wake losses.

- **Influence of dominant wind direction.**
  From the variation in dominant wind direction it can be concluded that the wind direction transpired to be a site dependent parameter significantly influencing the magnitude of LCoE reduction. It was obtained that the main point of interest is the orientation of the dominant wind direction towards

the geological feature. More specific, the results showed a doubling in LCoE reduction if the dominant wind direction was oriented parallel compared to perpendicular the geological channel.

- **Influence of variation in site density.**
  From the variation in site density, it can be concluded that a turning point exists for the increase in the magnitude of LCoE reduction. At a certain moment, the costs savings by placing WTs at cheaper locations are outweighed by the decrease in AEP, and as a result the WTs are placed in more expensive areas to compensate for the AEP loss they will otherwise encounter. However, the results showed that despite that the magnitude of LCoE reduction is lower, it is still beneficial to include MP costs in OWF with high WT density.

Case 2, the sand dunes, studied the influence of variation in water-depth ranges for deep and shallower water. The most important observations obtained are:

- **Peak to trough ranges at deeper and shallower water.**
  The benefits of including MP costs in OWFLO are more pronounced at greater water depths and with larger peak to trough ranges.

- **Variations in wave length.**
  The magnitude of LCoE reduction is sensitive for the wave length of the sand dune. With the configuration of the OWF of this study the WTs are being placed at the shallow areas when MP are included in the OWFLO. This implies that the reduction in MP costs outweighs the decrease in LCoE. It is important to consider where the peak or trough of a sand dune is located within the overall dimension of an OWF.

The following insights can be deduced from the results of the case with the representative OWF:

- **Moderate LCoE reduction obtained at Krieger's Flak OWF.**
  It can be concluded that areas with great water depths are avoided at the boundaries of the Krieger's Flak OWF. This resulted in a moderate reduction of LCoE. However, this LCoE reduction can be achieved without much effort and saves in this case 7.5 million Euro in MP costs. Combined with an AEP decrease of 0.4% this results in obtain total savings of $\sim$ 3 million Euro in PV.

# Chapter 7

# Conclusions and Recommendations

The ultimate goal of this thesis is to investigate the way to decrease the LCoE of OWF by including MP costs in the OWFLO process. This broad statement is formulated more specifically in the following objective:

*'Investigate the benefits and parameters that should be considered when including MP costs in OWFLO, by developing and implementing a method to include the MP costs in the OWFLO process.'*

This objective was subdivided into the following tasks:

1. Investigate the feasibility of including MP cost variation in OWFLO with respect to the LCoE.

2. Develop a method for MP cost estimation at specific locations within an OWF.

3. Implement the method in a location-specific MP cost estimator, which can be used in the OWFLO process.

4. Identify parameters specific to an OWF which are important to consider when including MP costs in OWFLO.

These tasks have been fulfilled. The most important findings are summarized in this chapter to accomplish the overall objective. The conclusions are stated in Section 7.1. Recommendations are offered in Section 7.2.

## 7.1 Conclusions

The conclusions presented in this section do not follow the order of the tasks listed above. For sake of coherence, the decision has been made to devote one section to a combination of Tasks 2 and 3, thereby resulting in Section 7.1.1: MP Cost Estimation at Specific Locations within an OWF. Furthermore, the conclusions of Task 1 are combined with the part of Task 4 which contains findings related to the LCoE discussed in Section 7.1.2: Influence of Including MP Costs in OWFLO to the LCoE. Finally, the conclusions of Tasks 4 with respect to the identified site-specific parameters are discussed in Section 7.1.3.

### 7.1.1 MP cost estimation at specific locations within an OWF

Variations in water depth and soil type are vary significantly within an OWF. In addition, it has been found that MP costs are highly dependent on water depth and soil type. The cost of an MP can be determined by using MP mass estimations multiplied with a cost factor in euros per kg of steel. By estimating the MP costs in this way, the influence of different soil types and water depths on the MP costs can be investigated and the MP cost variation can be implemented in the OWFLO process. Therefore, at least water-depth and soil-type variations should be included in the location specific MP cost estimation of the OWFLO process.

