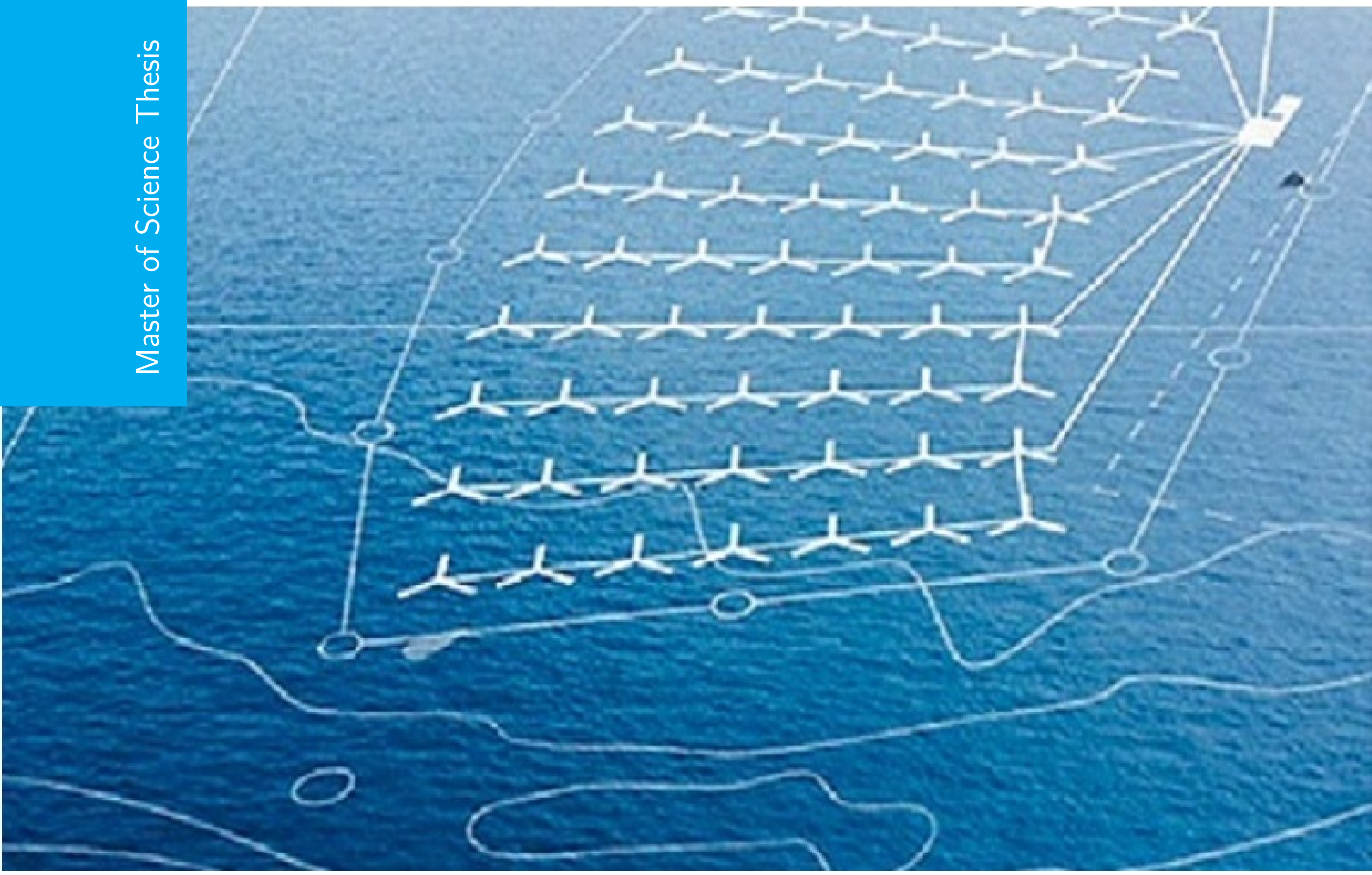
Infield Cable Topology Optimization of Offshore Wind Farms

Georgios Katsouris

Master of Science Thesis



Faculty of Applied Sciences

Infield Cable Topology Optimization of Offshore Wind Farms

Master of Science Thesis

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

Georgios Katsouris

September 16, 2015

Faculty of Applied Sciences
Delft University of Technology

DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
WIND ENERGY

The following members of the Thesis committee certify that they have read and recommend to the Faculty of Applied Sciences for acceptance a thesis entitled

INFIELD CABLE TOPOLOGY OPTIMIZATION OF OFFSHORE WIND FARMS

by

GEORGIOS KATSOURIS

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE SUSTAINABLE ENERGY TECHNOLOGY

Dated: September 16, 2015

Supervisors:	Dr. ir. Michiel Zaaijer
	PhD student Sílvio Rodrigues
Thesis committee:	Prof. dr. Gerard van Bussel
	Dr. ir. Michiel Zaaijer
	Dr. eng. Pavol Bauer

Abstract

As part of the effort to reduce the cost of offshore wind energy, this thesis addresses the problem of the design of the infield cable topology for offshore wind farms. The final outcome of the project is a tool that can be implemented in a more general optimization platform for offshore wind farm design. Therefore, the main objective is to approximate the optimal inter-array cable connections in affordable computation times.

A review of the state of the art collection system designs indicates the radial and branched designs as the designs with the highest potential among the conceptual designs. The key target of the optimization procedure is the minimization of cable cost. Regarding the design constraints, cable capacities are respected and inter-array cable crossings are strictly avoided. The literature review of the related research reveals the complexity of the problem and pinpoints the use of heuristic methods.

Planar Open Savings (POS) [1] and Esau-Williams (EW) [2] heuristics are chosen to treat the single cable radial and branched designs respectively. Both algorithms are saving heuristic methods, starting from a star design. At each iteration, the merging of two routes is considered that could yield to the maximum cost saving. After the implementation of the algorithms is validated, a methodology is proposed to allow the possibility for multiple cable types.

The behaviour of the heuristics is evaluated both cost and time-wise in a wide range of instances. The results show that the parameters that differentiate their behaviour are the use of single or multiple cable types and the position of the substation, which can be located either centrally or outside the area of the farm. Moreover, a hybrid approach between POS and EW is developed that improves the performance of EW for multiple cable types. Finally, specific recommendations are made regarding the use of the best algorithm for each case.

The practicality of the developed tool is enhanced by including the possibility to choose the switchgear configuration and by eliminating the crossings between inter-array cables and transmission lines. Last, modifications allow the minimization of crossings with pipelines/cables that are possibly laid on the seabed. Throughout the report, the comparison of results provided by the tool with the actually installed layouts shows the prospects of inter-array cable cost reductions.

Acknowledgements

First of all, I would like to thank my supervisors Michiel Zaaijer and Sílvio Rodrigues for their guidance throughout my thesis. Our discussions were always a source of new insights and helped me in staying on track.

On a personal level, I wish to thank first my partner Valentina, for bearing with me all these months. Her valuable support helped me overcome the difficulties that I encountered through this work. Moreover, I have to thank my family for believing in me and supporting me throughout my studies. Last, I should not forget my friends, both in Delft and Greece, for the relaxing moments we shared.

Georgios Katsouris
Delft, September 2015

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Chapter 1

Introduction

This Chapter presents the motivation for this Master Thesis. First, the importance of optimization in offshore wind farms is outlined with emphasis given to the inter-array cable topology. Next, the problem statement and the objectives are described and finally, the layout of the report is given.

1-1 Motivation

The continuously increasing energy demand which has led to the depletion of fossil fuels alongside with the evident signs of climate change have escalated the efforts towards an energy transition. Over the past years, Renewable Energy Sources (RES) such as solar, biomass, geothermal, hydroelectric and wind energy have emerged as potential alternatives to fossil fuels. The main driver behind this transition is the fact that the exploitation of RES can reduce the global warming emissions and offer secure and inexhaustible energy supply.

The regulations which have been established in an international level, among which the most significant are the Kyoto Protocol and European Commission 20-20-20 targets, contributed to the implementation of RES. The penetration of RES reached 19% of the global final energy consumption for 2011 where particularly, Wind Energy was 39% of the global renewable power added in 2012 [3].

Furthermore, over the past decade Offshore Wind Farms (OWF) have gained attention as power stations. The increased wind potential and the area availability compared to onshore sites are the key factors for the offshore wind energy exploration. The European Wind Energy Association (EWEA) predicts installed capacity in Europe to rise from currently 8 GW to 150 GW by 2030, meeting 14% of EU electricity demand [4].

However, a highly dissuasive factor for the further implementation of offshore wind energy still is the relatively high Levelized Cost of Electricity (LCOE) compared to fossil fuels and other RES, mainly due to high investment and operation and maintenance costs. Particularly, compared to an onshore wind farm where costs are dominated by the wind turbine, as far as OWF are concerned the wind turbines, support structures, electrical infrastructure, installation and maintenance all contribute significantly to the LCOE. Figure 1-1 presents the capital cost breakdown of an OWF.

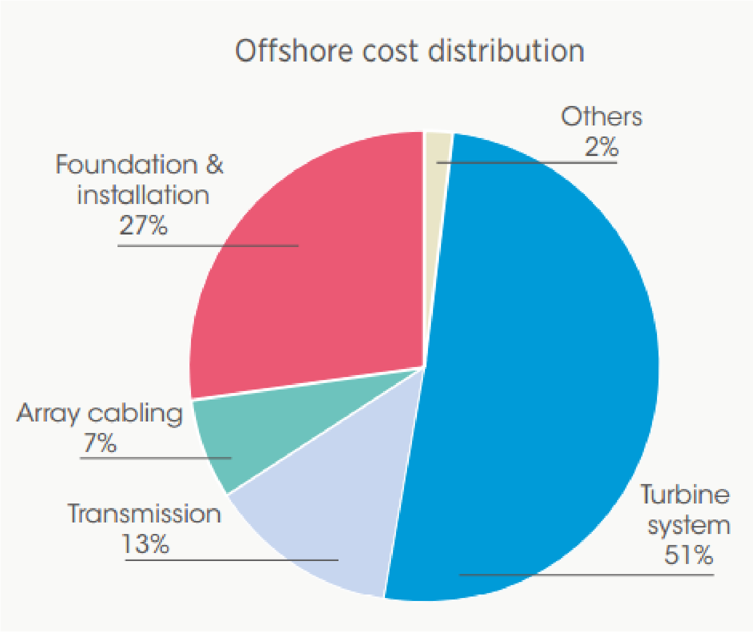

Figure 1-1: Capital cost breakdown for typical OWF [5].

In an effort to reduce the LCOE of offshore wind energy, research has been focused on the optimization of the design of OWF, a multidisciplinary procedure which is required to take into account the interactions between various parts of the system. One of the most important design decisions includes the spacing between wind turbines, which directly affects the wake losses and the cost of the inter-array cables. The latter, as it can be seen in Figure 1-1, account for 7% of the capital cost. By taking into account the cable losses and the issue of reliability, the optimization of the inter-array cable topology becomes vital for the design procedure.

The review of the literature (Section 3-2) indicates that the optimization of the electric design of OWF has developed relatively recently. Moreover, emphasis has been placed on finding the optimal solution for the transmission of the generated power from the substation to the onshore connection point. Considering also the plans for the North Sea Offshore Grid [6], the optimization problem of the electric layout is narrowed down to the area of the farm. Thus, the current project is intended to contribute to the infield cable optimization of OWF.

1-2 Objective

Taking into account all the above, the objective of the project can be summarised as follows: *Given the position of the turbines and substations, find the optimal inter-array cable topology*

that minimizes the total cable cost without violating the cable capacity.
The final outcome of the project is a tool that can be implemented in a more general optimization platform for OWF design. Therefore, the main aim is to approximate as much as possible the optimal solutions in affordable computation times. The approach that is used to achieve the aforementioned objective can be described in the following steps:

- Analyse the state of the art inter-array cable topologies.
- Define the key requirements for the design of the inter-array cable topology.
- Develop and implement algorithms to satisfy these requirements.
- Validate the tool by applying it in layouts of existing OWF.
- Compare the results with the actually installed topologies.

1-3 Layout of the Report

The layout of the report is organized as follows:

Chapter 2 presents an overview of the state of the art electrical collection system designs for OWF and presents the design requirements.

Chapter 3 explains how the Offshore Wind Farm Infield Cable Topology Problem (OWFICTP) is formulated and provides a literature review of the related research.

Chapter 4 and **Chapter 5** present the heuristics that treat different configurations of the Infield Cable Topology (ICT).

Chapter 6 contains the approaches that were developed to incorporate multiple cable types in the aforementioned heuristics.

Chapter 7 provides a comparison of the developed approaches and proposes improvements in terms of a hybrid algorithm.

Chapter 8 presents practical improvements to the algorithms and a case study.

Chapter 9 includes the conclusions and recommendations of the thesis.

Chapter 2

Electrical Collection System for Offshore Wind Farms (OWF)

This Chapter gives an overview of the electrical system of OWF and then focuses on the collection system by presenting its conceptual designs and the design requirements.

2-1 Electrical System Overview

The electrical system for OWF usually consists of a medium-voltage electrical collection grid within the wind farm and a high-voltage electrical transmission system to deliver the power to an onshore transmission line. Figure 2-1 presents a typical electrical layout of an offshore wind farm.

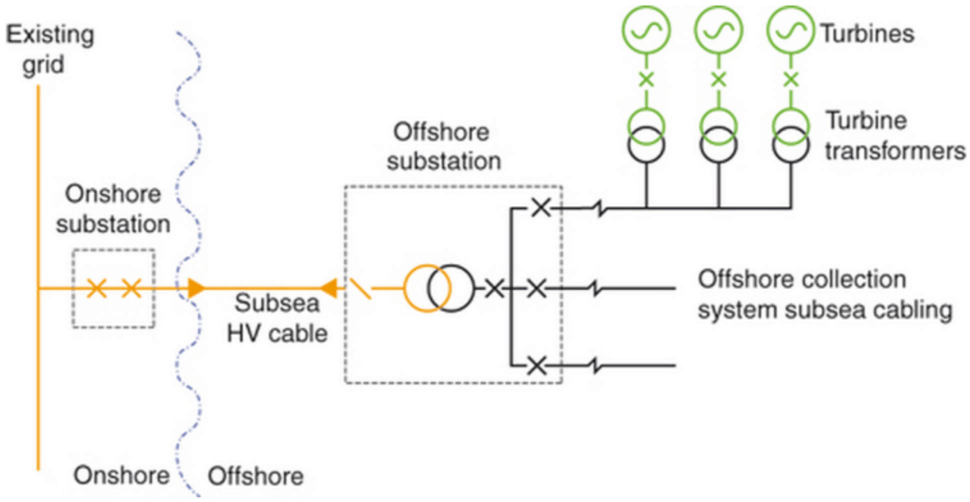

Figure 2-1: Typical electrical layout of an offshore wind farm [7].

2-1-1 Collection System

The turbine generator voltage is typically 690 V. In order to minimize the losses in the inter-array cables of the collection system, transformers at each wind turbine step up the generation voltage to a medium voltage in the range 10 to 35 kV. Also, medium voltage submarine cables, buried 1 to 2 meters deep in the seabed, are used to inter-connect the wind turbines and transmit the power to an offshore substation. Section 2-2 presents the typical configurations that are used for the collection system.

2-1-2 Transmission System

The transmission system starts at the offshore substation, which steps up the voltage to a transmission voltage of 150 kV. Currently, this is the most common voltage level for submarine power cables, but it can reach nowadays 500 kV. The high-voltage submarine cables transmit the power to the point of connection with the onshore grid, where possibly an onshore substation steps up the voltage to match the voltage of the transmission onshore grid.

The two technologies that are used for the transmission system are: High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC). The key parameter for the choice between these two technologies is the transmission distance. For distances shorter than 100 km, HVAC is the most economical option whereas for longer distances, HVDC is preferred [8]. Some limiting factors of HVAC include the thermal limitation of cable current and therefore the limitation of the transmitted power, the significant Ohmic losses of the cables and the necessary reactive power compensation. On the other hand, HVDC does not need reactive power compensation, suffers lower electrical losses but has high initial costs because of the AC/DC and DC/AC converters and filters at both ends of the transmission line.

2-2 Electrical Collection System Designs

There are several configurations for the electrical collection system of OWF. The design decision depends mainly on the size of the wind farm and the desired level of reliability. In the past years, the size of OWF was relatively small, thus simplified designs were used for the collection system and reliability was not taken into account. But as wind farm sizes increase, the amount of energy lost during a fault might be high enough to overcome the initial costs of a design that provides reliability to the wind farm. The conceptual designs that are widely used in OWF, as described in [9], are:

- Radial design, where wind turbines are connected to a single series circuit
- Ring design, where reliability is established through loops between wind turbines
- Star design, where the wind turbines are distributed over several feeders, allowing the use of lower rated equipment.

2-2-1 Radial Design

The most straightforward arrangement of the collection system in a wind farm is a radial design (Figure 2-2), in which a number of wind turbines are connected to a single cable feeder within a string. The power rating of the wind turbines and the maximum rating of the cable within the string determine the maximum number of wind turbines on each string feeder. The advantages of this design is that it is simple to control, the total cable length is relatively small and allows the use of low capacity cables further out in each feeder. The major drawback of this design is its poor reliability as cable or switchgear faults at the end of the radial string closer to the substation have the potential to prevent all downstream turbines from exporting power. Nevertheless, it is considered to be the best choice for relatively small OWF.

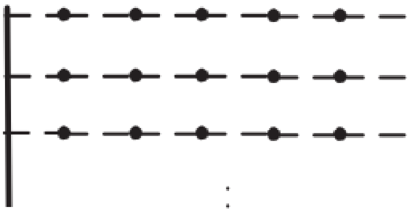

Figure 2-2: Radial Design [10].

2-2-2 Ring Design

Ringed layouts can supply the reliability, which the radial design lacks of, by incorporating a redundant path for the power flow within a string. The additional security comes at the expense of longer cable runs for a given number of wind turbines, and higher cable rating requirements throughout the string circuit. There are two ring designs for the collection system, namely the single-sided ring (Figure 2-3) and the double-sided ring (Figure 2-4).

A single-sided ring design requires an additional cable running from the last wind turbine of the feeder to the substation. This cable must be able to handle the full power flow of the string in the event of a cable fault connecting the first turbine of the strict to the substation. The cost of this design is doubled, compared to the cost of a radial layout. However, it is also the most reliable and the one with the least losses.

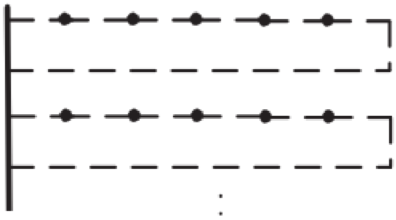

Figure 2-3: Single-Sided Ring Design [10].

In a double-sided ring design, the last wind turbine in one string is interconnected to the last wind turbine in the next string. Compared to the radial design, the cable length will only increase by the distance between the turbines at the end of the feeders. However, the cables, at least those connecting the first turbines of the feeders to the substation, should be able to handle the power output of more than double the number of wind turbines which are connected in a single feeder. This option is thought to be around 60% more expensive than a radial design but in the long-term and depending on the size of the wind farm and the possible faults, it can be the most economical choice.

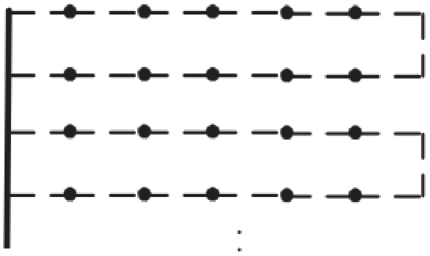

Figure 2-4: Double-Sided Ring Design [10].

Also, the concept of multi-ring design has been proposed. The difference from the double sided ring is that instead of simply connecting two feeders in parallel, a higher number of feeders are connected in parallel. The idea is to reduce the high power rating of cables and equipment which is necessary in the double sided feeder design.

2-2-3 Star Design

The star design, as presented in Figure 2-5, can be used to reduce cable ratings and to provide a high level of security for the wind farm, since a cable fault can only affect one wind turbine except for the case when a fault occurs in the feeder cable to the substation. Voltage regulation along the cables between wind turbines is also likely to be better in this design. However, cables can be longer and the switchgear more complex, especially at the centre of the star, so the cost advantage depends on the specific case under study.

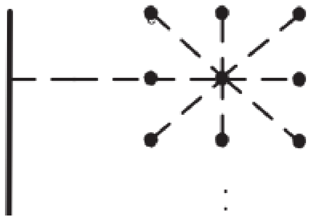

Figure 2-5: Star Design [10].

2-2-4 Branched Design

In addition to the aforementioned conceptual designs, the branched design (Figure 2-6), which is widely used for communication networks, has gained attention for its use in OWF. In a branched topology, there are more than one endpoints that are created by adding branches to the main feeder. In principle, it is a hybrid between the ring and star designs. The advantages of the branched design are comprehensively presented in Section 5-1 among which, its lower cost and higher reliability compared to the radial design are mentioned.

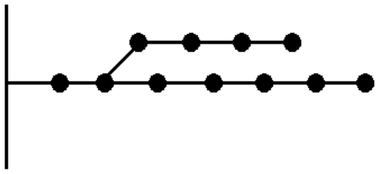

Figure 2-6: Branched Design.

2-3 Requirements of the Collection System Design

In order to tackle the problem of the collection system design for OWF, firstly the engineering requirements need to be defined. These requirements include the targets of the optimization approaches, constraints that need to be respected and options that could be given to the designers.

2-3-1 Targets

To start with, the optimization of the inter-array cable topology is a part of a more general cost-wise optimization of the entire OWF. As it was shown in Figure 1-1, the cost of the infield cables represents 7% of the total capital cost. Therefore the key target of the optimization procedure is to achieve the lowest cable costs in terms of cable length, if one cable type is available or in terms of total cable cost, if more than one cable type is available.

Furthermore, reliability is a key factor for the economic viability of an OWF project. Taking into account the offshore harsh conditions that make maintenance difficult or sometimes even impossible, and the amount of power that can be lost during a cable fault, makes clear the importance of reliability especially for large OWF. In Section 2-2, layouts were presented that provide reliability but choosing between layouts that provide reliability or not is a multi-objective process, highly site-specific and includes probabilistic analysis. Nevertheless, the reliability is an important design driver.

Lastly, minimization of collection system losses is another goal that could be implemented in the optimization procedure. The electrical losses depend mainly on the voltage level but they can significantly vary between different cable configurations.

2-3-2 Constraints

The main constraint of the Infield Cable Topology (ICT) design is imposed by the fact that the inter-array cables are trenched into the seabed. Taking this into account, it is a strict design requirement that cables should not cross each other. Also, as far as the cases where the substation is centrally located inside the farm, between the turbines, the transmission lines should not cross the infield cables.

Another aspect that can be involved during the design of the collection system is area constraints. There can be areas within the OWF where wind turbines cannot be put and cables cannot cross them such as shipwrecks or due to shallow waters. Also, there are areas such as pipelines, over which cables can be installed but the installation cost is significantly higher. Finally, there are areas where wind turbines cannot be put but it is possible to lay cables within them (e.g. areas close to oil platforms which should be accessible from helicopters). Thus, treating the aforementioned area constraints is another challenge of the optimization process.

2-3-3 Options

Regarding the options that could be given to the designers, the possibility to choose between different configurations is of great importance. For the current project, only radial and branched designs are treated, since currently they show the highest potential among the conceptual designs.

In addition, as it was mentioned earlier, one of the features of the recent OWF is the use of multiple cable types. The reason is that by using the available cables close to their rated capacity, a significant cost reduction can be achieved. Thus, the possibility for multiple cable types should definitely be included.

Finally, considering the uptrend in OWF sizes, more than one substation is used nowadays to handle the power production from the turbines. As a result, there is a need to define which turbines will be allocated to the available substations.

Chapter 3

The Infield Cable Topology Problem

In this Chapter, the Offshore Wind Farm Infield Cable Topology Problem (OWFICTP) is presented. A first definition of the problem was given in Section 1-2. Including the key requirements as given in Section 2-3, the objective of the OWFICTP is to optimize the cable topology of the collection system, given the positions of turbines and substations, while the cable capacities are not exceeded, the cables do not cross each other and area constraints are respected.

3-1 Problem Formulation

The basic assumption for the formulation of the problem is that all turbines in a wind farm have the same power rating. To the best of the author's knowledge, only one type of wind turbine is used within one farm. Therefore, the cable capacities' constraints can be simply expressed in numbers of turbines, instead of current or power. In addition, having in mind the fact that the positions of turbines and substations are predetermined, it is assumed that there is not a limitation in the power that each substation can handle. In order to clarify the latter, if we imagine the layout of typical Offshore Wind Farms (OWF) with two substations, they are put in a way that the turbines are more or less equally distributed over the substations. Thus, for the purposes of the thesis, a possible limitation of the substation capacity is out of scope.

The input data of the problem are the following:

- A set $T = \{t_1, ..., t_T\}$ of wind turbines, described by their coordinates: $t_i = (x_i, y_i)$
- A set $S = \{s_1, ..., s_S\}$ of substations, described by their coordinates: $s_i = (x_i, y_i)$
- A set $R = \{r_1, ..., r_R\}$ of cables, described by their capacity n and cost c: $r_i = (n_i, c_i)$.

Merging the set of turbines T and substations S, yields the set of given sites: $G = \{u_1, ..., u_G\} = T \cup S$. Now, assuming that the points in G are given in the Euclidean plane, thus discarding any terrain elevation, the distance between two sites u_k and u_v is equal to: $d(u_k, u_v) = \sqrt{(u_{k,1} - u_{v,1})^2 + (u_{k,2} - u_{v,2})^2}$. Furthermore, including the cost of the cable r_i that is installed between u_k and u_v, yields the cable cost that is needed to connect these points: $C(u_k, u_v) = d(u_k, u_v) * c_i$. It should be noted that the additional cable cost, induced by the cable from the bottom of the foundation to the transformer and back down, is irrelevant for the optimization problem and hence, it is not taken into account.

The solution of the OWFICTP is a set of connections $P = \{(u_{k_1}, u_{v_1}, r_i^{kv})_1, ..., (u_{k_p}, u_{v_p}, r_i^{kv})_p\}$ where $u_k, u_v \in G$ and $r_i^{kv} \in R$ and denotes which cable type has been used for the connection between the nodes u_k and u_v. This set of connections corresponds to a graph, as it is defined in graph theory. Thus, the objective function of the optimization problem is the following:

$$\sum_{(u_k, u_v, r_i^{kv}) \in P} d(u_k, u_v) * c_i^{kv} \tag{3-1}$$

where $d(u_k, u_v)$ is the distance between nodes u_k and u_v and c_i^{kv} is the cost of the cable that is used for the connection between these nodes.
The cable installation should connect every turbine with exactly one substation over one distinct path, since ring designs are not treated. Also, the capacity of the cable with the highest capacity among the available cables ("thickest" cable) should not be exceeded. In addition, the cables should not cross each other and the option to choose between radial and branched designs is given to the designer.

3-2 Literature Review

Although research has been focused on the optimization of the transmission system of OWF, due to its higher cost compared to the collection system, considerable work has been done in the optimization of the total electrical layout. Moreover, algorithms that have been developed with a focus on onshore wind farms may be applicable to OWF as well. Hence, this Section gives an overview of the previous work that has been done in the field.

Dutta [11] optimizes the collector system design of an onshore wind farm with regard to the cable length. First, she uses a Minimum Spanning Tree (MST) algorithm which is improved in a second version by allowing Steiner points. In order to incorporate the limitation on the number of turbines that can be connected on a feeder, she uses k-means clustering for restricting the maximum number of turbines. Then, the MST is calculated for each cluster. Last, for each resulting tree, the cable installation can be calculated by selecting a terminal node and choosing the best cable for transporting the power of the terminal node along its incident edge.

Berzan et al. [12] decompose the problem in three layers: the Circuit Problem, the Substation Problem and the Full Farm Problem. The Substation Problem corresponds with the OWFICTP where only one substation is available. For their model, they consider costs which take into account the type of cable and the terrain used by the installation. For the single cable type version of the problem, they formulate it as a Capacitated Minimum Spanning

Tree (CMST) Problem and use the Esau-Williams (EW) heuristic to approximate its solution. They report solutions to problems with up to 1000 turbines but cable crossings are allowed. Lastly, they do not treat the multiple cable types Substation Problem, where more than one cable type is available.

Hertz et al. [13] formulate the design of an onshore wind farm collection system as a Mixed-Integer Linear Programming (MILP) problem. Therefore, they assume that two cable types are available, one for underground and one for above-ground connections between a set of nodes which includes the turbines, the substation and transmission line endpoints. After tightening the MILP formulation by including some cutting planes, they managed to find the optimal solutions in most instances tested, but they report CPU time of one hour on average.

In his work [14], Fagerfjäll addresses two models: the production model and the infrastructure model. The cable installation is a subset of the infrastructure model and he also formulates a MILP version of the problem. The difference with Hertz et al. [13] is that the positions of the turbines are not fixed. Also, he reports computation times of over 10 minutes to find the optimal solution for a problem with 30 turbines.

Lumbreras and Ramos [15] have developed an Offshore Wind Farm Layout optimizer (OWL) that calculates optimal electrical layouts in affordable computation times. Their model receives the characteristics and positions of wind turbines, the Point of Common Coupling (PCC) and the possible locations of offshore substations, as well as the cable, transformer and converter types available and incorporates losses, reliability of the components and wind scenarios. The problem is formulated as a stochastic Mixed-Integer Programming (MIP). In order to reduce the computational time, they apply Benders' Decomposition and Scenario Aggregation techniques and they use Progressive Contingency Incorporation (PCI) to address the reliability issue.

