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# Stochastic optimisation of floating offshore wind farm layout with electrical interconnection

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# Executive summary

The positioning of the elements of an offshore wind farm, the definition of its connections and the selection of the required cables are related tasks subject to optimisation. While simple problem definitions of small wind farms can be treated by means of deterministic methods, large or complex problems are typically solved using heuristics. Despite not guaranteeing an exact solution, heuristic methods are able to provide valuable solutions in reasonable computation times.

The literature review shows that the genetic algorithm and the particle swarm optimisation are common approaches to conduct the mentioned tasks. Although less frequent, other methods are also used achieving good results. To simplify the procedures, increase problem convergence or speed up the optimisation, many researches conduct a stepped optimisation focusing on the tasks sequentially. While doing it, different methods, including deterministic approaches, are used to obtain good results. This sequential approach does not guarantee global optimums but may simplify the problem or split it in manageable problems. It should also be noted that the works developed so far focus on the bottom-fixed wind farms, while only one paper was found dealing with floating wind farms.

The problem formulated in this report addresses the task of locating on the site the wind turbines, the offshore substations and the submarine cable joints, if any. To simplify the problem solution, the cable connections as well as the cable types are predefined, although the cable lengths are varied according to the position of their ends. The levelised cost of energy is set as the objective function of the problem because it is a way to measure the cost-efficiency of any generation technology, allowing its comparison with other technologies and virtually applicable regardless of the country policies. The formulation particularly addresses the floating problem, considering the water depths to calculate the lengths of the cables and mooring lines; in addition, the area lease is also considered to provide realistic results. The restrictions applied include a minimum distance to shore, a minimum distance between turbines to avoid mooring footprint overlap and the prohibition of cable crossings.

Although all the variables are coordinates, the definition of the objective function and the restrictions are complex and allow any number of wind turbines, therefore a heuristic method is selected to solve the problem. In particular, the particle swarm optimisation is selected due to its simplicity and its good performance caused by the cooperation of the candidate solutions to improve the value of the objective function, as opposed to the algorithms where their competition is imposed to advance as the genetic algorithm. The selected algorithm has been modified to deliver better results faster for this particular task, improving its convergence and reducing the number of unfeasible solutions, which is particularly relevant when a large number of wind turbines are considered.

Eight scenarios are optimised, showing a reduction of the objective function between a 0.9% and a 3% compared to the initial solution. The in-depth analysis of six scenarios shows that the algorithm performs better with small and medium scenarios, while large scenarios would require more than 12h of optimisation, advanced computers or parallel computing. In general, the obtained layouts present reduced costs due to elements positioning in shallow waters and close to the onshore substation and increased energy yields due to shorter power cables, while meeting all the constraints.

Although the algorithm successfully achieved the goal increasing the cost-effectiveness of the floating offshore wind farms, several improvements could be applied to improve its performance in scenarios with a large amount of turbines, highly irregular bathymetries and highly irregular boundaries.

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# Acronyms

| Acronym | Description |
|---|---|
| **AC** | Alternating Current |
| **ACO** | Ant Colony Optimisation |
| **AEP** | Annual Energy Production |
| **BFOWF** | Bottom-Fixed Offshore Wind Farm |
| **CAPEX** | Capital Expenditure |
| **DC** | Direct Current |
| **DECEX** | Decommissioning expenditure |
| **FCM** | Fuzzy Cluster Means |
| **FOW** | Floating Offshore Wind |
| **FOWF** | Floating Offshore Wind Farm |
| **FOWT** | Floating Offshore Wind Turbine |
| **GA** | Genetic Algorithm |
| **GRASP** | Greedy Randomised Adaptive Search Procedure |
| **LCA** | Life-Cycle Assessment |
| **LCOE** | Levelised Cost Of Energy |
| **MILP** | Mixed Integer Linear Programming |
| **MIQCP** | Mixed Integer Quadratically Constrained Program |
| **MST** | Minimum Spanning Tree |
| **MTS** | Multiple Traveling Salesmen |
| **NPV** | Net Present Value |
| **OPEX** | Operational Expenditure |
| **OSS** | Offshore Substation |
| **OWF** | Offshore Wind Farm |
| **PSO** | Particle Swarm Optimisation |
| **QT** | Quality Threshold |
| **SA** | Simulated Annealing |
| **SPGA** | Single Parent Genetic Algorithm |
| **TLP** | Tension-Leg Platform |
| **VNS** | Variable Neighbourhood Search |
| **WF** | Wind Farm |
| **WT** | Wind Turbine |

# 1 INTRODUCTION

One of the key actions to be carried out by the developers of the FOWFs (Floating Offshore Wind Farms) is the wind farm micro siting (e.g., the definition of the wind farm layout), which consists of the establishment of the exact location of each turbine and the offshore substations, if any. This task is deemed relevant and critical due to the fact that it affects the lengths of the mooring lines and cables, as well as the wind farm footprint. These variations change the LCOE and the LCA of the wind farms because they modify the costs, quantities, efficiency and installation duration, among others.

Initially, the COREWIND project did not consider the wind farm layout optimisation. For this reason, the electrical interconnection optimisation has been included into the layout optimisation, as only optimising the interconnections of a regular layout is likely to lead to suboptimal results.

There are a number of layout types that can be applied to the wind farms. In wind farms without offshore substations, the layouts can be classified by increasing complexity as per Figure 1. Rectangular matrices with equidistant turbines in both directions are simple layouts in which the only variable is the turbine separation, which drives the wind farm efficiency and power density. However, other layouts are more complex but deal better with the wind directionality, boundaries or site bathymetry; therefore, these can lead to lower LCOE values.

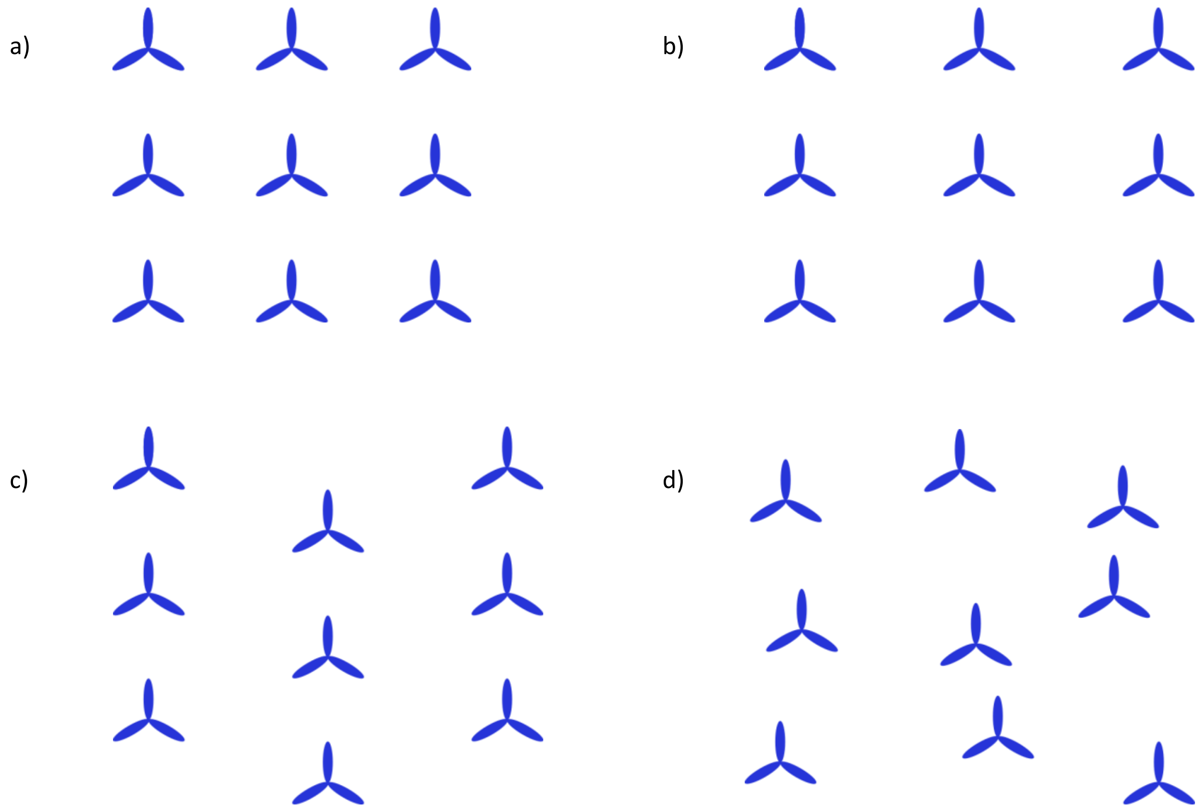


Figure 1. ***Typical wind farm layouts: a) Rectangular matrix with equidistant turbines in both directions, b) Rectangular matrix with direction-dependent spacing, c) Staggered matrix and d) Irregular matrix.***

## 2 STATE OF THE ART OF OPTIMISATION PROBLEMS FOR CABLE ROUTING

This chapter presents a review of the cabling optimisation techniques found in the literature. It must be noted that most of the developed works are focused on BFOWFs (Bottom-Fixed Offshore Wind Farms), as this is the prevailing technology commercially available. Hence, the applicability and conclusions must be extracted carefully. Four types of optimisation works are identified:

- The initial optimisation works related to wind farms focused on improving their productivity without taking into account the inter-array cabling nor the offshore substation position and therefore neglected their impact on the LCOE. Their approach was highly dependent on the distancing of turbines, related to wake effects and mechanical disturbances within the farm [1].
- On the other hand, several works whose aim was the optimisation of the cable layout [2] [3] [4] [5] [6] considered fixed turbine and OSS positions, despite the fact that the chosen placements have a significant impact on the internal cable network. Slightly more sophisticated models integrated variable OSS positions in the optimisation process while still considering fixed turbine positions [7] [8] [9] [10] [11] [12].
- A third group of works [13] [14] integrates the previous in a two-step optimisation of the wind farms, first maximising the power output of the turbines to define the layout considering the wake effect and then designing the inter-array cable system based on the optimised layout in the first step. However, [15] proves that this procedure might not lead to an optimal solution.
- A reduced number of works optimise simultaneously the inter-array cabling and the turbines and OSS positions [15], [16], [17].

Works from all the previous bullets except the first one are reviewed in the following sections.

Some formulations allow the determination of the WT and OSS connections solving a combinatorial optimisation problem using deterministic mathematical methods [2] [3] [6] [10] [16]. However, these may be difficult to apply with large number of WTs and/or more degrees of freedom regarding WT or OSS placements due to its sheer complexity [12]. These formulations are usually simplifications of the problem that include strong assumptions that limit their applicability. Researchers solving the problem with deterministic linear methods always assume non-convexity; with discrete decision variables, they mostly solve the problem by using a Mixed Integer Linear Programming (MILP) approach.

Problems not fully described in an analytical form are usually more precise but unsolvable by means of classical analytical optimisation techniques [14]. These problems cannot be solved by an exact solver, but require sophisticated heuristic techniques to find a good, though perhaps suboptimal, solutions [9]. The heuristic techniques are also applied to large problems that would require long computation times if solved with a deterministic method. Therefore, most authors have solved the problem using heuristic optimisation techniques [7] [8] [4] [5] [9] [11] [12] [13] [14] [15] [17]. Population-based algorithms are particularly popular, as they perform the optimization with a sufficient quality in a reasonable simulation time and can cope with large problems.

### 2.1 Works found in the literature

#### 2.1.1 Deterministic methods

In [3] it was developed an algorithm to find the optimal location for a voltage source converter to achieve the most cost-effective design for power transmission to the onshore substation. They limited the computational time to 2h and were able to find optimal solutions for several layouts with up to 20 fixed turbines. A higher turbine number leaded to non-optimal results within the given computational time. They suggested using a heuristic approach for higher turbine numbers.

In [16] a PSO was developed (see Particle Swarm Optimisation), being one of the works optimising a whole wind farm design including WT and OSS positioning as well as the impact on the inter-array cabling and vice versa. Even though a PSO was developed their work is assigned to the deterministic section because the inner-grid optimisation in the PSO loop was done by a commercial MILP solver. Nevertheless, a complete overview is given. Starting with a possibly not feasible initial turbine layout, firstly the electrical model is assessed. The OSS position is determined by clustering the WT in their given layout using a k-means++ algorithm. With the OSS positions obtained the horizontal length of cables are determined, formulating a capacitated minimum spanning tree problem, which is solved with MILP. In a third and a later fourth step in the PSO loop the annual energy production (AEP) and the LCOE is calculated, being the latter the fitness parameter.

In [6] it is presented a MILP model in which segments of different cables are allowed to share a common trajectory. Cables can be placed close to turbines to which they are not connected. This is accomplished by introducing the so-called “Steiner points” on arbitrarily small circles centred on the turbines to which the cables may be connected. A similar procedure is used for (multiple) cables routed around possible obstacles on the seabed. They point out that the potential cost savings can be significant taking into account the high cost per meter of cables in offshore wind farms. Even though their MILP model proves to have an adequate performance, they point out that it would be a challenge handle large-scale wind farms, with 200 or more turbines.

In [2] it is recognised that most OWFs cabling optimisations are based on radial topologies; therefore, they focus on the development of cyclic layouts that mitigate the consequences of cable failures. As in their previous work [6], they allow joint trajectories without cable crossings. They encountered exponential growth in variables and constraints so that traditional column generation methods do not apply. This leads them to a solution method that inherits from both column generation and row generation, which can be described as a two-layered optimisation process. The outer layer is associated with an integer-programming problem that generates new and unexplored possible cable paths, while the inner layer identifies feasible low-cost paths guided by optimal dual variable values in the continuous relaxation of the former problem.

### 2.1.2 Basic heuristic tools

In [18] focus on the overall micro-siting problem to minimise the LCOE, working with grid-like layouts because those enable the problem to be defined with few variables. They compare the outputs of a GA (see Genetic Algorithm) and a PSO, in addition to a local search operator that improves each potential solution. Prim’s Algorithm is used to find a MST that minimises the overall length of cables of the inner grid. They assume that the OSS location is a parameter or that it is located at the electrical centre of gravity because its position is typically defined beforehand by the offshore system operator. Furthermore, they only consider one cable type for the inter array cabling.

In [10] the economic efficiency of the wind farm is optimised, allowing multiple cable types. The internal connection begins with the Fuzzy C-means clustering of the WTs and the location of an AC/DC substation in the centre of each cluster. A MST based on Prim's Algorithm is applied to define the internal connections, starting at the substation and propagating them through the cluster in a radial topology until all turbines are connected. Finally, the substations are connected to a bigger DC/DC offshore converter substation.