Other conclusions that can be drawn with respect to this method are as follows: The location specific MP cost estimation is relatively easy to perform in a limited amount of time. Furthermore, this method is applicable to variations in site dimensions including water-depth and soil-type variation. However, new MP cost estimations are required when this method needs to be applied to other OWF configurations, including WT type and wind and wave climate.

### 7.1.2 The influence on the LCoE of including MP costs in OWFLO

From the optimisations performed we can see that OWFLO which includes MP costs is able to improve the layout of the OWF and hence reduce the LCoE in every situation in which variations in water depth or soil type occur. Depending on the water depth, soil type, and other site-specific parameters, LCoE reductions between 0.2 - 2% were obtained. This is in line with the expectations stated in the introduction. By including MP costs at the Krieger's Flak OWF - which showed significant but not very large variations in MP costs - a LCoE reduction of 0.3% was obtained. Though this LCoE reduction is moderate, it resulted in a total saving of $\sim$ 3 million euros in PV. Therefore, it can be concluded that if variations in MP costs occur, it is in any case beneficial to include MP costs in the OWFLO process.

Furthermore, it can be concluded that when wrongly estimated MP costs are included in OWFLO, the deviation in LCoE reduction is moderate. An error of $\pm$50% in the estimation of MP costs results in a deviation of 20 - 24% in the LCoE reduction. This implies that OWFLOs which include wrongly estimated MP costs still result in an improved OWF layout with reduced LCoE. One reason for this is that the relative difference in MP costs governs, compared to an off-set in the absolute magnitude of the MP costs. However, the MP costs needs to be estimated as accurately as possible, as such precision ensures that the OWFLOs result in the most optimal layout and a precise approximation of the LCoE.

### 7.1.3 The site-specific parameters important to consider when including MP costs in OWFLO

It has been found that various site-specific environmental parameters should be considered when including MP costs in OWFLO. Most important to consider is variations in water depth and soil type.

**The effect of variations in soil type at different water depths**
The obtained effect on LCoE reduction depends on a combination of variations in the soil type and the magnitude and ranges of water depth within an OWF. At constant water depths, the spread between MP costs which result from variations in soil type govern the LCoE reduction. In general, for OWFs with a combination of sand soil type and clay soil type, WTs move to areas with sandy soil. One reason for this is that in most cases, sandy soil results in lower MP costs. However, at greater water depths, a specific type of clay soil can result in lower MP costs than sandy soil. As a result, it is shown that, in certain cases, the WTs tend to move to areas with clay soil.

**The effect of variations in magnitude and range of water depths**
One type of sandy soil is used to investigate the effect of variations in magnitude and range of water depths. In general, the obtained effect on LCoE reduction increases for greater water-depth ranges. Reasons for this include the higher spread in MP costs. Furthermore, it has been found that this effect is more pronounced at greater water depths as a result of the steeper slope in MP costs. For clay soil, this effect has not been investigated. However, based on the MP-costs graph, the effect on LCoE reduction is expected to be larger for shallower water. One reason for this concerns the slope of the MP costs, which is steeper at shallow waters.

**The effect of the location of variations in water depth and soil type**
For variations in both water depth and soil type, the geometry and location of the variation influences the degree of LCoE reduction. This is a result of the trade-off between MP costs savings (which is obtained by placing WTs in areas suited to cheaper MPs) and reduction in AEP.

**The effect of other site-specific parameters**
Other site-specific parameters which affect this trade-off include the density of the OWF site - expressed in number of WTs - and the orientation of the dominant wind direction with respect to variations in water depth and soil type. Both aspects exhibit a capacity to double the obtained LCoE reduction in the most favourable situation.

## 7.2 Recommendations

The recommendations based on this study are differentiated into directly applicable actions for the OWF industry and interesting topics for further research.

### 7.2.1 Directly applicable actions

Based on the conclusions drawn from this thesis, the following actions are recommended.