One of the first articles that treats explicitly the internal electric connection of Large OWF was developed by Li et al. [16]. In order to solve the problem, they use a hybrid of genetic and immune algorithms. After producing the scenarios for the internal connection, they calculate the annual cost for each alternative, by including power losses in cables and a depreciation period of the investment of 20 years.

A Genetic Algorithm (GA) has been used also by González-Longatt et al. [17] in order to find the optimal collection system for large OWF. In their model, they combine the GA with the classical multiple Traveling Salesman Problem (mTSP) which designs a local collection system, considering multiple radial feeders connected to the PCC. They report a computation time of 10.2 minutes for a wind farm with 100 turbines and cable crossings are also allowed.

Bauer and Lysgaard [1] developed a hop-indexed formulation with planarity constraints in order to find the optimized inter-array cable connections in OWF that are composed only by open routes, which means that cables cannot cross each other and branching is not allowed. Also, they adapted the Vehicle Routing Problem (VRP) heuristic of Clarke and Wright to a Planar Open Vehicle Routing Problem (POVRP) that calculates sub-optimal open routes. They report on average 2% sub-optimal solutions with a computational time of less than 0.1 s. Also, they treat the optimization problem of two cable types but only for the hop-indexed formulation.

3-3 Discussion

The OWFICTP is a Non-deterministic Polynomial-time hard (NP-hard) problem in combinatorial optimization. In the found literature, different ways to tackle the optimal collection system of OWF have been developed. Classical mathematical optimization methods with additional integer constraints and techniques to decompose the problem can produce optimal solutions in affordable computation times but for relatively medium sized OWF. On the other hand, hybrids of GA seem promising for optimizing the collection systems of Large OWF.

However, if we take into account the trend for larger OWF in the future, composed by up to 200 wind turbines, it is not guaranteed that an optimal solution for the collection system can be found, at least for the time being. On the other hand, sophisticated heuristics have been developed that can efficiently approximate the optimal solution for the OWFICTP. A good example, as presented in Section 3-2, that calculated near-optimal open routes, is the POVRP heuristic developed by Bauer and Lysgaard [1]. Also, EW is considered the most efficient algorithm for finding a near-optimal solution for the CMST, which corresponds to the OWFICTP if branched topologies are desirable.

Furthermore, the objective of the thesis is to develop an optimization tool for the collection system of OWF that can be implemented in a more general optimization platform for OWF design. Such a platform optimizes every aspect of the design, including the positions of the wind turbines, support structures, electrical connection scheme and operation and maintenance strategy. In most cases, it is an iterative multidisciplinary procedure that starts from an initial guess and converges to an optimized design. Thus, it is clear that there is a need for fast solutions, as close to optimal as possible.

To sum up, heuristics are the only option for providing efficient solutions for NP-hard problems as the design of the collection system, in terms of computation time and final cost. Therefore, the focus on the next chapters will be on implementing the most efficient heuristics that have been developed so far and adapting them to the needs of the OWFICTP.

Chapter 4

Radial Offshore Wind Farm Infield Cable Topology Problem (OWFICTP)

This Chapter treats the radial OWFICTP, where the feeders that connect the turbines to the substation are in the form of open routes and requirements as cable ratings and the condition that cables do not cross each other are respected.

4-1 Planar Open Savings (POS) Heuristic

As presented in Section 3-2, POS heuristic, as developed by Bauer and Lysgaard [1], is one of the most efficient heuristic algorithms for the radial internal connection of Offshore Wind Farms (OWF). They report solutions for the single cable type problem, 2% worse than optimal. POS is an adaptation of the Clarke and Wright savings heuristic [18]. The differences between these two are the open routes and planarity constraints as imposed by the cable crossings condition.

POS is a greedy heuristic in the sense that in every step, it considers merging of two routes that could yield the maximum saving of the cost of the current solution. In the initial solution, every wind turbine is connected with a single line to the substation. The following Sections presents the features of the two versions of POS, namely POS1 and POS2.

4-1-1 POS1

POS1 is the first version of the POS heuristic. For the analysis of the algorithm, the terminology as given in Section 3-1 will be used.

Starting from the solution, it should only contain open routes of the form $i - j - ... - k - s$, where $i, j, k \in T$ and $s \in S$. The initial solution, as it was mentioned, takes the form $i - s$. Merging two routes of the form $i - j - ... - k - s$ and $u - v - ... - w - s$ in the route $i - j - ... - k - u - v - ... - w - s$ yields a saving $sv_{ku} = d(k, s) - d(k, u)$ where d is the distance function between two points. All possible savings sv_{ku}, that can be achieved through merges of routes, are calculated beforehand and then are inserted in a Savings matrix, denoted as SV, in order of decreasing value.

In the example given above, the merging of routes by connecting client k to u requires that k and u are the last and first clients respectively, in their corresponding routes. In open routes, as the ones mentioned, the turbine that is directly connected to the substation is called last client whereas first client is considered the turbine that is connected with only one turbine.

Referring now in Section 3-1, it is required that $(k, s) \in P$ and u has only one neighbour in P. In addition, merging of routes requires that the capacity n of the available cable will not be exceeded and that (k, u) does not cross any other connection in P. To account for multiple substations, the turbines in T are allocated to the substations in S based on the minimum cost of the initial solution, meaning that each turbine is connected with the closest substation. A limitation on the capacity of the substations is not taken into account.

The structure of the algorithm, found in [1] and adjusted according to the OWFICTP, is as follows:

```
POS1 (Graph ($T \cup S$, $P$), distance $d(k,u)\ \forall\ (k,u) \in P$, Capacity $n$):
1 foreach $i \in T$ do $s_i = argmin_{s \in S}\{d(i,s)\}$
2 $P \leftarrow \bigcup_{i \in T}\ (i, s_i)$
3 foreach $k$,$u \in T$, $if\ s_k \equiv s_u$ do $sv_{ku} = d(k, s_k) - d(k,u)$
4 $SV \leftarrow$ sorting of $sv_{ku}$ according to decreasing saving
5 repeat
6     (k,u) $\leftarrow$ next element in $SV$
7     if k and u are in different routes,
8     and $(k, s_k) \in P$
9     and u has only one neighbour in P,
10    and the total number of turbines in the routes containing k and u does not exceed n,
11    and (k,u) does not cross any connection in P then
12        $P \leftarrow P \setminus ((k, s_k) \cup (k,u))$
13 until end of SV is reached
14 return P
```

As far as the end of the heuristic method (line 13) is concerned, it is not clarified in [1] and the analysis showed two possible versions. In principle, the Savings matrix SV contains not only positive but also negative elements. Therefore, it is possible that towards the end of the iterative process, merges of routes will be achieved that will lead to a worse solution, compared to the one achieved if only positive savings were examined. It should be noted though that negative saving merges are less likely to happen since at this point, most of the routes that have been formed, use the full capacity of the cable. Therefore, it is possible to stop the heuristic method when the last positive saving has been examined or allow also negative saving merges. In the first approach (POS1), the best solution is achieved whereas the second approach (POS1(-)) will eliminate routes with a small number of turbines connected to it, but with the disadvantage of a slightly higher cost. A thorough comparison between POS1 and POS1(-) can be found in Section 7-4.

The algorithm was implemented in Python [19]. The results of POS1 and POS1(-) implementations for Walney1 OWF [20], for a cable capacity of 10 wind turbines, can be seen in Figures 4-1 and 4-2 respectively. The substation has an index equal to 0 and the turbines 1 to 51. The coordinates that are used, are given in Universal Transverse Mercator (UTM) form and were converted from the corresponding latitude and longitude coordinates [21].

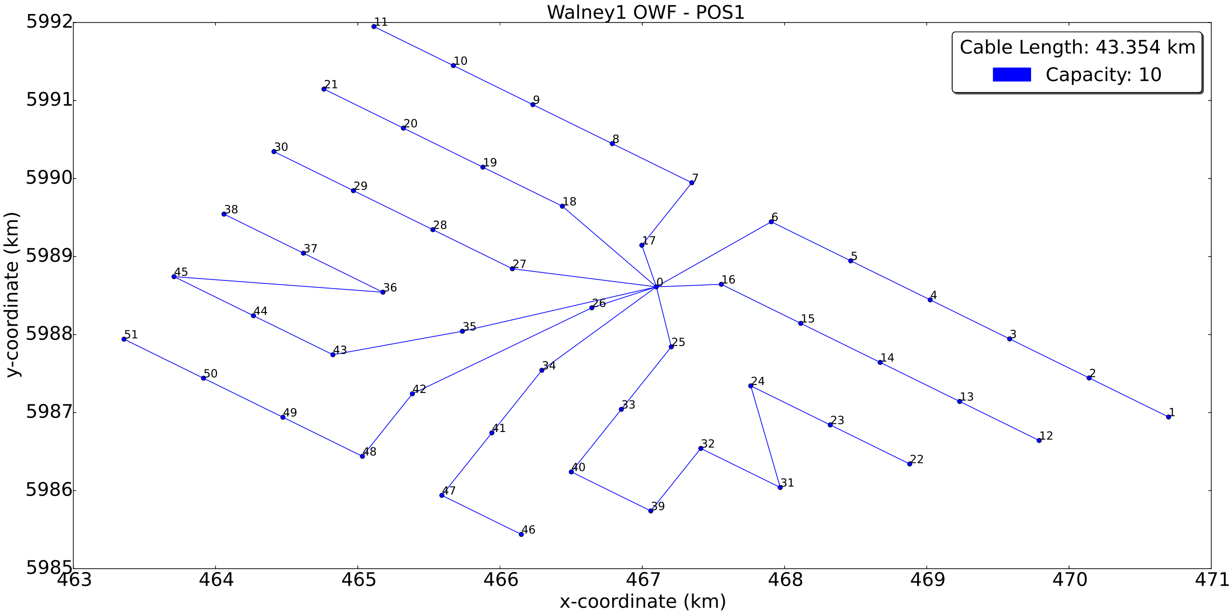

Figure 4-1: ICT generated by POS1 for Walney1 OWF.

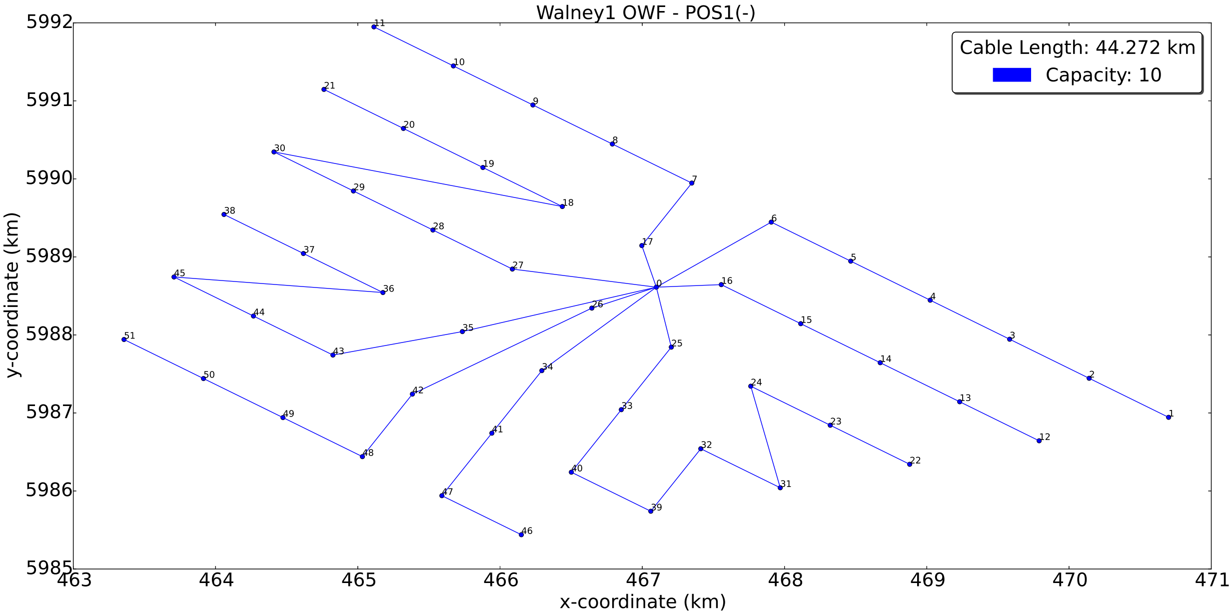

Figure 4-2: ICT generated by POS1(-) for Walney1 OWF.

As it can be seen in the two Figures, POS1(-) achieves an additional merging of the routes

$21-20-19-18-0$ and $30-29-28-27-0$ by connecting turbine 18 with turbine 30, but the solution is $2,12\%$ more expensive than the one calculated by POS1.

Moreover, Figures 4-1 and 4-2 reveal one clearly visible sub-optimality of POS1. As the algorithm proceeds by examining at each iteration the maximum possible saving of merging two routes, two specific routes that have been formed are $22-23-24-0$ and $31-32-39-40-33-25-0$. The merging that is achieved between these routes, from POS1, removes the connection $24-0$ from P and adds the connection $24-31$. On the other hand, merging of these two routes by connecting turbine 22 to 31 could yield a higher saving. But, for POS1 it is not possible since only connections between last and first clients are allowed.

In order to remedy this sub-optimality of POS1, Bauer and Lysgaard developed a more sophisticated version of POS and a local search heuristic that improves sub-optimal routes, namely POS2 (Section 4-1-2) and RouteOpt (Section 4-2) respectively.

4-1-2 POS2

POS2 follows in a great extent the logic of POS1 but it gives more freedom for merges, by allowing not only last to first client connections but also first to first client connections.

The structure of POS2, found in [1] and adjusted according to the OWFICTP, is as follows:

```
POS2 (Graph $(T \cup S,\ P)$, distance $d(k,u)\ \forall\ (k,u) \in P$, Capacity $n$):
foreach $i \in T$ do $s_i = argmin_{s \in S}\{d(i,s)\}$
$P \leftarrow \bigcup_{i \in T} (i, s_i)$
foreach $k$,$u \in T$, $if\ s_k \equiv s_u$ do $sv_{ku} = d(k,s_k) - d(k,u)$
$SV \leftarrow$ sorting of $sv_{ku}$ according to decreasing saving
repeat
    (k,u) $\leftarrow$ next element in $SV$
    if k and u are in different routes,
    and $(k, s_k) \in P$, or k has only one neighbour in $P$
    and u has only one neighbour in $P$,
    and the total number of turbines in the routes containing k and u does not exceed $n$,
    and (k,u) does not cross any connection in $P$ then
        if $(k, s_k) \in P$ then $P \leftarrow P \setminus ((k, s_k) \cup (k,u))$
        else // $k$ has only one neighbour in $P$, which is not $s_k$
            $i \leftarrow$ last client in the route containing $k$
            $P \leftarrow P \setminus ((i, s_i) \cup (k,u))$
            re-insert into $SV$ all arcs $(j,i)$ that were discarded earlier
            because $i$ had two neighbours in $R$
        $v \leftarrow$ first client of the merged route
        $w \leftarrow$ last client of the merged route
        foreach $z \in T$ do
            if z has only one neighbour in $P$ then
                $sv_{vz} \leftarrow d(w, s_w) - d(v,z)$, and update $SV$ accordingly
until end of SV is reached
return $P$
```

The major difference compared to POS1 can be seen in line 8 where also first clients can be examined for a possible merging with a first client of another route. In order to achieve this, lines 14 to 22 contain the necessary adjustments of the algorithm. First, in lines 14-15, if we assume two routes of the form $k - ... - i - s_i$ and $u - ... - w - s_w$, where $s_i \equiv s_w$ and the connection that is examined corresponds to (k, u), the connection between client i and the substation is erased and (k, u) is added in P. So, the merged route is $i - ... - k - u - ... - w - s_w$. Furthermore, it is possible that merging of routes by connecting turbine $j \in T$ with turbine i, have been examined and discarded during the sequence of iterations, since i was neither the last nor the first client in its route. Thus, the reinsertions in lines 16-17 are necessary, in the sense that now, turbine i is the first client in its route. Lastly, if v is the first client of the merged route, a possible merging between v and z, where $z \in P$ and has only one neighbour in P, would erase the connection (w, s_w) from P, corresponding to saving, as given in line 22. Thus, sv_{vz} needs to be updated in SV accordingly.

Figure 4-3 presents the cable topology for Walney1 OWF, as calculated from POS2 for cable capacity of 10 turbines. Compared to POS1 (Figure 4-1), a significant cable length reduction, and therefore cable cost, was achieved of $6,56\%$.

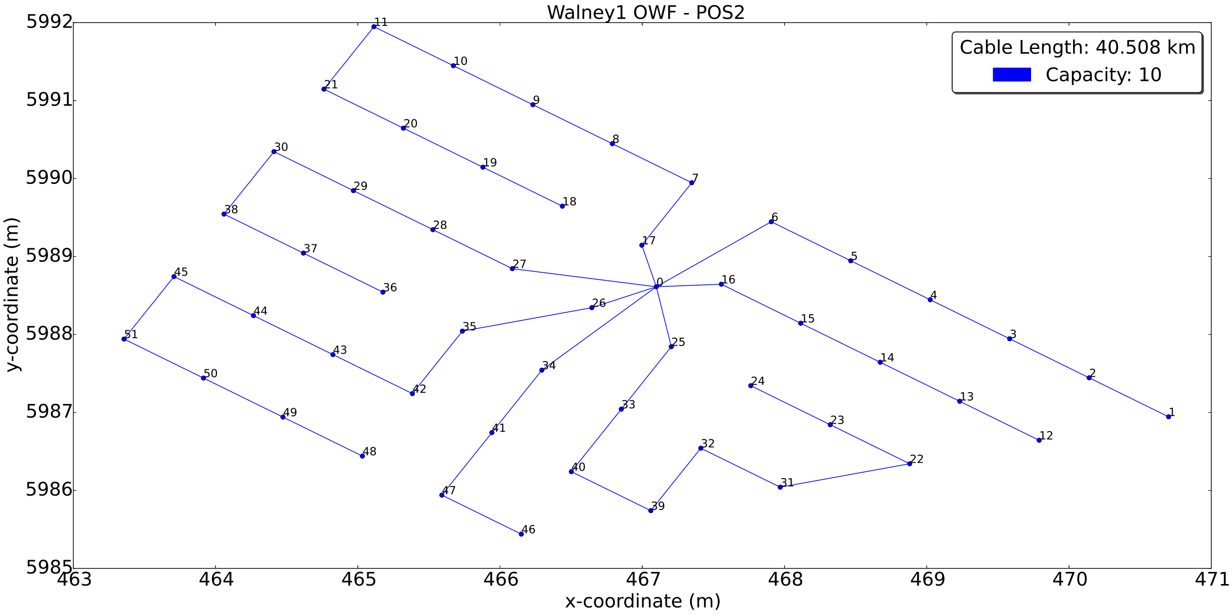

Figure 4-3: ICT generated by POS2 for Walney1 OWF.

4-2 RouteOpt

RouteOpt is a local search heuristic, developed by Bauer and Lysgaard [1] that can improve the generated sub-optimal routes of POS1 and POS2. It should be noted that firstly, the topology is obtained by POS1 or POS2 and then RouteOpt is applied to each individual route. As it can be seen from the results for Walney1 OWF (Figures 4-1, 4-2 and 4-3), RouteOpt is expected to be more effective, in terms of cost reduction, for POS1 compared to POS2, and especially for the version which includes negative savings, namely POS1(-).

Let $r = i_0 - i_1 - i_2 - ... - i_{l-1} - i_l - ... - i_k$ be a route, where $i_k \in S$. RouteOpt examines every feasible route $r_l = i_{l-1} - ... - i_2 - i_1 - i_0 - i_l - ... - i_k$, which is generated from r by exchanging connection (i_{l-1}, i_l) with (i_l, i_0) and where the new connection (i_l, i_0) does not cross any other connection in P. The improvement that is achieved by this exchange is equal to: $d(i_{l-1}, i_l) - d(i_l, i_0)$. For every route that is generated from POS1 or POS2, RouteOpt searches within the route for a maximum improvement, and if it is positive, the exchange is achieved and the procedure carries on until there are no more positive improvements.

The structure of RouteOpt, found in [1] and adjusted according to the OWFICTP, is as follows:

```
RouteOpt (Graph $(T \cup S,\ P)$, distance $d(k,u)\ \forall\ (k,u) \in P$):
foreach route $r = i_0 - i_1 - i_2 - ... - i_{l-1} - i_l - ... - i_k$ do
    repeat
        $sv \leftarrow max_{l \in 1,...,k-1}\{d(i_{l-1}, i_l) - d(i_l, i_0)\}$ if $(i_l, i_0)$ does not cross any connection
        if $sv > 0$ then
            $l \leftarrow$ index for which $d(i_{l-1}, i_l) - d(i_l, i_0) = sv$
            $P \leftarrow P \setminus ((i_{l-1}, i_l) \cup (i_l, i_0))$
            $r \leftarrow i_{l-1} - ... - i_2 - i_1 - i_0 - i_l - ... - i_k$
    until no improvement in r exists
return $P$
```

Figure 4-4 presents the cable topology for Walney1 OWF, after RouteOpt was applied to the results of POS1. Compared to Figure 4-1, RouteOpt eliminated the sub-optimalities of routes $38 - 37 - 36 - 45 - 44 - 43 - 35 - 0$ and $22 - 23 - 24 - 31 - 32 - 39 - 40 - 33 - 25 - 0$.

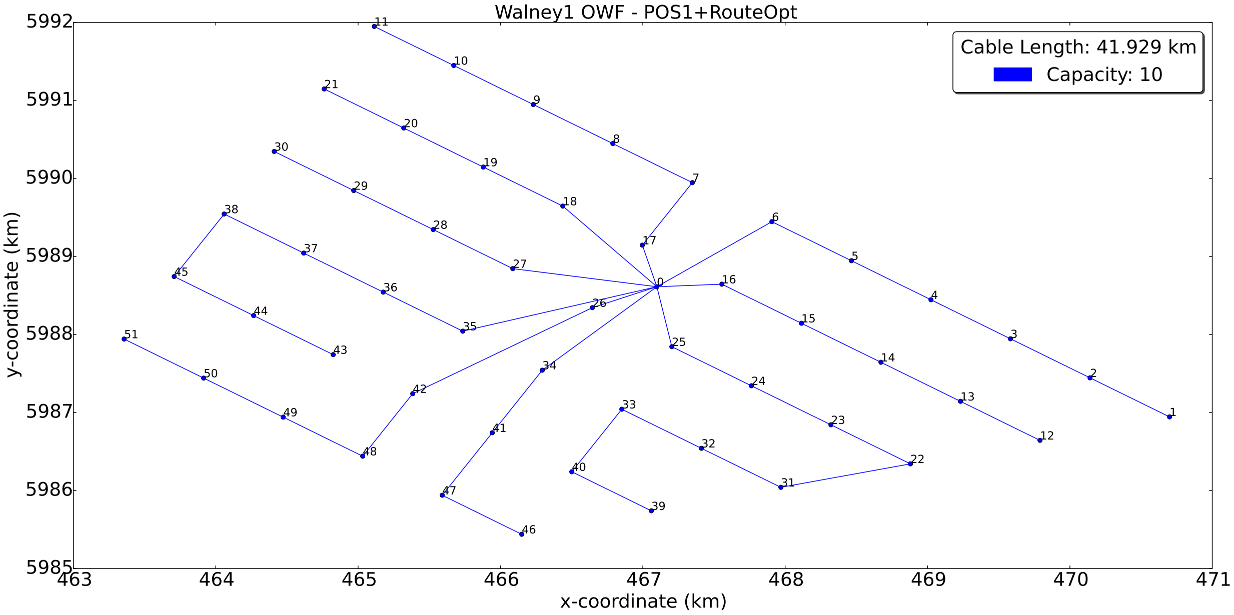

Figure 4-4: ICT generated by POS1 and RouteOpt for Walney1 OWF.

Next, Figure 4-5 shows the corresponding solution of POS1(-)+RouteOpt. In addition to the aforementioned routes, RouteOpt improved route $21 - 20 - 19 - 18 - 30 - 29 - 28 - 27 - 0$.

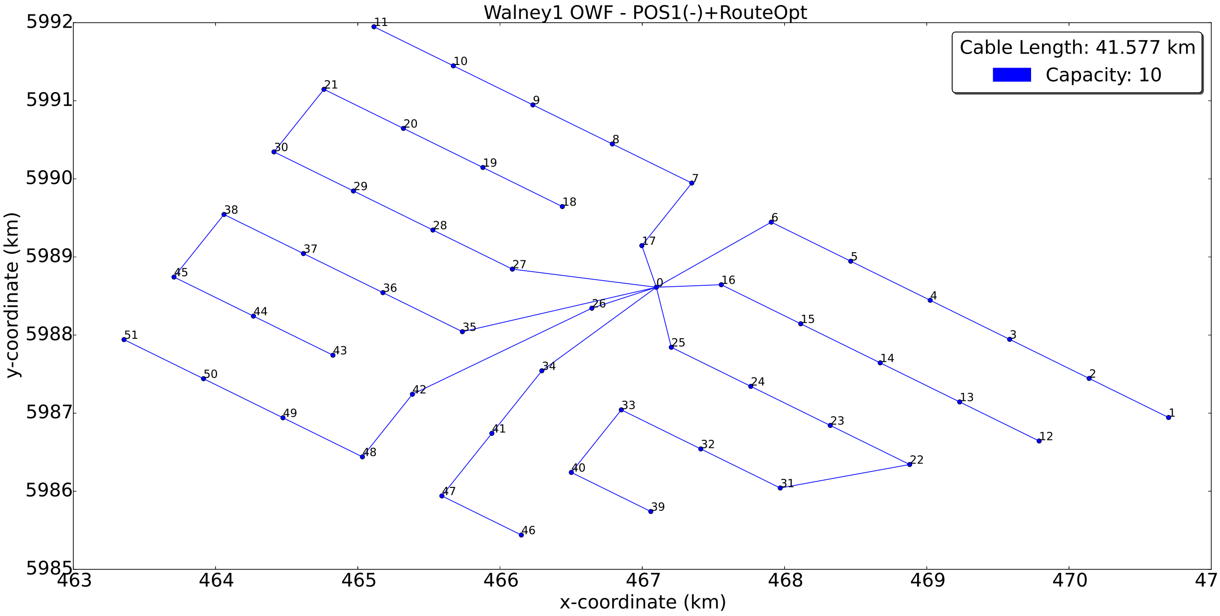

Figure 4-5: ICT generated by POS1(-) and RouteOpt for Walney1 OWF.

Last, Figure 4-6 presents the solution generated by POS2+RouteOpt for Walney1 OWF.

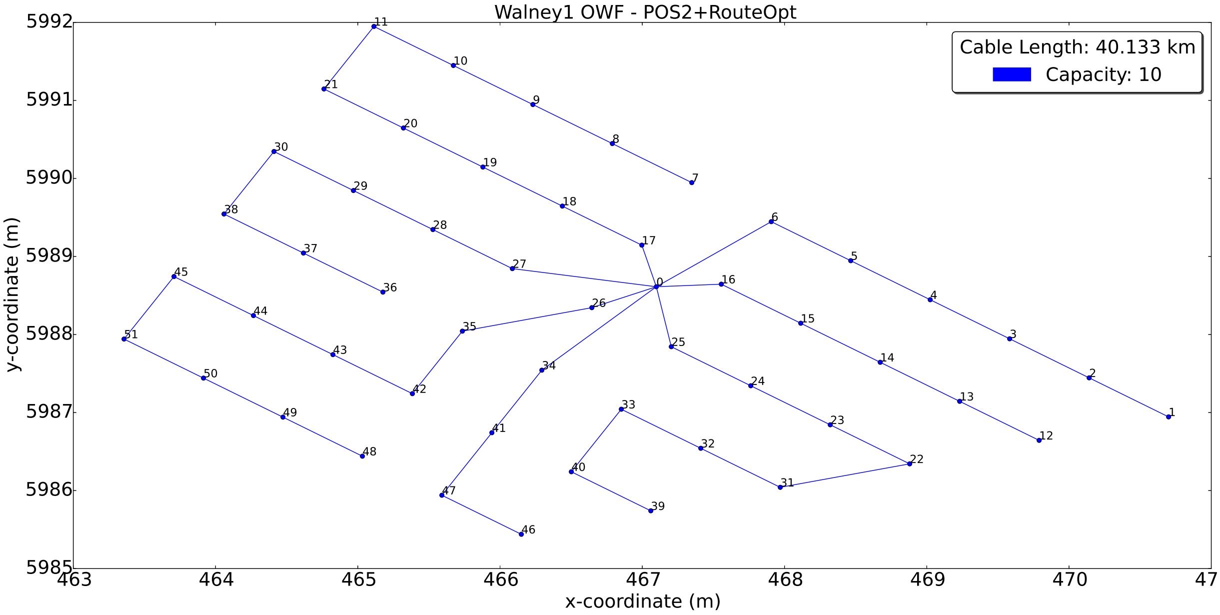

Figure 4-6: ICT generated by POS2 and RouteOpt for Walney1 OWF.

In this case, RouteOpt improved only route $24 - 23 - 22 - 31 - 32 - 39 - 40 - 33 - 25 - 0$, compared to Figure 4-3. Generally, the reduction in cable length that was achieved after the implementation of RouteOpt for POS1, POS1(-) and POS2 was respectively 3.29%, 6.09% and 0.93%. Overall, POS2+RouteOpt yields the best topology for this particular case. In addition, it is worth mentioning that after RouteOpt implementation, POS1(-) outperformed POS1, even if initially the solution of POS1 was better than that of POS1(-).