### 2.1.3 Genetic Algorithm

The GA got its name because it uses principles from biology and evolutionary processes to create and test new solutions. Every GA generation begins with a selection, where pairs of individuals already in the population are chosen based on the quality of their solutions to provide genetic material for the next generation. These pairs of individuals are combined using crossover and mutation operators to produce new solutions, called child solutions. Using these two operations, the GA tries to preserve the good elements of the parent solutions in the new child solutions, and a random element is used to avoid local optima solutions. The "replace the weakest first" strategy is then used to determine which of the newly created children will be included in the next generation. This process of selection, crossing, and mutation is repeated until a certain portion of the population has been replaced and the quality of the entire population has improved, marking the end of a generation. Generally, GA continues for a predetermined number of generations or until there is sufficient diversity in the population, e.g., until the number of individual members of the population falls below a threshold. Although both crossover and mutation take into account constraints, after crossover and mutation, constraints are explicitly imposed and if a child solution does not satisfy a constraint, crossover and mutation is repeated until it does. [19]

In [4] the morpho-dynamic seabed conditions were first considered for a cable route optimisation. Their work can be divided into two parts. Firstly, they develop a GA to find the optimal turbine interconnection considering a static seabed. Herein after, they optimise the connections by the means of variations of vertical (initial burial depths) and horizontal offsets to avoid cable exposure due to seabed movements (migrating sand waves). In the GA, the initial population consists of multiple solutions for the layout problem, each solution being one string containing all turbines in a random order. For every possible connection between turbines and between turbines and OSS, a “weight” is calculated according to seabed restrictions and saved into a matrix. In a second step, the total population is divided in sets of eight solutions. Later on, the fitness of all solutions is evaluated by assessing that all turbines are connected to the OSS and that the string capacity is not exceeded and the solution with the lowest total weight is chosen as the best solution for each set. The fourth step consists of applying eight mathematical operations independently to the best solution in a subset; this is repeated until the elapsed computational time or the number of iterations reach a limit or no significant improvement in the solution is identified. Internal and external risks are analysed and included in the cost function as well as required burial depth for each possible hazard. The vertical determination is achieved by sectioning the connection and varying the burial depth per section. Then, for each section, the optimal initial burial depth in terms of minimised costs is determined and all segments are combined. Independently, the horizontal offset is determined by the use of Dijkstra´s algorithm, which searches the shortest path between two given vertices in a graph. It can be observed that the cheapest parts are located in the sand wave troughs, since they already represent the lowest seabed level where predicted seabed lowering is equal to the uncertainty band.

Reliable double-sided ring structures are developed in [7]. Their optimisation model is divided into different layers that intervene in each other, namely the offshore substation layer, the wind turbine layer, and the submarine cable layer. A FCM algorithm divides the substation layer into several partitions, where each cluster centre represents the location of an offshore substation; the number of wind turbines in each partition is limited by the current carrying capacity and short-circuit characteristics of the high-voltage submarine cables exiting the substations. A SPGA is applied in the wind turbine layer to divide the collection network partitions into strings and a MTS model is applied to connect the wind turbines in the cable layers. With the number of wind turbines in each string being constrained by the current carrying capacity and short circuit characteristics of the medium voltage submarine cables, the cross-sectional area and the length of the cable are optimised in the cable layer. A fitness value is calculated for each solution, allowing cable crossings but highly penalised so that they are not chosen. It is worth noting that the entire algorithm is embedded in a global loop comparing each studied topology with the previously obtained global best. Using this methodology, they compare a double-sided ring structure with a classic radial design approach and find out that the CAPEX is significantly higher than with a radial design. On the other hand, with same failure rates and repair times, the reliability of double-sided ring structure is higher and the cost over the lifetime is significantly reduced. A comparison of their FCM + SPGA + MTS approach with a classic FCM + GA approach shows higher capacities of the structure constructed by their model.

An OSS location optimiser and an inner-grid optimiser are developed in [12] to minimise costs. While the former considers predefined OSS positions and is based on the Pattern Search heuristic, the latter generates alternative cable layouts for each candidate OSS location and searches the optimal by iteratively performing a k-clustering-based GA, an MST and an automated cable type selection. The k-clustering method divides WTs into feeders based on their angle to the investigated OSS position. To prevent the k-clustering method from sticking to a local optimum, two GA operators are applied to two neighbouring strings randomly selected at a given time: the crossover operator exchanges randomly selected elements in the strings and the mutation operator inserts a randomly selected element of one string into a marginal position in the other string. After the feeders have been defined, the closest WT to the OSS within each feeder is connected to it and from there the connection of the remaining WTs within each feeder is conducted by the MST while selecting the cable based on the feeder size. After feeders and cables have been determined for one OSS location, the OSS location optimizer goes on to the next OSS position identified by the pattern search. The range of the pattern during searching is modified in order to prevent a fall into a local optimum. In case a better OSS location is found compared to the present location, the distance between candidates within the exploration pattern is doubled at the next exploration. If not, the distance is halved to search the range closer to the present location. These processes are repeated until a better candidate is no longer found even if the distance is reduced below a threshold.

### 2.1.4 Particle Swarm Optimisation

The PSO is a population-based metaheuristic optimisation algorithm like the GA but is inspired by the collective behaviour of social animals. Within the PSO, the set of candidate solutions to the optimisation problem is defined as a swarm of particles that can move freely in the multi-dimensional search space defining trajectories. Each particle updates its position in each iteration of a loop based on its velocity, its personal best solution found so far and the global best solution found so far, moving the swarm toward the best solutions [8].

A mixed integer PSO algorithm is proposed in [15] to optimise simultaneously the positions of the WTs and OSS, as well as the cable connection configuration, including cable selection. They consider the WTs work at the maximum power point, wake effect losses by the Jensen Model and power losses in the electrical grid. Two OSSs are placed in the layout in order to achieve the lowest LCOE and an adapted PSO-MST based on [20] is used for the cable connection. Unfeasible solutions are penalised to avoid being selected due to a bad fitness.

A discrete PSO to optimise simultaneously the cable connection scheme, cable section and OSS positions is proposed in [17]. For each particle, the two OSS and the WT positions are selected from a predefined range. The energy yields are calculated and the electrical layout is optimised considering the OSS locations as the starting node for the turbine inter-connections. A selection of suitable cable types with different cross-sections is conducted and the CAPEX for the cabling grid is calculated, penalising cable crossings. Finally, the energy yield is calculated and the LCOE is determined as the fitness value.

In [5] it is used a Voronoi diagram based adaptive PSO with local search in order to optimise the cable routing of a fixed OWF. The problem includes multiple WT types and different rated powers. Their objective function consists of the CAPEX for initial cable installation but also takes into account the energy losses due to cable resistance over the WF lifetime. By considering the cable energy losses, they prove that the full consideration of the lost energy is conducive to reducing the total cost of OWF during the operational period. The integrated local search enhances the algorithm´s ability to improve the solution. The authors show by comparison with a PSO algorithm working with an MST designed by [20] that the Voronoi distances are better to judge the proximity between points in the layout.

The first PSO algorithm specifically developed for the inter-array cabling of FOWF is presented in [8]. They considered fixed FOWT locations, wake losses and losses due to cable resistance. In order to find a realistic layout, the probability of connecting to another wind turbine in the vicinity is higher than to a distant one. The acquisition cost of the inter-array cabling is calculated considering multiple possible cable types and the expected energy flow. Installation costs as well as the cost of the energy not supplied due to connection-dependent failures are also taken into account. To assure feasible solutions are found, the energy leaving a turbine must be supported by a single cable between two turbines and cannot exceed its capacity and cable crossings are not allowed (according to the practical recommendations). The model is successfully validated by comparing it to a deterministic mixed integer quadratic constraint programming (MIQCP) developed by [21], demonstrating a much lower computational time for the exact same solution: while the MIQCP needed 26h for the exact calculation, the adapted PSO only took 14s.

### 2.1.5 Mix of metaheuristic approaches

Some papers have not only used one heuristic but a mixture to solve a specific problem or to be able to give a direct comparison of the associated feasibilities. These papers are presented next.

Three cabling structures for fixed WT and OSS locations are investigated in [11], considering a heterogeneous seabed. They first explore a ring structure. In order to find a route of the cabling they use a process originally introduced by [22], which is similar to the k-clustering method applied by [12] which groups the WT according to their angle to the OSS. To find the optimal routing through this cluster the savings algorithm by Clarke and Wright is used. This procedure optimises the use of cable capacities and naturally reduces the occurrence of forbidden cable crossings. Secondly, the string structure is explored. This design comes with the shortest cable lengths but offers small to none reliability in case of cable failure. To obtain a feasible cable route, the previously explained ring structure is cut in two strings. In case the last string structure is not fully utilised, they point out to cut the structure so that the total distance is minimised. As a last structure, they introduce a new reliable design they call the “Multi Loop structure”. This design is based on the previous ring structure but uses WTs as nodes to connect other rings. To find those nodes the turbines in each ring are counted clockwise and anti-clockwise up to the (n+1)-*th* turbine which is identified as the interconnecting node. When all interconnecting nodes have been found, the sweep algorithm is applied and interconnecting nodes that are swept will be connected to the next swept connecting point. After exploring the multi-loop cable routing, particle swarm methods are developed to find the optimal OSS position (on a flat seabed) adapted to instances demanding a possibly higher redundancy level than is offered by purely cyclic cable layouts.

Five different heuristic schemes have been tested in [9] on a case with 220 turbines with fixed placements and one substation with three predefined possible positions. The heuristics tested are GA, Simulated Annealing (SA), Ant Colony Optimisation (ACO), Tabu Search and the Variable Neighbourhood Search (VNS). All these heuristics require an initial solution, which is calculated in two steps. As a first step, they used the Prim´s Algorithm as well as the Greedy Randomized Adaptive Search Procedure (GRASP). The results of these algorithms are possibly unfeasible and cannot include the restriction that limits the amount of collector cables entering the OSS. Furthermore, all five heuristics cannot distribute the turbines in groups in a balanced way so that their total power can be supported by a single cable. The second step deals with this issue, for which they developed the so-called SWEEP heuristic, which is similar to the k-clustering method used in [12]: the turbines are ordered by the angle defined with respect to the substation, a node is picked as the starting turbine, and the other turbines are swept according to a chosen direction. The number of turbines in each a group is limited by the maximum number of OSS cable connections and the maximum number of turbines supported by one cable. Within those groups, Prim's algorithm is used to choose the best edges towards the substation, selecting the less expensive cable with enough capacity. This procedure typically finds an initial high-quality solution in a very short computing time. The four heuristics not described so far are explained shortly below based on [9]:

- Simulated Annealing comes from re-heating and cooling of metals in order to get rid of impurities by lowering the energy in the system (here the solution costs). Originally, the main parameter is called temperature and it is updated at each step controlled by a parameter describing the cooling speed.

Another important feature of SA is the probability of accepting a move, which favours the procedure of passing from a solution to another one. A move is always to accept when an improvement in terms of energy of the solution is possible. A move is allowed for a worsening with good probability only when the temperature is high and the acceptance probability must depend on the magnitude of the difference between the energy of the candidate move and the energy of the current solution.

- The Tabu Search works with a memory structure called tabu list that registers which moves the algorithm is not allowed to repeat. This allows the heuristic to reach new solutions while avoids returning to a previous local optimum. Tabu list forbids nodes where the connection is coming from and nodes to which the connection is going. Furthermore, newly chosen arcs cannot be removed.
- The Variable Neighbourhood Search (VNS) consists of three main steps, which are repeated until a time limit is reached. Only one parameter k is needed, which describes the current neighbourhood considered in the set of neighbourhoods; this makes (VNS) easy to adjust. The first step is "Shaking" where random k arcs are changed in the k-*th* neighbourhood. Secondly, a local search is applied finding the best arc change until the solution cost stops improving. Finally, if the overall solution has been improved, the new solution is saved and the neighbourhood counter is reset. If not, the initial solution is kept and the next neighbourhood is considered.
- The Ant Colony Optimisation is another population-based heuristic which mimics the behaviour of ants when randomly looking for food and leaving a trace of pheromones along its path. When a food source is found, the ant returns to the nest and thus increases the pheromone concentration on that particular path. The other ants notice this and then tend to follow the paths with the highest pheromone density. In this way, the paths leading from the anthill to a food source are reinforced. Due to the initial random fluctuation, the shorter paths are preferred because the ants return to the nest earlier and the pheromones have less time to fade than the amount on the longer paths. Vital parameter for building the heuristic is the pheromone decay probability, which is used to calculate edges probability when building the solutions. It needs to be large enough to allow "wrong" edges to be forgotten, but not too strong to delete the previous "good" edges found in good solutions.

In [9] it was found out that the tested metaheuristics are capable of improving the initial SWEEP solution by only a 4-5%. The overall best performance was achieved by VNS, as it reached the best solution in over 92% of the tested cases. The Tabu Search performed second best with a gap to the VNS solution costs of less than 2%. A possible explanation is that the local search allows the VNS and Tabu Search to reach good local minima while Simulated Annealing and the Genetic Algorithm seem to arrive close to good solutions but struggle to reach the global minimum. The Ant Colony Optimisation even struggles with reaching feasible solutions since it tends to connect few cables to the OSS (anthill), which are not able to support all the power produced by the wind farm.

A different work [13] aimed to find an overall optimal wind farm layout. In a first step, they optimised the WT placement using a Simulated Annealing approach under consideration of the Jensen wake model. Nevertheless, the losses in the electrical grid were neglected. They later optimised the substation location with PSO minimising the Euclidean distances of cables in a radial structure, concluding that its optimal position is the middle of the WF. After that, they optimised the inter-array cabling using both a ring and radial collector topologies, only considering one cable type. A combination of a GA with an MTS-Problem was used for the ring structure, whereas the GA was adapted with a single depot non-returning MTS-Problem for the radial topology.

## 2.2 Methods discussion

In this section, the most common approaches and methodologies presented in literature are evaluated and compared with particular focus on their applicability and accuracy.

### 2.2.1 Deterministic methods

Even though deterministic models guarantee an optimal solution and, as literature review has shown, they can be applied to offshore wind cabling optimisation, the computational time they require increases significantly with the number of turbines. Several authors trying to solve large problems have therefore pledged for the use of heuristics, which is likely to happen more often in the future, as WFs tend to grow. It must also be considered that most authors using a deterministic model have solely focused on the optimisation of the electrical layout and have not taken into account the overall optimisation of WT and OSS positioning together with the electrical grid. With more systems to consider, more variables and constraints will need to be incorporated into the model, which makes it even more time consuming. As pointed out in [11], for designing more reliable ring structures a capacitated vehicle routing problem can be solved. The most effective exact algorithms dealing with this problem are branch and cut [23] and branch-and-cut-and-price [24] algorithms. Nevertheless, these are impractical to address large WFs, since they are computationally expensive.