- **Include MP cost variation in the OWFLO process.**
  It is beneficial with respect to the LCoE of OWFs to include MP costs in OWFLO. The LCoE can be reduced between approximately 0.2 to 2%, which is on the order of other LCoE reductions which result from developments in the offshore wind sector. Also, when the precise absolute values of the MP costs are unknown, it is recommended to include them in the OWFLO process, so long as the relative variation gives a correct approximation.
- **Use at least variations in water depth and soil type in the location specific MP cost estimation.**
  Variations in water depth and soil type are environmental parameters vary within an OWF: they strongly influencing the cost variation of MPs.
- **Use MP mass estimations to determine MP costs at specific locations.**
  The following method of estimating MP costs is suited to the aim of including them in OWFLO: Use MP mass estimations multiplied with a cost factor in euros per kg of steel. The creation of support-structure designs is required to estimate the MP mass. Using this method, it is possible to assess the influence of variations in water depth and soil type on MP costs for the conditions specific to the assessed OWF.
- **The geometry and location of variations in water depth and soil type, the dominant wind direction and the site density should be considered when including MP costs in OWFLO.**
  All these parameters are characteristic of an OWF and strongly influence the trade-off between MP cost savings and decrease in AEP. Therefore, they must be considered for optimal utilization of the OWFLO which includes MP costs.

### 7.2.2 Further research

While conducting this study, the analysis discovered some points of interest that may warrant further in-depth analysis. Potential topics to investigate include the following:

- **Investigate the possibility to develop an interpolated MP-costs model based on design locations within an OWF if sufficient soil data is available at early project phases.**
With the increasing amount of extensive soil data available at early phases of OWF projects, it might be worth investing in the creation of support-structure designs at all locations with sufficient soil data. Using interpolation of the resulting MP costs, a complete model of the MP cost distribution throughout the OWF can be developed. This MP cost distribution can then be used in OWFLO. Given this method, it is unnecessary to make standard designs with variations in soil type at several water depths, to subsequently convert the resulting MP cost graph into MP costs at specific locations, as performed in this study. Furthermore, an additional benefit is that, with this method, non-uniform soil is considered instead of uniform soil, which result in a more precise estimate of the MP costs.

- **Investigate variations in magnitude of the cost factor describing MP costs in euros per kg.**
In this study, a constant cost factor is used which describes MP costs in euros per kg. However, it is expected that the cost factor for MPs with an exceptional length or diameter is significantly higher. If this is the case, the spread in MP cost variation in OWFs might become even higher. This can result in an increase in magnitude of LCoE reduction when MP costs are included in the OWFLO process.

- **The influence of including installation costs in the MP cost estimations.**
For simplicity, variations in installation costs are not considered in this study. However, it is expected that installation costs depend on the location-specific parameters water depth and soil type. On the one hand, a direct influence of those parameters to the installation costs exists with respect to the positioning of the installation vessel. On the other hand, an indirect influence exists regarding the dimensions and mass of the MPs which must be installed. It is recommended that someone investigate how and to what extent location-specific MP costs are influenced by the installation process and what the impact is on the possible reduction in LCoE when included in the OWFLO process.

- **Propose a joint-industry project in order to succeed OWFLO which includes MP costs and to collectively profit from the obtained benefits.**
  Several industry partners need to collaborate to make the principle of including MP cost in OWFLO a success and jointly reduce the LCoE of offshore wind energy. Companies able to perform detailed soil investigation, for example Fugro, are required to provide sufficient soil data at early project phases. Foundation designers and manufacturers, such as Atkins and COWI, should be transparent in their MP cost estimates with respect to their mass, length and diameter. The latter also applies to installation companies as Van Oord, who should share specific information about how the location and MP mass, diameter and length effects the installation costs. The competence of Siemens itself is key in this join-industry project proposal. The reason for this is that Siemens features unique knowledge about the trade-off between MP costs and AEP during the OWFLO process. With the results of these OWFLOs including MP costs they can advice OWF project developers, such as Eneco, Vattenfall or Shell. This advice can contain information about the layout and its expected MP costs and EAP. As a result of this join-industry the total savings in PV can be shared, based on the degree of contribution each participator provided.
- **Discover the benefits of including foundation costs in OWFLO with foundation types other than a MP foundation.**
  The scope of this study with respect to the type of foundation is devoted to a MP foundation because MP foundations are predominantly used in the current OWF projects. Besides, MP foundation cost variation is reportedly influenced more by variations in water depth and soil type than jackets do. However, because jacket foundations are upcoming, it might be useful to perform the same study for jacket foundations.
- **Discover the implications of combining electrical cabling costs and MP costs included in OWFLO.**
  The introduction of this thesis, mentions that including inter-array cabling costs in OWFLO is already partly being done and is therefore considered out of scope of this study. It might be interesting to investigate the benefits and implications of OWFLO - including MP costs and inter-array cabling costs combined.
- **The influence of including wave variation in the MP cost estimation.**
  Though waves are considered in the MP designs and indirectly influence the costs of the MPs, they are assumed to be constant in this study. However, this is not fully correct, because waves do vary within an OWF. The reason for this assumption is that soil type and water depths vary directly while variation in waves results from variation in other factors, such as water depth and wind climate. Because waves can have a high impact on the MP mass, and hence on costs, it is recommended to investigate their influence on MP costs.