4-3 Test Instances

In order to verify the implementation of the algorithms and check their performance, they are tested to the layout of three OWF, namely Barrow [22], Walney 1 [20] and Sheringham Shoal [23], for cable capacities ranging from 5 to 10 turbines. The coordinates of the turbines and substations, are given in UTM form and were converted from the corresponding latitude and longitude coordinates found in [24], [21] and [25] respectively. The test instances that are used, correspond to the ones presented by Bauer and Lysgaard [1].

Table 4-1 lists the performance ratios of POS heuristics, for the aforementioned OWF. The first column presents the instance (name and cable capacity) and the second column gives the optimal solution, according to Bauer and Lysgaard [1]. They solved the test instances to optimality with a hop indexed formulation, in order to evaluate the performance of the heuristics. In the columns three to six, the performance of POS1, POS1+RouteOpt, POS2, POS2+RouteOpt according to the author's implementation, is presented respectively. In addition, the brackets in columns 3 and 4, show the performance ratios of POS1(-) which includes negative savings and POS1(-)+RouteOpt respectively, only for the cases for which POS1(-) produced different results compared to POS1. Finally, the last column lists the performance ratio of the best between all heuristics for each particular instance.

Table 4-1: Performance of POS1, POS1(-) and POS2 (+RouteOpt)

Instance	**opt**	**Performance Ratio**				
		POS1 (POS1(-))	**POS1(POS1(-))+RouteOpt**	**POS2**	**POS2+RouteOpt**	**POS**
Barrow						
n=5	20739	1.01339	1.01339	**1.00428**	**1.00428**	1.00428
n=6	18375	1.02980	**1.02974**	**1.02974**	**1.02974**	1.02974
n=7	17781	**1.00289**	**1.00289**	**1.00289**	**1.00289**	1.00289
n=8	16566	**1.00000**	**1.00000**	**1.00000**	**1.00000**	1.00000
n=9	16553	**1.00995**	**1.00995**	**1.00995**	**1.00995**	1.00995
n=10	16317	**1.00000**	**1.00000**	**1.00000**	**1.00000**	1.00000
Sheringham Shoal						
n=5	64828	1.04439	**1.03236**	1.03353	**1.03236**	1.03236
n=6	62031	1.08822 (1.09154)	1.07565 (1.06768)	1.04655	**1.04533**	1.04533
n=7	60667	1.09062 (1.12097)	1.07902 **(1.04313)**	1.05131	1.04769	1.04313
n=8	59836	1.08223 (1.10847)	1.07046 (1.04239)	1.02477	**1.02349**	1.02349
n=9	59274	1.08696 (1.12352)	1.07508 (1.06863)	1.01709	**1.01581**	1.01581
n=10	58960	1.09275 (1.12951)	1.08080 (1.07432)	1.02917	**1.02336**	1.02336
Walney 1						
n=5	43539	**1.02448**	**1.02448**	**1.02448**	**1.02448**	1.02448
n=6	41587	**1.05583**	**1.05583**	1.06818	1.06818	1.05583
n=7	40789	1.06568	1.04568	**1.03178**	**1.03178**	1.03178
n=8	40242	1.08016 (1.12068)	1.05989 **(1.03938)**	1.04297	1.04297	1.03938
n=9	39752	1.09061 (1.11370)	1.05476 (1.04591)	1.02925	**1.02297**	1.02297
n=10	39541	1.09643 (1.11965)	1.06039 (1.05149)	1.02445	**1.01497**	1.01497
Average		1.0530 (1.06523)	1.04279 (1.03595)	1.02613	**1.02445**	1.02331

The results that were obtained, correspond to an acceptable extent with those presented by Bauer and Lysgaard [1]. Particularly, for most instances, the results deviate for less than 1%, and only for Sheringham Shoal OWF, a few instances deviate for 3%. The differences may occurred due to a slight deviation in the coordinates used, which can alter the sequence of the merges and thus the overall solution. As expected, POS2 outperforms POS1 in most instances and RouteOpt improves greatly the results of POS1 and especially POS1(-), for which it was designed for. On average, the best between the two heuristics gives only 2.33% more expensive solutions than the optimal.

One characteristic of POS2 that preliminary results revealed is that its performance may vary depending on the decision of including reinsertions in the Savings matrix or not. Thus, it is possible for the algorithm to achieve a better solution in less computation time for the case where reinsertions are omitted (POS2*). For the particular instances of Table 4-1, POS2 and POS2* did not differentiate and therefore POS2* results were omitted. The comparison between POS2 and POS2* can be found in Section 7-5. In general, Chapter 7 presents a comprehensive comparison of the algorithms, regarding their performance time and cost-wise.

Chapter 5

Branched Offshore Wind Farm Infield Cable Topology Problem (OWFICTP)

Besides radial designs for the Infield Cable Topology (ICT) of Offshore Wind Farms (OWF), also branched topologies are of great interest. In the following Sections, the problem of finding efficiently near-optimal branched topologies for the collection system of OWF is treated.

5-1 Branched vs. Radial Topologies

In Chapter 4, it was shown that efficient algorithms exist that generate sub-optimal radial solutions for the OWFICTP. Thus, the question arises why branched topologies are desirable, especially if the complexity and size and consequently cost of the switchgear required at turbines where a branch is formed is taken into account.

The main reason is the saving in total cable length that can be achieved from a branched topology compared to a radial one. This conclusion results from the fact that the global minimum cable length of a radial problem is part of the possible solutions of the branching problem. Thus, by solving to optimality the branching problem, it is not possible to get a solution which is not at least equal to the optimal solution for the radial problem.

In addition, including the possibility of the utilisation of multiple cable types, it is far more possible that a greater number of cable connections in the branching design use lower rated and thus less costly cables. So, an additional cost saving can be achieved through the use of a branched ICT.

Another advantage of branched over radial topologies is the power flow through the network. The electrical losses in one cable are proportional to the square of the current that flows through the cable. So, for each cable connecting two turbines, the losses are proportional to the square of the number of turbines upstream of that cable. In order to make clear the advantage of branched compared to radial routes, in terms of the power losses, an example of a radial and branched route is considered, as given in Figure 5-1. The difference in terms of cable losses between the two routes, if equal cable length for every connection is assumed, can be found after counting the number of upstream turbines for every connection. For the radial route, it accounts to 15 where for the branched route, the number of upstream turbines for all connections in total is equal to 13. Thus, the branched route in this case has 15% less losses than the radial route. It should be noted that the more branches and the closer they take place to the substation, the greater the savings are in terms of power losses.

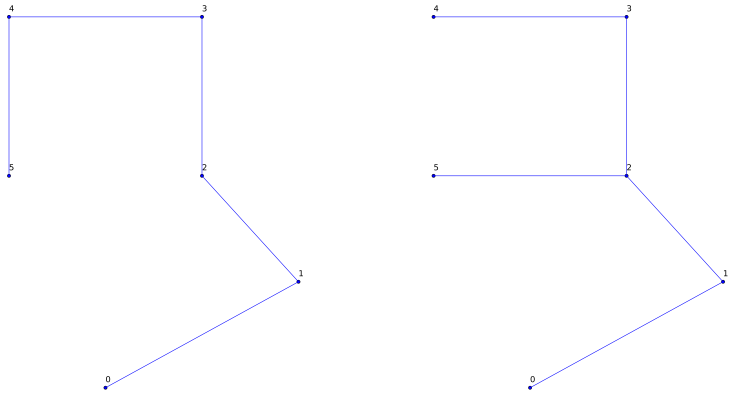

Figure 5-1: Radial (left) and Branched (right) routes.

Lastly, the reliability increases if a branched topology is employed. Referring again to Figure 5-1 and assuming that a cable fault occurs between turbines 2 and 3, for the radial route, the power coming from three upstream turbines is lost. On the contrary, a cable fault in the same connection for the branched route will only cause power from two turbines to be lost. It is obvious that a cable fault in a connection close to the substation will have the same effect for both designs. Therefore, the reliability in terms of cable faults is always better for branched topologies.

On the other hand, computation time-wise, the branched solution space is essentially larger than the radial solution space. Thus, finding the optimal solution for the branching problem is even more difficult than the radial problem. But since the approach of the thesis is to find near-optimal solutions in the least possible time, an heuristic algorithm will be also used for the branching problem. This means that it is not guaranteed, that the branched topology, in terms of cable length, will be always better than the radial topology for a particular problem, as it is the case for the global optimum solution. Nevertheless, the undeniable advantages of the branched over the radial topologies is a strong motivation to explore this problem.

5-2 Capacitated Minimum Spanning Tree (CMST) Problem

Finding the optimal branched solution of the OWFICTP corresponds to the well defined CMST problem [26], which has mainly been studied for the design of minimum cost centralised communication networks. CMST is a minimal cost spanning tree of a graph that has a designated root node, and satisfies a capacity constraint n. The capacity constraint ensures that all subtrees (maximal subgraphs connected to the root by a single edge) incident on the root node have no more than n nodes. It is Non-deterministic Polynomial-time hard (NP-hard) problem and both exact and heuristic methods have been developed [26]. In order to fully correspond it to the OWFICTP, we need also to include the cable crossing condition.

5-3 Esau-Williams (EW) Heuristic

One of the first heuristic algorithms that was developed for the CMST problem is EW heuristic [2]. Even if numerous additions to the algorithm have been proposed and different approaches have been developed so far, it is considered the most efficient, regarding the computation time and optimality of results [26]. Berzan et al. [12] used it to solve the CMST problem for large-scale wind farms. In this section, it is adapted to approximate the near-optimal branched topology for OWF.

EW heuristic is a Saving procedure, starting from a star tree, similar to Planar Open Savings (POS). In each iteration the best feasible merging is performed, meaning that it yields the largest saving. The saving sv_{ij} for joining routes r_i and r_j by connecting nodes i and j is defined as:

$$sv_{ij} = \begin{cases} max\{\chi_i, \chi_j\} - d(i,j), & \text{if joining } i \text{ and } j \text{ is feasible} \\ \infty, & \text{otherwise.} \end{cases} \tag{5-1}$$

where χ_i and χ_j represent the distance of the last clients of the routes r_i and r_j from the substation respectively and $d(i,j)$ is the distance between nodes i and j.

By using the terminology provided in Section 3-1 and the knowledge gained from POS, the adaptation of the EW heuristic for the OWFICTP is as follows:

```
EW (Graph ($T \cup S$, $P$), distance $d(k,u)$ $\forall$ $(k,u) \in P$, Capacity $n$):
foreach $i \in T$ do $s_i = argmin_{s \in S}\{d(i,s)\}$
$P \leftarrow \bigcup_{i \in T} (i, s_i)$
foreach $k$,$u \in T$, $if$ $s_k \equiv s_u$ do $sv_{ku} = d(k, s_k) - d(k,u)$
$SV \leftarrow \bigcup_{k,u \in T} sv_{ku}$
repeat
    (k,u) $\leftarrow$ maximum saving $sv_{ku}$ in $SV$
    if $k$ and $u$ are in different routes,
    and the total number of turbines in the routes containing $k$ and $u$ does not exceed $n$,
    and (k,u) does not cross any connection in $P$ then
        $i \leftarrow$ last client in the route containing $k$
        $j \leftarrow$ last client in the route containing $u$
        $P \leftarrow P \setminus ((i, s_i) \cup (k,u))$
        foreach client $z$ of the merged route do
            if $n \in T$ and $sv_{zn} \in SV$ do
                $sv_{zn} \leftarrow d(j, s_j) - d(z,n)$ and update $SV$ acccordingly
    delete $sv_{ku}$ from $SV$
until $sv_{ku} < 0$
return $P$
```

Compared to POS, EW gives more freedom and possibilities for merging of routes since there is no limitation on the position of the turbines in their corresponding routes. Also, the savings list SV is more dynamic in the sense that after a merging between routes, the saving that can be achieved by connecting each turbine of the newly merged route to a turbine belonging to another route, needs to be updated (line 15) according to which connection will need to be erased then.

Figure 5-2 presents the cable topology for Walney1 OWF, as calculated from EW for cable capacity corresponding to 10 turbines.

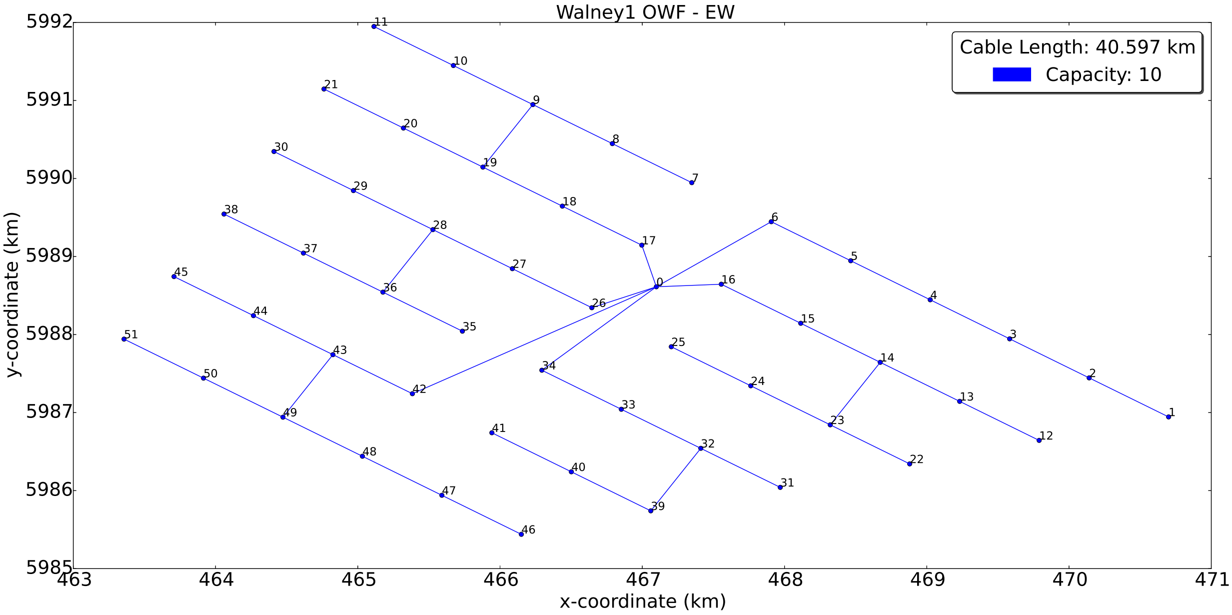

Figure 5-2: ICT generated by EW for Walney1 OWF.

In comparison with the routes generated from POS1+RouteOpt (Figure 4-4) and POS2 (Figure 4-3), EW performs slightly worse than POS2 (-0.9%) and 3.4% better than POS1 and RouteOpt. Even if this behaviour is not desirable, it is not unexpected as explained in Section 5-1. Heuristic methods can guarantee an acceptable and efficient local solution to the problem but the level of optimality is highly case-dependent and thus unpredictable.

The main characteristic of EW heuristic is that it first tries to connect the turbines that are relatively further from the substation into clusters. After a cluster has been completed, meaning that the capacity of the cable is full, the algorithm continues with a different cluster, closer to the substation and so on.

Chapter 6

Multiple Cable Types Approaches

The use of multiple cable types in Offshore Wind Farms (OWF) can eliminate the pointless use of a high capacity and thus expensive cable and contribute to the total cost saving. This Chapter presents the three approaches that were developed for the purposes of the current project, to solve the Offshore Wind Farm Infield Cable Topology Problem (OWFICTP) where more than one cable type is available, in order of increasing complexity. As a reference, the installed layout of Sheringham Shoal OWF (Figure 6-1) will be used [25]. The two cables that are used have a capacity of 5 and 8 turbines and cost 110 and 180 €/m respectively [1].

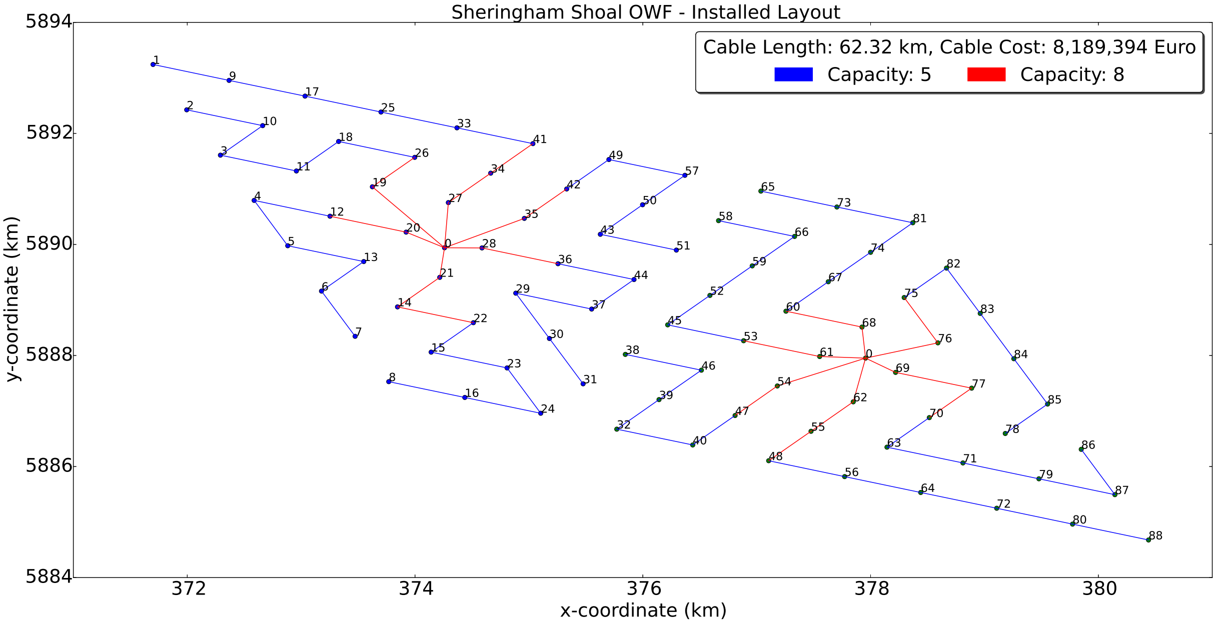

Figure 6-1: Installed Layout Sheringham Shoal OWF [1].

6-1 High to Low Approach

The first and simplest approach that was developed to include the possibility for multiple cable types in OWFICTP is first to find the solution for the cable with the maximum capacity, by using any of the heuristics that were presented in the previous chapters, and then replace the expensive cable by cables of lower capacity where possible. In order to achieve that, a routine was developed that returns the connections for which, the low capacity cable can handle the incoming power. This is straightforward for radial designs but it gets more complicated for branched topologies. Figure 6-2 presents the result of the High to Low cable choice approach, applied to Esau-Williams (EW) for Sheringham Shoal OWF and the two cable types correspond to the ones used at the installed layout.

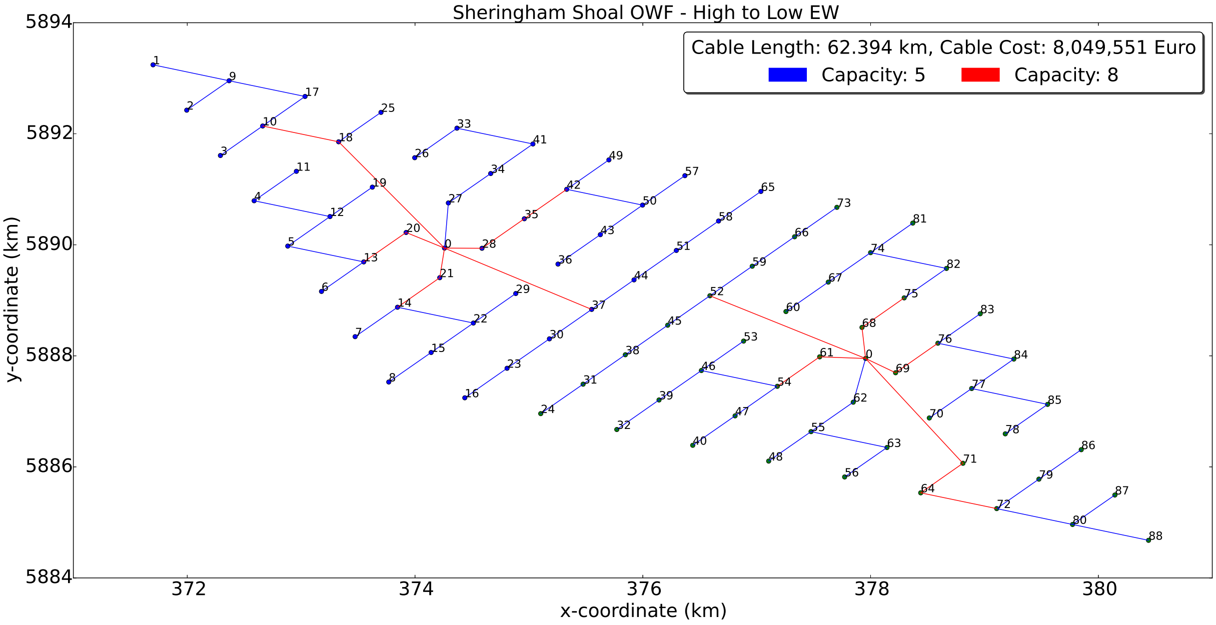

Figure 6-2: ICT generated by High to Low Cable Choice - EW for Sheringham Shoal OWF.

Basically in this approach, the heuristics approximate the near-optimal solution in terms of total cable length, for the cable with the highest capacity and then replace it with a cheaper one where possible. The biggest disadvantage of this approach is that the optimization is related to the total cable length and not total cost. Hence, particularly for EW, where clusters of turbines are formed away from the substation, an excessive use of the expensive cable is required.

6-2 Low to High Approach

The Low to High approach follows the opposite direction compared to the previous approach. First, the problem is solved for the lowest capacity cable and then merges between two routes are examined, which could lead to a lower overall cost. Thus, the algorithm studies if the saving in cable length could overcome the necessary additional cost of a cable upgrade. It is required though that every possible merging will not cause overcapacity to the cable with the highest capacity. In order to achieve this, an additional Savings Matrix is created and at each iteration the merging that will lead to the highest possible cost saving is examined. Figure 6-3 presents the result of the Low to High cable choice approach, applied to the result of Planar Open Savings (POS)1+RouteOpt for Sheringham Shoal OWF.

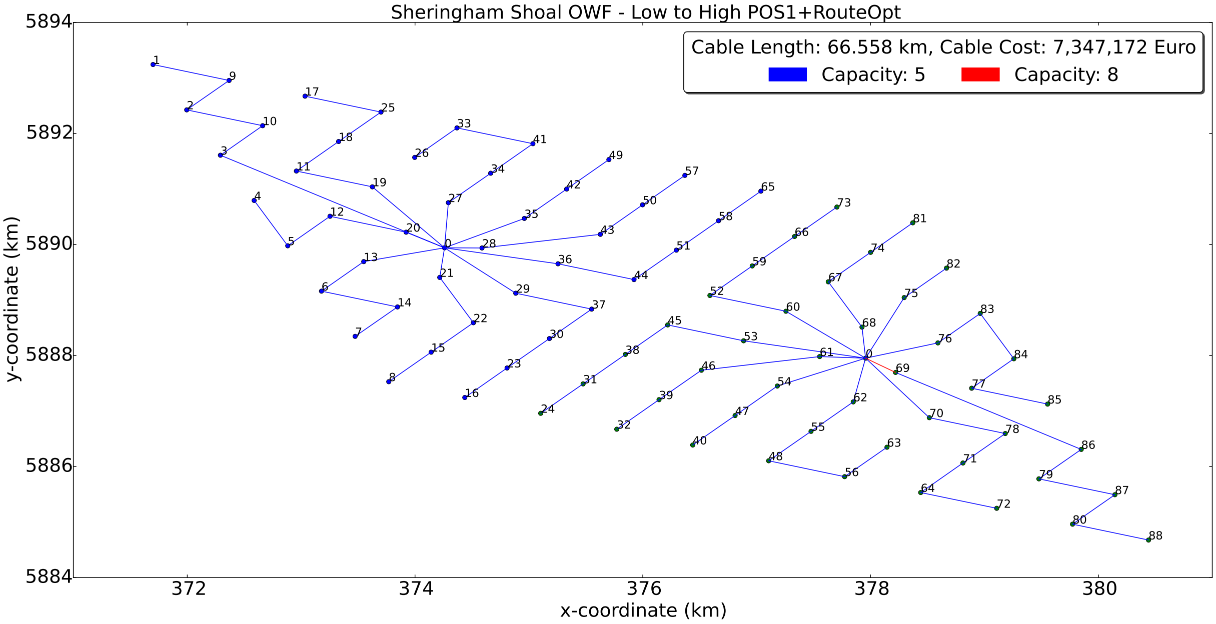

Figure 6-3: ICT generated by Low to High Cable Choice - POS1+RouteOpt for Sheringham Shoal OWF.

The most significant disadvantage of this approach is the fact that only a few merges of routes are achieved and the use of the expensive cable is limited. This results in a high total cable length, especially for cases where the high capacity cable has a rating less than double of the rating of the low capacity cable.

6-3 Online Approach

The third and most sophisticated solution to the multiple cable types problem was developed in order to address the dis-functionality of the Low to High approach, when the largest cable capacity is not at least twice as much as the smallest cable capacity. In this case, every possible merging of routes leads to a route that cannot be supported by the available cables. Compared to the previous approaches, the Online Approach is a balance between the optimal cable length and optimal overall cost. In order to show the structure of the algorithm, its adaptation for the EW heuristic will be shown but the logic is similar for POS. Also for simplicity, we assume that two cable types are available but the implementation allows a maximum of three cable types.

EW Multiple Cable Types
(Graph $(T \cup S,\, P)$, distance $d(k,u)\ \forall\ (k,u) \in P$, Cables $r_1 = (n_1, c_1)$, $r_2 = (n_2, c_2)$):

```
1 foreach $i \in T$ do $s_i = argmin_{s \in S}\{d(i,s)\}$
2 $P \leftarrow \bigcup_{i \in T}\ (i, s_i, r_1)$
3 foreach $k$,$u \in T$, $if\ s_k \equiv s_u$ do $sv_{ku} = (d(k,s_k) - d(k,u)) * c_1$
4 $SV \leftarrow \bigcup_{k,u \in T}\ sv_{ku}$
5 repeat
6     (k,u) $\leftarrow$ maximum saving $sv_{ku}$ in $SV$
7     if k and u are in different routes,
8     and the total number of turbines in the routes containing k and u does not exceed $n_1$,
9     and (k,u) does not cross any connection in $P$ then
10        $i \leftarrow$ last client in the route containing $k$
11        $j \leftarrow$ last client in the route containing $u$
12        $P \leftarrow P \setminus ((i, s_i, r_1) \cup (k, u, r_1))$
13        foreach client z of the merged route do
14            if $n \in T$ and $sv_{zn} \in SV$ do
15                $sv_{zn} \leftarrow (d(j, s_j) - d(z, n)) * c_1$ and update $SV$ acccordingly
16        delete $sv_{ku}$ from $SV$
17    elif k and u are in different routes,
18    and the total number of turbines in the routes containing k and u exceeds $n_1$
19    and does not exceed $n_2$,
20    and (k,u) does not cross any connection in $P$ then
21        $i \leftarrow$ last client in the route containing $k$
22        $j \leftarrow$ last client in the route containing $u$
23        $P_{tmp} \leftarrow P \setminus ((i, s_i, r_1) \cup (k, u, r_1))$
24        Upgrade connections in $P_{tmp}$ where necessary
25        Downgrade connections in $P_{tmp}$ where necessary
26        $sv_{ku} \leftarrow Cost(P) - Cost(P_{tmp})$ and update $SV$ acccordingly
27        if $sv_{ku} = max_{sv \in SV}\{sv\}$ then
28            $P \leftarrow P_{tmp}$
29            foreach client z of the merged route do
30                if $n \in T$ and $sv_{zn} \in SV$ do
31                    $sv_{zn} \leftarrow (d(j, s_j) - d(z, n)) * c_1$ and update $SV$ acccordingly
32            delete $sv_{ku}$ from $SV$
33        else continue
34 until $sv_{ku} < 0$
35 return $P$
```

The differences between EW and the aforementioned adaptation which includes multiple cable types can be seen in lines 3 and 17 to 33. First, the Savings matrix is related to cost saving and not cable length saving in order for the heuristics to follow a path of maximum cost savings at each iteration. Thus, it is initialised based on the cost of the lowest capacity cable. Then, merges of routes are achieved successively until the point where a merge yields a route that exceeds the capacity of the low capacity cable. At this point, the saving of this merge is updated according to the cost induced by the necessary cable upgrading or downgrading. In order to achieve this, a temporary set of all the connections which assumes that the merging has been achieved is formed. Now, it is necessary to find the connections that need to be upgraded or downgraded (line 24-25). Especially for POS1, line 25 can be omitted since last to first client connections are not possible to lead to a downgrade. After the saving has been updated by subtracting the total cost of the previous solution from the cost of the assumed solution (line 23), it is examined whether or not, the updated saving is the maximum possible. If it is the maximum, then the merging is achieved and the assumed solution is assigned to P. Otherwise, the algorithm continues to the next saving element.

Figure 6-4 presents the result of the Online cable choice POS2 approach for Sheringham Shoal OWF. It should be noted that for POS adaptations of the Online Approach, RouteOpt is also applied to the connections for which the low capacity cable is used.