### 2.2.2 Basic heuristic tools

A widely used method to find quickly an optimal or at least feasible solution for the inner grid cabling is to cluster the turbines. Once the WTs have been grouped, optimal interconnections within those groups/clusters are investigated. Quality threshold (QT) and K-clustering methods are representative clustering algorithms. The QT clustering method determines a cluster quality, e.g., the cluster diameter and the minimum number of WTs contained in each cluster (i.e., [25]), without exceeding a given diameter. While QT methods use only the diameter as a clustering criterion, two criteria were introduced for k-clustering methods in [26]. One is the distance between WTs and the centre of each group and the other is the angle of each WT in respect to the OSS (similar to the sweep algorithm in [9]). In [12], it is pointed out that using the distance criteria within each feeder, WTs can be connected in close proximity to each other. However, collecting the electricity far from the OSS the main cables used between each feeder and the OSS may become longer, which implies increased cost. The angle criterion naturally avoids crossings of collector cables to the OSS with cables within other clusters. Nevertheless, local minimum may not be easily avoided depending on k and the initial angle of the sweep. Overall, clustering-based methods can help to solve the inner-grid cabling problem in a relatively short time but are keen to fall into a local minimum as they explore a relatively narrow space.

Prim´s Algorithm is an easy procedure to identify a MST given the nodes. It is able to find an optimal solution if only one type of cables is allowed and no constraints other than connectivity are considered. Solutions found in problems that are more complex were often unfeasible because the few arcs connected to the OSS exceeded the cables capacity. As it is pointed out in [9], the algorithm is useful to find an initial solution for other heuristics. By considering the cheapest cable for each edge in the MST and ignoring the cable capacity, the solution of Prim´s algorithm provides an approximate lower bound on the cost of the optimal solution.

Clarke and Wright’s savings heuristic is frequently used for cabling layouts where loops are intended. However, it does not include strategies for avoidance of cable crossings, which is a major concern in feasibility regarding installation and O&M activities [11].

### 2.2.3 Population-based metaheuristics

From the above literature, it can be concluded that heuristic or stochastic methods are mostly used to solve the layout optimisation problem. The main reason is that given the problem complexity, it cannot be completely described using analytical equations. The GA as well as the PSO are widely used metaheuristics in the offshore wind optimisation field. As all heuristics, they involve a risk of premature convergence and the optimal solution is not guaranteed [16]. Nevertheless, these methods show good performance in solving non-convex problems.

Since methodologies based on the GA explore a very wide solution space, they are able to search good and feasible solutions but require more computational effort [12]. In [27] implemented the mutation and crossover in terms of probability functions of the quality of the solution. The solution's fitness value is therefore compared to the population's mean fitness value so that better solutions not only have a higher probability of being selected, but have also a higher probability of contributing through crossover effects. Another option in order to enhance the quality of the solution is to use single parent mutation operators, which, according to [7], can guarantee that all the new individuals have feasible solutions. It also contributes to the convergence speed since any parent can produce the new individual with limited amount of "gene" exchange.

Some recent works used the PSO method more frequently instead of GA to optimise the wind farm layout, obtaining better results [15]. The PSO performance is highly dependent on its parameters. While greater weights ensure a stronger global searching ability of the swarm, smaller inertia ensures a greater local searching ability. Learning factors can be used to enhance the algorithm's local convergence. Parameters can be controlled linearly, non-linearly or intelligently as for the GA [15]. Large swarm sizes are valuable in complex problems to avoid premature convergence [16].

The main difference between the GA and the PSO is the fact that the PSO is based on swarm intelligence leading to the promotion of a cooperative environment where individual decisions directly influence each other, while in the GA different solutions compete for survival [16]. All particles in the PSO are therefore aware of the improvements found by other members of the swarm and are able to adapt that information to their own movements in the search space. With that in mind, it is not surprising that different benchmarking studies have concluded that a PSO is more likely to find high-quality solutions in less time than a GA (i.e. [28] [29]).

Considering the ongoing wind farm growth and the complexity and constraints for the development of FOWFs, in [16] it is pointed out that PSO might be of interest to wind farm developers because this method allows identifying better solutions than industry standard approaches using commercial software tools, leading to more efficient wind farm layouts.

### 2.2.4 Local search phase for heuristics

The risk of sticking to local optima of the metaheuristics can be decreased by allowing the algorithm to search near the newly found solution in the same iteration step. Many of the described research point out that the integration of a so-called local search phase can significantly improve the solution found by any metaheuristic. This behaviour was reported by [12], [5], [9] and [14]. In [9] even identified this to be the crucial difference in order to find the best solution when comparing metaheuristics that included a local search phase with some which did not.

## 2.3 Typical problem considerations and findings

As opposed to the previous sections where the optimisation techniques are assessed, this section evaluates common technical aspects of the problem considered and modelled in the literature as well as some derived conclusions. As most of the articles refer to BFOWFs, particular attention is paid to their applicability to FOWFs.

A common approach in literature is to forbid the crossing or even the shared trajectory of cables. It must be noted that cable crossings are feasible; nonetheless, it is a reasonable constraint, especially for buried cable sections. Trenching and cable laying in the close vicinity of already laid cables increases the risk of mechanical damages on both cables. Additionally, heat generated by the cable resistance can damage the cables and partial discharges in one cable could therefore influence the performance of the other cable implying that two crossing cables would have to be insulated against each other. In addition, O&M activities would be more time consuming, i.e., in case the cable that is buried lowest fails and has to be replaced, both cables would have to be dug up. In FOW, the same reasons apply to the static sections; for the dynamic sections, it is assumed that crossings are also not favourable due to the risk of entangling and development of sharp-shaped marine growth.

Most papers also assume a tree/radial structure originating from the OSS. This structure is in fact most commonly used in practice due its advantages of low investment costs and being simple to control [10].

Nevertheless, it lacks of redundancy and is therefore more prone to blackouts than other structures. The consequences may last longer for FOWF, where cable repair work can be quite extensive and travel times may be longer. These factors imply a need to wait for suitable weather windows, which makes failures even more costly [30].

During the optimisations, the OSS is often centred in the wind farm in order to reduce the total length of the inter-array cabling while mostly ignoring the fact that the length of the costly export cable might be increased (see [13]) and that the number of strings connected to the OSS might be larger. This might be critical for FOWFs since the off-hanging dynamic cables all around the OSS cause congestion near it, which in turn creates obstacles for other cables and increases the risk of failures. A failure in the proximity of the OSS would be critical as whole branches would blackout or in case of cyclic cable layouts, an affected cycle would immediately experience overloading [9]. As well, the congestion might limit boat landing possibilities and therefore accessibility for O&M purposes. In addition, there is a risk of entangling and unwanted interactions with the OSS mooring lines as well as the development of thick marine growth between cables that may affect their maintainability.

As seen in literature, in order to have a reasonable trade-off between low CAPEX and low cable losses, different cable types should be installed. However, it is likely that WF developers will also take advantage of economies of scale depending on the capacities of their cable suppliers, reducing the amount of cable types used. For offshore wind farms in general, the nominal operating voltage of existing inter-array cabling systems is typically 33 kV. With the development of larger and more efficient wind turbines and the increasing size of the farms, higher voltage levels such as 66 kV have become necessary [31].

A common approach in literature for bottom-fixed wind turbines is to calculate the length of the cables as per the Euclidean distance between wind turbines; however, for FOW the water depth is a crucial factor for the cost assessment. In [8] the authors obtain the length of the inter-array power cables by the following equation:

$$L_{Cable} = 1.05 * D_{FOWT} + 2 * (L_{dynamic} - D_{h,FOWT-TD})$$

In the above equation $D_{FOWT}$ is the distance between FOWTs, $L_{dynamic}$ is the dynamic cable section length and $D_{h,FOWT-TD}$ is the horizontal distance from the FOWT to the touchdown point. The equation takes into account a 5% elongation of the static part of the cable to avoid anchors and moorings. As the authors consider a lazy wave design for the dynamic cable, the length of the dynamic section can be estimated by dividing it into three catenaries and calculating the arc length of each catenary. A purely floating option, where dynamic cables do not touch the seabed but are kept floating via buoys was not assessed even though this could shorten the overall cable length significantly. It must be noted that this configuration would expose the cables to large motions and forces near the water surface induced by currents, waves and wind.

Seabed restrictions are largely neglected by literature, in which it is considered flat and homogeneous. This assumption may invalidate the results obtained for FOW because these farms are located in areas with great slopes and large areas due to the turbine spacing and quantity. Overall, this results in a higher probability of dealing with a more heterogeneous seabed. Identifying sharp/rocky grounds will be crucial for the dynamic cable, as friction will damage the protective sleeve and eventually the dynamic cable. It could also be crucial for the placement of the submarine joints since suitable anchoring positions might be limited, leaving the submarine joints with less options. Finally, the dynamic seabed areas also pose a potential danger for the cabling (see [4]).

# 3 PROBLEM FORMULATION

In the previous chapter, multiple optimisation problems related to offshore wind farms have been reviewed, including the turbines placement, the offshore substation placement, the cable type selection, the inter-array connection and combinations of two or more of them. These problems are solved in a single step or in more than one to increase the speed of the process, reduce the problem complexity or increase the feasibility of the results. On the other hand, different methods applied to solve these problems are analysed, highlighting their benefits and weaknesses.

In this chapter, a different though related problem is proposed, taking into consideration the lessons learned from the literature revision and analysis.

## 3.1 Decision variables

In short, the aim of the proposed methodology is the wind farm micro siting of FOWFs considering a wide range of parameters and constraints. For that reason, the layout is defined using an algorithm and not a regular pattern, expecting significant improvements on the objective function. The main variables of the problem are as follows:

- Turbine positions (two coordinates).
- Offshore substation positions (two coordinates), if any.
- Submarine cable joint/hub positions (two coordinates), if any.

Together with the onshore substation, the previous elements integrate the nodes of the problem. The algorithm is designed to allow any number turbines (at least one), offshore substations (including none) and submarine joints (including none). These nodes allow the definition of both simple and complex floating wind farms, covering the needs of current and future projects, and therefore increasing the applicability of the proposed method.

There are many types of offshore substations (transformer substations, converter substations, reactive compensation substations, etc.) that may be needed in a FOWF depending on its capacity and distance to shore. While large wind farms located far from shore require different substations and even more than one per type, the first floating wind farms located in deep waters but close to shore may be connected directly to the onshore substation. For that reason, the algorithm is designed to work with many, few, one or none offshore substations.

Similarly and with particular relevancy for FOWFs, the connections cannot always be considered as a single cable type because static to dynamic transitions may be required, and vice versa. This leads to the usage of submarine joints (that can also be used as hubs of 3+ cables) whose position must also be defined. Due to economies of scale or proximity to the coast, cable joints may not be present in a project; therefore, the algorithm must also deal with scenarios without them.

## 3.2 Objective function

The decision variables are changed in order to minimise the LCOE of the wind farm. This value is deemed the appropriate objective function as it is one of the main factors taken into account to decide whether a wind farm project is developed. It is calculated based on the NPV method [32] and assuming that decommissioning costs correspond to the first year after the farm has stopped its production:

$$LCOE = \frac{CAPEX + \sum_{y=1}^{n} \frac{OPEX_y}{(1+i)^y} + \frac{DECEX}{(1+i)^{n+1}}}{AEP \cdot \sum_{y=1}^{n} \frac{1}{(1+i)^y}}$$

Where:

- *CAPEX* is the capital expenditure.
- $OPEX_y$ is the operational expenditure of the year *y*.
- *DECEX* is the decommissioning expenditure.
- *AEP* is the annual energy production.
- *i* is the discount rate.
- *n* is the project lifetime.

The usage of the LCOE as the objective function can be considered as a multi-objective optimisation because it tries to find a balance between maximum energy yield and minimum costs over the lifetime of the project, as these values would vary in opposite directions if only one of them were optimised.

Some of the values needed for the LCOE calculation are independent of the selected layout. However, many of them depend on it and their calculation method is described in the following sections. The OPEX is assumed constant and the only DECEX variation considered is related to the cables end of life as described below.

### 3.2.1 Energy calculation

To calculate the energy yield of the wind farm, the site wind rose at the turbine hub height is used. The wake effect is considered during the calculation as a relevant driver of the turbine spacing that depends on the wind climate. The implemented wake model is based on the Jensen/Katíc (Park) model [33], where mass conservation is applied. Such model allows a fast calculation and is precise enough for energy calculation purposes. Additionally, the turbine internal losses associated to the mechanical/electrical transformation and internal cabling are considered.

The energy losses in the electrical grid, which includes both export and inter-array cables, are calculated using power flows. This method allows any grid configuration, providing great flexibility. To conduct the power flows, a modified version of MATPOWER [34] is used. The introduced modifications speed up the power flow calculation around a 30% while determining the AEP of each layout, based on the idea of a time series that goes through the wind rose:

- The admittances matrix is only calculated once per layout.
- The initial solution for the solver is the solution in the previous calculation, except for the first calculation, where the default initial solution is used.

Although the cable connections in the wind farm are not decision variables, their lengths are updated in each objective function evaluation according to the turbine, substation and joint positions. The updated lengths are calculated in a similar way to [8] but considering the specific depth at each turbine or substation. Submarine joints are considered to be on the seabed. Once the lengths are determined, the electrical parameters of each connection are calculated according to IEC standards and adapted as inputs for the power flow.

The availability of the wind farm is also considered to reduce the energy output as per its downtime.

### 3.2.2 Layout-dependent costs considered

The cable acquisition costs are updated in each objective function evaluation according to the cable lengths used for each cable type. The cable length calculation is described in the previous subsection. Additionally, the variation of the time required for the cable laying is also updated before each objective function evaluation depending on the updated cable lengths, therefore modifying the cable installation cost. The cost of the cable end of life (landfill, incineration, etc.) is also updated as per the variation on the cable weight.

In addition, the costs associated to the mooring system are also updated to reflect the variation on the mooring lines length. While the anchors cost is assumed constant regardless of the position of the turbines or substations, the mooring lines cost is assumed to vary linearly depending on the depth.

Finally, the model also includes an initial area lease fee in the CAPEX. The larger the offshore area footprint, the larger the fee. This reflects the current tenders in several countries and can be a major cost to be considered. The offshore site area is calculated as the convex hull of the turbines plus a buffer equal to the radius to the farthest anchor, particularly relevant in small wind farms where turbines may be aligned.