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# Appendix A

# Influence of Surface Roughness and Wake Decay in OWLFO

As discussed in Section 2.2.1 the influence on the LCoE of using a surface roughness length of 0.002 m or 0.0002 m is investigated in this Appendix. According to equation 2.3 these values corresponds to wake decay constant of 0.046 and 0.038. For the analysis, the same site configuration of the feasibility study of Chapter 3 is used with a MP cost variation of 1M - 2M €. The results are shown in Table A.1 below.

**Table A.1:** Comparison of OWFLO using 0.002 and 0.0002 as surface roughness length. Expressed are the change in AEP, initial investment costs and LCoE if 0.0002 is used instead of 0.002.

| Type of OWFLO | AEP | Initial investment costs | LCoE |
|---|---|---|---|
| Original | − .18% | − .06% | + .11% |
| Enhanced | − .16% | + .12% | + .27% |

From the results, it transpired that the using a surface roughness length of 0.0002 m instead of 0.002 m influences the AEP, Initial investments costs and LCoE, especially for enhanced OWFLO. Considering the enhanced OWFLO, the predominant reason for this is that the turbines are forced to be placed in more expensive areas with respect to the MP costs in the 0.0002 m situation. This is due to the increased length of the wakes, otherwise leading to further reduction in AEP. Using a roughness length of 0.0002 m reduces the LCoE using enhanced OWFLO with with 0.89% instead of 1.05% achieved with 0.002 m. To conclude, despite the small influence on LCoE reduction using a roughness length of 0.0002 instead of 0.002 m has, the use of 0.002 in the analysis of this study will not undermine the main conclusions drawn.

# Appendix B

# Monopile Mass of Locations Within Existing Wind Farms

Table B.1 shows the MP mass and the water depth of MPs at different locations within existing OWFs. The MP mass is normalized between 0 and 1 for confidentiality reasons, with 0 being the MP with the lowest mass and not being absolute zero.

**Table B.1:** MP mass at locations within existing OWFs having different water depths. The design locations consist of a farm number (F) and a design location (DL). The MP mass is normalized between 0 and 1 for confidentiality reasons, with 0 being the MP with the lowest mass and not being absolute zero.

| Design location | Water Depth [m] | MP Mass [-] |
|---|---|---|
| F01DL1 | 30 | 0.20 |
| F01DL2 | 21 | 0.07 |
| F02DL1 | 18 | 0.12 |
| F02DL2 | 18 | 0.28 |
| F03DL1 | 32 | 0.16 |
| F03DL2 | 36 | 0.30 |
| F03DL3 | 29 | 0.13 |
| F03DL4 | 33 | 0.24 |
| F03DL5 | 37 | 0.32 |
| F04DL1 | 33 | 0.24 |
| F04DL2 | 34 | 0.32 |
| F05DL1 | 45 | 1.00 |
| F05DL2 | 45 | 0.77 |
| F05DL3 | 45 | 0.90 |
| F05DL4 | 45 | 0.73 |
| F06DL1 | 31 | 0.33 |
| F06DL2 | 39 | 0.45 |
| F07DL1 | 22 | 0.00 |
| F07DL2 | 32 | 0.09 |
| F08DL1 | 24 | 0.15 |
| F08DL2 | 26 | 0.14 |
| F08DL3 | 30 | 0.29 |
| F08DL4 | 38 | 0.44 |
| F09DL1 | 24 | 0.39 |
| F09DL2 | 36 | 0.62 |
| F10DL1 | 25 | 0.17 |
| F10DL2 | 33 | 0.24 |
| F11DL1 | 26 | 0.35 |
| F11DL2 | 33 | 0.39 |
| F11DL3 | 37 | 0.44 |
| F12DL1 | 29 | 0.41 |
| F12DL2 | 34 | 0.42 |
| F12DL3 | 38 | 0.41 |
| F13DL1 | 35 | 0.12 |
| F14DL1 | 40 | 0.56 |
| F15DL1 | 40 | 0.60 |
| F15DL2 | 40 | 0.59 |