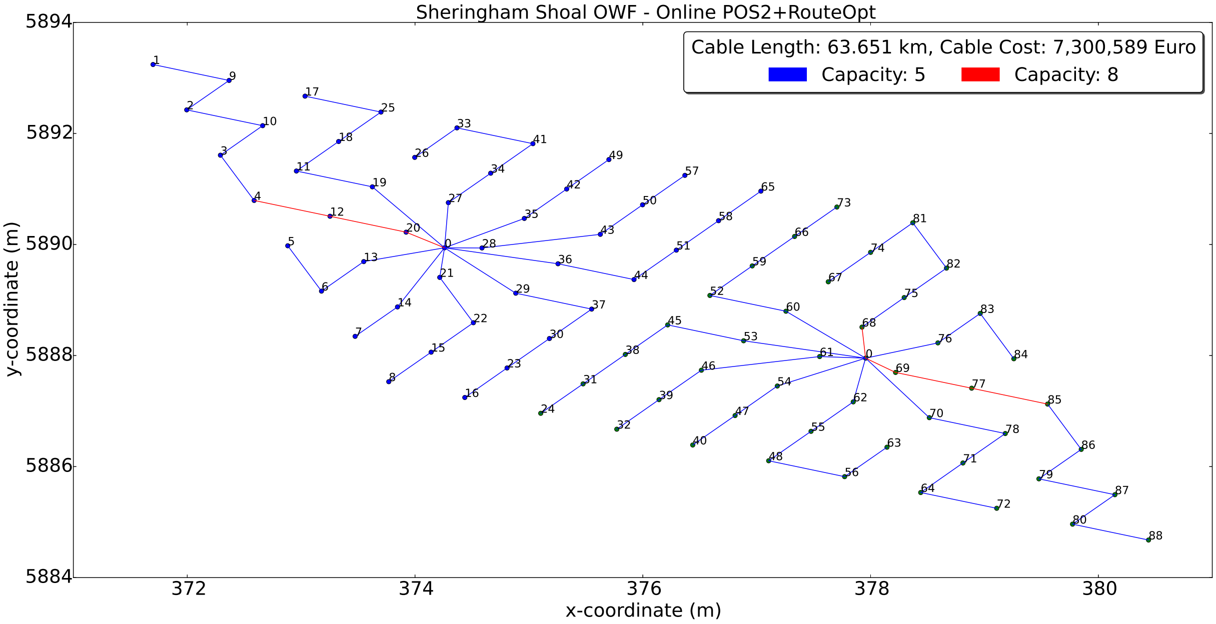

Figure 6-4: ICT generated by Online Cable Choice - POS2+RouteOpt for Sheringham Shoal OWF.

6-4 Comparison of Approaches

In order to compare the approaches, the installed and the optimal radial layout as presented in [1], with two cable types will be used, as they can be seen in Figures 6-1 and 6-5 respectively. Table 6-1 presents the performance of the three multiple cable types approaches as implemented in POS1, POS2 and EW for Sheringham Shoal OWF with two cables of capacities 5 and 8 turbines and cost 110 and 180 €/m respectively. Also, the total cost of the solutions for the single cable type problem is included, in order to indicate the cost saving that the use of multiple cable types can offer.

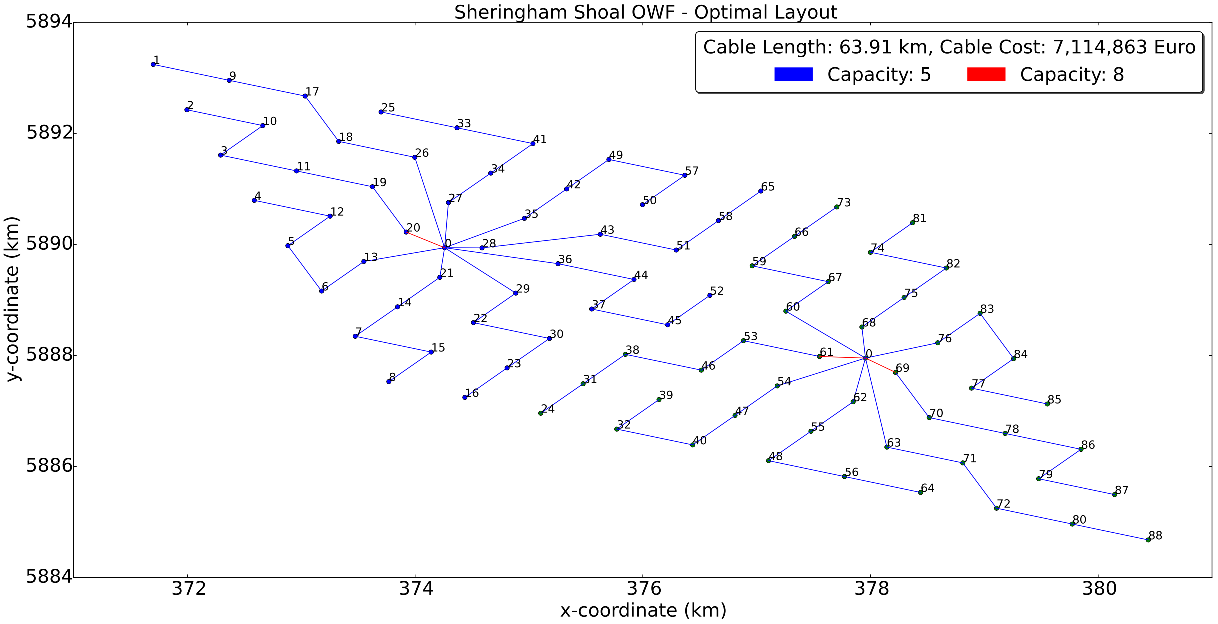

Figure 6-5: Optimal Layout Sheringham Shoal OWF [1].

Table 6-1: Performance of Cable Choice Approaches for POS1, POS2 and EW.

Instance	**Performance Ratio**	
	Optimal cost (7, 114, 863 €)	**Installed cost** (8, 189, 394 €)
POS1		
n=5	1.035	0.899
High to Low	1.058	0.919
Low to High	1.033	0.897
Online	**1.028**	**0.893**
n=8	1.620	1.408
POS2		
n=5	1.035	0.899
High to Low	1.099	0.955
Low to High	1.031	0.895
Online	**1.026**	**0.891**
n=8	1.549	1.346
EW		
n=5	1.046	0.909
High to Low	1.131	0.983
Low to High	**1.035**	**0.899**
Online	1.037	0.901
n=8	1.579	1.371

As it can be seen in the Table, the best instance for each algorithm yields a solution $2.5-3.5\%$ more expensive than the optimal, which is considered acceptable. At this point, it should be noted that the optimal result concerns a radial design and probably the optimal result for a branched design would be better. Compared to the installed layout, all instances except the one where for every connection the expensive cable is used, yield a more economical solution. The best among them (Online approach for POS2) provides a cost reduction of $888,795$ € $(10,9\%)$ compared to the installed layout.

Furthermore, looking closer to the solutions of the different approaches for each algorithm gives a better insight for their behaviour. Starting with the High to Low approach, POS1 performs better since less merges are achieved and the use of the expensive cable is limited. On the other hand, EW for the High to Low approach yields the worst results as expected, since the possibilities for merges are higher and clusters of turbines are formed away from the substation.

Next, the Low to High approach offers a relatively small cost reduction compared to the solution of the small capacity cable ($n = 5$), especially for POS where only a few merges are possible. As far as EW is concerned, this cost reduction is higher due to the freedom of merges between turbines at any point of the routes.

In addition, the Online approach performs better than the other two for POS, as it was designed for, but for EW it is not the case. In order to explain this, we have to do it graphically by looking at Figures 6-6 and 6-7, where the results of Low to High and Online approach are shown respectively.

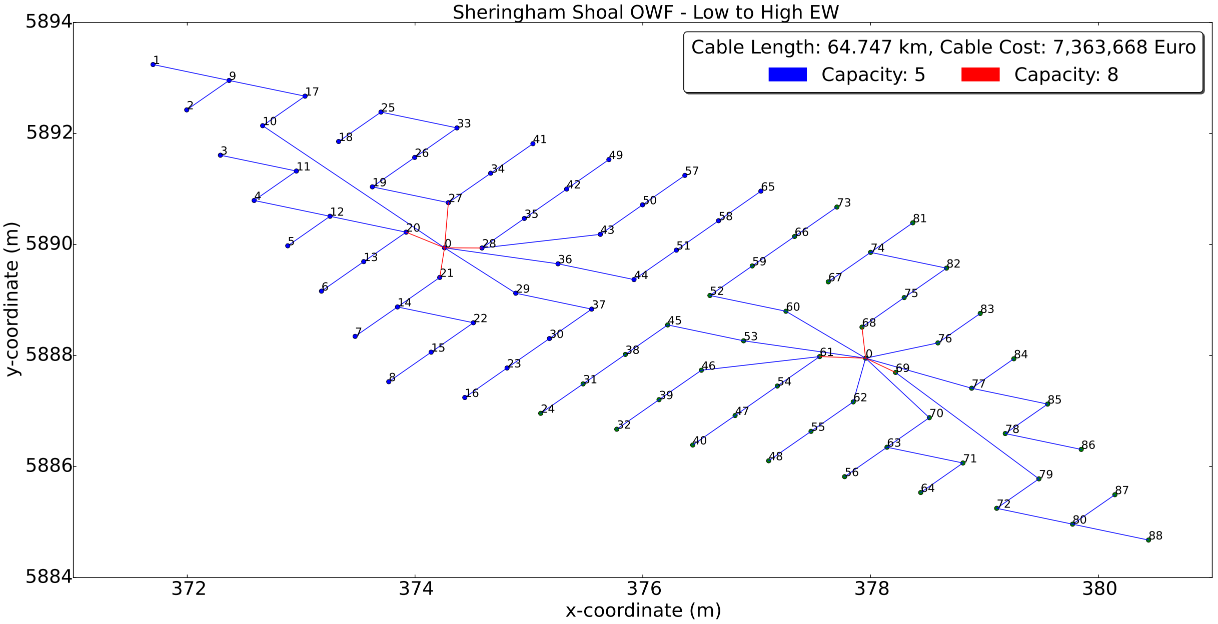

Figure 6-6: ICT generated by Low to High Cable Choice EW for Sheringham Shoal OWF.

The difference between the two layouts can be found to be the additional connection of the turbine 13 to turbine 20 for the Low to High Approach. This difference leads to two conclusions. First, the connections that led to upgrading of cables for the Online approach were achieved towards the end of the iterations and that is the reason why the results of the two approaches are so similar. Second, the reason why the Online approach did not perform the connection $13 - 20$, even if it lowers the cost, is that during the sequence of the iterations, the merging between turbine $13 - 20$ was examined, before the merging of $12 - 20$ was achieved. Thus, because of the fact that the connection $13 - 20$ will have caused a cable crossing with connection $12 - 0$, it was discarded by the algorithm.

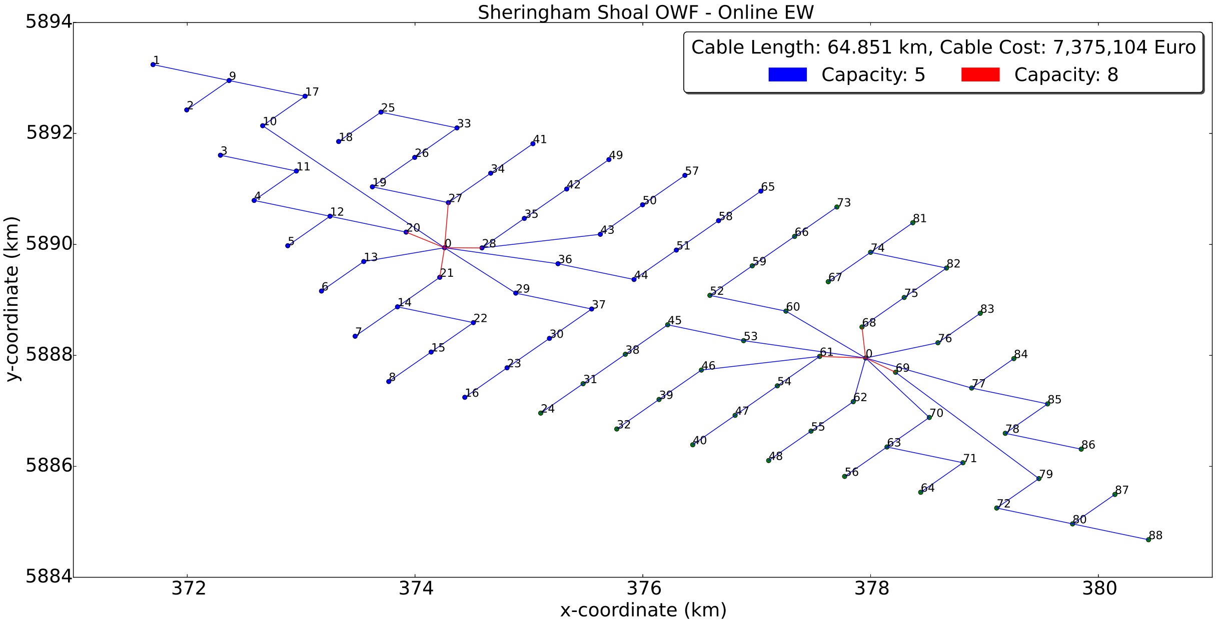

Figure 6-7: ICT generated by Online Cable Choice EW for Sheringham Shoal OWF.

In general, the Online approach for the multiple cable types OWFICTP will be used in the following chapters, since it performs better on average than the low to high and high to low approaches.

Chapter 7

Comparison of Algorithms and Hybrid

In this Chapter, the behaviour of the algorithms is examined in a wide range of test instances, a new hybrid approach is presented and finally, recommendations are given regarding the choice of the best algorithm for each case.

7-1 Cable Cost Model

One of the objectives of this chapter is to compare the developed algorithms for a wide range of cable capacities. Therefore, it is necessary to incorporate their cost as related to their capacity. The cable cost that will be used, includes cable procurement cost and cable installation cost. It should be noted that the additional cable length that extends from the seabed to the turbine's transformer and back down is not taken into account. Thus, the cable cost model is used mainly to express the relative cost difference among the available cables and in order to allow the comparison between the solutions provided by each algorithm. By no means can it be used to approximate the total cost of the collection system.

Several cable procurement cost models have been proposed in the literature. Some of them present cable costs as a function of conductor cross-sectional area [27], [28]. Lundberg's model correlates the cable cost with the voltage level [29]. On the other hand, Zaaijer expresses cable costs as the amount of copper and insulation material that is used [30]. Moreover, it is mentioned in his work that the coefficients of the model were obtained after it has been calibrated with the model of Lundberg and that Lundberg's model has been validated with data of existing cables.

For the purposes of the current work, Lundberg's model is used for the cable procurement costs by implementing the cable specifications from ABB [31]. Particularly for AC submarine cables, their cost is given by the following equation [29]:

$$Cost_{AC} = A_p + B_p \exp\left(\frac{C_p S_n}{10^8}\right) \tag{7-1}$$

where A_p, B_p and C_p are cost constants and S_n is the rated power of the cable in VA.

In order to express the cost constants in current values (Euro 2014), an average inflation rate of 1.18 [32] for Sweden and an exchange rate of SEK to Euro of 0.1083 [33] are used. Assuming also a voltage level of 33 kV and using the equation of the cable rated power, $S_n = \sqrt{3}U_n I_n$, the cable procurement costs are equal to:

$$Cost_{AC} = 52.52 + 76.16 \exp\left(\frac{234.35 I_n}{10^5}\right) \quad (Euro/m) \tag{7-2}$$

where I_n is the rated current of the cable in A.

The aforementioned cost function compares well with the costs given by Dicorato et al. [34]. Lastly, Table 7-1 gives the cost of AC, XPLE 3-core, copper conductor cables according to their cross-sectional area and rated current, as given in [31]. The cable costs are calculated by using the rated currents of the Table in Equation 7-2.

Table 7-1: Cable procurement Costs.

Cross section (mm^2)	**Current Rating** (A)	**Cost** (€ $/m$)
95	300	206
120	340	221
150	375	236
185	420	256
240	480	287
300	530	316
400	590	356
500	655	406
630	715	459
800	775	521
1000	825	579

Furthermore, by incorporating cable installation costs, the relative cost difference between the cables becomes smaller and hence, the comparison of algorithms can be made at a more practical level. The cable installation costs, which consist of transportation and laying costs, are usually given as a linear function of cable length and in some cases, the fixed costs are separated by the variable costs [28], [30]. For the current comparison, a separation between fixed and variable costs is not helpful, thus a fixed value of 365 € /m is used, as given in [34], which compares well with the 2400 SEK/m (SEK 2003) found in [29].

7-2 Parameters

The inputs of the Offshore Wind Farm Infield Cable Topology Problem (OWFICTP), as presented in Section 3-1, are the coordinates of turbines and substations and the capacities and associated costs of the available cables. In order to evaluate the performance of the algorithms, as it is explained in the following Sections, the parameters that vary are the number of turbines, the position of the substation and the cable combinations. The same type of wind turbine is used for all test instances.

7-2-1 Number of Turbines

As it was shown in previous chapters, Planar Open Savings (POS) and Esau-Williams (EW) heuristics solve the OWFICTP by starting both from the same initial solution, where the turbines are directly connected by single lines to the closest substation. Thus, the number of substations is irrelevant for the comparison of the performance. This allows us to use as parameter, only the number of turbines that are connected to a single substation.

In order to choose a range for the number of turbines, the current substation ratings are taken into account. In London Array [35], which is one of the biggest Offshore Wind Farms (OWF) nowadays, 88 turbines of 3.6 MW are connected to a single substation. If we also consider possible uptrends in substation ratings, 100 is the maximum number of turbines connected to a single substation that is chosen for the current comparison. As far as the minimum number is concerned, 30 turbines are chosen. It is highly unlikely that fewer turbines are connected to a single substation and even if it is the case, the optimal solution could be probably calculated by hand.

7-2-2 Position of Substation

Regarding the position of the substation, the current trend shows that in most OWF, the substations are located within the farm, more or less in the centre of the area defined by the turbines. This configuration yields less losses of the collection system compared to the configuration where the substation is located outside the farm. Nevertheless, both configurations are widely used and preliminary results showed that the position of substation is an important parameter for the comparison of the algorithms.

7-2-3 Cable Capacity

Another parameter that differentiates the performance of the algorithms is the cable capacity. The main differentiation is the choice between single or multiple cable types and additionally, the cable capacity or the range of capacities respectively. In order to define the range of cable capacities that will be treated, cable specifications [31] as well as layouts of existing OWF were reviewed. The review showed that in most OWF, 5 to 10 turbines are connected in a feeder. Hence, a range of 5 to 11 turbines is chosen for the current performance comparison in order to account for possible upgrades in cable sizes. For the multi-cable problem, any combination of two or three of the cable capacities in the aforementioned range could be used. Table 7-2 shows the cable combinations that are used, which correspond to the most practical ones and yield useful insights.

7-2-4 Selection of Turbine

The selection of turbine is not a parameter that differentiates the performance of the algorithms but its purpose is to correspond cable current ratings (Table 7-1) to cable capacities, given as number of turbines. A wind turbine with a rating of 3.6 MW is chosen, in order to allow the use of a wide range of cables.

The current rating of one 3.6 MW wind turbine, at a voltage level of 33 kV (line to line) and assuming a power factor $cos\phi \sim 1$ is equal to:

$$I_n = \frac{P}{\sqrt{3}U_n cos\phi} = 63 \quad A \tag{7-3}$$

In order to correspond the total costs to cable capacities in terms of number of turbines, firstly the cable installation costs are included to the data of Table 7-1. Then, by using the current rating which was computed in Equation 7-3, it is possible to calculate the maximum number of turbines that can be connected to each cable. The results are presented in Figure 7-1.

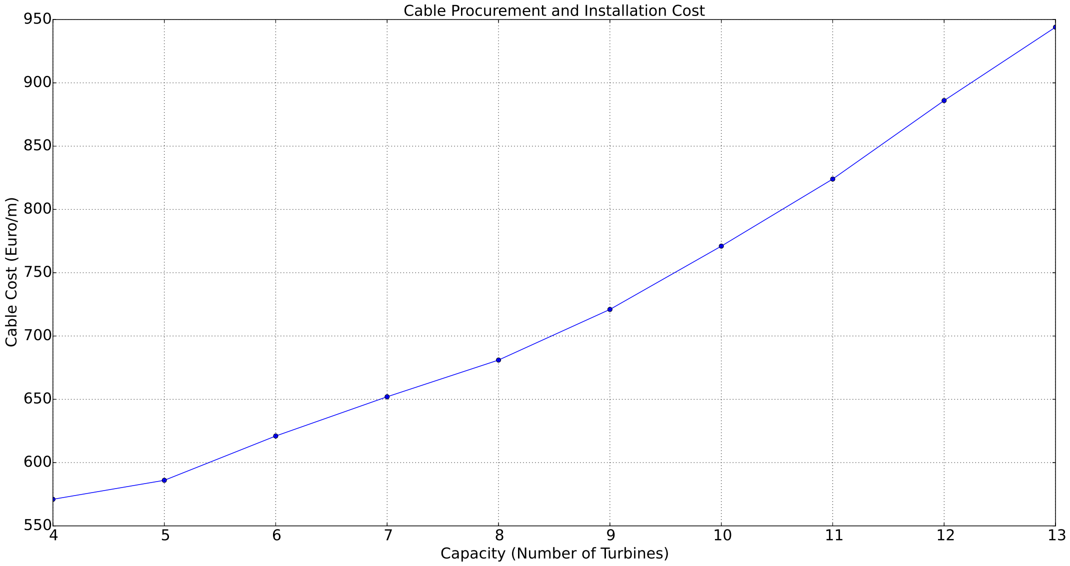

Figure 7-1: Cable procurement and installation costs with respect to cable capacity.

It should be noted that both 120 mm^2 and 150 mm^2 cables can withstand the current from no more than 5 turbines with a power rating of 3.6 MW. Therefore, the cost of the 150 mm^2 cable has been omitted from the graph.

7-3 Setup of the Comparison

Since the parameters that differentiate the performance of the algorithms have been indicated, a systematic way to perform the comparison is developed. The main idea is to create random layouts of wind turbine positions for a wide range of the parameters and calculate for each test instance, the cost of the topology generated by each of the algorithms.

Firstly, for a given number of turbines, a set of random coordinates is created with the condition that there is not a turbine that is closer than 500 m or further than 1000 m from its closest turbine. Therefore, layouts are designed which correspond well with conventional layouts, where a spacing of 5 to 9 rotor diameters between the wind turbines is used.

Next, for each generated layout, two sub-cases are studied, depending on the substation's position. In the first case, the coordinates of the substation correspond to the centre of the square area, as defined from the most "remote" turbines ("substation in" case). In the second case, the substation is located outside the wind farm ("substation out" case), by keeping its x-coordinate same as for the "substation in" case and moving it vertically outside the aforementioned square area.

After the two sub-cases have been defined, a set of cables needs to be included in order to complete the inputs for the OWFICTP. Then, the OWFICTP is solved for all combinations of cables as given in Table 7-2, by using all algorithms. Particularly, the algorithms that are studied are POS1, POS1 including negative savings (POS1(-)), POS2, POS2 without reinsertions (POS2*) and EW. For all versions of POS, RouteOpt is included.

Table 7-2: Setup of the Comparison.

Parameters	**Values**
Number of Turbines	30-100 (step 10)
Position of Substation	In, Out
Cable Capacities	Single Cable: 5-11 (step 1)
	Two Cables: 5 and 8, 5 and 9, 5 and 10, 5 and 11
	Three Cables: 5, 8 and 11
Algorithms	
POS1, POS1(-) POS2, POS2*, EW	
Outputs	
Cable Length (m), Cable Cost (€), Computation Time (s)	

In addition, 20 random layouts are calculated for each number of turbines, in order to eliminate the uncertainty. Taking into account all the above, it amounts to 8*20*2*12=3840 test instances. Last, the coordinates of the wind turbines and substations are saved to allow the visual representation of the results. The comparison was performed on a standard personal computer with $i7 - 2.40$ GHz processor and 8.00 GB of RAM. The algorithms were implemented in Python (2.7 release) and the Savings matrix was implemented as a heap priority queue. The following Sections first compare the two versions of POS1 and POS2 respectively. After the best version for each algorithm is selected, they are finally compared with EW.

7-4 POS1 vs POS1(-)

The difference between POS1 and POS1(-), as described in Section 4-1-1, lies in the fact that POS1(-) forces negative saving merges of routes. By doing so, routes are formed that contain a greater number of turbines, compared to POS1 solutions. Initially, POS1(-) yields a more expensive solution compared to POS1 but after RouteOpt is applied, their cost difference may be reversed, as shown in Figures 4-4 and 4-5. It should be noted that the possible advantage of POS1(-)+RouteOpt over POS1+RouteOpt is explored only for the single cable type problem. The reason is that for the multiple cable types problem, negative savings could lead to unnecessary use of the expensive cable and thus significantly higher cost.

Table 7-3 presents the comparison of POS1 and POS1(-), in terms of number of instances for which each algorithm performed better. The results have been summed according to the substation's position. The first two rows show the number of instances for which POS1 outperformed POS1(-) and POS1(-) outperformed POS1 respectively, whereas the third row gives the number of instances, for which the algorithms performed equally. In total, 2240 instances were tested which correspond to 20 layouts, for each number of turbines (30-100 turbines), for each cable capacity (5-11 turbines per cable) and for two positions of the substation (in and out).

Table 7-3: POS1 vs POS1(-).

	Substation In	**Substation Out**
POS1>POS1(-)	378	18
POS1<POS1(-)	124	20
POS1≡POS1(-)	618	1082
Total	1120	1120

As it can be seen in the Table, for the vast majority of the "substation out" instances, both algorithms generated the same solution. On the other hand, the results for which the substation was centrally located, showed a higher variability and particularly POS1 performed better for 34% of the instances, while POS1(-) outperformed POS1 for only 11% of the instances. The two versions of POS1 heuristic differentiate more for the "substation in" instances because essentially, it is more possible that at the point when all positive savings merges have been examined, routes have been formed that contain less turbines than the full capacity of the cable. It should be clear that POS1(-) can achieve merges of two routes only if the sum of the turbines of these two routes does not exceed the cable capacity and this merging should not cause any cable crossing.

In order to demonstrate the effect of the substation's position on the performance of the two algorithms, Figures 7-2, 7-3 and 7-4 will be used. To start with, Figure 7-2 presents the topology generated by POS1+RouteOpt for a random layout where 80 turbines are used, the substation is centrally located and the capacity of the cable corresponds to power generated from 10 turbines. As it can be seen in the Figure, there are routes (e.g. routes $0-1-15-33-28-68-63$ and $0-18-67$) that contain in total, less than 10 turbines and a merging between them will not cause a cable crossing with an existing cable. However, since this merging would lead to a worse solution, at least before RouteOpt is applied, POS1 ignores it. On the other hand, for the corresponding "substation out" case (Figure 7-3), POS1 yields less routes for which the cable is not used in its maximum capacity and even if there are routes with less than 10 turbines, a merging between them (e.g. routes $0-80-37$ and $0-66-24-13-11-6$) would cause a cable crossing.

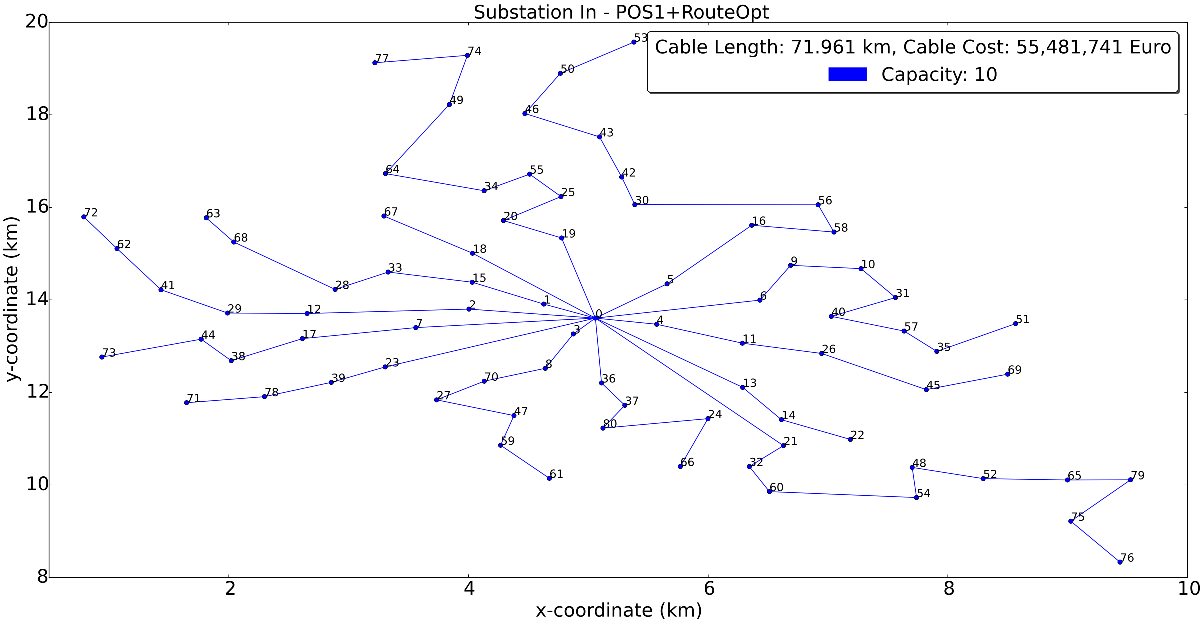

Figure 7-2: POS1 and RouteOpt - 80 turbines - Substation In.