## 3.3 Parameters

The following list includes the required problem parameters. It can be observed that it is quite extensive due to the level of detail and accuracy of the objective function:

- Site: constant water depth or bathymetry, average water temperature, wind climate, centre coordinates.
- Wind turbine: rotor diameter, hub height, price, power and thrust coefficient curves, electrical efficiency, materials, turbine count.
- Substructure and tower: price, materials.
- Cables: origin and end of all cables, electrical specifications of all cable types used, prices, materials, joints.
- Grids: electrical frequency, voltages.
- Mooring system: default cost and materials for a given depth of the mooring lines, hardware and anchor cost, materials, radius to anchor (mooring footprint radius).
- Substation: price, electrical specifications and materials of each substation type, onshore substation location.
- Project: availability, lifetime.
- Life cycle costs and contingencies for: development, installation, operation, maintenance, pre-decommissioning, decommissioning, end of life.
- Discount rate.

## 3.4 Restrictions

The restrictions applied to the problem are as follows:

- No turbine can be placed closer than a given distance to shore. This restriction is defined to deal with decentralised tenders, as they are the first to occur. The problem can be reformulated to work with centralised tenders where the site boundaries are predefined. This restriction is considered necessary because the distance to shore is a major concern for the governments, environmental institutions, fishery, individuals and others.
- Cable crossings are not allowed. Following the recommendations found in the literature revision, cable crossings are deemed bad practice in offshore wind farms. More details can be found in the previous chapter.
- Mooring footprints of different turbines or substations cannot overlap. These footprints are defined as the circle centred on the turbine whose radius equals the maximum radius to anchor. This restriction prevents mooring lines from crossing, which would lead to extreme abrasion and fatigue damage.

Additionally, it allows the usage of asymmetric mooring designs without any other restriction. It also facilitates the routing of the cables without having to be positioned below mooring lines. For TLP mooring systems, the mooring footprint radius should be replaced by the turbine blade length plus the substructure extreme excursion.

- Submarine cable joints and hubs must be on the seabed to reduce the risk of failures due to cable motions. Hence, a minimum distance must be kept to any turbine or substation to ensure a feasible riser configuration.

# 4 OPTIMISATION ALGORITHM

In this chapter, the method to solve the problem described in the previous chapter is defined in detail, taking advantage of the literature revision in chapter 2.

Due to the complexity of the defined problem, and according to the discussion in section 2.2, the deterministic methods are discarded. Consequently, a heuristic algorithm is selected, in particular the PSO (described in subsection 2.1.4). Given the advantages of the algorithm stated in the literature discussion, in particular the cooperative solving process, the algorithm simplicity, its performance and convergence, the PSO is deemed the best candidate of the studied options.

## 4.1 The PSO overview

Although a brief description of the algorithm is included in section 2.1, below the algorithm is depicted in detail, which allows the understanding of the introduced modifications. Its architecture is shown in Figure 2, being the main concepts of the algorithm:

- Particle: it is a candidate solution, therefore includes a value for each decision variable.
- Swarm: it denotes a set of particles.
- Velocity: it is the difference between the values of a particle in two consecutive iterations.

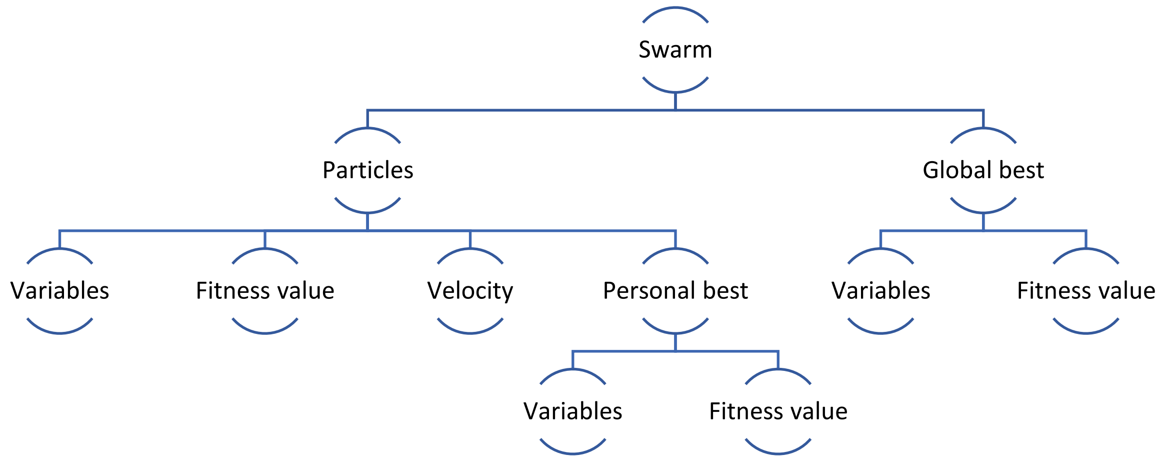


Figure 2. ***Swarm architecture.***

As all heuristics, the PSO requires an initial solution; such solution is typically random generated and covers the complete domain of the variables. Once the particles have been initialised, the algorithm follows an iterative process:

- Firstly, the objective function is evaluated for each particle, updating the best fitness value of each particle (the personal best) and from all the particles (the global best), as well as the corresponding variable states.
- Secondly, the velocity of each particle is calculated as the sum of three effects: its previous velocity (inertia), its personal best so far and the global best so far. While the inertia impulses the particle in the previous search direction, the other two effects tend to approximate the particle to their personal and global best solutions achieved by the algorithm until the current iteration.
- Finally, the particle variables are updated so that their new position equals the previous position plus the velocity and ensuring they are not out of bounds.

The optimisation process ends when a specified number of iterations is reached.

## 4.2 Algorithm parameters

The following characteristics must be specified before the iterative process of the algorithm starts:

- Number of particles.
- Maximum iterations.
- Variables upper and lower bounds.
- Objective function
- Initial solution.

On the other hand, the following parameters are used for the velocity calculation, driving the algorithm performance:

- Weight. This value controls the inertia when calculating the velocity of the particles. Although it can be constant, it is common practice defining as parameters its maximum and minimum values and linearly decrease its value from the maximum to the minimum according to the algorithm progress. This procedure enhances the exploration at the beginning of the algorithm and its convergence at the end.
- Constants *c1* and *c2*. The former constant is related to the impulse of the particle towards its personal best: if it was the only effect to be considered to calculate the velocity, the particle would move towards its personal best a random distance between 0 and *c1* times its distance to its personal best. The same effect is achieved for *c2* and the global best.
- Maximum and minimum velocities. These parameters are usually opposed and with an absolute value equal to a fraction of the variables range. Limiting the velocity allows the algorithm to search close to the current positions even when the particle is far from the best results or at high speeds.

## 4.3 Modifications to the standard algorithm

While the basic PSO is capable of solving the described problem, a number of modifications are introduced to improve its performance (speed), enhance its execution control and its ability to find feasible solutions. These changes proved to be crucial to solve large problems.

A major issue found was that the turbine footprints overlapped after adding the velocity component to the particles position. Although the objective function greatly penalised such layouts, this issue significantly decreased the performance in large problems, where it struggled to find feasible solutions. For this reason, a new function was introduced with the purpose of radially scattering the nodes to ensure their footprints do not overlap. The origin of the scattering is set as the centre of mass of the turbines. Despite the fact that the turbines footprint may be overlapped again if they are out of the variables boundary, this solution greatly improved the algorithm performance.

Another problem was related to the initial solution calculated as a purely random distribution of nodes in the search space. Given the characteristics of the problem, in particular the predefined connections, a random positioning of the turbines leaded to unfeasible initial solutions due to cable crossings, or at least solutions far from the optimal layout. In the latter case, many iterations were required only to reach a layout with the same fitness value as one drawn directly by an expert. The solution was defining a single feasible layout as a base case and assign it to the first particle, and randomly shake the nodes to generate values for the remaining particles. This process ends by applying the function defined in the previous paragraph to increase the feasibility of the initial solution.

A different upper and lower bound can be defined for all variables; as all the decision variables are coordinates components, this means that a rectangle can be defined as the domain for each node. Instead of defining the bounds for each node and each problem, a function was defined. This function added flexibility, in particular to compare wind farms with different capacities. The function establishes the variables domain depending on the node type: for wind turbines and substations, the domain is defined as the square centred on the site centre coordinates whose area guarantees a specified power density given the wind farm capacity; for the submarine joints, the previous domain is extended to include the onshore substation.

A function was also defined to establish the maximum and minimum velocities. In this case, both velocities have the same absolute value, being close to the radius to anchor. The larger the problem, the closer to the radius to anchor value. This function increased the algorithm speed solving small problems, while improving the chance to find feasible solutions in large problems.

A last modification introduced into the algorithm was the option to control the optimisation time. The reason is that depending on the scenario to solve, a certain number of iterations may require different execution times. In addition, using the time to control the execution penalises less the problems where feasible solutions are hard to find because the evaluation of unfeasible layouts is very fast. To maintain the algorithm functionality where the weight decreases after each iteration, the progress was measured as the relative elapsed time instead of the elapsed iterations compared to the maximum iterations.

# 5 CASE STUDIES

The presented algorithm was implemented in MATLAB and connected to the FowApp database, to work with the scenarios defined in the COREWIND project [35]. All the optimisations were run using a laptop with an Intel core i5 processor (8th gen) without parallel computation. The optimisation time was based on the number of turbines of the studied scenario: 1h for 4 turbines, 4h for 20 turbines and 12h for 80 turbines. In all cases, the initial weight was set as 0.7 and the final weight as 0.1 as values that improved the algorithm performance.

## 5.1 Results

The proposed algorithm is applied to six different scenarios. One scenario includes four turbines to demonstrate its functionality with small farms, but the value added by the proposed method is much greater in larger cases, therefore the remaining cases studied reflect topologies that are more complex. Some scenarios only include wind turbines and the onshore substation, while others also include one or two offshore substations and submarine cable joints. The same substructure has been considered for all the scenarios (ActiveFloat), as the purpose of this report is evaluating the performance of the algorithm and not the comparison of the substructures. The differences introduced by using the WindCrete substructure would be minimal and the algorithm performance would be the same.

It is worth noting that the reference scenarios were initially defined without considering the site bathymetry; instead, a single average depth was taken into account. This would lead to inaccurate results in all the cases studied because the seabed is not flat in any of them; the mooring system cost would be constant and the distance between turbines and the wake effect would clearly drive all the results. All the cases studied in this report include the detailed bathymetry of the site, extracted from GEBCO [36], which has shown that the reference scenarios 6A&W would require that many turbines were installed in water depths greater than 1000 m due to the great slope of the seabed. For that reason, such scenarios have been considered unfeasible in the mid-term and have not been evaluated.

### 5.1.1 Reference scenario 4A – Gran Canaria, 60 MW

This small scenario includes 4 wind turbines and the onshore substation. Its electrical grid consists of a single string at 66 kV, connected at the same voltage to the onshore substation. The wind climate is shown in Figure 3, in which it can be observed that there is a clear prevailing wind from NNE.

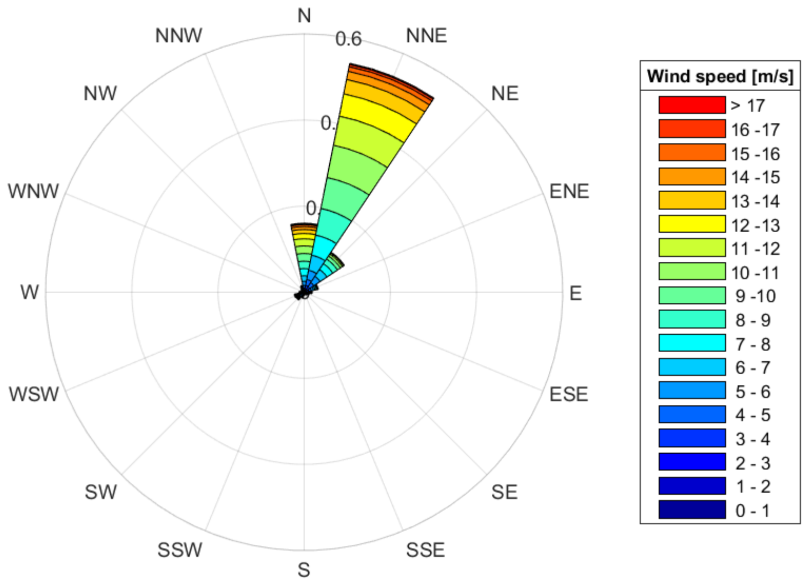


Figure 3. *Wind climate in site B – SE of Gran Canaria*

Figure 4 includes the bathymetry of the site, with severe slopes for being a volcanic area and relatively shallow waters only in a portion of the area. The land area is represented by the brown polygon. An 8 km buffer is considered to keep turbines away from shore, shown in blue in the figure, and the site boundaries are delimited by a purple square according to the criteria described in the previous chapter.

The proposed initial solution is arbitrary although it takes into account the prevailing wind in the site to avoid wake effects. The cables are drawn with black straight lines, although it must be remarked that the longitudes include an extra 5% due to curved planar paths and that the bathymetry and riser shapes are considered. The large grey circles represent the mooring footprint according to the mooring system design, which cannot overlap according to the problem constraints. The small black circles represent the swept area by the turbine rotor if the excursions are omitted.

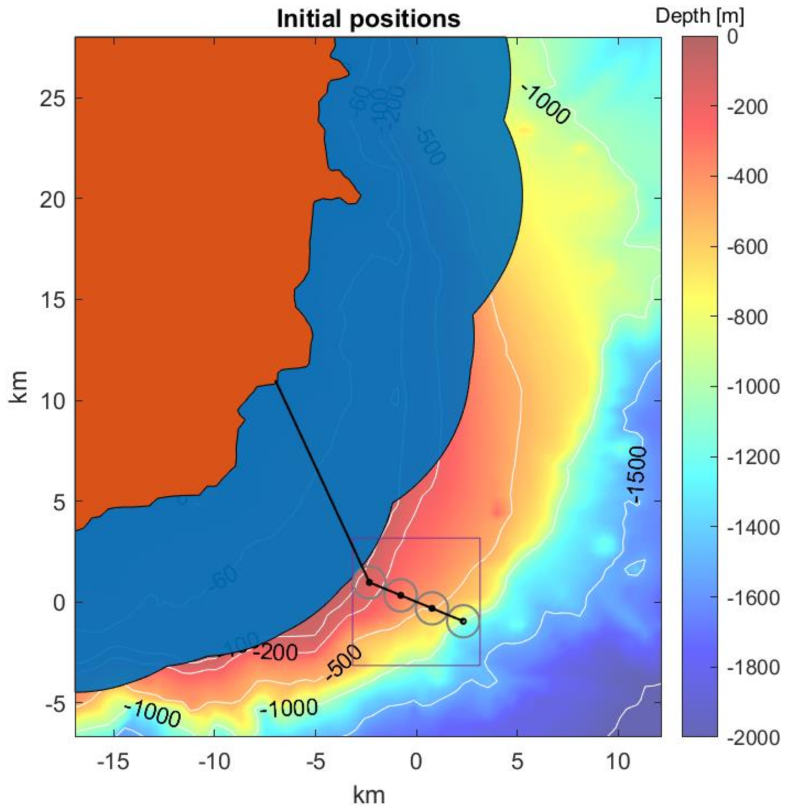


Figure 4. *Initial solution of the reference scenario 4A.*

The achieved solution by the algorithm is shown in Figure 5. It can be seen that the turbines move towards shore and shallower areas, while maintaining a configuration that avoids wake effects. Furthermore, the mooring footprints constraint is clearly relevant as all grey circles are touching at least another one.