# Appendix C

# Shortcoming Tool 2

Figure C.1 shows the MP mass based on support structure designs created with Tool 1 & 2. The graph visualised the shortcoming of Tool 2 to make proper designs at water depths below 10 m.

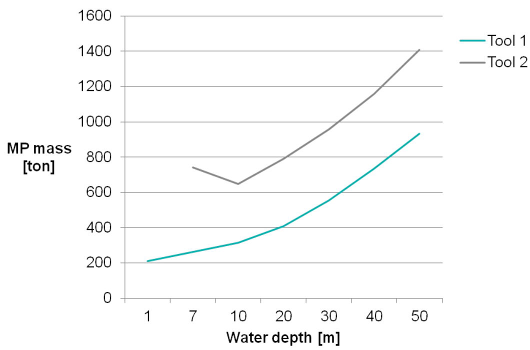



**Figure C.1:** MP mass estimations with Tool 1 & 2. Designs based on sand dominated soil with a friction angle of 37.5°. Visualising the shortcoming of Tool 2 to make proper designs at water depths below 10 m.

# Appendix D

# Assumptions of the Support-Structure Designs Created With Tool 3

In this Appendix, the assumptions of the support structure designs created with Tool 3 are described for every design step individually.

**Step 1: Define initial geometry** The initial geometry is characterised by a hub height and interface level of 100 m, respectively 18.5 m above MSL. Those values are held constant for all designs. The diameter of the tower at interface level is 6 m. The MP diameters vary dependent on water depth with respectively 7.5, 7.8 and 8 m at 20, 30 and 40 m water depth.

**Step 2: Determine diameter based on natural frequency** In the designs a natural frequency check is performed, however, the natural frequency is not used as parameter in the designs. For the check, the value of the natural frequency must be at least 10% above the 1P frequency. With the chosen diameters in step 1 the natural frequencies did not coincide with this criterion.

**Step 3: Identification of loads** The aerodynamic loads are held constant. The wind climate used is Hollandse Kust Zuid [58] of which the frequency and directional distribution can be found in Figure D.1. The hydrodynamic loads are varying with the water depth. However, in this study the significant wave height, maximum wave height and the wave period are held constant at respectively 7.4 m, 14.5 m and 12.9 s. Waves are held constant to reduce complexity of research. The design process is mainly FLS driven, which determined the wall thickness and diameter. The penetration depth is ULS driven.

**Step 4: Determine length based on foundation stability** The pile length is determined by the water depth and the penetration depth. The penetration depth is determined by the application of the ULS loads on the structure and check whether the displacement and rotation at the mudline were within the specified limits.

**Step 5: Determine wall thickness based on strength checks** No buckling checks are performed, because this is not relevant for a MP since buckling is most of the time occurring at the tower top with small wall thickness. The MP is optimised for a $\frac{D}{t}$-ratio of less than 130.