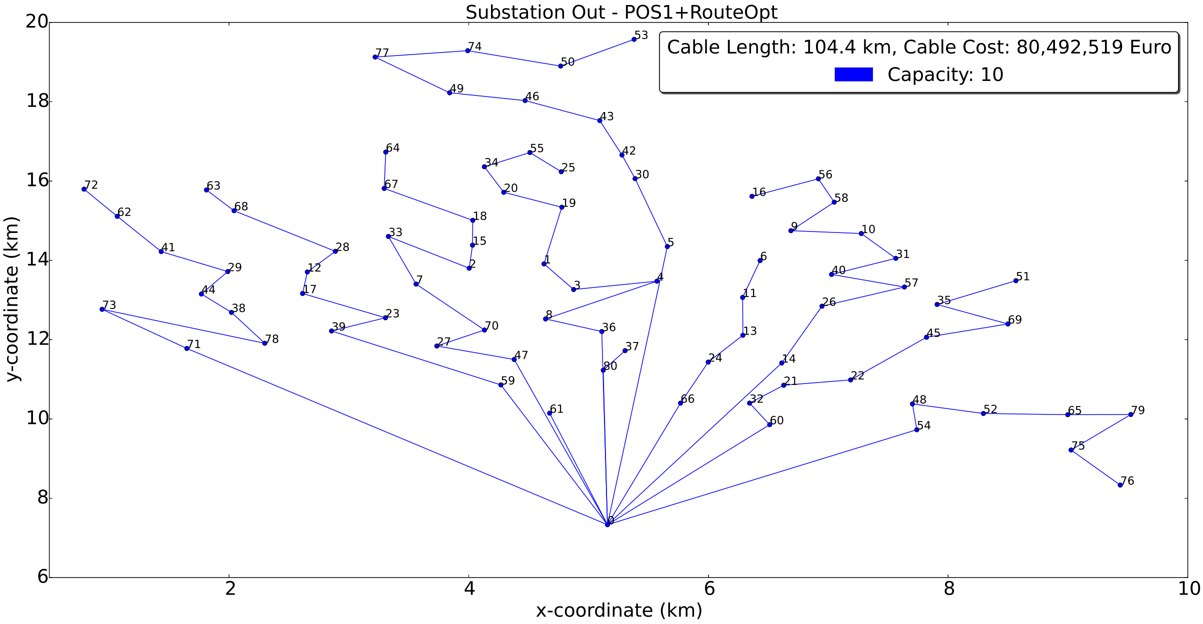

Figure 7-3: POS1 and RouteOpt - 80 turbines - Substation Out.

Figure 7-4 presents the topology generated by POS1(-)+RouteOpt for the same layout as in Figure 7-2. In this case and after RouteOpt has been applied, the final solution is better compared to the solution generated by POS1+RouteOpt. Thus, it corresponds to one of the 124 test instances of Table 7-3.

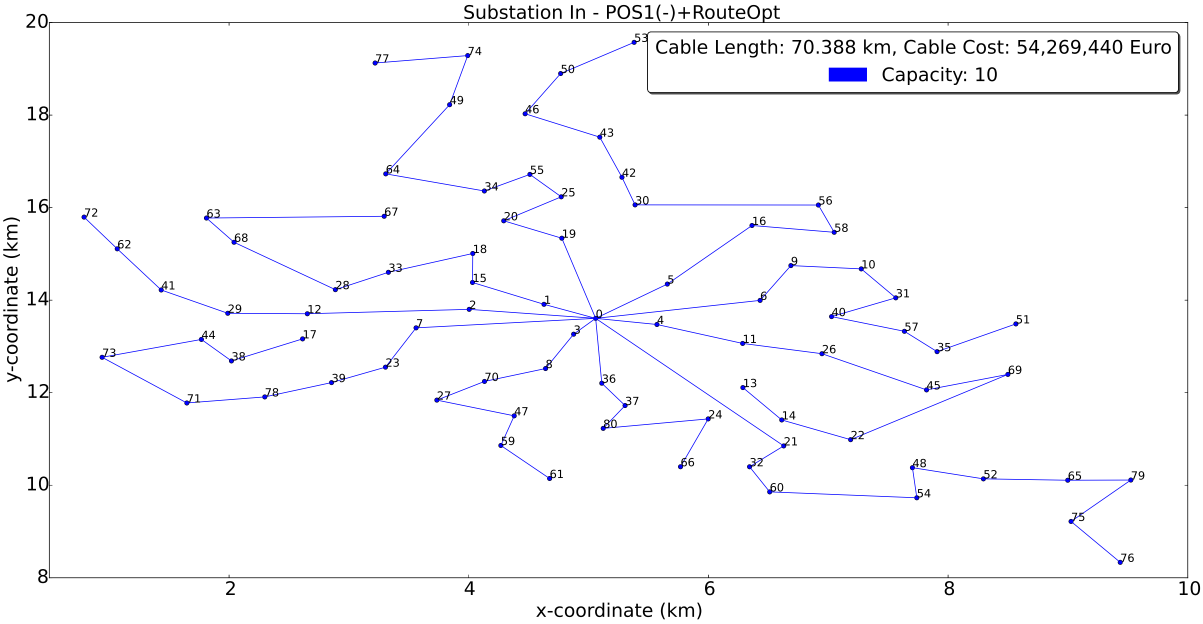

Figure 7-4: POS1(-) and RouteOpt - 80 turbines - Substation In.

As Table 7-3 indicates, POS1(-) performs better than POS1 for considerable number of test instances. However, this comes with the disadvantage of higher computation time compared to POS1, since always a greater number of saving elements is examined. Ideally, it is desirable to get the best solution of POS1 either it includes only positive savings or also negative savings. This can be done efficiently by calculating the solutions of POS1 and POS1(-) and choosing the best between them. Since the calculations for the positive part of the Savings matrix have already been performed in order to get the solution of POS1, this strategy requires only additional time of 10^{-4} to 10^{-2} s compared to POS1(-), which corresponds to the time needed from RouteOpt to examine the solution of POS1 for improvements. In order to explore the potential of the aforementioned strategy, the relative performance of POS1 compared to the best solution between POS1 and POS1(-) is studied. This study includes the relative cost difference between the two algorithms and the way it varies for different cable capacities, as well as the computation time required by the two algorithms.

Regarding the cost difference, the best solution between POS1 and POS1(-) is used as a reference for each test instance. Then, the ratio between the cost of the best solution and the cost of the layout generated by POS1 is calculated for each test instance. Finally, the ratios are averaged for each cable capacity, after they have been split according to the position of the substation. Figure 7-5 presents the average performance of POS1. The solid and dashed lines that extend horizontally represent the average performance for the "substation in" and "substation out" instances respectively, for each cable capacity. Furthermore, the vertical lines show the span of the results. In order to alleviate the uncertainty imposed by the use of only the extreme values, the 70th percentile is used as a representative measure of the distribution of the results. Thus, for the test instances that lie above (below) the mean value, the vertical lines indicate the value below (above) which 70% of these test instances lie.

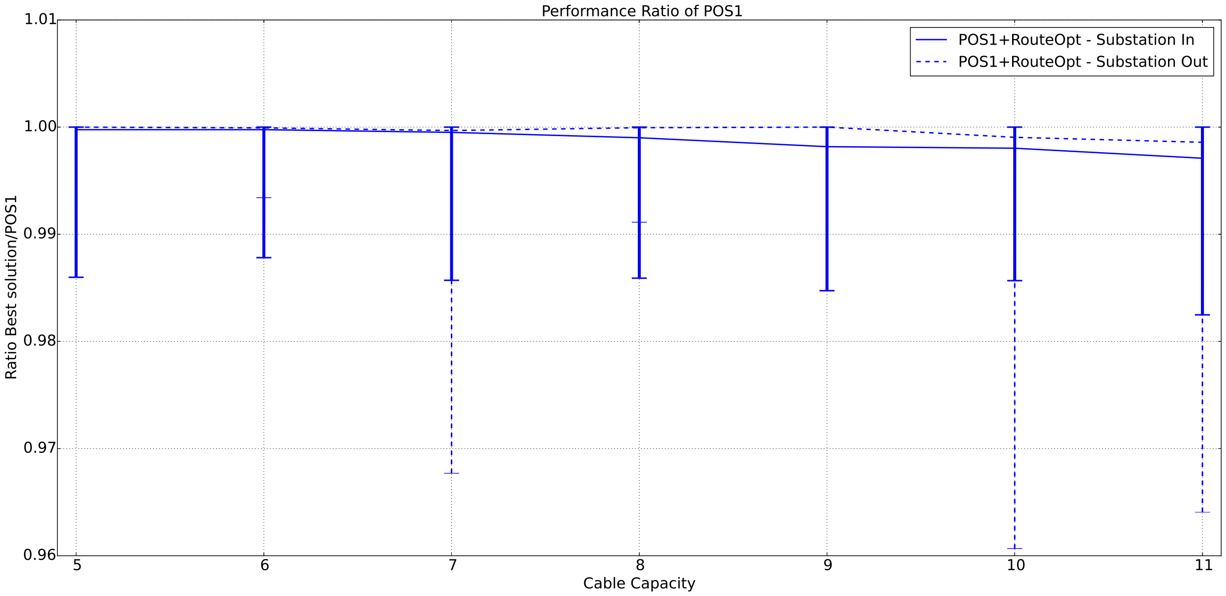

Figure 7-5: Performance ratio of POS1 - Single Cable.

As it can be seen in the Figure, for the instances above the mean value, the 70th percentile corresponds to the best solution. This is expected if we take into account the results of Table 7-3 even if they are summed for all cable capacities, where 996 and 1100 out of 1120 instances correspond to the best solution for the "substation in" and "substation out" instances respectively. On the other hand, the 70th percentile is more useful for the instances that lie below the mean value. The Figure indicates that for a considerable percentage of the "substation in" instances, POS1 performs $1-2\%$ worse than the best solution between POS1 and POS1(-). For the "substation out", the deviation of POS1 from the best solution is higher (up to 4%) but it should be noted that the number of instances for which POS1 and POS1(-) differentiate is relatively small.

Moreover, a comparison between the computation time of POS1 and the algorithm that generates the best solution between POS1 and POS1(-) is included, in order to illustrate the trade-off of getting the best solution by consuming higher computation time. Figure 7-6 presents the computation time of POS1 and the algorithm that returns the best solution between POS1 and POS1(-) (+RouteOpt) with respect to the number of turbines. The choice of the number of turbines as a variable is due to the fact that the computation time is determined mainly by the size of the Savings matrix. The Savings matrix, as defined in Section 4-1-1, is determined in turn, by the number of turbines. For instance, a wind farm with 80 turbines connected to one substation yields a Savings matrix with $80 * (80 - 1) = 6320$ elements (positive and negative). Subsequently, if we choose to examine only the positive saving elements, the computation time is lower but as it was shown, this may lead to a worse final solution. In the following Figure, the computation time for a particular number of turbines is first summed for all cable capacities and then it is averaged depending on the substation's position. By doing so, the effect of the cable capacity on the computation time is overlooked but it should be noted that it has only a minor effect on the computation time. It should be clear that as the cable capacity increases for a particularly test instance, the computation time increases slightly, since it is "easier" time-wise for the algorithm to discard merges of routes than applying them. But essentially, the number of turbines is the factor that influences mostly the computation time.

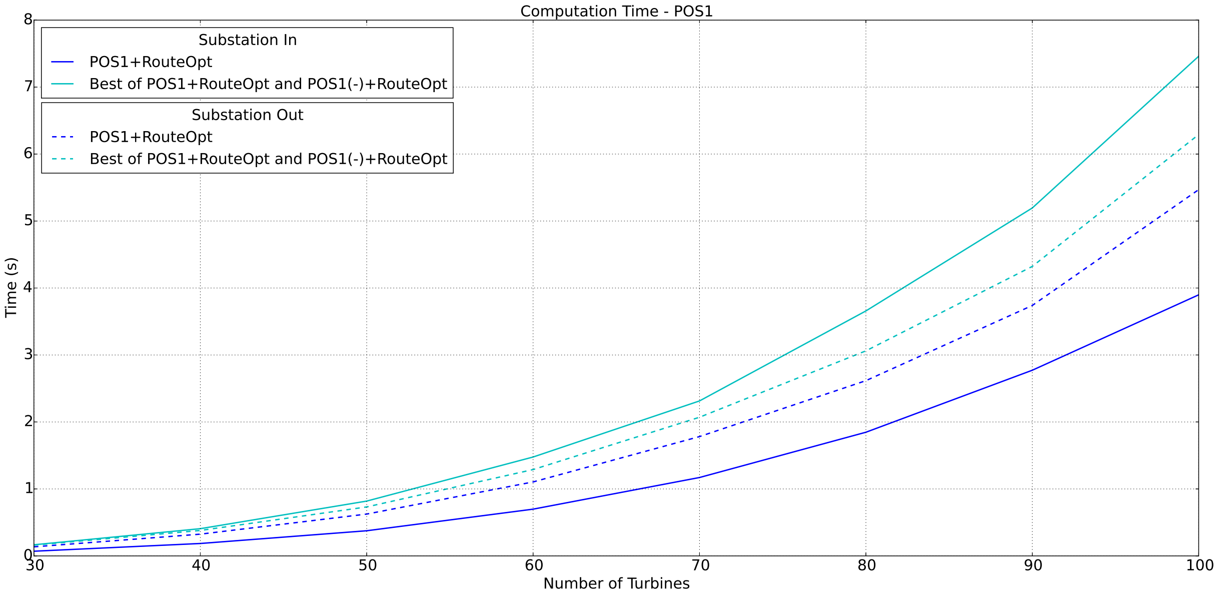

Figure 7-6: Computation time of POS1 and Best of POS1 and POS1(-).

Figure 7-6 shows that for the "substation in" instances (solid lines), the computation time required from the algorithm to return the best solution between POS1 and POS1(-) is almost double than POS1. On the other hand, for the "substation out" instances (dashed lines), the best solution requires insignificantly more time than the solution of POS1. This can be explained from the fact that, according to Table 7-3, it is more possible for the two algorithms to differentiate for the "substation in" than the "substation out" instances meaning that more time is required from the algorithm to calculate a new solution, even if same number of saving elements is examined. In addition, regarding the time difference of POS1 for the "substation in and out" instances (solid and dashed blue line respectively), Figures 7-2 and 7-3 will be used to demonstrate the difference. In principle, two farms with 80 turbines and one substation are depicted in the two Figures. Thus, the Savings matrix contains 6320 elements as explained earlier. But only its positive elements are examined and particularly they correspond to 1809 and 5103 for the two Figures (substation in and out) respectively. Essentially, this is the case for all layouts meaning that the position of the substation outside the wind farm yields always more possibilities for positive saving merges compared to the "substation in" case and therefore requires higher computation time. On the contrary, one may assume that since the routine that finds the best solution examines both the positive and negative parts of the Savings matrix, the computation time for the "substation in" and "substation out" instances (cyan solid and dashed lines respectively) should be more or less the same. As it can be seen in the Figure, the best solution for the "substation out" instances is calculated faster than the "substation in" instances and the reason is, as stated above, the additional time required from the algorithm to achieve the merges, which happens more often for the "substation in" instances.

To sum up, this section provided a comparison between POS1 and POS1(-) and illustrated the importance of finding the best solution between the two algorithms as well as the additional time that is required to achieve that. As it was shown, this can be done in affordable computation times, at least according to the author's opinion. Hence, the developed strategy will be used in the comparison provided in Section 7-6. In order to avoid misinterpretation, POS1 hereafter will correspond to the algorithm that returns the best solution of POS1 either it includes only positive or also negative saving elements.

7-5 POS2 vs POS2*

The difference between POS2 and POS2* was described in Section 4-3 and as it was mentioned, the reinsertions in the Savings matrix (Section 4-1-2) is the reason of their differentiation. In principle, by forcing reinsertions in the Savings matrix, POS2 examines the merging that would lead to the maximum possible saving at each iteration. However, this does not necessarily mean that the final solution will be better than the one generated by POS2*, for which reinsertions are not considered. In contrast to POS1, where POS1(-) uses as starting point the solution provided by POS1, the reinsertions in POS2 occur while the solution is calculated and thus, in order to select the best solution between POS2 and POS2*, the final solution of each algorithm needs to be calculated separately. In this section, the performance of the two versions of POS2 are analyzed statistically through the test instances defined in Table 7-2.

To start with, Table 7-4 presents the comparison of POS2 and POS2*, in terms of number of instances for which each algorithm performed better. The results have been summed according to the use of single or multiple cable types and successively depending on the position of the substation. The first two rows show the number of instances for which POS2 outperformed POS2* and POS2* outperformed POS2 respectively, whereas the third row gives the number of instances for which both algorithms yielded the same solution. In total, 2240 and 1600 instances were tested for single and multiple cables respectively.

Table 7-4: POS2 vs POS2*.

	Single Cable		**Multiple Cables**	
Position of Substation	**In**	**Out**	**In**	**Out**
POS2>POS2*	45	39	42	16
POS2<POS2*	143	89	26	13
POS2≡POS2*	932	992	732	771
Total	1120	1120	800	800

The results indicate that the two versions of POS2 differentiate more for the single cable instances than the instances for which multiple cable types are used. Particularly, for the single cable instances, POS2* outperformed POS2 in $10,4\%$ of the test instances compared to $3,8\%$ for which POS2 outperformed POS2*. On the other hand, for the multiple cable instances, POS2 yielded a better solution than POS2* for $3,8\%$ of the instances while POS2* performed better for $2,4\%$ of the instances.

Besides the number of instances, the average performance of the two algorithms for different cable capacities is depicted in Figures 7-7 and 7-8. The average ratios were calculated as in Figure 7-5 and the best solution between POS2 and POS2* has been used as reference for each instance. Since the substation's position has only a minor impact on the results, the performance ratios were first summed and then averaged according to the use of single or multiple cables. In addition, the vertical lines represent the 70th percentile which has been chosen to represent the relative deviation of the results from the mean value. As it can be seen in Figure 7-7, POS2* is on average better than POS2 for all cable capacities and as cable capacity increases, its performance becomes better, meaning that it gives the best solution more often than POS2. Also, the 70th percentile for the test instances below the mean value indicate that there is a significant number of instances for which POS2 yielded solutions approximately 3% worse than the solution of POS2*. The corresponding percentage for the solutions of POS2* is on average 2% worse than the solutions of POS2.

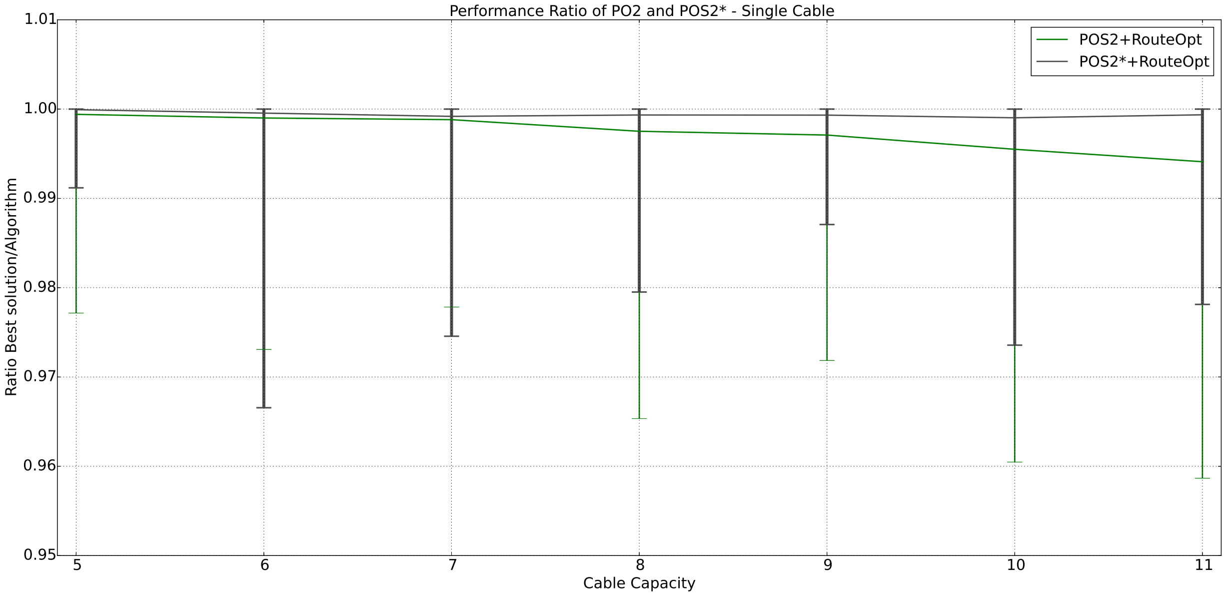

Figure 7-7: Performance ratio of POS2 and POS2* - Single Cable.

Regarding the instances for which multiple cable types were used (Figure 7-8), the average performance of POS2 is slightly better than POS2*. However, it should be noted that the number of instances for which the two algorithms differentiated, according to Table 7-4, is relatively small. Moreover, the 70th percentiles below the mean value indicate that there are solutions 1 – 2.5% worse than the corresponding best solutions for both algorithms. Particularly, POS2* showed higher deviation than POS2 from the mean value of their average performance, for most of the cable combinations.

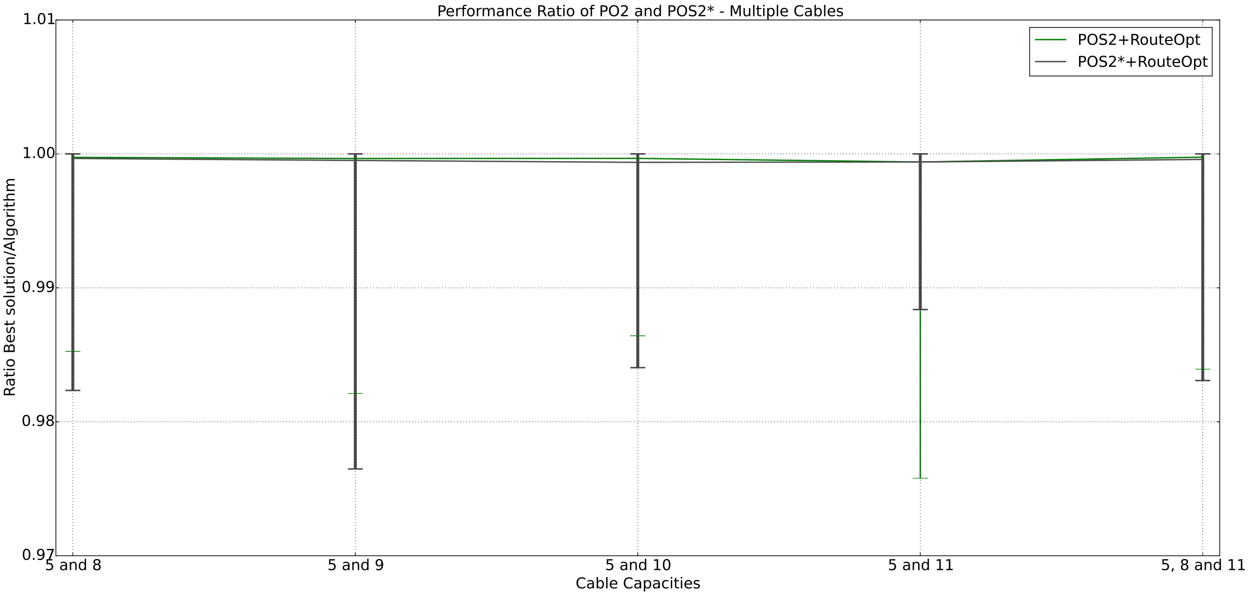

Figure 7-8: Performance ratio of POS2 and POS2* - Multiple Cables.

To sum up, the statistical comparison of POS2 and POS2* revealed that POS2* is the best choice for the single cable type problem, whereas for the multiple cable types problem, the results are slightly in favour of POS2. Regarding their computation time, the formation of the Savings matrix as a heap priority queue allows the reinsertions to happen in negligible time, thus resulting in almost equal speed for both algorithms. Moreover, as it was mentioned earlier, the computation time that is required to get the best solution between the algorithms is almost twice as much as the time required from one algorithm, which results in an overall poor performance. Taking into account all the above, POS2 without reinsertions and POS2 with reinsertions will be used for single and multiple cable types respectively, for the further comparison in the following sections.

7-6 POS1, POS2 and EW

This section provides the comparison of POS1,POS2 and EW. Based on the results of the previous sections, POS1 corresponds to the algorithm that returns the best solution of POS1 including or not negative savings, POS2 without reinsertions is used for the single cable instances and POS2 with reinsertions is used for the multiple cable instances. The comparison includes the computation time and performance ratio of each algorithm. Also, it should be noted that POS algorithms concern radial routes whereas EW concerns branched routes.

7-6-1 Computation Time

The computation time is an important parameter for the comparison of the algorithms. In combination with their performance, it could provide useful insights for the final selection of the best algorithm. The parameter that mainly affects the computation time is the number of turbines that are connected to the substation. The number of turbines defines initially the size of the Savings matrix, which is equal to number of turbines*(number of turbines - 1). In principle, all algorithms use as starting point for a particular instance, the same Savings matrix. However, the position of the substation, the choice of single or multiple cables and the implementation of each algorithm affect significantly their computation time. It should be noted that the implementation of EW is slightly different than POS implementation due to the need to denote the branches in every route.

Particularly for all algorithms, except POS1 for the single cable instances, only the positive saving elements of the Savings matrix are used. Thus, only the positive part of the Savings matrix is relevant for the computation time. For a particular instance, the number of positive saving elements vary according to the position of the substation. The reason is that the relative distance of most turbines from the substation increases for the "substation out" case compared to the "substation in" case. Therefore, more interconnections between turbines are less costly than their direct connection to the substation, resulting in more positive saving elements for the "substation out" instances. Hence, a higher computation time is expected for the "substation out" instances. In addition, the use of multiple cables and the way it is implemented (Section 6-3), require sufficiently more calculations and thus more time compared to the single cable problem. The reason is that for every possible merging which leads to a cable with a greater capacity, the saving of the particular merging needs to be calculated and then it is checked, if this merging is indeed the most cost-efficient among all other possible merges. Essentially, because of the fact that EW gives more freedom for merges, the effect of the multiple cable types on its computation time is expected to be higher compared to POS.

Figures 7-9 and 7-10 present the average computation time of POS1, POS2, and EW depending on the number of turbines, for single and multiple cable types respectively. The solid and dashed lines correspond to the "substation in and out" instances respectively.

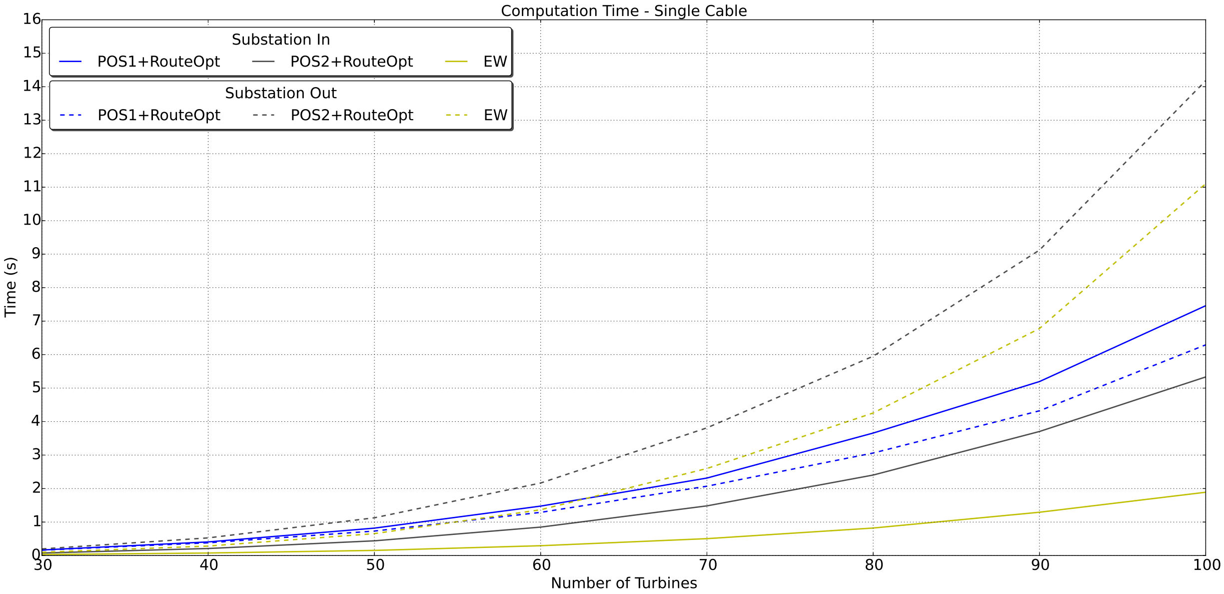

Figure 7-9: Computation Time of POS1, POS2 and EW - Single Cable.

As it can be seen in both Figures, the effect of the position of the substation on the computation time of POS2 and EW is clear. On the other hand, POS1 for the single cable instances shows different behaviour, as explained in Section 7-4. Regarding the multiple cable instances, POS2 computation time slightly increases due to its fewer possibilities for merges and thus less calculations required. The relative increase of the computation time of EW from single to multiple cable types is significantly higher, as it was expected.