Figure 6 shows that the algorithm quickly reaches a value close to the final one, therefore for reference purposes the optimisation duration could be reduced to around 20 minutes.

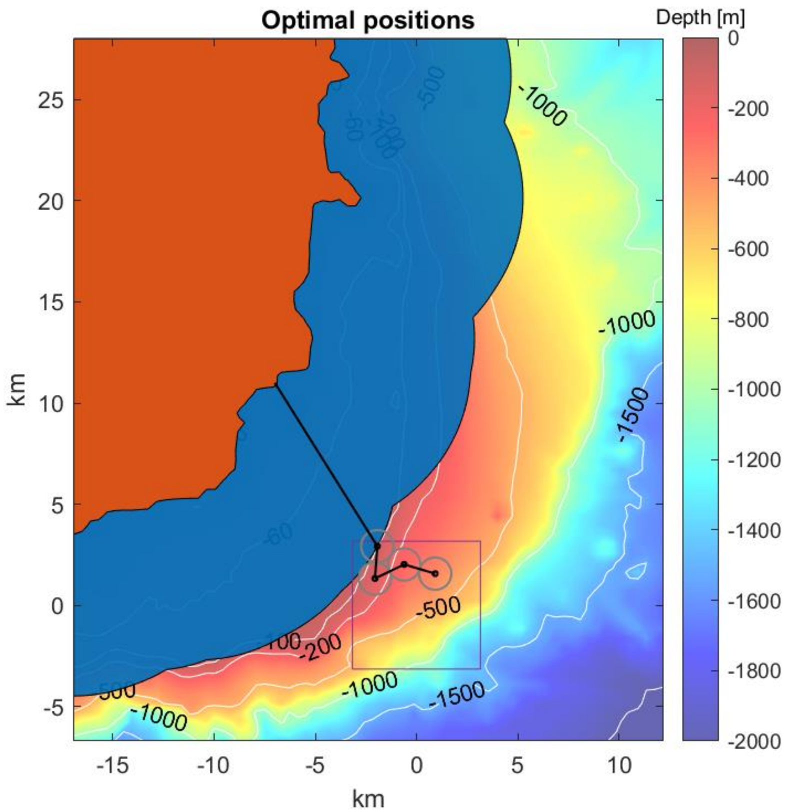


Figure 5. ***Optimal positions determined for scenario 4A.***

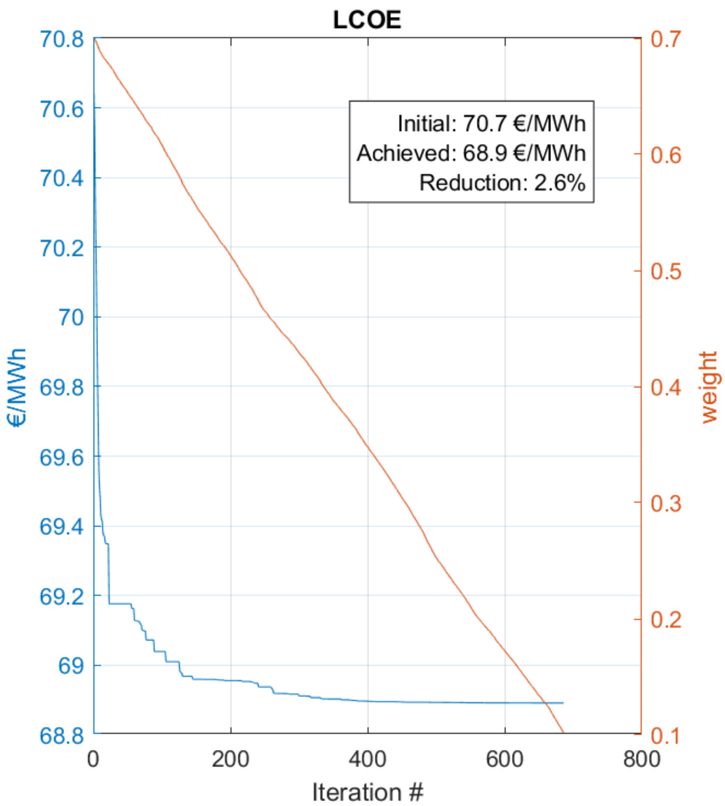


Figure 6. ***Convergence curve of the PSO for scenario 4A.***

## 5.1.2 Reference scenario 5A – Gran Canaria, 300 MW

This study case includes 20 wind turbines and the onshore substation. Its electrical grid consists of a five strings of four turbines each, directly connected to the onshore substation. All the connections are at 66 kV. The wind climate is shown in Figure 3.

Figure 7 shows the same 8 km buffer as in the previous reference scenario and the proposed initial solution. In this case, the solution has been defined as a compact area to reduce the lease fee and close to the buffer boundary to locate the turbines in shallower waters. The symbols are defined in the previous case.

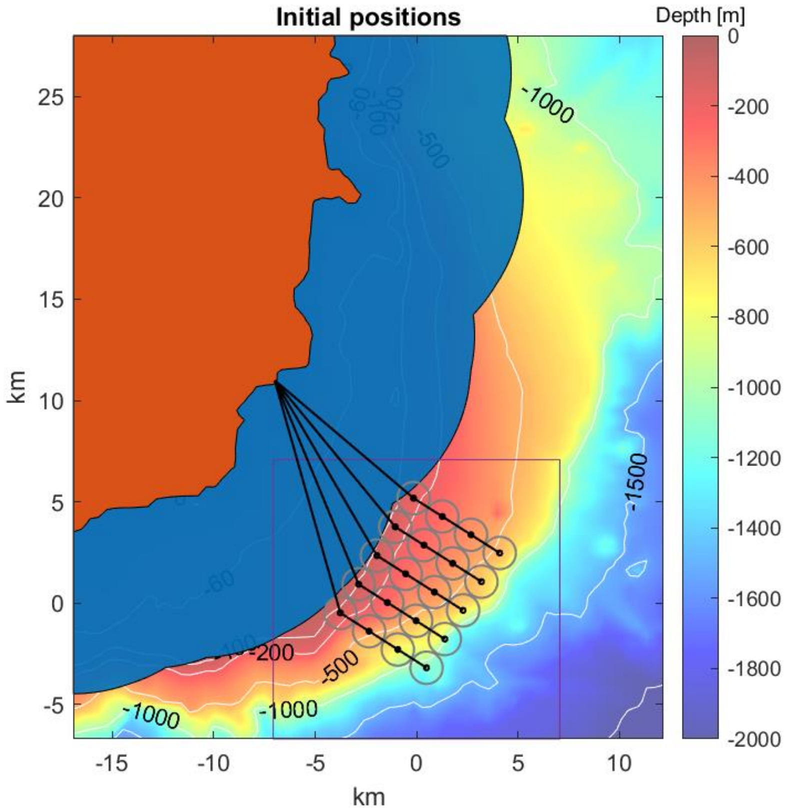


Figure 7. *Initial solution of the reference scenario 5A.*

The achieved solution by the algorithm is shown in Figure 8. It can be seen that the turbines remain close to the buffer boundary, being distributed in the shallower areas. The mooring footprint constraint is not as relevant as in the previous case, particularly in the prevailing wind direction.

Figure 9 shows the convergence curve of the algorithm. The flat areas and the elevated number of iterations indicate that during the optimisation a significant number of unfeasible candidates are generated, which are quickly discarded.

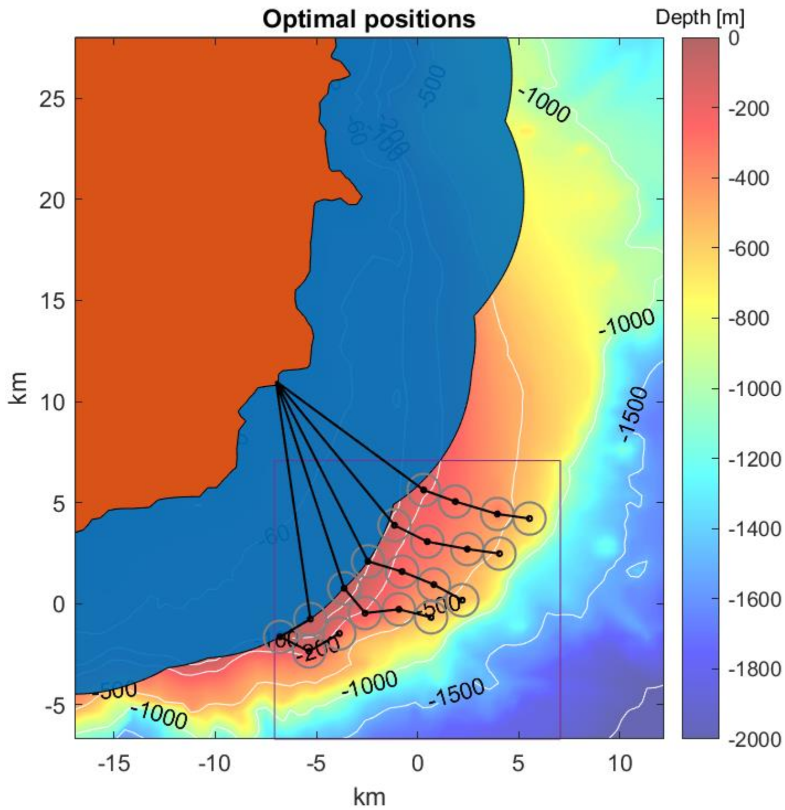


Figure 8. *Optimal positions determined for scenario 5A.*

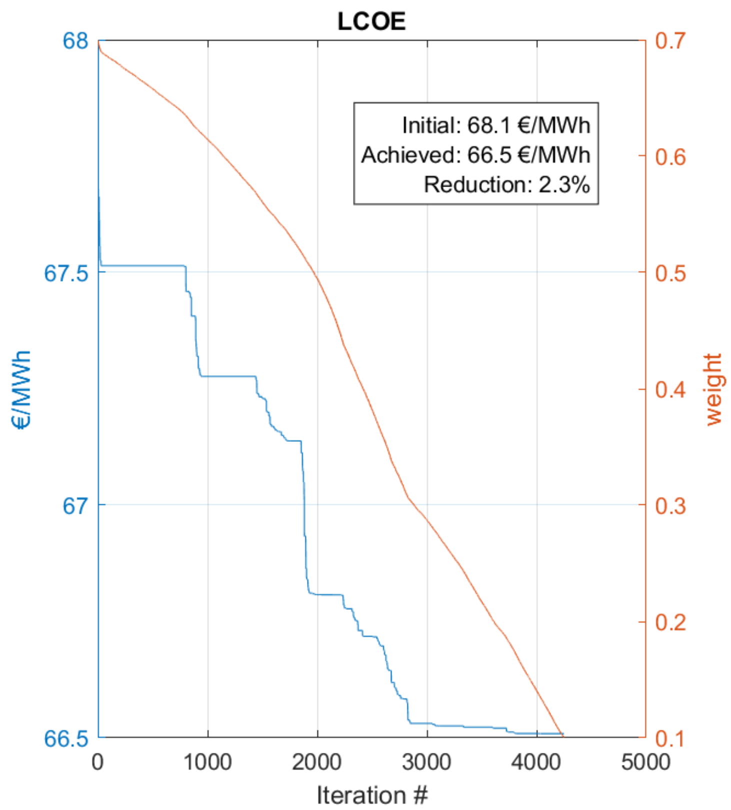


Figure 9. *Convergence curve of the PSO for scenario 5A.*

### 5.1.3 Reference scenario 2A – Barra, 300 MW

This scenario includes 20 wind turbines grouped in five strings at 66 kV, connected at the same voltage to the onshore substation as in the previous case, but is located in a different site. The wind climate is shown in Figure 10, unveiling a prevailing wind from SW although not as dominant as in the previous scenario.

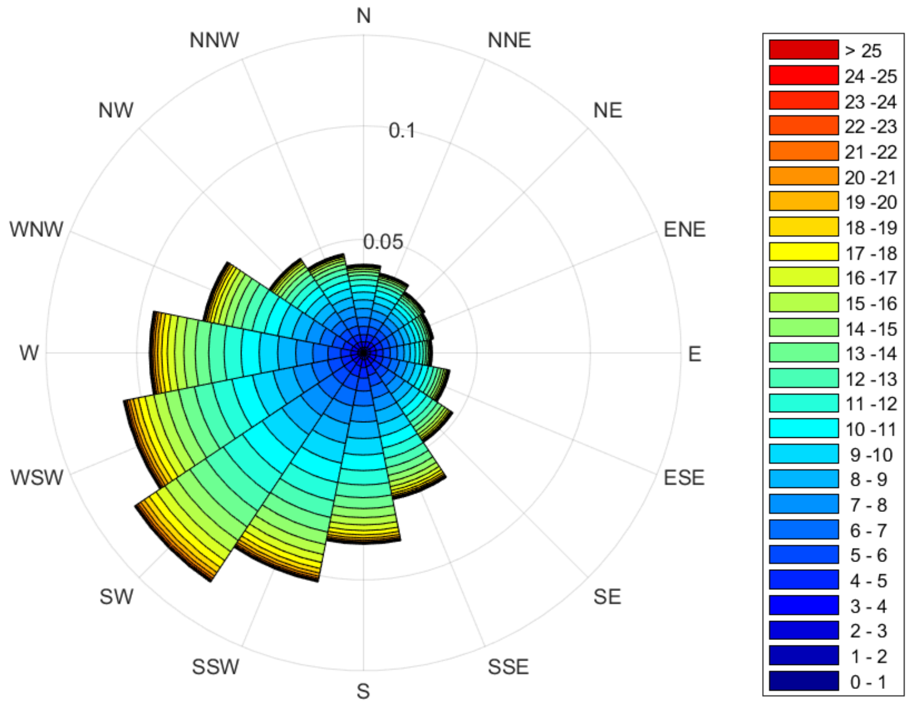


Figure 10. *Wind climate in site B – W of Barra*

Figure 11 includes the bathymetry of the site, without great slopes and quite monotonous, but quite bumpy. An 8 km buffer is also considered to keep turbines away from shore, although such constraint is not active because the site is located farther than in the previous cases. The proposed initial solution is placed close to the onshore substation and in the shallowest area.