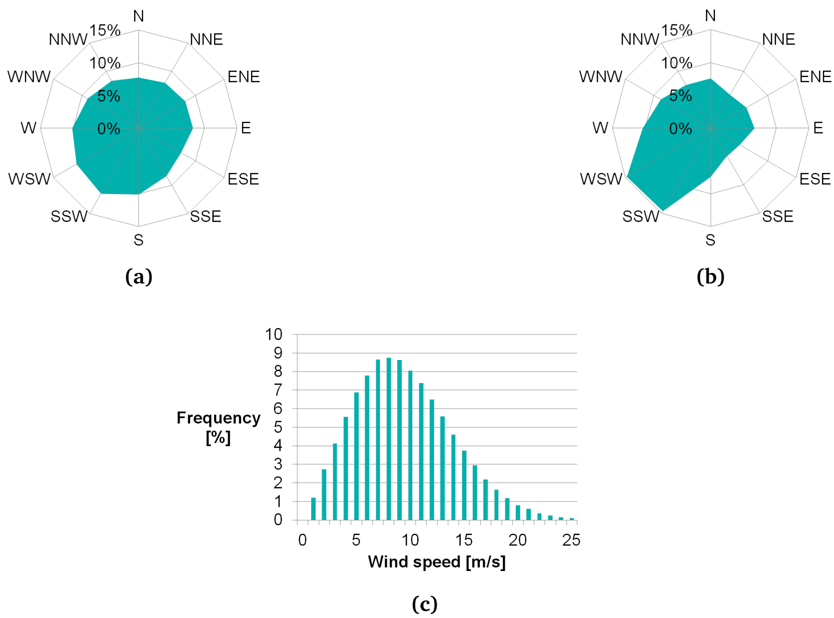
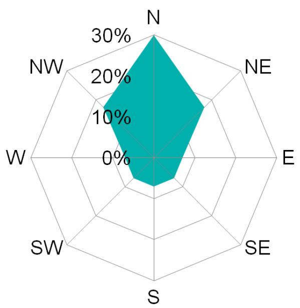



**Figure D.1:** Wind climate of Hollandse Kust Zuid. Expressed are the mean wind speed (a) and frequency (b) distribution with respect to the wind direction and the frequency distribution of wind speed (c).

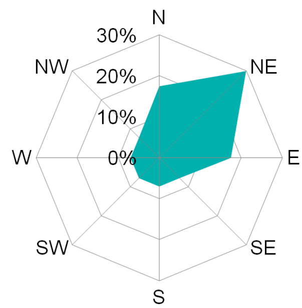
# Appendix E

# Variations in Dominant Wind Direction

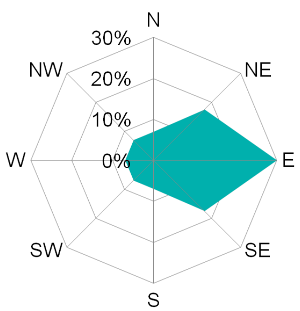
Figure E.1 on the next page shows the frequency distributions of the four dominant wind directions used in sub-case 1c of Section 6.2.



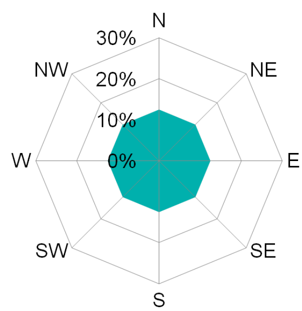

(a)




(b)




(c)




(d)

**Figure E.1:** Frequency distributions of the four dominant wind directions used in sub-case 1c. Expressed are North (a), North-East (b), East (c) and Uniform (d)

# Appendix F

# Krieger's Flak Project Costs

In Table F.1 an estimation of the project costs of Krieger's Flak are displayed. This is used as input for the OWFLOs. The CapEx are based on the breakdown, explained in Section 2.3.3. The OpEx valued at 2% of the CapEx, including an estimation of the MP costs at 20 meters, described in Section 2.3.2.

**Table F.1:** Project cost estimation of Krieger's Flak.

| Aspect | Cost per WT [$k$€] | 70 WTs [$k$€] |
|---:|:---:|:---:|
| WT [a] | 7,200 | 504,000 |
| Electrical equipment | 2,357 | 164,990 |
| Installation | 1,802 | 126,140 |
| Other | 1,386 | 97,020 |
| Total CapEx [b] | 12,745 | 892,153 |
| OpEx | 277 | 19,408 |

[a] Including TP and tower.
[b] Excluding MP.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