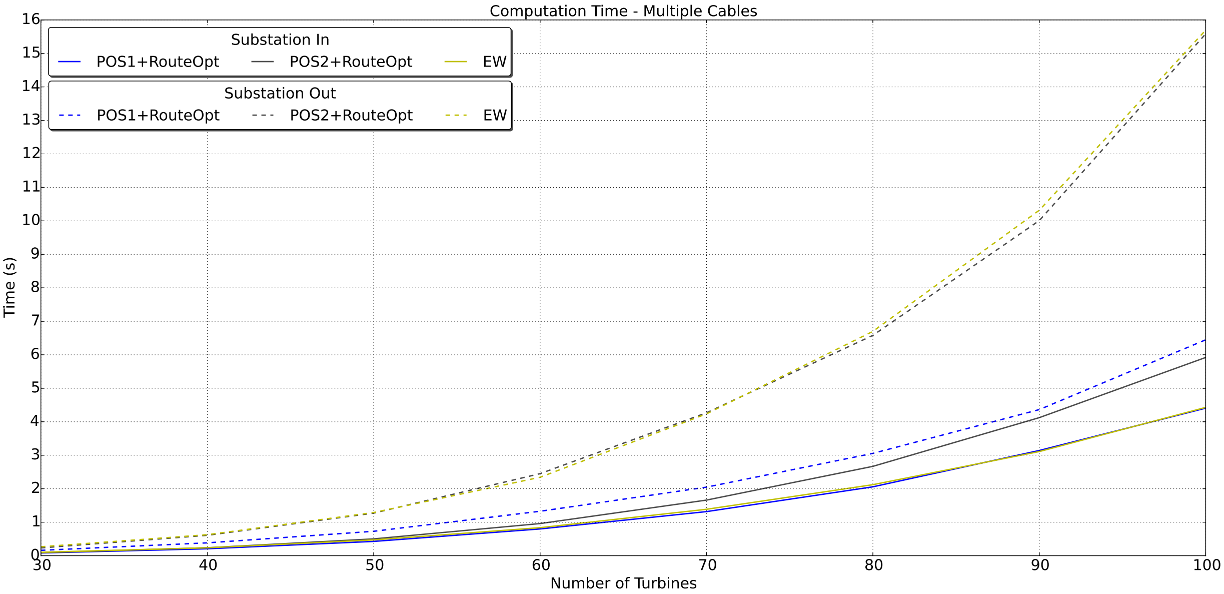

Figure 7-10: Computation Time of POS1, POS2 and EW - Multiple Cables.

As it was mentioned, depending on the parameters that define each instance, the speed of the algorithms is associated mainly to the calculations that are made. But since the implementation for POS and EW is different, especially for the merging conditions, the results of the Figures cannot be fully explained by using only quantitatively arguments. Therefore, further analysis is not possible but still, the results of the two Figures provide sufficient input for the further comparison of the algorithms. In general, EW and POS1 are the fastest algorithms for the "substation in" and "substation out" instances respectively. Last, it should be noted that the results concern only one substation. Therefore, assuming that a wind farm has t turbines and s substations with t/s of the total turbines connected to each substation, the corresponding computation time is s times as much as the time corresponding to t/s turbines, in the Figures.

7-6-2 Performance

The performance of the algorithms, in terms of cost of their solutions, is statistically studied in this Section. The results showed that the performance of the algorithms varies according to the position of the substation and the use of single or multiple cables. Therefore, four cases in total are used to categorize the results that correspond to "substation in" and "substation out" cases for both single and multiple cables. It is also noted that EW generates branched routes and hence its performance is expected in principle, to be better than POS. However, due to the unpredictability of the heuristics, this is not always the case as it will be shown.

First, Table 7-5 provides the comparison of the algorithms in terms of number of instances, for which each algorithm yielded the best solution. The first two rows correspond to POS1 and POS2 respectively. The third row shows the number of instances for which POS1 and POS2 yielded the same solution which was better than the solution provided by EW, whereas the fourth row corresponds to EW. Also, there was an instance (single cable - substation out) which is not included in the Table, for which all algorithms yielded the same solution. The results of the Table indicate foremost the effect of the substation's position on the performance of EW. As it can be seen, the number of instances for which EW provided the best solution, drops significantly for the "substation out" case compared to the "substation in" case. In addition, for the "multiple cables" instances, POS algorithms outperform EW for a wide range of instances, especially for the "substation out" case.

Table 7-5: Comparison of POS1, POS2 and EW.

	Single Cable		**Multiple Cables**	
Position of Substation	**In**	**Out**	**In**	**Out**
Best Algorithm				
POS1	95	197	101	157
POS2	86	178	169	228
POS1≡POS2	73	232	128	261
EW	866	512	402	154
Total	1120	1120	800	800

In order to include the relative cost difference between the algorithms, Figures 7-11 to 7-14 present the performance ratios of POS1, POS2 and EW with respect to the cable capacity. The instances are categorized according to Table 7-5, hence four graphs are depicted in total and they follow the same pattern as previous graphs which included performance ratios. Particularly, as reference for each instance, the cost that corresponds to the best solution between the algorithms is used. Then for each algorithm, the performance ratio is calculated by diving the cost of the best solution over the cost that corresponds to the solution of the particular instance. By doing so, the dependence on the size of the problem, which is defined by the number of turbines, is eliminated. Finally, the performance ratios are averaged according to the cable capacities that are used in the farm. Thus, the lines that extend horizontally in the following graphs represent the average performance of each algorithm and the closer these lines are to the horizontal line equal to 1.00 in the vertical axis, the better their performance is. In addition, the vertical lines represent for each algorithm, the 70th percentiles of the solutions above and below their average performance. The percentiles are used as a measure of the deviation of the solutions from the average value and to indicate the possible overlap between the algorithms.

Figures 7-11 and 7-12 concern the single cable instances and they show the performance ratios of POS1, POS2 and EW for the "substation in" and "substation out" instances respectively.

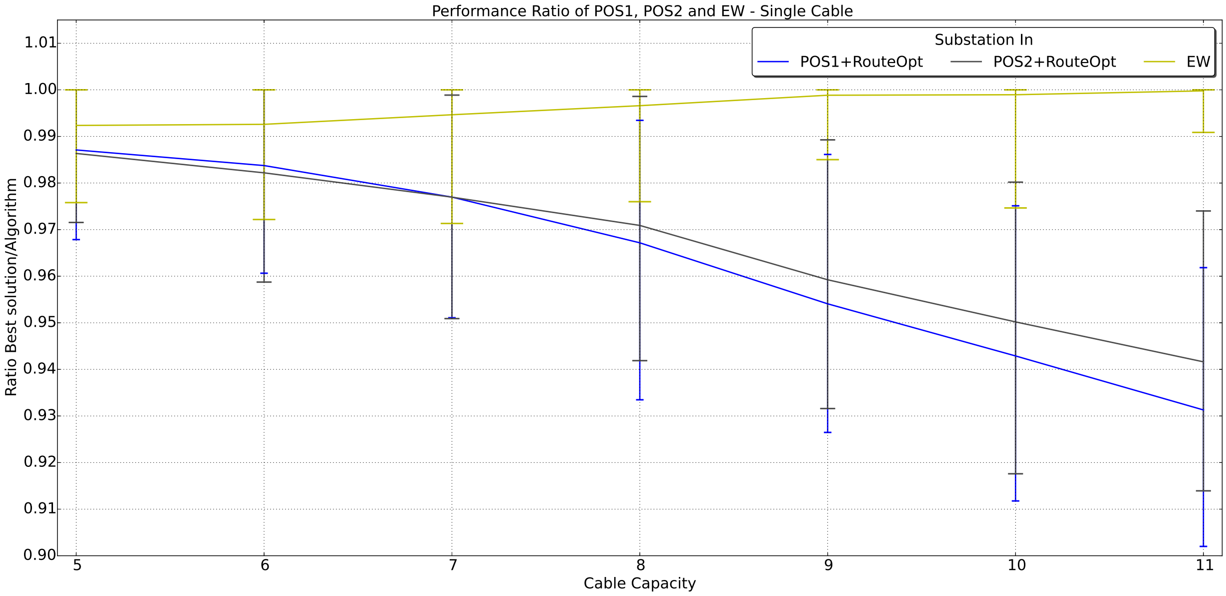

Figure 7-11: Performance ratios of POS1, POS2 and EW - Single Cable - Substation In.

For the "substation in" case, the average performance of EW is higher than POS1 and POS2 for all cable capacities and ranges from 0.99 to 1.00. Furthermore, as cable capacity increases and thus more complicated solutions are possible, the performance of EW increases compared to POS. In addition, POS1 is slightly better than POS2 for low capacities but after cable capacity corresponding to 7 turbines, POS2 outperforms POS1. The 70th percentile for EW indicates that the majority of the results lie above 0.97 whereas for POS they can reach 0.90.

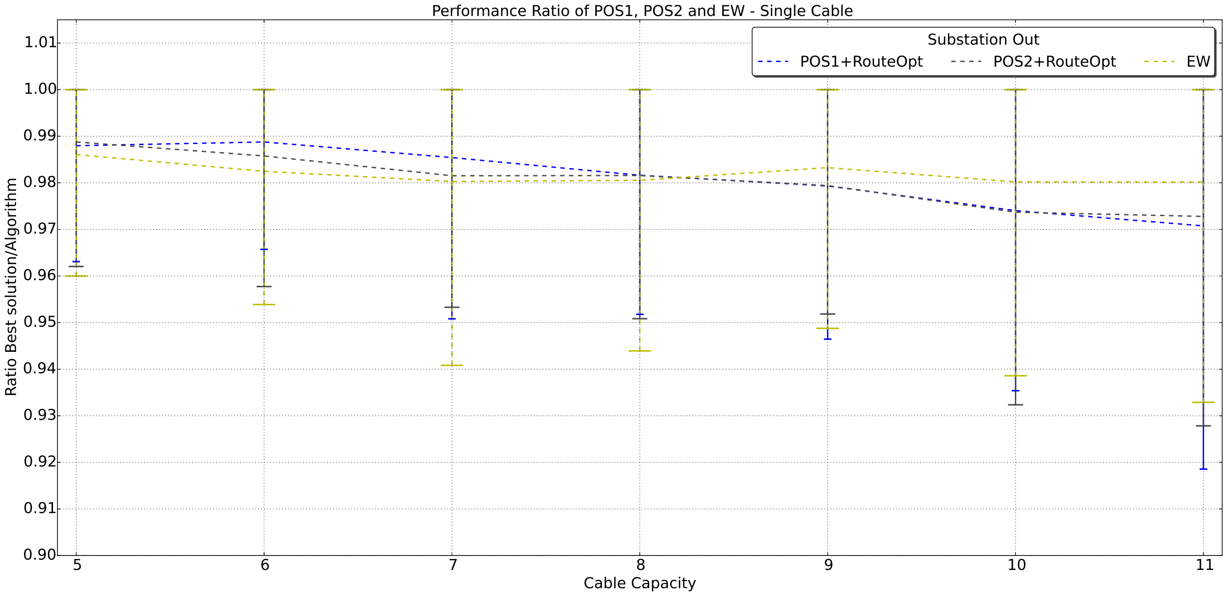

Figure 7-12: Performance ratios of POS1, POS2 and EW - Single Cable - Substation Out.

On the other hand, the results are not so straightforward for the "substation out" instances where single cable is used (Figure 7-12). As it can be seen, the average performance of EW is ranging from 0.98 to 0.99 whereas that of POS ranges from 0.97 to 0.99. The increasing performance of EW with the increase in the cable capacity can also be observed in this case, while POS1 is on average better than POS2. Lastly, the 70th percentile for the results below the average values show that the deviation from the average performance can reach 5%.

Next, Figures 7-13 and 7-14 concern the instances for which multiple cable types were used.

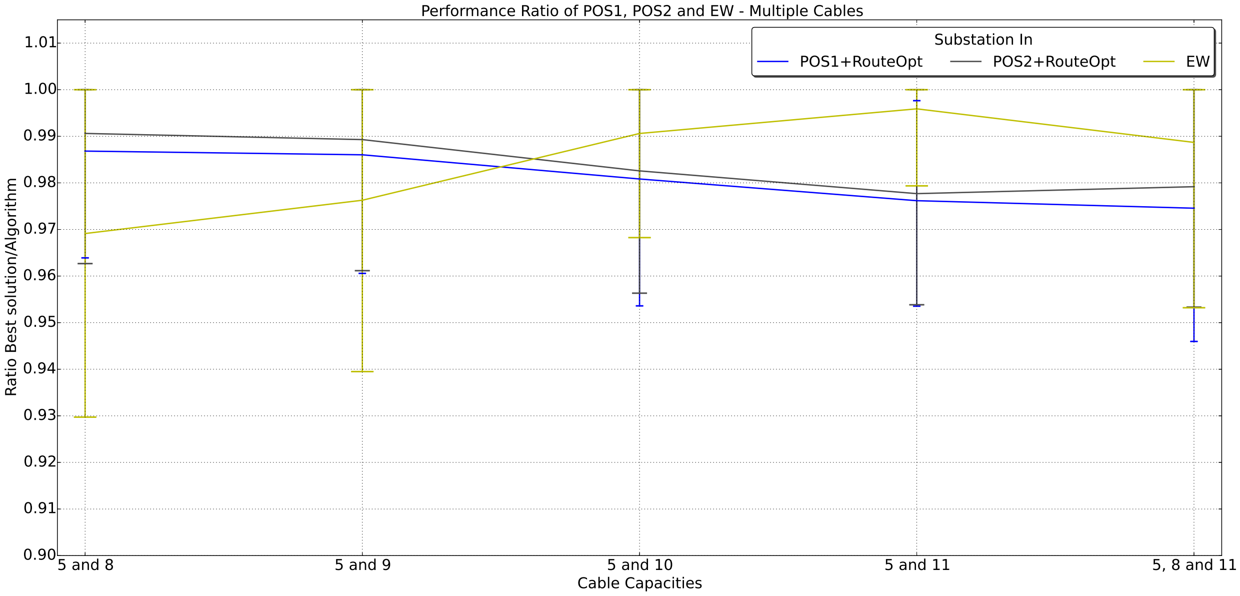

Figure 7-13: Performance ratios of POS1, POS2 and EW - Multiple Cables - Substation In.

As it can be seen in Figure 7-13, POS2 is on average better than POS1 for all cable combinations. Regarding the performance of EW, it is affected significantly by the range of cable capacities. Particularly, the performance of EW ranges from 0.97 to 1.00 and it outperforms POS when the cable capacity of the "expensive" cable is at least double than the capacity of the "cheap" cable. Moreover, the percentiles indicate that EW shows higher unpredictability compared to POS for narrow range of cable capacities while POS shows a relatively constant deviation from the average performance for all cable capacities.

Finally, Figure 7-14 presents the average performance ratios for the multiple cables - substation out instances. The effect of the range of cable capacities on the performance is similar as depicted in Figure 7-13. Hence, in both Figures, the average values of the performance evolve in a similar way depending on the range of cable capacities. However, the substation's position affects significantly the performance of EW, as it is also the case for the single cable. The results show that EW performs on average worse than POS for all cable combinations and particularly for narrow ranges of cable capacities, it yields 6% worse solutions compared to POS. In addition, POS2 is slightly better than POS1 for all cable combinations. Last, the percentiles indicate a significant overlap between the performance of POS and EW for the cable combinations "5 and 10" and "5 and 11", where EW approaches the performance of POS.

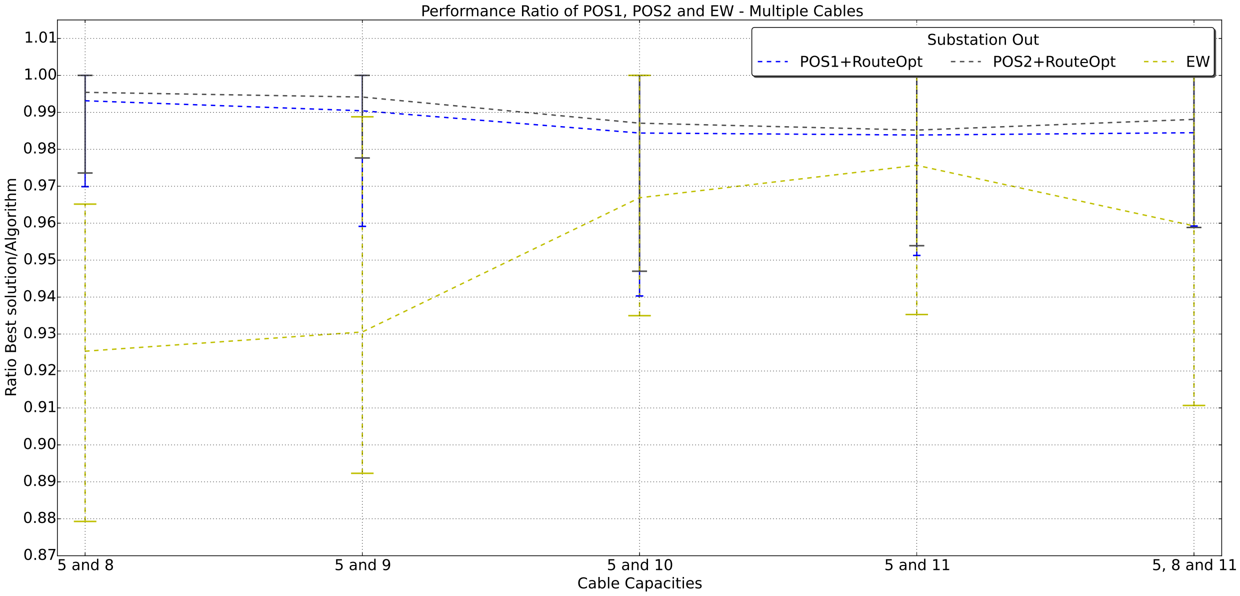

Figure 7-14: Performance ratios of POS1, POS2 and EW - Multiple Cables - Substation Out.

Summing up the results, the main outcome is the dependence of the algorithms' performance on the position of the substation. Particularly, the average performance of EW drops significantly for the "substation out" instances compared to the "substation in" instances. Another conclusion that can be drawn from the results is the relatively poor performance of EW when multiple cables are used. For this reason, a hybrid approach that improves the behaviour of EW for multiple cables is proposed in the following Section. Thus, final recommendations regarding the use of each algorithm are made in Section 7-8, after the introduction of the Hybrid.

7-7 Hybrid

As it was mentioned, a hybrid approach is proposed in this Section that improves the performance of EW when more than one cable type is available. The name Hybrid denotes that it is a combination of two algorithms, particularly POS1 and EW, and hence it concerns branched routes.

7-7-1 Motivation

The motivation to develop a hybrid by combining POS1 and EW was based on the results of the aforementioned algorithms after tested in the layout of the Gwynt y Môr OWF [36] and compared with its installed Infield Cable Topology (ICT) [37].

In Gwynt y Môr OWF, 160 turbines are used with a power rating of 3.6 MW. Furthermore, two cables are used with cross sections 180 and 500 mm^2 forming a branched cable topology. The cost of these cables can be found in Table 7-1. Since a turbine of the same rating was assumed to associate the cable costs with cable capacities in terms of number of turbines in Figure 7-1, the inter-array cables that are installed in Gwynt y Môr can withstand 6 and 10 turbines respectively. Hence, by using the coordinates of turbines and substations found in [37] and the aforementioned cables, the OWFICTP for Gwynt y Môr is solved by using POS1+RouteOpt and EW. The results are presented in Figures 7-15 and 7-16 respectively.

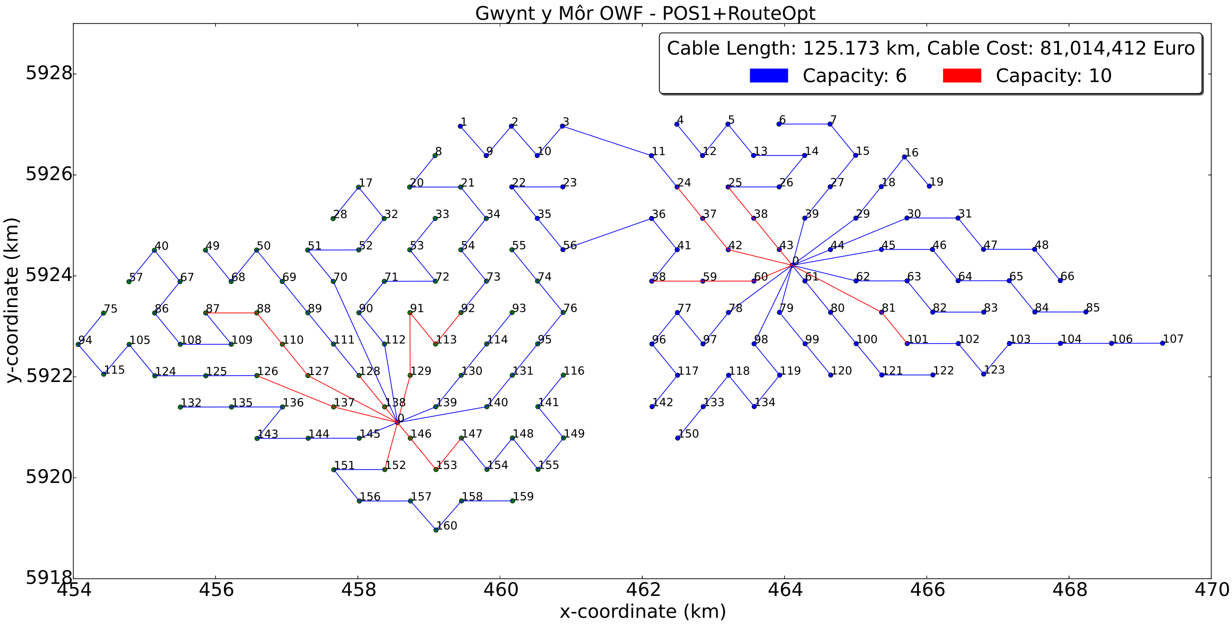

Figure 7-15: ICT generated by POS1 and RouteOpt for Gwynt y Môr OWF.

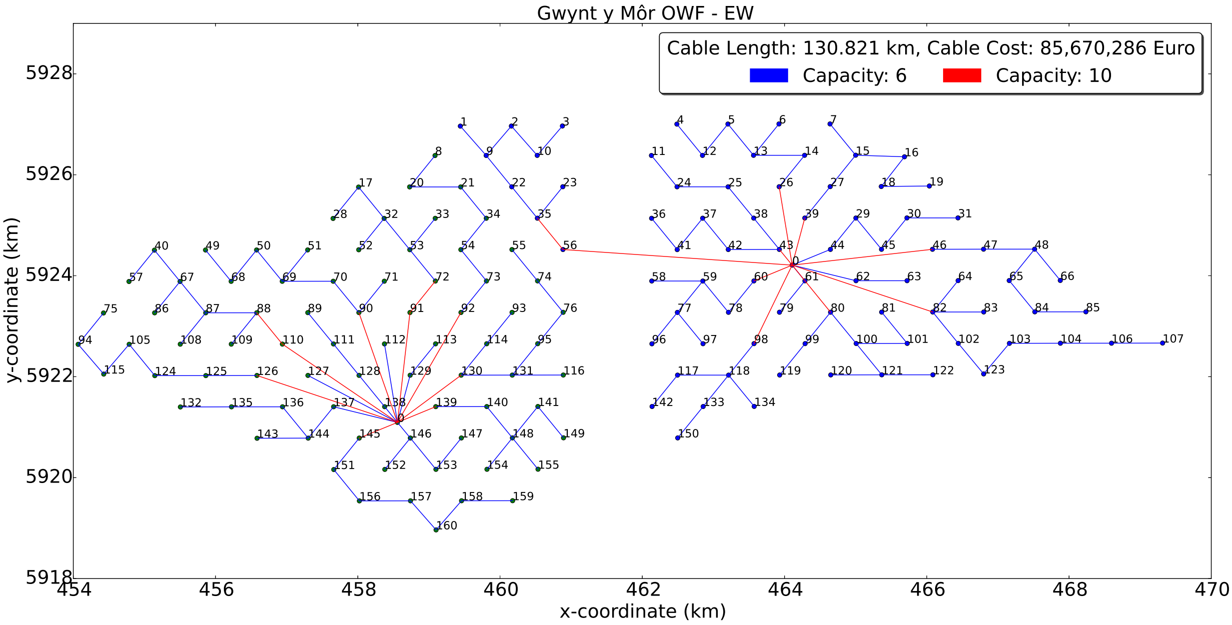

Figure 7-16: ICT generated by EW for Gwynt y Môr OWF.

As it can be seen, the solution of POS1+RouteOpt is significantly better than EW. Next, the installed layout of Gwynt y Môr OWF is presented in Figure 7-17.

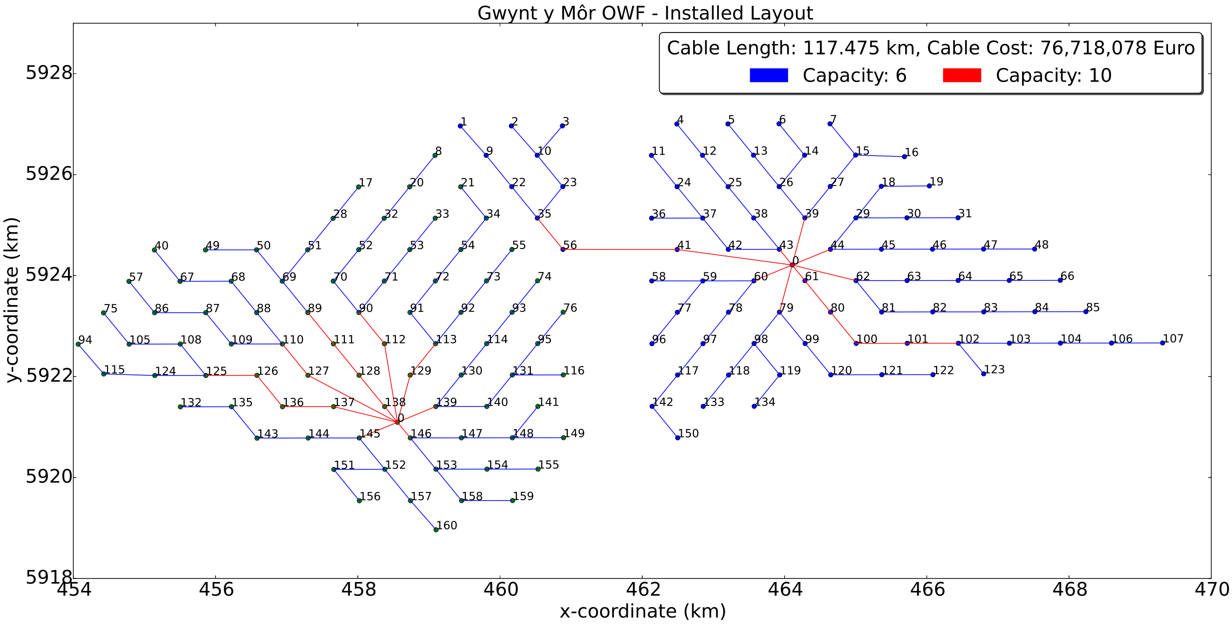

Figure 7-17: Installed Layout Gwynt y Môr OWF.

In terms of total cost, the infield cable topologies generated by EW and POS1+RouteOpt are 11.7% and 5.6% worse than the installed layout respectively. A closer look at the installed layout of Gwynt y Môr indicates that most of the routes extend radially towards the substations and branches are formed relatively close to the substations. On the other hand, EW yields a more random layout with branches away from the substation. The reason is that the structure of the algorithm forces initially the creation of clusters of turbines that are located relatively away from the substation. Subsequently, the connection of these turbine clusters to the substation requires often the use of the expensive cable and hence, results in a costly final solution. Regarding the solution of POS1, it follows satisfactorily the installed layout in the sense that radial routes towards the substation are formed. Therefore, this attribute of POS1 is combined in the following Section, with the possibility of branching provided by EW in order to develop a hybrid approach.

7-7-2 Approach

The hybrid approach is developed to improve the performance of EW when more than one cable type is available. Based on the results of Figures 7-15 to 7-17, it is desirable to achieve initially radial routes and then inter-connect these routes to form branched routes. Therefore, the Hybrid starts by using POS1 for the low capacity cable. This means that initially, the inter-array cable topology is calculated by solving the single cable OWFICTP for radial routes with the use of POS1 and cable capacity corresponding to the low capacity cable. Then, EW for multiple cable types calculates the branched layout by using as initial solution, the layout generated by POS1. Finally, RouteOpt is applied to every radial part of the routes and only if the cheap cable is used. It should be noted that POS1 was chosen instead of POS2 because both algorithms provide equivalent solutions for single cable but POS1 is faster.

The structure of the Hybrid is as follows:

```
Hybrid Multiple Cable Types
(Graph $(T \cup S,\ P)$, distance $d(k,u)\ \forall\ (k,u) \in P$, Cables $r_1 = (n_1, c_1)$, $r_2 = (n_2, c_2)$):
1 $P \leftarrow$ POS1 (Graph $(T \cup S,\ P)$, distance $d(k,u)\ \forall\ (k,u) \in P$, Capacity $n_1$)
2 $P \leftarrow$ EW Multiple Cable Types
  (Graph $(T \cup S,\ P)$, distance $d(k,u)\ \forall\ (k,u) \in P$, Cables $r_1 = (n_1, c_1)$, $r_2 = (n_2, c_2)$)
3 $P \leftarrow$ RouteOpt (Graph $(T \cup S,\ P)$, distance $d(k,u)\ \forall\ (k,u) \in P$)
4 return $P$
```

As it can be seen in line 1, the radial solution P is calculated by using POS1 as described in Section 4-1-1, for the capacity n_1 of the cheap cable r_1. Then, line 2 calculates the branched layout by using EW for multiple cable types, as presented in Section 6-3. However in this case, line 2 of the EW Multiple Cable Types algorithm is omitted since the initial solution is already available. Last and because of the fact that POS1 is used, RouteOpt examines the generated layout for local improvements in the routes. However, only the radial parts of the routes are used as inputs for RouteOpt and specifically the radial parts for which the cheap cable is used. The reason is that RouteOpt, as it was mentioned, can only be applied to the cheap connections of the POS solutions. It should also be noted that the description of the Hybrid for simplicity concerns two cable types. A detailed overview of the algorithm including the additions of Chapter 8 can be found in Appendix A. Figure 7-18 presents the cable topology for Gwynt y Môr OWF as it was generated by the Hybrid.