The achieved solution by the algorithm is shown in Figure 12. Turbines are at the edges of the site domains, achieving shorter lengths of both the cable and the mooring systems. In addition, the strings present a significant spacing, which indicates that the extra area lease cost and slightly longer cables compensate the reduction of the wake effect. A possible explanation is that the wind rose does not present a clearly dominant wind direction.

Finally, Figure 13 displays the convergence curve of the algorithm. As for the first case analysed, the optimisation time could be shorter to generate a similar layout almost as good as the obtained.

corewind

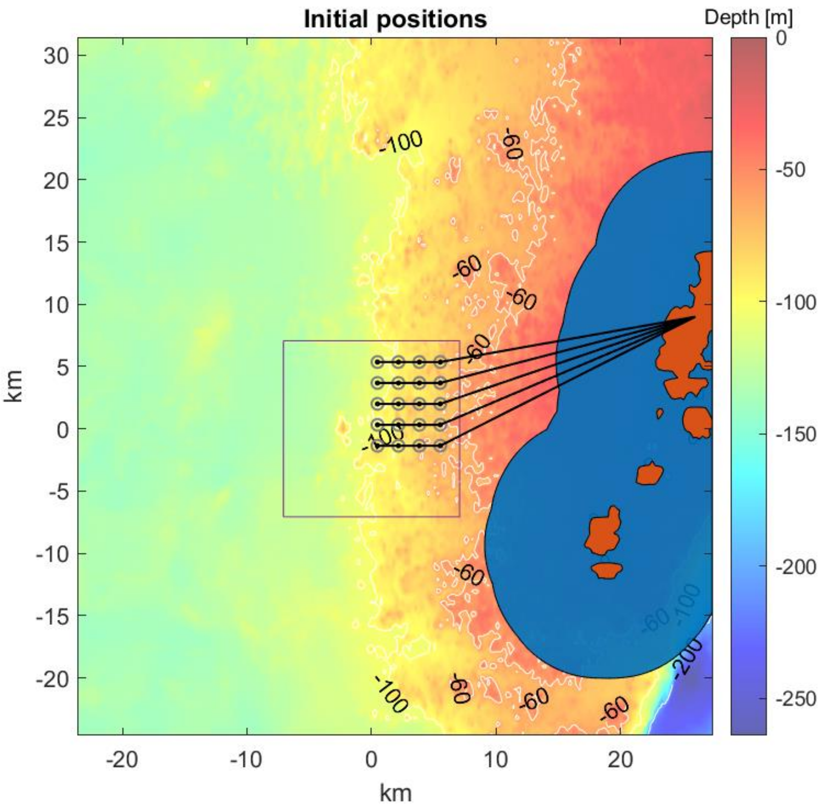


Figure 11. ***Initial solution of the reference scenario 2A.***

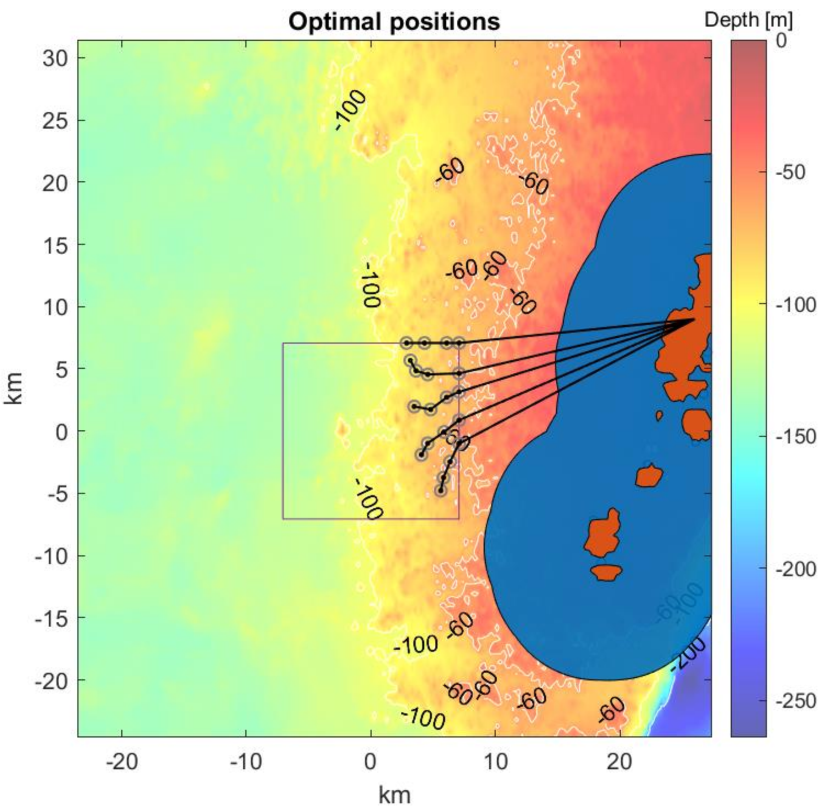


Figure 12. ***Optimal positions determined for scenario 2A.***

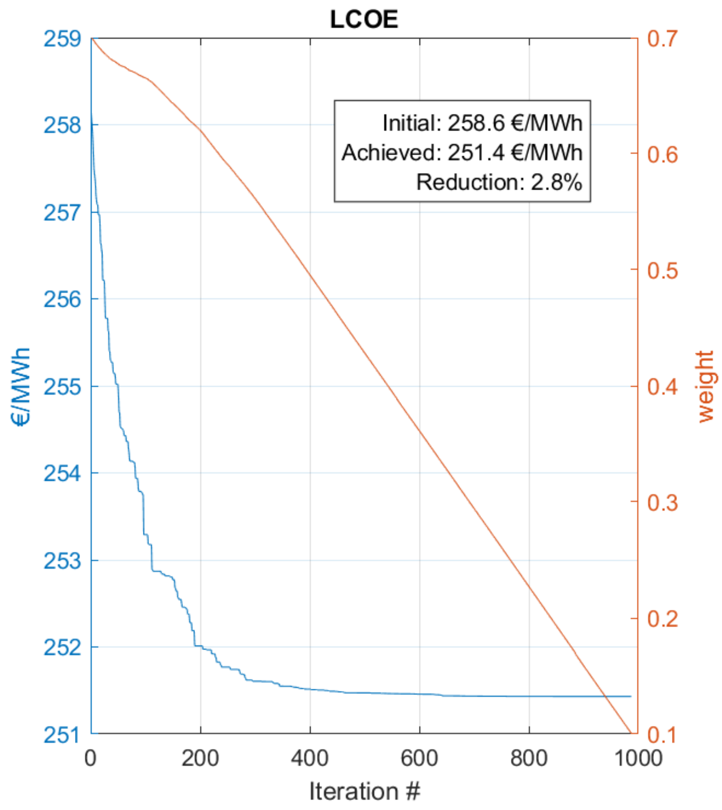


Figure 13. ***Convergence curve of the PSO for scenario 2A.***

### 5.1.4 Reference scenario 3A – Barra, 1200 MW

This study case includes 80 wind turbines, 2 offshore substations, 2 cable joints and the onshore substation. The offshore substations are added because there are potential savings on cable costs and losses given the wind farm capacity. The electrical grid consists of 8 strings per offshore substation of 5 turbines each and 2 export cables (with an initial dynamic section and a final static section) connected to the onshore substation. While the inter-array cables work at 66 kV, the export cables operate at 220 kV. The wind climate is shown in Figure 10.

Figure 7Figure 14 shows the same 8 km buffer as in the previous reference scenario, which is an active constraint in this case. The proposed initial solution follows the same philosophy as in the previous scenario, seeking shallow waters close to the onshore substation.

Figure 15 shows the achieved solution, which apparently can be improved by moving turbines closer to the offshore substations and these, in turn, closer to the onshore substation. A possible reason is that the algorithm cannot reach an optimal solution for 80 turbines in a reasonable time with the configuration used (laptop, 12h, no parallel computation). Another option is that the bumpy bathymetry leads to local optimums where the nodes are stuck.

The convergence curve in Figure 16 reflects a small relative improvement of the solution and a slow progress during the algorithm execution, reinforcing the possibilities of its poor performance for this case.

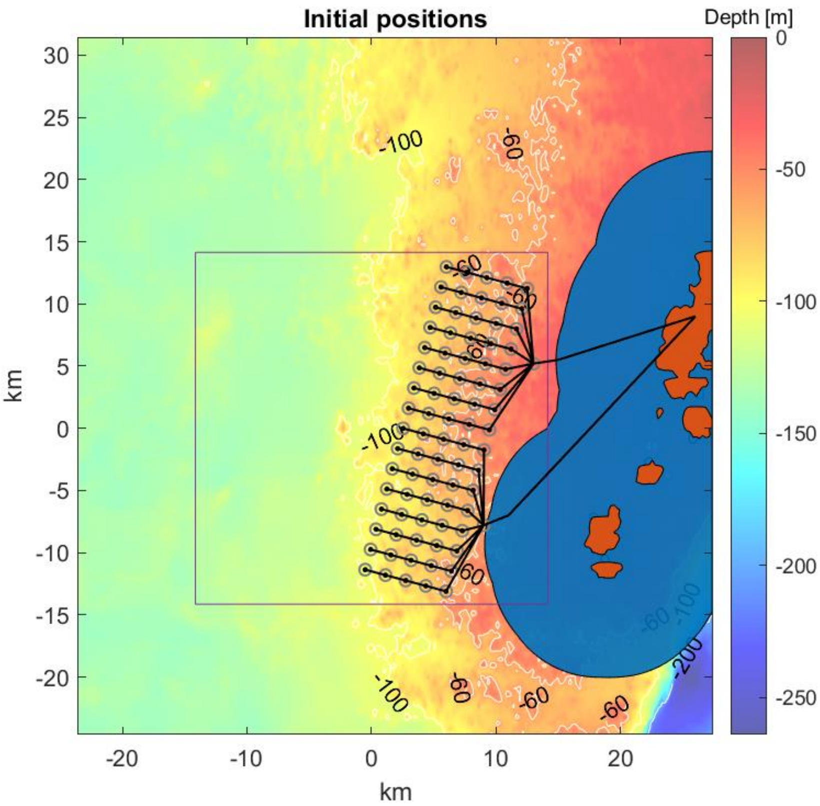


Figure 14. ***Initial solution of the reference scenario 3A.***

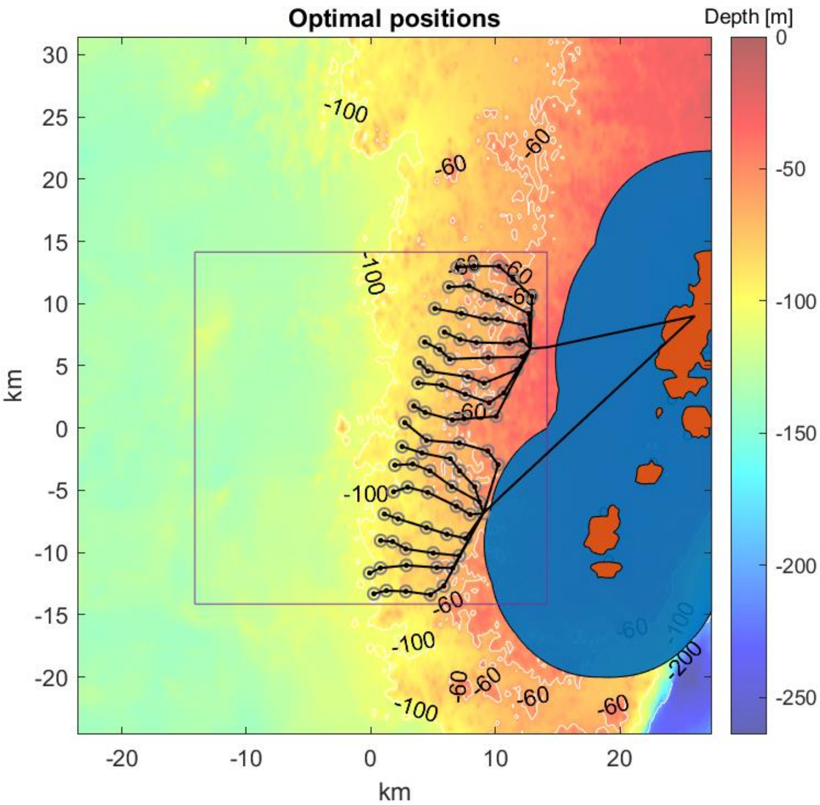


Figure 15. ***Optimal positions determined for scenario 3A.***

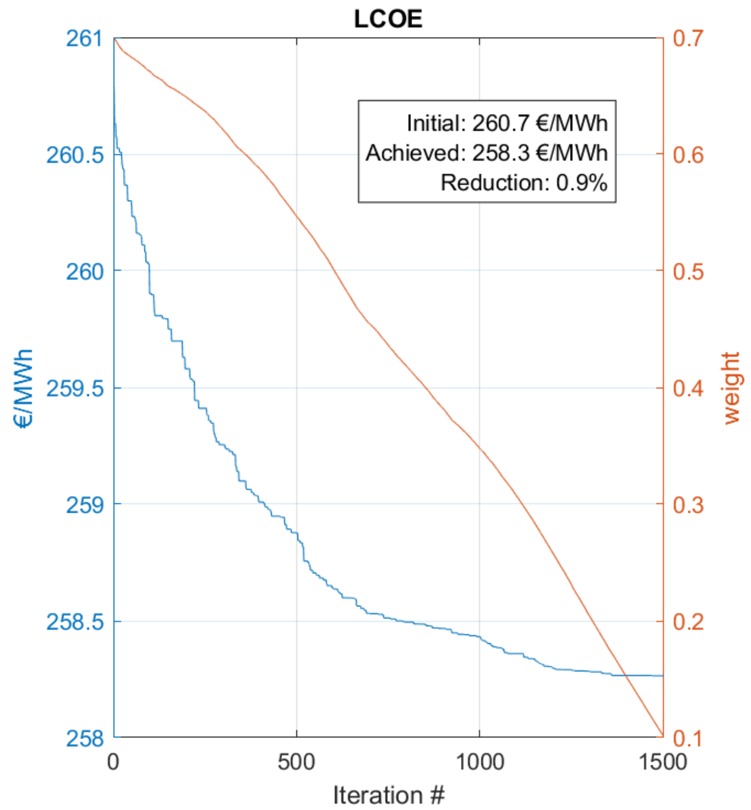


Figure 16. ***Convergence curve of the PSO for scenario 3A.***

### 5.1.5 Reference scenario 8A – Morro Bay, 300 MW

This scenario includes 20 wind turbines grouped in five strings connected to an offshore substation. This, in turn, delivers the power to the onshore substation by means of an export cable with a subsea transition joint. The inter-array grid works at 66 kV and the export cable at 220 kV. The reason to include an offshore substation in this intermediate scenario is the distance from the site to shore, greater than the previous cases. The wind climate is illustrated in Figure 17, in which it can be observed that the prevailing wind direction is NW, with an intermediate directionality between the previously described sites.