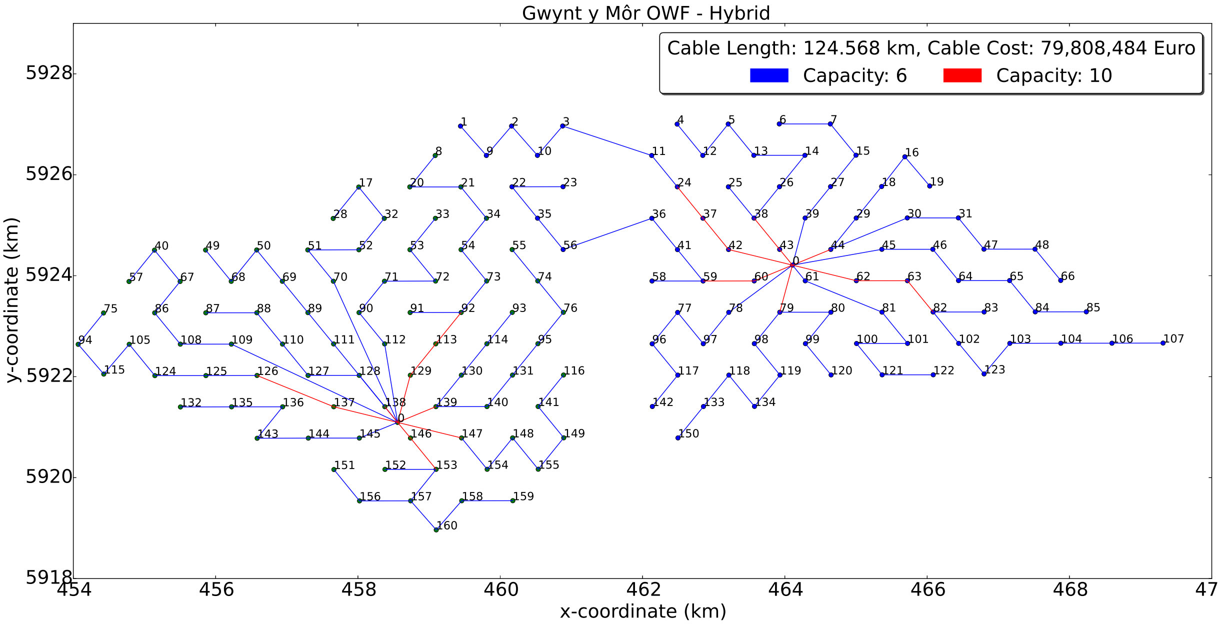

Figure 7-18: ICT generated by Hybrid for Gwynt y Môr OWF.

The solution is 4.0% worse than the installed layout but 7.7% better than EW. The performance of the Hybrid is tested according to the instances of Table 7-2 in the next Section.

7-7-3 Results

Table 7-6 presents the number of instances for which each algorithm yielded the best solution.

Table 7-6: Hybrid vs EW - Multiple Cables.

	Substation In	**Substation Out**
Hybrid>EW	542	538
Hybrid<EW	258	261
Total	800	800

The results indicate that the Hybrid outperforms EW for the majority of the instances. Moreover, the same behaviour is observed for both positions of the substation ("in" and "out"). It should be noted that for one "substation out" instance, both algorithms yielded the best solution and it is not depicted in the Table. Next, the average performance ratios of the algorithms for the substation in and out instances are compared in Figures 7-19 and 7-20 respectively. Since the performance of the Hybrid compared to POS is also of interest, POS performance ratio is also included. Furthermore, the cost that corresponds to the best solution between POS and EW is used as reference for each test instance. Hence, the performance of Hybrid can surpass the 1.00 horizontal line, meaning that it provides on average better solutions than POS and EW.

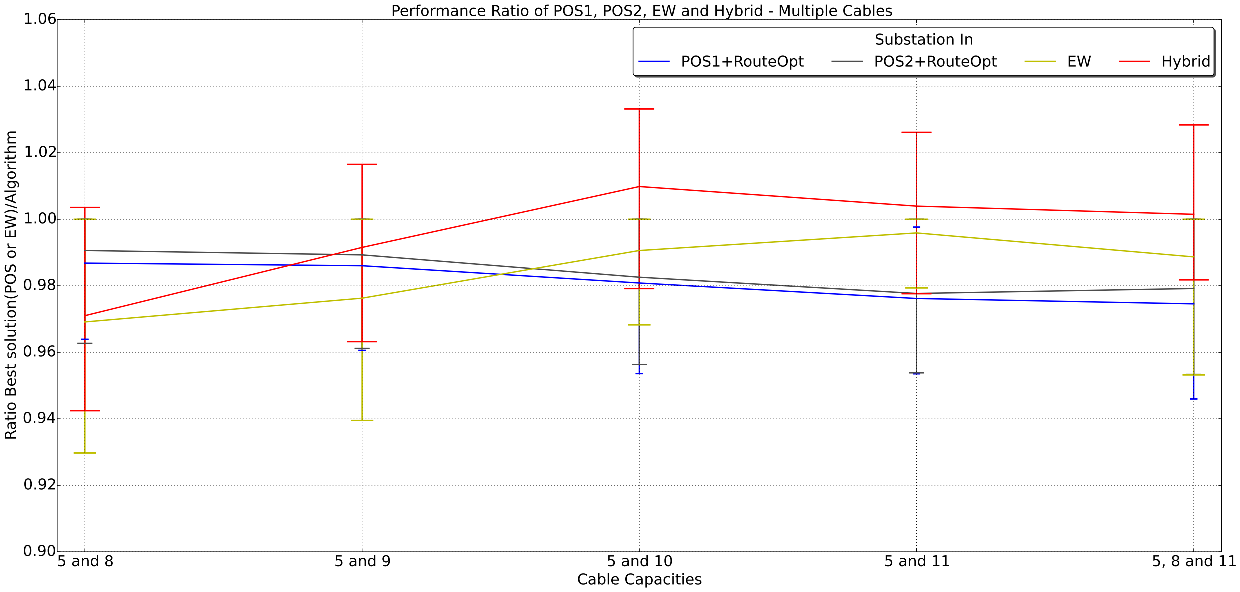

Figure 7-19: Performance ratios of POS, EW and Hybrid - Multiple Cables - Substation In.

Starting from the "substation in" instances and Figure 7-19, the Hybrid is on average better than EW for all cable combinations. The improvement on EW reaches 2% for the cable capacities "5 and 10" turbines and the range of capacities does not affect the relative performance of the Hybrid compared to EW. In addition, the percentiles indicate a significant overlap between the algorithms, especially for the instances below the mean value. Last, the performance of the Hybrid compared to POS depends heavily on the range of the cable capacities. As the range becomes wider, the Hybrid is on average $2-3\%$ better than POS. Figure 7-20 presents the comparison of POS, EW and Hybrid for the "substation out" instances.

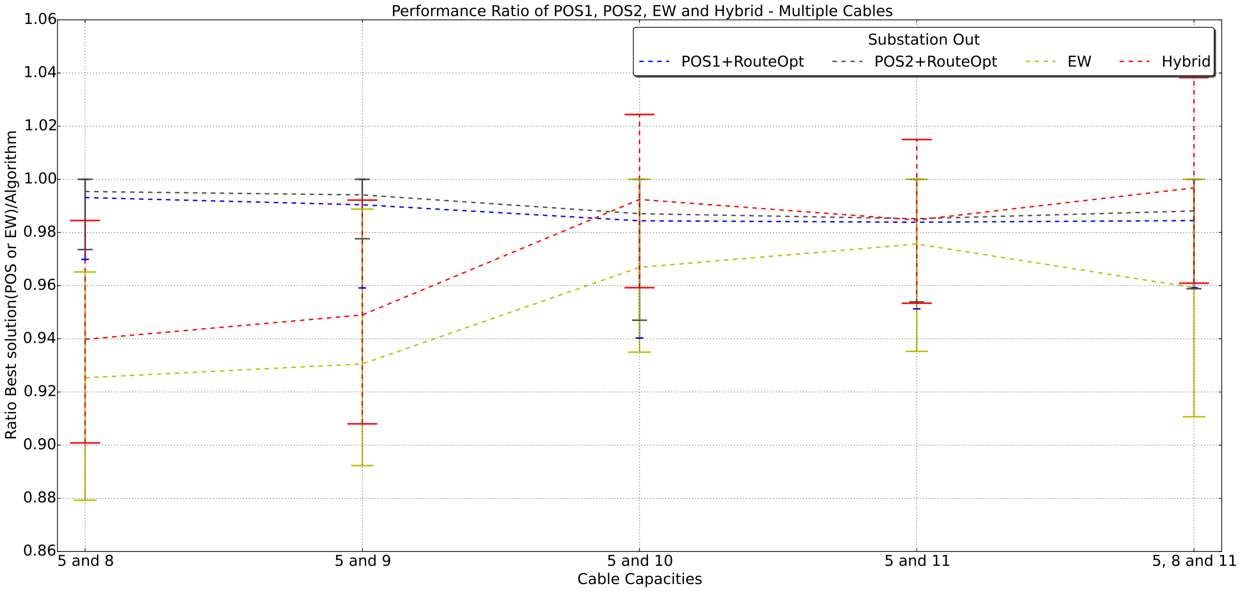

Figure 7-20: Performance ratios of POS, EW and Hybrid - Multiple Cables - Substation Out.

As it can be seen, the improvement provided by the Hybrid to EW is greater for all cable combinations, compared to the "substation in" instances. Moreover, the percentiles show the higher probability for the solutions of the Hybrid to be better than those of EW. On the other hand, the performance of the Hybrid compared to POS is $4-6\%$ worse for the cable capacities "5 and 8" and "5 and 9" turbines. Only when the capacity of the expensive cable is at least double than the capacity of the cheap cable, the performance of the Hybrid slightly overcomes the performance of POS.

In order to complete the comparison of the algorithms for the multiple cables' case, the average computation time of each algorithm needs to be included. Figures 7-21 and 7-22 present the average computation time of POS1, POS2, EW and Hybrid depending on the number of turbines connected to one substation for the substation in and out cases respectively. Particularly, the computation times of POS1, POS2 and EW correspond to the ones presented in Figure 7-10. Thus, the computation time of the Hybrid is added and in order to present the results clearly, they are split according to the position of the substation. As it has been mentioned, the position of the substation outside the wind farm increases significantly the number of the positive saving elements compared to the "substation in" case and thus the computation time increases.

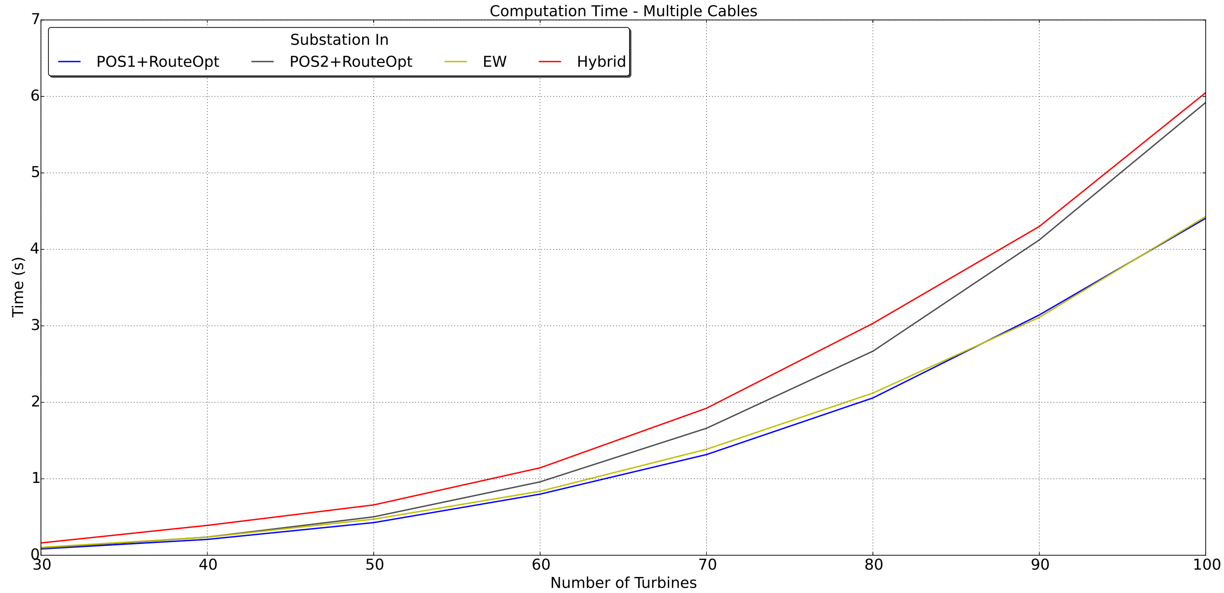

Figure 7-21: Computation Time of POS, EW and Hybrid - Multiple Cables - Substation In.

Regarding the "substation in" case, the computation time of POS1 and EW is approximately equal whereas POS2 and the Hybrid are slightly slower. Generally for this case, only minor differences in the computation times are observed and the decision over the choice of the best algorithm will be governed by the performance of each algorithm.

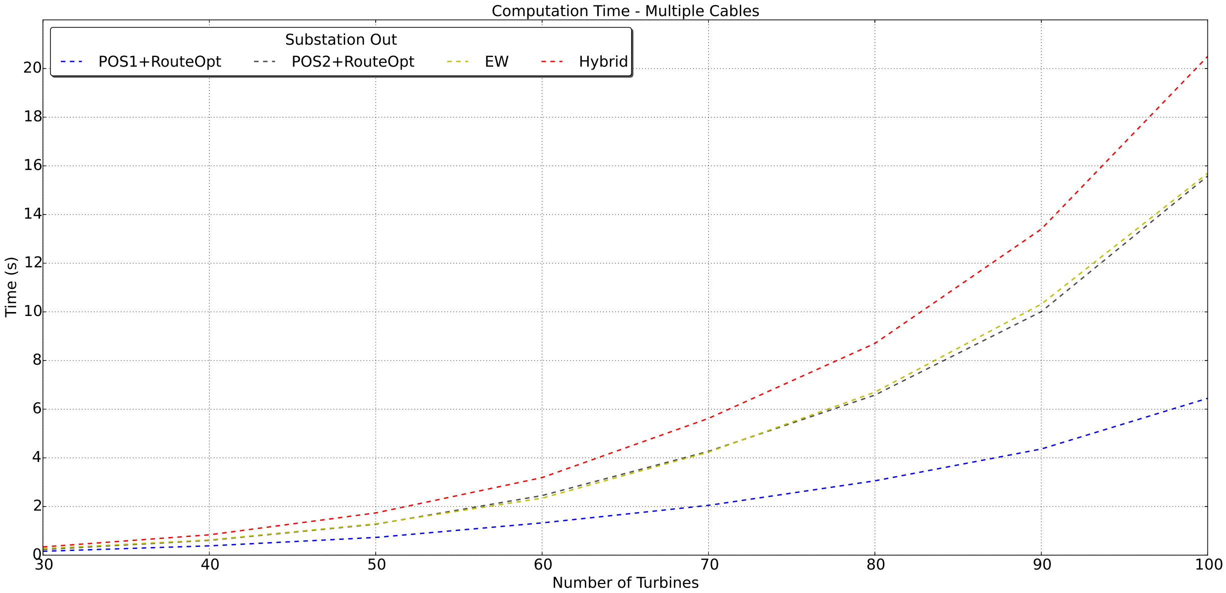

Figure 7-22: Computation Time of POS, EW and Hybrid - Multiple Cables - Substation Out.

As far as the "substation out" case is concerned, significant differences in the computation times of the algorithms are observed. For POS1, the effect of the substation's position is minor and it is by far the fastest algorithm. Moreover, EW computation time is approximately equal to POS2 time whereas the Hybrid is the slowest between the algorithms.

In general, as it was expected, the improvement of EW performance by the Hybrid comes with a trade-off in the computation time. The reason is that two algorithms (POS1 and EW) are used by the Hybrid and hence, two Savings matrix are browsed. It should also be noted that the the computation time of the Hybrid is not equal to the sum of the computation times of POS1 and EW, since both algorithms are only partially used by the Hybrid.

7-8 Discussion

To sum up, the objective of this Chapter was to compare the performance of the algorithms, in order to provide recommendations regarding their use. This could only be achieved statistically since the comparison concerns heuristic algorithms. Thus, a wide range of instances was used that simulated possible layouts of OWF. The results indicated two major distinctions: the use of single or multiple cables and the position of the substation inside or outside the wind farm. In addition, a hybrid approach was proposed for the branched OWFICTP where multiple cables are used. In this Section, the final recommendations are made based on the results of the previous Sections.

Starting from the case for which a single cable is used, Figures 7-9, 7-11 and 7-12 provide the comparison of POS1, POS2 and EW time and cost-wise. For the "substation in" case, EW is the best algorithm, time and cost-wise. As far as radial layouts are concerned, the best choice is POS2 without reinsertions, since it is faster than POS1 and better for most cable capacities. Next, for the "substation out" case, POS1 is the best of POS algorithms and especially the approach, which returns the best solution between POS1 with only positive savings and POS1 including negative savings . Last, EW provides adequate branched solutions, particularly for high cable capacities.

On the other hand, the recommendations regarding the use of the algorithms for multiple cables are not so straightforward. Figures 7-19 and 7-20 provide the cost comparison of POS1, POS2, EW and Hybrid whereas Figures 7-21 and 7-22 present the computation times of the algorithms. Starting from the branched layouts and according to the author's opinion, the improvement provided by the Hybrid to EW overcomes the additional time that is required. Regarding POS algorithms and hence radial layouts, the cost performance of POS2 is slightly better than POS1 but POS1 is substantially faster, especially for the "substation out" case. Therefore, the best choice is POS1, since it can provide more efficiently solutions close to POS2 solutions. Last, the choice between the Hybrid and POS1 depends on the position of the substation and the range of cable capacities. For the case where the substation is centrally located, the Hybrid provides on average better solutions in slightly higher computation times and hence, it is the best choice. Regarding the "substation out case", the Hybrid is slightly better than POS1 only when the range of cable capacities is relatively wide but it requires sufficiently higher computation time. Therefore and assuming that the computation time is also an important parameter for the user, POS1 is the best choice for this case.

In conclusion, Table 7-7 includes the final recommendations regarding the use of the best algorithm for each case. The first two rows concern the best algorithm for radial and branched topologies respectively. The third row indicates the best choice for each case, among all possible algorithms.

Table 7-7: Choice of Best Algorithms.

	Single Cable		**Multiple Cables**	
Position of Substation	**In**	**Out**	**In**	**Out**
Radial Topology	POS2	POS1	POS1 or POS2	POS1
Branched Topology	EW	EW	Hybrid	Hybrid
Overall	EW	POS1	Hybrid	POS1

It should be noted that the recommendations were made according to the author's opinion and possibly each user's priorities could lead to a different result. In addition, the recommendations were based on average performances and hence for a particular instance, a behaviour that does not comply with the Table is not totally unexpected. Nevertheless, the opportunity is given to the user to get efficiently the infield cable topologies generated by all algorithms and then choose according to his/her needs.

Chapter 8

Pipeline/Cable Crossings and Case Study

In this Section, additional features that were added to the algorithms are presented and modifications to the algorithms are proposed that treat area constraints, imposed by pipelines/cables. Finally, a case study is used to indicate the importance of the aforementioned modifications.

8-1 Additional Features

In order to enhance the practicality of the developed tool, two features are added to the algorithms. The first feature concerns only branched topologies, whereas the second one is applicable to all algorithms.

8-1-1 Switchgear

Switchgears are necessary building blocks for the operation of Offshore Wind Farms (OWF). The switchgear acts as a connection point for the turbines in a feeder and enables the connection of several feeders to the substation. Also, it protects the wind turbine's equipment from possible faults.

As it has been mentioned, branched infield cable topologies require more complicated switchgear arrangements at turbines where branches are formed. Hence, this results in a greater size of the switchgear and consequently in a higher cost. Moreover, the number of cable system connections which a switchgear can accommodate affects also the size and the cost of the switchgear. Nowadays, commercial switchgears can accommodate up to three incoming cables but typically, double cable connections are most common. Therefore, the option is given to the user to limit the number of connections in the switchgear to 2 or 3. This feature is implemented in both Esau-Williams (EW) and the Hybrid heuristics.

8-1-2 Transmission Lines

The main constraint for the Offshore Wind Farm Infield Cable Topology Problem (OWFICTP) is the crossing between cables. A cable crossing could lead to excessive costs and thus, it is strictly avoided from all algorithms that have been developed.

Moreover, the transmission lines from the substation to the onshore connection point, even if they are not part of the collection system, are laid between the inter-array cables in the case where the substations are centrally located in the wind farm. Therefore, an additional constraint is imposed to the OWFICTP. Taking this into account, all algorithms are modified to include the coordinates of the transmission lines in their inputs and they now strictly avoid crossings between the inter-array cables and the export cables.

Figure 8-1 presents the Infield Cable Topology (ICT) for Gwynt y Môr OWF generated by EW, which avoids the crossings with the transmission lines[37] and allows maximum double cable connections at the turbines. Compared to Figure 7-16, the total cost is significantly less. Hence, additional constraints to the heuristics could lead to a better final solution but on the other hand, the computation time increases.

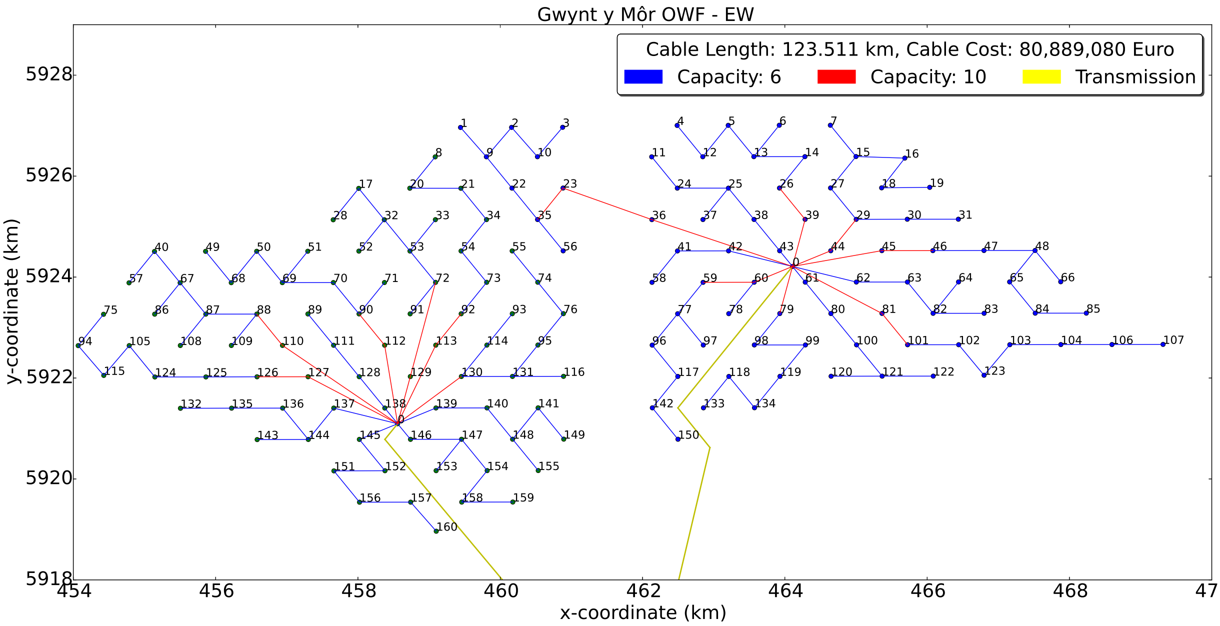

Figure 8-1: ICT generated by EW for Gwynt y Môr OWF including Export Cables and Double Switchgear.

8-2 Pipeline/Cable Crossings

In this Section, area constraints are treated that are imposed by pipelines or cables (e.g. gas pipelines and telecommunication cables) which are laid on the seabed. In most cases, the crossing of the inter-array cables with these pipelines cannot be entirely avoided and hence, it is desirable to minimize the crossings and subsequently the associated costs.

The approach that was developed, aims to find a balance between the final cost of the ICT and the minimization of crossings. Therefore, a penalty function is used that associates the crossing with a fixed cost in monetary terms. This means that a possible crossing is considered as one-dimensional and the dimensions of the obstacle (i.e. pipeline) are irrelevant. At this point, it is reminded that all algorithms start from an initial solution, which connects every turbine to the substation with a single line. Next, merges of routes are achieved that lower the cost at each iteration. Thus, in order to force the algorithm to eliminate as much as possible the crossings, it is required to intervene in the Savings Matrix. As it has been defined, the cost saving sv_{ku} by connecting turbine k to turbine u is equal to: $sv_{ku} = (d(i,s) - d(k,u)) * c$, where $d(\cdot)$ is the distance function between two points, s denotes the substation, i is the turbine of the route that contains turbine k which is directly connected to the substation and c represents the cost of the cable.

Assuming a fixed cost p for the penalty function for crossing a pipeline/cable and in order to account for multiple crossings, the aforementioned saving is updated accordingly:

$$sv_{ku} = (d(i,s) - d(k,u)) * c + (N_{is} - N_{ku}) * p$$

where N_{is} and N_{ku} represent respectively, the number of crossings of the connections $i - s$ and $k - u$ with the obstacles.

The aforementioned formula is used for the calculation of the initial Savings matrix, as well as for every point where an update in the Savings matrix is made, for all algorithms. As far as the penalty function is concerned, the higher its value is, the more crossings are avoided. Nevertheless, it can affect significantly the cost of the final layout and hence, reasonable values should be used. In the following Section, a case study is presented as a representative example of an offshore wind farm with the aforementioned area constraints.

8-3 Case study: Borssele OWF

The Borssele Wind Farm Zone (BWFZ) is located at the southern border of the Dutch Exclusive Economic Zone (EEZ), approximately 0.5 km from the Belgian EEZ. The total area is approximately 344 km^2 [38]. The area is expected to be divided into four wind farm sites to be used for the development of four wind farms with a total capacity of 1,400 MW. Several operational cables and pipelines cross the wind farm zone. Furthermore, several abandoned cables/pipelines run through the Borssele area. These pipelines and cables, together with their safety zones (500 metres for pipelines and 750 metres for cables), are excluded from the parcels, where turbines can be put.

Figure 8-2 presents the BWFZ according to the parcel points, found in [39]. In the Figure, the four designated sites are depicted as well as the cables/pipelines with their safety zones. The Wind Farm Sites at the BWFZ will be tendered in two separate tenders of which the first will open in 2015 and the second in 2016. Wind Farm Sites I and II will be part of the tender of 2015 whereas Wind Farm Sites III and IV will be part of the tender of the 2016.

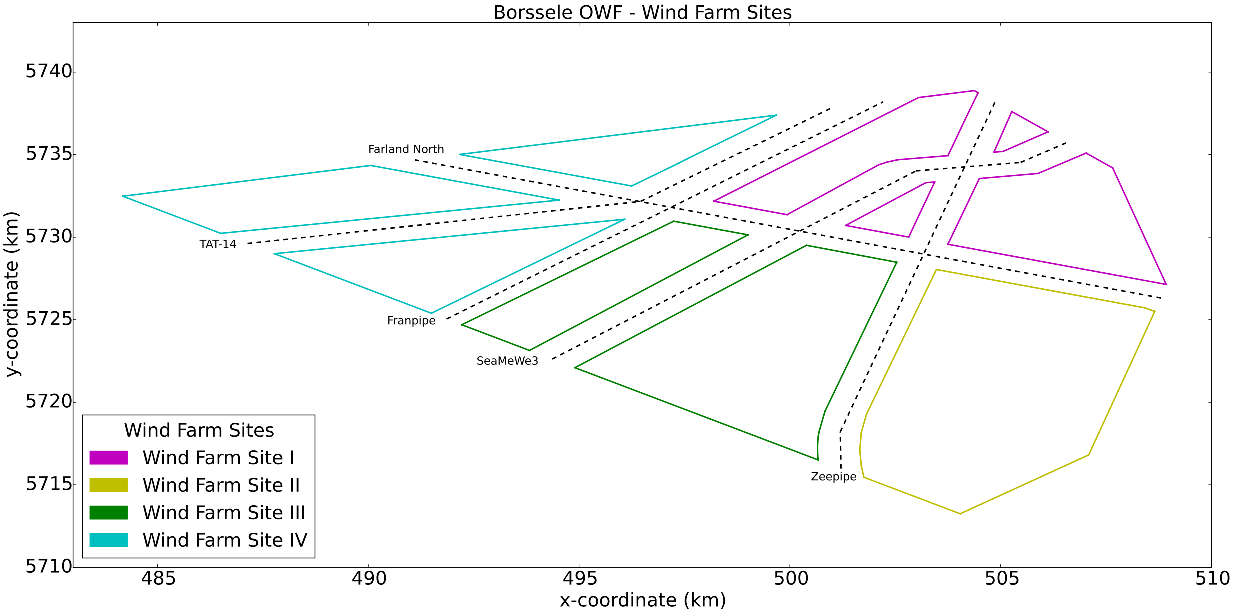

Figure 8-2: Borssele OWF - Wind Farm Sites including Cables/Pipelines.

TenneT in collaboration with DNV GL proposed an array cable layout for BWFZ, where there are two substations collecting the output of 234 x 6 MW wind turbines [40]. A voltage level of 66kV has been chosen for the collection system and 630 mm^2 and 240 mm^2 copper conductor inter-array cables are used. These cables can carry the output of 13 and 8 wind turbines respectively and their corresponding costs are 425 and 200 €/m (medium-cost estimate). Figure 8-3 presents the proposed layout for Borssele OWF by DNV GL.