As per Figure 18, the bathymetry of the site is quite smooth, without great slopes nor bumps in the area where the turbines are located. The minimum distance to shore is set to 45 km, much greater than in the previous scenarios, although such constraint is not active for the 20-turbine case. The figure also displays the proposed initial solution.

Figure 19 shows the optimal positions determined for the scenario, in which it can be observed a circular-shaped perimeter of the turbines. Due to the smooth slopes, the wake effect appears to be more relevant for the turbines positioning, as the resulting layout is not compact.

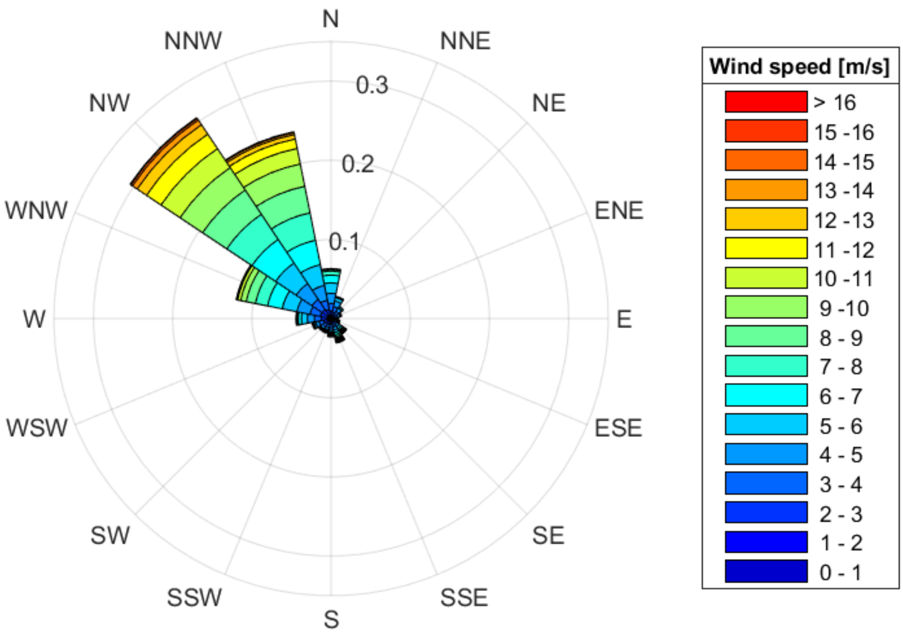


Figure 17. ***Wind climate in site C – Morro Bay***

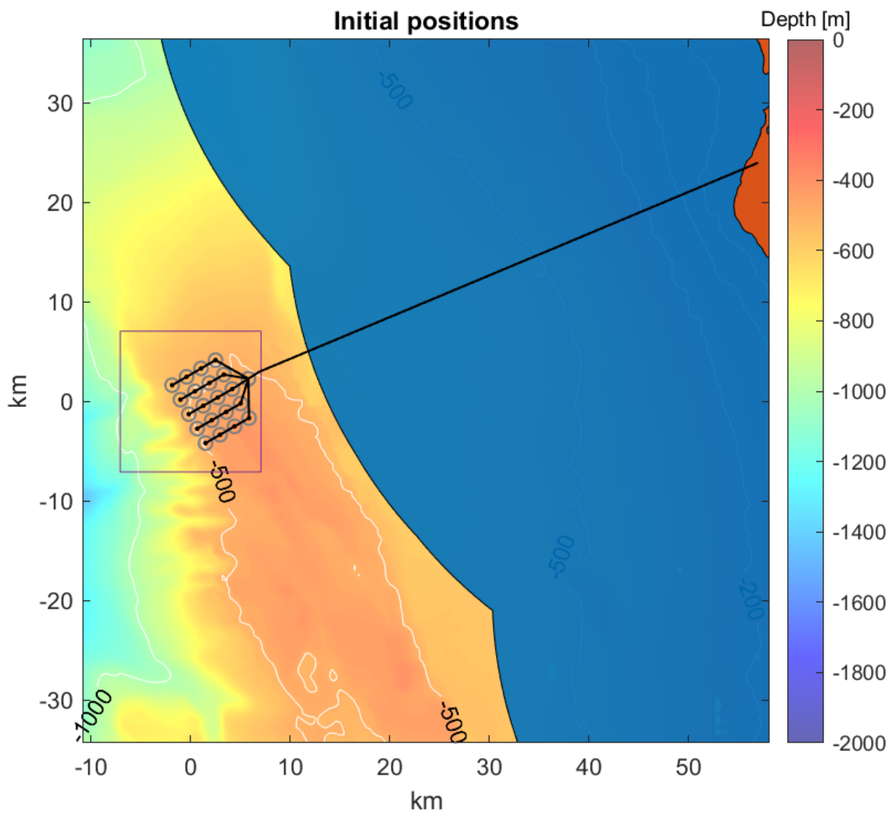


Figure 18. ***Initial solution of the reference scenario 8A.***

Figure 20 includes the convergence curve of the algorithm. Due to the comparison if its shape with the previous curves, allowing additional iterations might lead to better results.

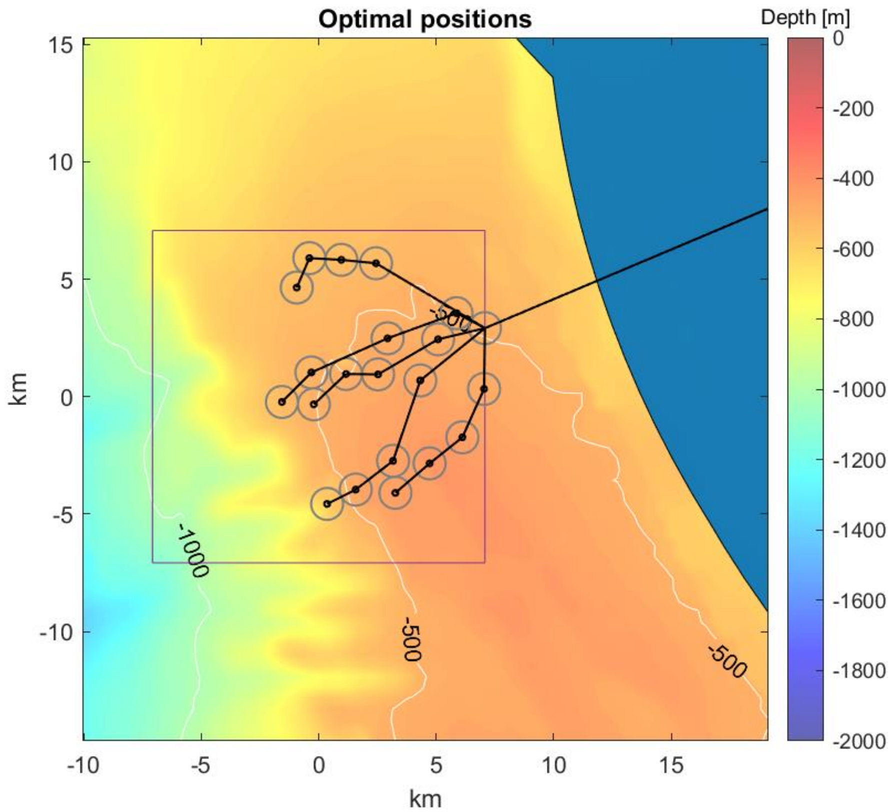


Figure 19. ***Optimal positions determined for scenario 8A.***

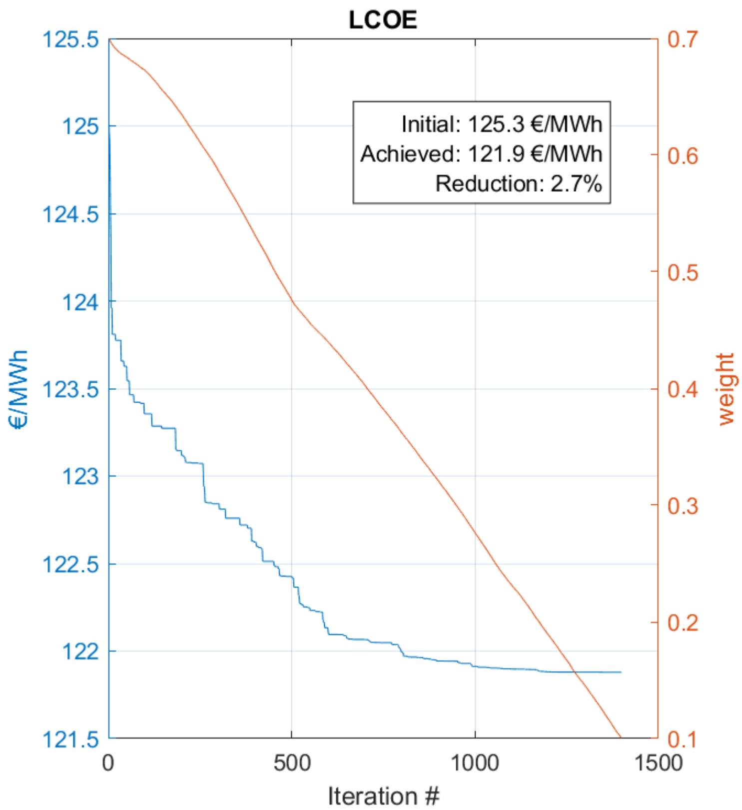


Figure 20. ***Convergence curve of the PSO for scenario 8A.***

### 5.1.6 Reference scenario 9A – Morro Bay, 1200 MW

The last scenario analysed is composed by 80 wind turbines, 2 offshore substations, 2 cable joints and the onshore substation. The electrical grid consists of 8 strings of 5 turbines per offshore substation and 2 export cables connected to the onshore substation. The inter-array cables work at 66 kV and the export cables operate at 220 kV. The wind climate is shown in Figure 17.

Figure 21 shows in blue the 45 km minimum distance to shore, equal to the previous case. The proposed initial solution is also displayed, close to the onshore substation and in the shallowest waters.

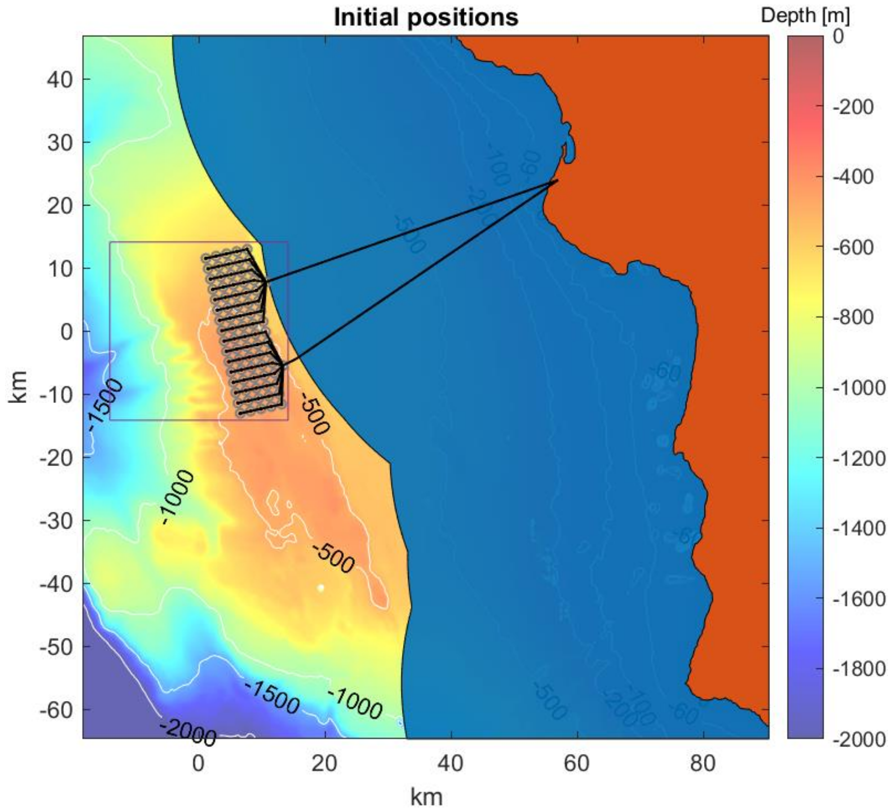


Figure 21. ***Initial solution of the reference scenario 9A.***

The algorithm output is represented in Figure 22. The variation of the positions compared to the initial solution is moderate; together with the shape of the convergence curve in Figure 23, where sustained improvements are observed in the iterations except for low weights, these observations may indicate insufficient optimisation time.