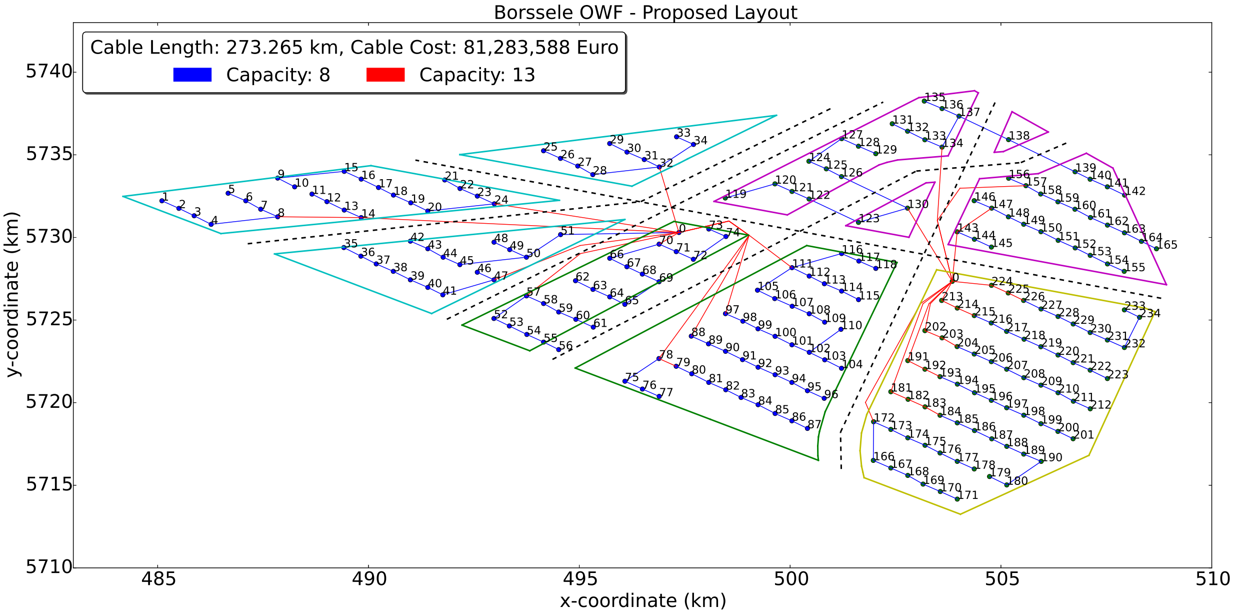

Figure 8-3: ICT for Borssele OWF - DNV GL Proposal [40].

Since the coordinates of the turbines are not available, the layout of the Figure is only an approximation of the proposed layout but nevertheless, significant effort has been put for the maximum possible accuracy. As it can be seen, there are turbines that are located outside the designated wind farm sites, possibly due to misinterpretation of the parcel points. However, it does not affect the final results. Moreover, it can be observed in the Figure that crossings with the cables/pipelines are minimized. In total, there are 26 crossings. As far as the final cost is concerned, it accounts to approximately 81 M€. The total cost that is reported in [40] is equal to 91 M€. The difference is due to the fact that in the current calculation, only the cost of the cables that are laid on the seabed is included whereas most probably in [40], the cost of the cables in the foundations and towers is included. However, rough calculations that were made about the additional cable length, since information about the height of the tower and the support structures are not available, agree with the aforementioned cost. It should be noted that for the following cost comparisons, the cost of 81 M€ is used. Moreover, the cost of crossings is not included in the cost calculations. Hence, the comparison of cable costs and number of crossings is made separately.

Next, EW and the Hybrid are used to calculate the ICT of Borssele OWF, with the same inputs as in Figure 8-3. The resulted layouts are presented in Figures 8-4 and 8-5. For both Figures, the algorithms without area constraints were used.

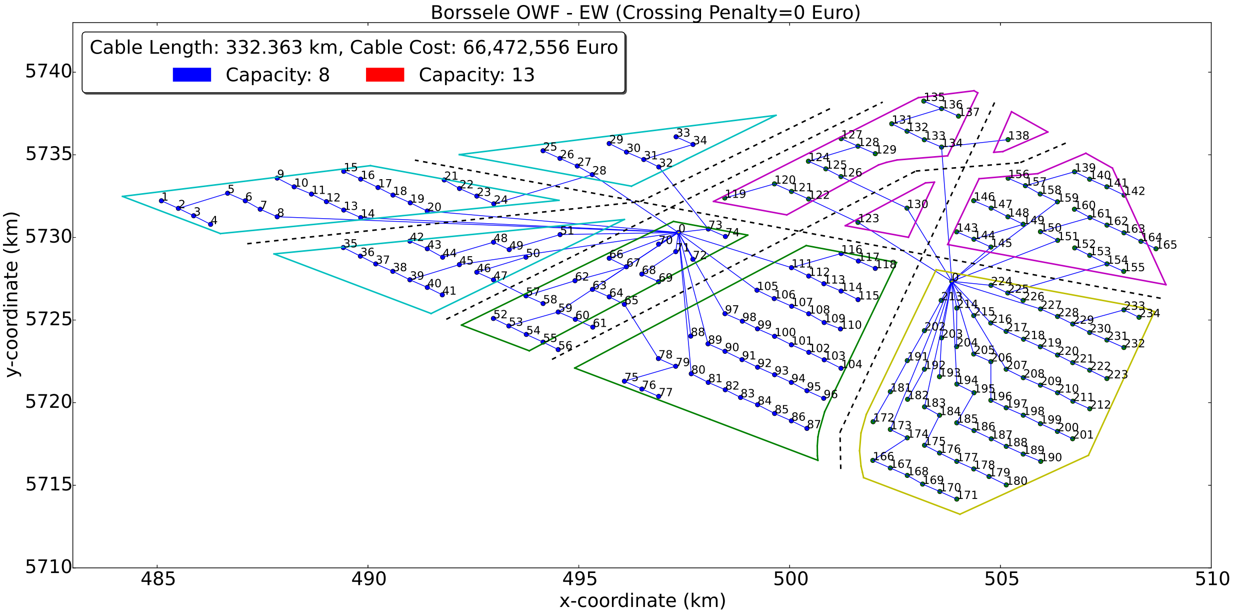

Figure 8-4: ICT generated by EW for Borssele OWF.

As it can be seen in Figure 8-4, the expensive cable is not used for any connection. This is not entirely unexpected, since the price of the expensive cable is more than double of the price of the cheap cable, whereas the range of cable capacities is relatively small (8 and 13 turbines). Probably, if installation costs were included in the cable's price, the result would be different. In total, the inter-array cables cross the pipelines/cables 37 times. Regarding the cable cost, it is 18.2% less compared to the proposed layout of Figure 8-3. Last, some cables in Figure 8-4 are laid close to each other (e.g. 59 – 0 and 63 – 0) and thus, even if it is not so clear in the Figure, all constraints (cable capacity and inter-array cable crossings) are met.

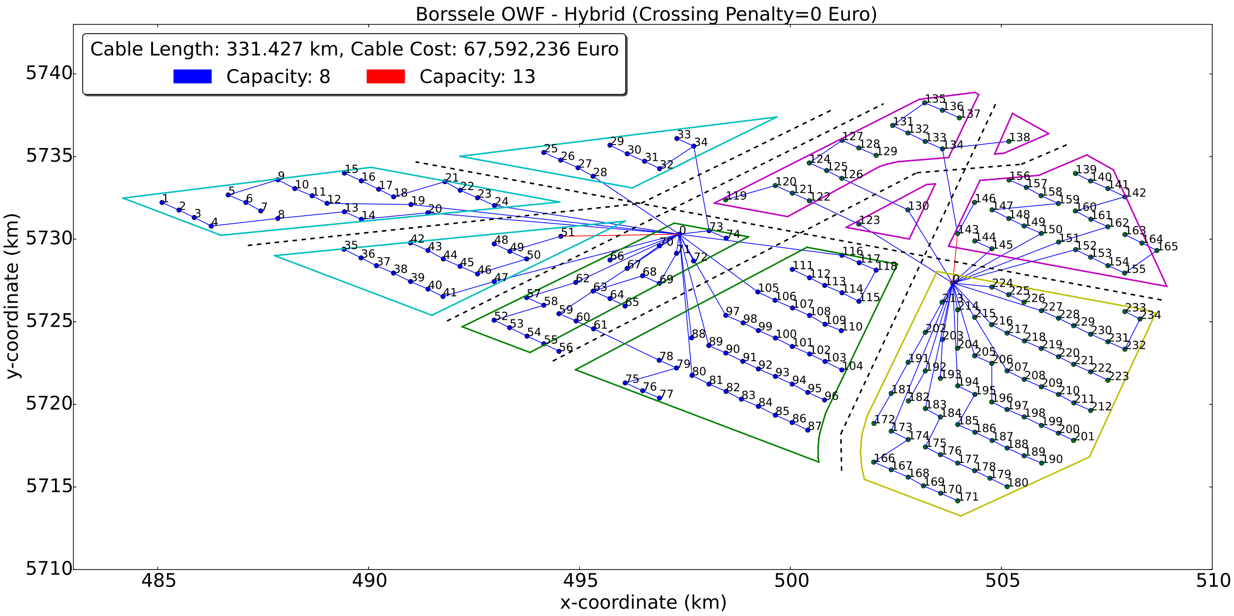

Figure 8-5: ICT generated by the Hybrid for Borssele OWF.

As far as the solution of the Hybrid is concerned, the use of the expensive cable led to 35 crossings but a slightly higher cable cost compared to Figure 8-4. In total, the final cost is 16.8% less compared to the proposed layout. Furthermore, Figure 8-6 presents the cable topology which EW yielded, with a pipeline/cable crossing penalty function of 2 M€.

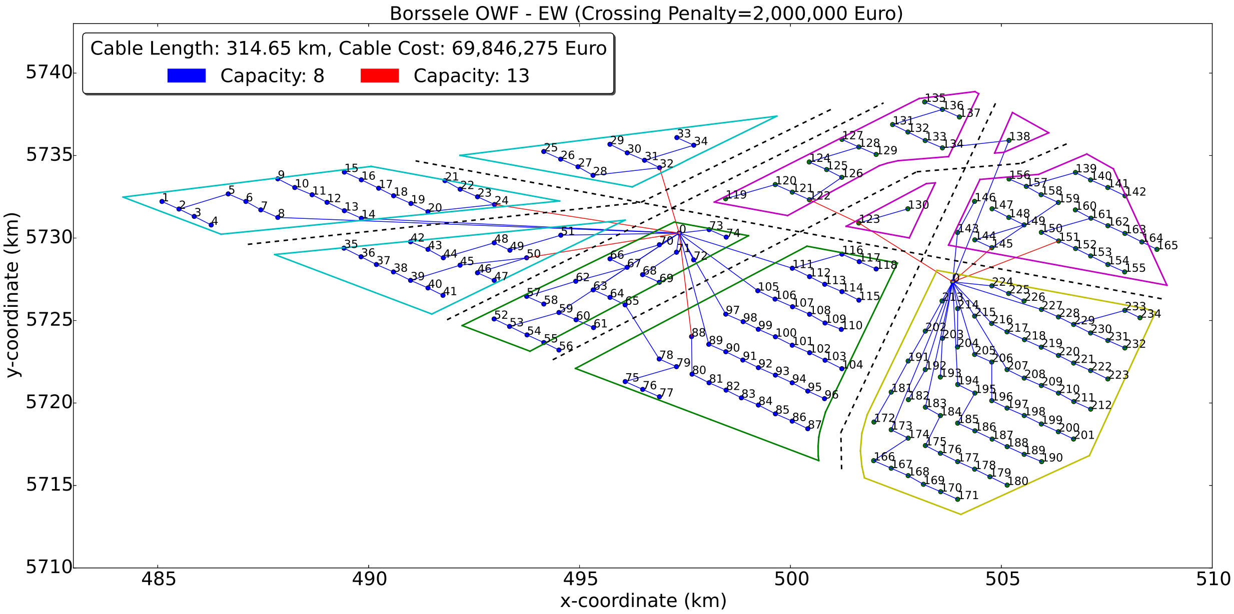

Figure 8-6: ICT generated by EW for Borssele OWF including penalty function.

As it can be seen, the expensive cable is used in order to reduce the cable crossings. In total, 26 crossings between the inter-array cables and the pipelines/cables are included in the resulted topology. This is the same number as for the proposed layout of Figure 8-3. As far as the final cost is concerned, it is 14% cheaper compared to the proposed layout by DNV GL. It should be noted that the final cost does not include the additional cost of the penalty function. Finally, Figure 8-7 presents the cable topology which the Hybrid including area constraints calculated for Borssele OWF. Same cost (2 M€) has been used for the penalty function as in Figure 8-6. The solution of the Hybrid yielded 28 area crossings whereas the total cable cost is 15.9% less compared to the proposed layout.

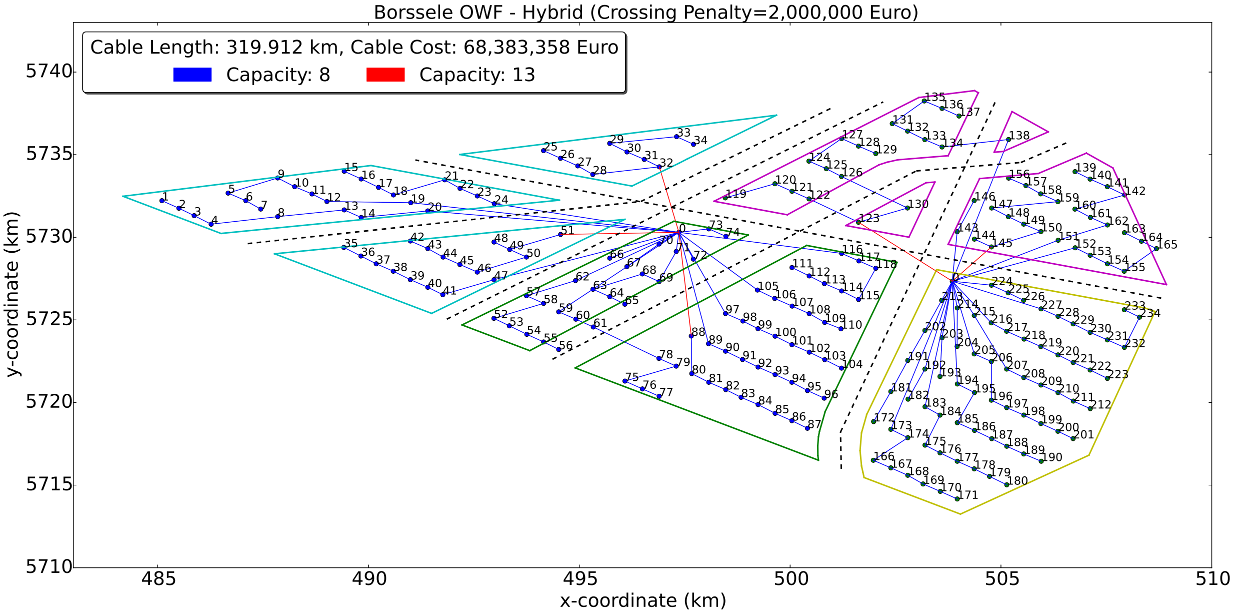

Figure 8-7: ICT generated by the Hybrid for Borssele OWF including penalty function.

In order to indicate the effect of the crossing cost that is used by the two algorithms, Table 8-1 presents the total cost of the ICT and the number of crossings according to various costs of the penalty function for EW and Hybrid.

Table 8-1: Effect of Crossing Penalty Function on Borssele OWF layout.

	Total Cost (M€)		**Crossings**	
Crossing Penalty (€)	EW	Hybrid	EW	Hybrid
0	66.47	67.59	37	35
100,000	66.65	67.70	35	34
200,000	68.17	68.38	30	28
500,000	68.50	68.38	29	28
1,000,000	69.62	68.38	27	28
2,000,000	69.85	68.38	26	28
4,000,000	71.96	70.49	26	28

In order to interpret the results of the Table, it is reminded that EW does not include any restrictions for merges of routes compared to the Hybrid which, allows only radial routes for the small capacity cable. This means that some merges that could reduce the number of crossings are discarded by the Hybrid because they would violate the merging conditions. Hence, it is expected in principle that EW yields relatively less area crossings compared to the Hybrid. In addition, it should be noted that the choice for the cost of the penalty function is highly site-specific.

As it can be seen in the Table, the elimination of some area crossings results in a higher overall cost for both algorithms. Moreover, a threshold for the penalty function is identified, above which no more crossings are avoided but the sequence of merges changes in such a way that the final cost increases. The reason why the value of the threshold for EW (2 M€) is significantly higher than the Hybrid (0.2 M€) is that the elimination of crossings for the Hybrid occurs at merges between routes closer to the substation compared to EW. This differentiation between the two algorithms confirms also the dominance of the EW concerning the least number of area crossings that can be achieved. On the other hand, the Hybrid reduces faster the number of crossings and it is less susceptible to the choice of the crossing penalty function.

Last, regarding the computation time, the addition of area constraints to the algorithms increases the computation time, as it was mentioned. Particularly for Borssele OWF, the computation time of EW including area constraints is approximately 40 s, compared to 26 s for the version without area constraints. As far as Planar Open Savings (POS) heuristics are concerned, the crossing penalty function can also be incorporated in the algorithms. However, it is expected that the reduction in number of crossings would be worse compared to EW. The reason is the same as for the Hybrid and it is due to the additional merging conditions that POS algorithms impose.

To sum up, EW shows the highest potential in eliminating crossings among all algorithms. As far as the Hybrid is concerned, its dependence on the choice of the crossing penalty is relatively weaker and it provides overall good solutions, regarding both the final cable cost and the number of crossings. Thus, depending on the individual needs, EW would be the choice for the minimization of area crossings but if a good trade-off between the final cable cost and the number of crossings is desirable, the Hybrid should be used.

Chapter 9

Conclusions and Recommendations

The final chapter provides the main conclusions of the thesis and recommendations regarding future work.

9-1 Conclusions

The primary objective of the thesis was the development of a tool for the design of the Infield Cable Topology (ICT) of Offshore Wind Farms (OWF). This tool should be applicable to general optimization tools for the design of OWF. Hence, the main drivers throughout the project were efficient solutions and affordable computation times.

Two main configurations (radial and branched designs) were adopted as the designs for which the current work provides the ICT. The key objective throughout the project was chosen to be the cost minimization. The main constraint that guided all developed solutions was that crossings between inter-array cables should be strictly avoided. A compact literature review evinced the importance of the current work and indicated the potential that heuristic methods show in these types of problems.

The algorithms that were chosen to handle the radial and branched Offshore Wind Farm Infield Cable Topology Problem (OWFICTP) were Planar Open Savings (POS) and Esau-Williams (EW) heuristics respectively. The implementation of these algorithms was validated and the results indicated their overall good performance. Particularly, in terms of total cable cost, the algorithms provide solutions, only 2.5% worse than optimal. As far as the computation time is concerned, solutions are calculated in a few seconds, depending on the size of the problem.

The aforementioned algorithms in their standard versions are applicable to cases where only one cable type is available. For this reason, a novel methodology was proposed that incorporates the possibility for multiple cable types in the algorithms. In this case, each merging of routes evaluates the possible upgrade/downgrade of the cables that are used for these particular routes. Hence, additional calculations are required compared to the single cable type case, resulting in slightly higher computation time. Regarding the cost performance of the modified algorithms, it compares well with the corresponding of the original algorithms.

Furthermore, a significant part of the current work involved the statistical comparison of the algorithms that were developed. Through a wide range of test instances, the parameters that mainly affect the performance of the algorithms were identified. These parameters include the capacities of the cables, the position of the substation and the size of the wind farm. In addition, the results pinpointed the importance of a Hybrid approach that combines the advantages of POS and EW. The Hybrid that was developed concerns branched designs and can replace EW for multiple cable types cases. Last, based on the time and cost-wise performance comparison, specific recommendations were made regarding the use of the most efficient algorithms for each case. Regarding the layouts where the substation is centrally located, EW and the Hybrid show the best behaviour for single and multiple cable types respectively. As far as the layouts for which the substation is located outside the area of the farm are concerned, POS1 performance is the best cost and time-wise, among the algorithms that were studied in the current work.

In an effort to enhance the practicality of the tool, several additions were included at the final part of the work. First, the opportunity is given to the user to choose the switchgear configuration for branched designs. Moreover, crossings of the inter-array cables with the transmission lines are strictly avoided and most importantly crossings with pipelines/cables that are possibly laid on the seabed, are minimized. These additions have only a minor impact on the cable cost but they can reduce the combined cost of the procurement and installation of the infield cables.

In conclusion, the main outcome of the current project is a tool for the design of the ICT of OWF that can efficiently provide an accurate cost indication for the inter-array cables. Hence, it can contribute to the decisions regarding the design optimization of OWF. In addition, the comparison of results provided by the tool with actually installed topologies showed the prospects of inter-array cable cost reductions. Last, even if the primary focus is the design of the ICT for a given input of cables, the model can also suggest the most efficient cable combination in terms of total cable cost minimization.

9-2 Recommendations

The complexity of the OWFICTP made inevitable the use of heuristic methods. In general, heuristics approximate optimal solutions in reasonable time frames. Hence, even if the heuristics that have been implemented for the purposes of the current project perform on average at least satisfactorily, there are cases where their sub-optimality is clear. Particularly, one drawback is that in some cases routes are formed that include a relatively small number of turbines compared to the capacity of the cable. The reason behind this sub-optimality is that as long as a connection between turbines has been added from the algorithms, it will definitely be included in the final solution. Therefore, despite the fact that this connection provided the maximum cost saving at the particular point when it was added, it may prevent other connections due to the constraint of cable crossings and thus, it may result in a clearly sub-optimal solution. These sub-optimalities can only be inspected and manually fixed by the user, after the solution has been calculated. Thus, a visual inspection of the result and subsequent possible improvements are recommended. Nevertheless, these routes appear only limitedly and have only a minor impact on the total cable cost.

Next, the design driver throughout the project was the cable cost minimization. Hence, every comparison that was made between the algorithms was based on this particular cost parameter. However, dealing with the problem from a higher level, demonstrates additional cost parameters that are involved in the ICT of OWF. Particularly, electrical losses and foremost the issue of reliability can significantly affect the cost in the long-term. The advantages of branched over radial designs concerning these two parameters were described in the report but possibly, their effect on the cost of the cable topology can be quantitatively modelled and included in a future extension of the current work.

Besides including cable losses and reliability in the cost overview, they could be incorporated as objective functions of the optimization problem. Regarding the reliability, heuristics could be developed that generate efficiently e.g. double-sided ring designs, if reliability is considered the key aspect. As far as cable losses are concerned, the existing algorithms could be modified in order to evaluate possible merges of routes based on the cable cost saving and the cost saving in terms of electrical losses. This modification would require the calculation of the electrical losses of the resulted layout at each iteration and their subsequent translation in monetary values.

Moreover, a feature that would drive the model to the next level is the use of non-linear segments for the cable connections. Curved lines would mainly be applicable to area constraints and possibly, the freedom they provide could offer significant cost advantages. In the current work, only a subset of area constraints was studied. However, other types of area constraints have been identified (e.g. shipwrecks) for which strict conditions apply. Hence, the use of curved segments for the cables could overcome efficiently these constraints.

Last, it should be noted that most of the current work involved programming. Taking into account that computation time was always part of the process, significant effort has been put to implement the algorithms in the most efficient way. Nevertheless, possible improvements and "smarter" implementations are always welcomed.

Appendix A

The Hybrid

This appendix provides the detailed structure of the hybrid approach that was developed in this work for the infield cable topology optimization. It includes every feature that has been presented throughout the report: avoiding of cable crossings including the transmission lines, multiple cable types, possibility to choose the switchgear configuration and minimization of crossings with pipelines/cables. First, the inputs/outputs of the algorithm are provided. Then, the structure of the algorithm is presented, followed by the adaptation of RouteOpt.

A-1 Inputs and Outputs

Inputs

Turbines: $T = \{t_1, ..., t_T\}$, $t_i = (x_i, y_i)$
Substations: $S = \{s_1, ..., s_S\}$, $s_i = (x_i, y_i)$
Infield Cables: $R = \{r_1, ..., r_R\}$, $r_i = (n_i, c_i)$
Transmission Lines: $((s_{x_0}, s_{y_0}),(s_{x_1}, s_{y_1}))\ \forall\ s \in S$
Pipelines/Cables: $((a_{x_0}, a_{y_0}),(a_{x_1}, a_{y_1}))$
Crossing penalty: p
Switchgear: $sw = 2$ or 3

Outputs

Connections: $P = \{(u_{k_1}, u_{v_1}, r_i^{kv})_1, ..., (u_{k_p}, u_{v_p}, r_i^{kv})_p\}$
Cable Length: $L = \{l_1, ..., l_R\}$
Cable Cost: C
Number of crossings: N

A-2 Hybrid

```
foreach $i \in T$ do $s_i = argmin_{s \in S}\{d(i,s)\}$
$P \leftarrow \bigcup_{i \in T} (i, s_i, r_1)$
foreach $k$,$u \in T$, $if\ s_k \equiv s_u$ do $sv_{ku} = (d(k,s_k) - d(k,u)) * c_1 + (N_{ks_k} - N_{ku}) * p$
$SV_1, SV_2 \leftarrow$ sorting of $sv_{ku} > 0$ according to decreasing saving
repeat
    (k,u) $\leftarrow$ next element in $SV_1$
    turbines $\leftarrow$ the total number of turbines in the routes containing k and u
    if k and u are in different routes and $(k, s_k) \in P$ and u has only one neighbour in P,
    and turbines $\leq n_1$,
    and (k,u) does not cross any connection in P and transmission line then
        $P \leftarrow P \setminus ((k, s_k, r_1) \cup (k, u, r_1))$
until end of $SV_1$ is reached
repeat
    (k,u) $\leftarrow$ maximum saving $sv_{ku}$ in $SV_2$
    turbines $\leftarrow$ the total number of turbines in the routes containing k and u
    if k and u are in different routes,
    and the number of (t,u) connections in P foreach $t \in T < sw - 1$,
    and (k,u) does not cross any connection in P and transmission line then
        $i, j \leftarrow$ last clients in the routes containing $k$ and $u$ respectively
        if turbines $\leq n_1$ then
            $P \leftarrow P \setminus ((i, s_i, r_1) \cup (k, u, r_1))$
        elif turbines $> n_1$ then
            $n_i \leftarrow$ cable capacity for which $n_{i-1} <$ turbines $\leq n_i$
            $P_{tmp} \leftarrow P \setminus ((i, s_i, r_1) \cup (k, u, r_1))$
            upgrade and downgrade connections in $P_{tmp}$ where necessary
            $sv_{ku} \leftarrow Cost(P) - Cost(P_{tmp}) + (N_{is_i} - N_{ku}) * p$ and update $SV_2$
            if $sv_{ku} = max_{sv \in SV_2}\{sv\}$ then
                $P \leftarrow P_{tmp}$
    if P was updated then
        foreach client z of the merged route do
            if $n \in T$ and $sv_{zn} \in SV_2$ do
                $sv_{zn} \leftarrow (d(j, s_j) - d(z, n)) * c_1 + (N_{js_j} - N_{zn}) * p$ and update $SV_2$
        delete $sv_{ku}$ from $SV_2$
    elif P and $sv_{ku}$ were not updated then
        delete $sv_{ku}$ from $SV_2$
until $sv_{ku} < 0$
$P \leftarrow$ RouteOpt (radial parts of the routes for which cable $r_1$ is used)
$L = \{\sum_{(u_k, u_v, r_1^{kv}) \in P} d(u_k, u_v), ..., \sum_{(u_k, u_v, r_R^{kv}) \in P} d(u_k, u_v)\}$
$C = \sum_{l_i \in L} l_i * c_i$
$N = \sum_{(u_k, u_v, r_i^{kv}) \in P} N_{u_k u_v}$
return $P, L, C, N$
```

A-3 RouteOpt Adaptation

```
RouteOpt (Graph $(T \cup S,\ P)$, distance $d(k,u)\ \forall\ (k,u) \in P$):
foreach route $r = i_0 - i_1 - i_2 - ... - i_{l-1} - i_l - ... - i_k$ do
    repeat
        $sv \leftarrow max_{l \in 1,...,k-1}\{d(i_{l-1}, i_l) - d(i_l, i_0)\}$ if $(i_l, i_0)$ does not cross any connection...
        ...or transmission line
        if $sv > 0$ then
            $l \leftarrow$ index for which $d(i_{l-1}, i_l) - d(i_l, i_0) = sv$
            $P \leftarrow P \setminus ((i_{l-1}, i_l) \cup (i_l, i_0))$
            $r \leftarrow i_{l-1} - ... - i_2 - i_1 - i_0 - i_l - ... - i_k$
    until no improvement in r exists
return $P$
```

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Glossary

List of Acronyms

OWF	Offshore Wind Farms
LCOE	Levelized Cost of Electricity
RES	Renewable Energy Sources
EWEA	European Wind Energy Association
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
OWFICTP	Offshore Wind Farm Infield Cable Topology Problem
ICT	Infield Cable Topology
MST	Minimum Spanning Tree
CMST	Capacitated Minimum Spanning Tree
EW	Esau-Williams
MILP	Mixed-Integer Linear Programming
PCC	Point of Common Coupling
MIP	Mixed-Integer Programming
PCI	Progressive Contingency Incorporation
GA	Genetic Algorithm
mTSP	multiple Traveling Salesman Problem
VRP	Vehicle Routing Problem
POVRP	Planar Open Vehicle Routing Problem

NP-hard	Non-deterministic Polynomial-time hard
POS	Planar Open Savings
UTM	Universal Transverse Mercator
BWFZ	Borssele Wind Farm Zone
EEZ	Exclusive Economic Zone