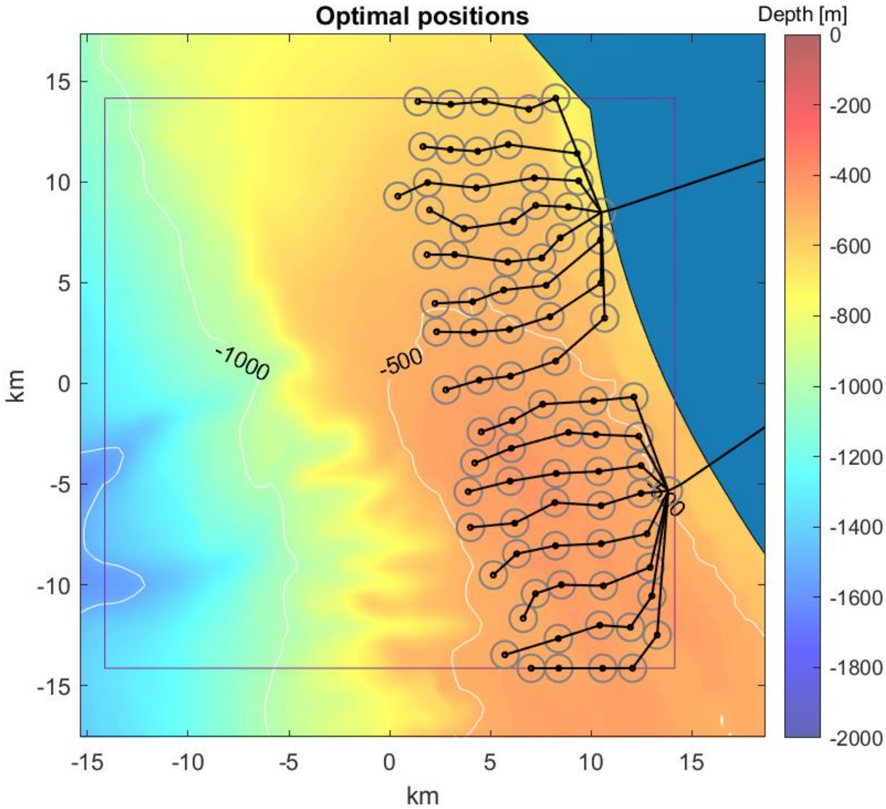


Figure 22. ***Optimal positions determined for scenario 9A.***

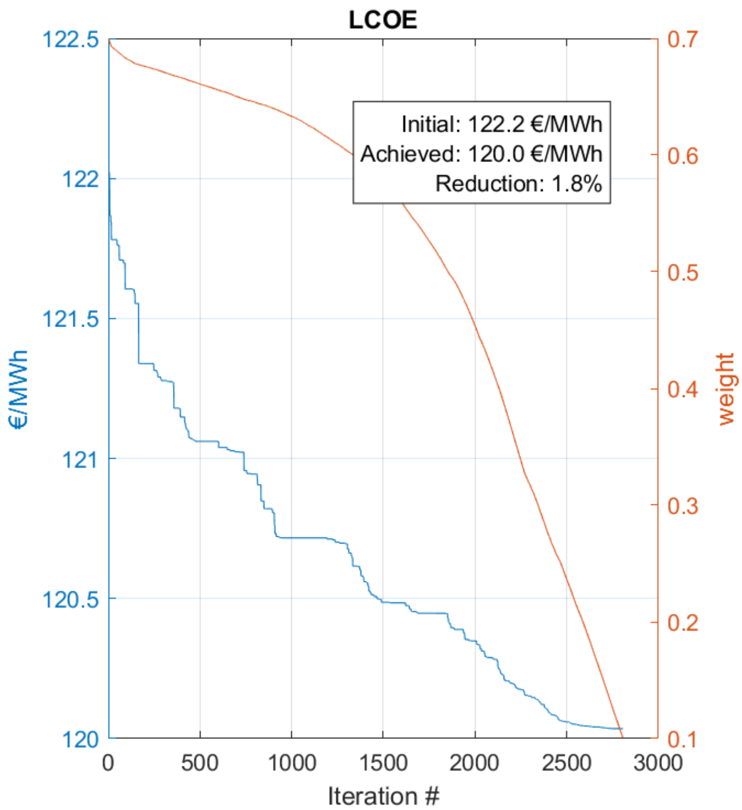


Figure 23. ***Convergence curve of the PSO for scenario 9A.***

## 5.2 Discussion

The mooring footprint constraint is typically active; therefore, it would be reasonable analysing additional mooring systems even if they were more expensive to compare the LCOE of the final layouts. However, this may be useful only for wide areas, as if increased power densities are forced, the turbines may separate in the medium and large scenarios.

The bathymetry appears to be a relevant driver of the algorithm performance because scenarios with irregular seafloor tend to stick to local optimums or at least require more iterations to achieve good results. The terrain slopes do not seem to affect greatly the behaviour of the optimisation.

The final layouts generally adapt well to the wind conditions of the site, which is easy to observe in the smallest scenarios. In the largest scenarios, this effect is reflected on the LCOE reduction, as the turbines displacements relative to their original positions are small, but the reductions are significant, indicating a positioning that reduces the wake effect.

The export cables have a relevant weight on the results because they tend to be as short as possible, even if turbines are located in deeper areas and there are few export cables. This can be explained by their purchase price, the cost of the laying vessel and the power losses associated with longer cables. This effect is also evident in some scenarios for the inter-array cables, as the separation between turbines of different strings is greater than between turbines of the same string.

Table 1 shows the results of the optimised layouts, including two additional small scenarios not detailed in the previous section. It can be observed that the LCOE reductions fluctuate between 0.9% and 3%, with the small scenarios in the upper range and the large scenarios in the lower range. This indicates the optimisation algorithm performance gets worse with the problem size, although such behaviour is normal. It must be noted that the LCOE reductions would have been greater if the layouts considered in the baseline scenarios [37] were established as the initial solutions of the problems. The reason is that the proposed initial solutions are based on such scenarios but the turbines have been moved and rotated inside the allowed boundaries to areas close to the onshore substation and with shallow waters to speed up the optimisation process.

Table 1. *Comparison of the results achieved.*

| Scenario | Initial LCOE [€/MWh] | Achieved LCOE [€/MWh] | Reduction |
|---|---|---|---|
| **1A (4 WT)** | 275.9 | 269.7 | 2.3% |
| **2A (20 WT)** | 258.6 | 251.4 | 2.8% |
| **3A (80 WT)** | 260.7 | 258.3 | 0.9% |
| **4A (4 WT)** | 70.7 | 68.9 | 2.6% |
| **5A (20 WT)** | 68.1 | 66.5 | 2.3% |
| **7A (4 WT)** | 141.3 | 137.1 | 3.0% |
| **8A (20 WT)** | 125.3 | 121.9 | 2.7% |
| **9A (80 WT)** | 122.2 | 120.0 | 1.8% |

## 5.3 Sensitivity analysis

A brief sensitivity analysis is presented in this section. The purpose is the evaluation of the results obtained in different runs of the algorithm for the same scenario. Due to the multiple scenarios optimised and the required computational time, the analysis inputs are limited. Figure 24 shows the LCOE reductions achieved in the already presented results plus additional runs for some of the scenarios. It can be observed that the differences in the results can be significant, therefore if a single scenario must be optimised, it would be wise the execution of the optimisation algorithm at least three times in order to obtain good results.

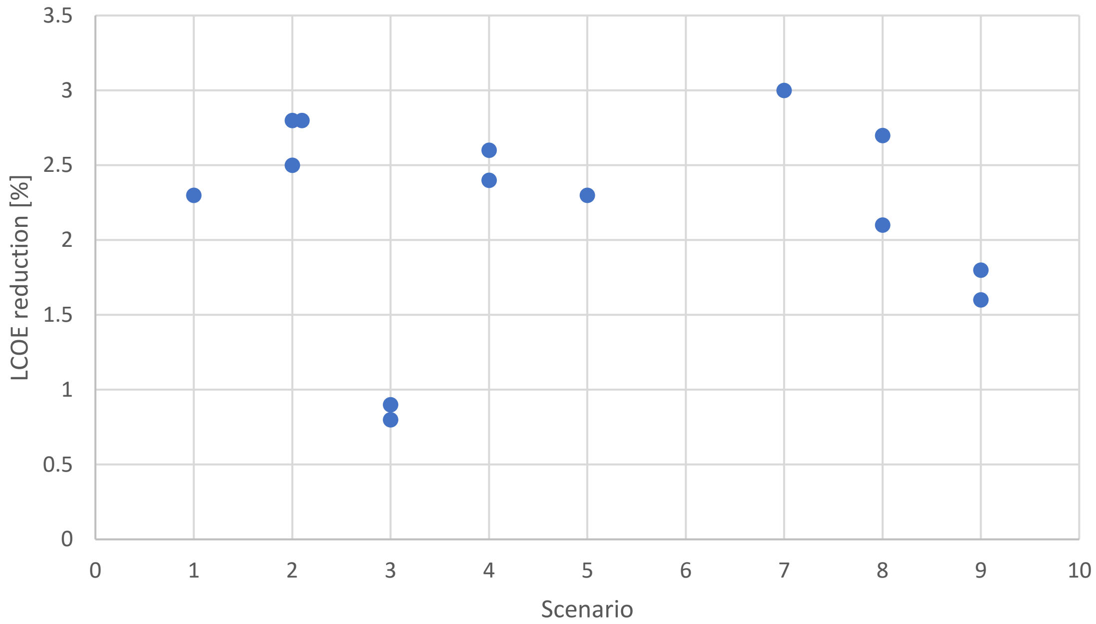


Figure 24. ***Values obtained in different runs.***

Figure 25 shows that the standard deviation of the LCOE reductions ranges 0.07% to 0.42%. Such values may appear to be small, but given the high costs of the FOWFs, this reinforces the idea of running multiple optimisations before selecting their final layout.

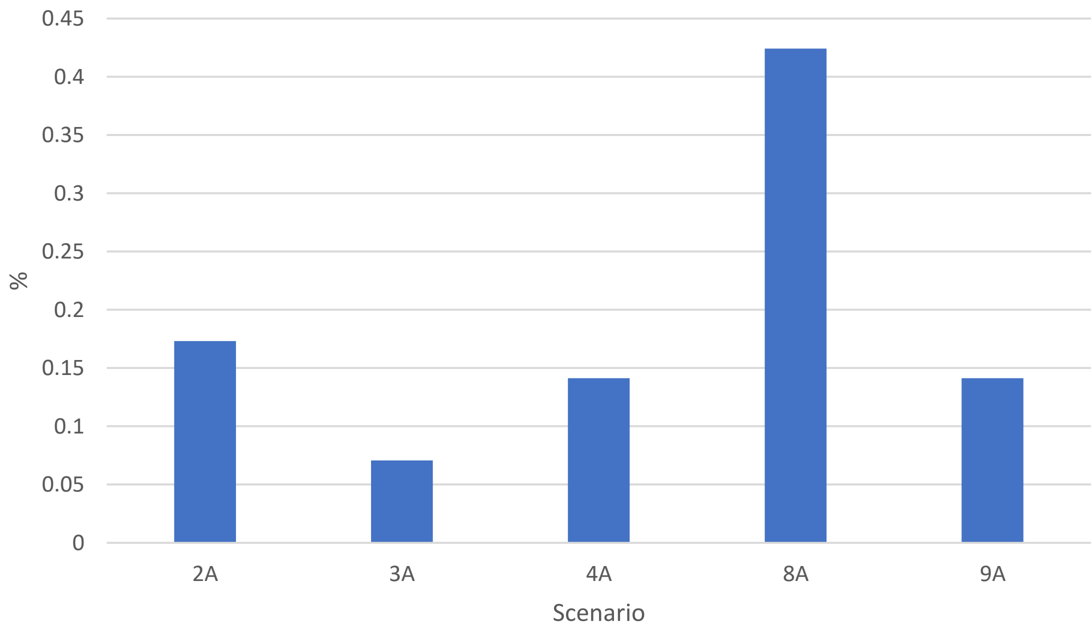


Figure 25. ***Standard deviation of the results in the scenarios where multiple runs were conducted.***

## 6 CONCLUSIONS

The state of the art revision aimed at identifying the current optimisation techniques applied to turbine and substation positioning as well as cable routing in OWFs. It has shown that the great majority of research is still concentrated on the bottom-fixed industry, as only one paper was found that specifically developed an optimisation algorithm for FOW.

In order to find an optimal cost-effective solution, WT positions, OSS positions, interconnectivity and cable types should be defined in a simultaneous process. Furthermore, power losses, installation and O&M activities, bathymetry and seabed characteristics should be considered in the objective function. However, the consideration of all the previous variables and characteristics may lead to a complex problem hard to solve in a reasonable time, therefore the variables should be reduced or the objective function simplified. Particular attention should be paid to the objective of the optimisation; for example, minimising the CAPEX may not lead to good results as the power losses in the system can increase. The LCOE is deemed a good objective function as it considers both the performance of the wind farm and its lifetime costs.

Including all or most of the decision variables and considerations generate a complex problem hard or impossible to solve using deterministic algorithms, which also struggle to solve large problems in a reasonable computational time. Therefore, most papers approach the cabling problem by using heuristic methods. The most common are the population-based metaheuristics genetic algorithm and the particle swarm optimisation. It seems that the PSO, in contrary to the GA, comes with less programming effort and can benefit of a cooperative behaviour of particles whereas the GA promotes the survival of the fittest while leaving poorer solutions to themselves as a product of random mutation and crossover. Besides PSO and GA, other metaheuristics seem to be able to cope with this complex problem too: the Variable Neighbourhood Search as well as the Tabu Search were only encountered in one work but seem to produce good results and it may be worth taking a closer look at them.

As the global optima is not guaranteed in the heuristic algorithms, researchers do underline the benefits of including a local search phase in order to prevent them from falling into a local optimum. On the other hand, literature has also shown that clustering heuristics can also greatly improve the found solution or generate high-quality initial solutions for metaheuristics in order to ease the finding process.

The problem solved in this report has been formulated with the LCOE as the objective function, using a detailed calculation that takes into account several characteristics of the wind farm that influence its value. On the other hand, the decision variables have been reduced to the positions of the turbines, substations and subsea cable joints. This definition results in a complex problem to be solved with a heuristic algorithm, but not too complex to reach feasible solutions in a reasonable time without the usage of advanced computers.

The PSO has been selected as the optimisation algorithm due to its good performance when solving complex problems in comparison with alternative solvers. The deterministic methods were not considered due to the lack of convexity of the problem definition. A number of modifications were included in the PSO to increase its controllability and performance to solve this particular problem. More precisely, the definition of the simulation time was included, a function to avoid overlapping of mooring footprints was implemented, and functions to control the initial solution and the maximum velocity of the particles were used.

The optimisation of the layout of eight reference scenarios concluded successfully, with LCOE reductions between 0.9% and 3% only because of the variation of the turbines, substations and submarine joints locations. The optimisation results of six scenarios have been analysed, revealing a good performance of the algorithm, in particular for the small and medium sizes, while it is expected that additional optimisation time would lead to better results for the large scenarios with 80 turbines. Thanks to the accurate problem formulation, the selection of the PSO as solving method and the modifications introduced to improve its performance, the results obtained are considered realistic.

Further planned work includes the improvement of the algorithms to avoid local optimums due to bumpy seabed as well as unfeasible solutions caused by nodes out of bounds. In addition, the adaptation of the method to deal with centralised tenders is also planned. Despite the further work, the results achieved are adapted to the site conditions such as the wind climate and the bathymetry, being already better than generic layout definitions or those defined by rules of thumb.

## 7 REFERENCES


[1] A. Wedzik, T. Siewierski and M. Szypowski, “A new method for simultaneous optimizing of wind farm’s network layout and cable cross-sections by MILP optimization,” *Applied Energy 182,* pp. 525-538, 2016.

[2] A. Klein and D. Haugland, “Optimization of reliable cyclic cable layouts in offshore wind farms,” *Engineering Optimization,* pp. 258-276, 2021.

[3] I. Ulku and C. Alabas-Uslu, “OPTIMIZATION OF OFFSHORE WIND FARM CABLE LAYOUTS,” in *6th Eur. Conf. Ren. Energy Sys. 25-27 June 2018*, Istanbul, 2018.

[4] T. Roetert, T. Raaijmakers and B. Borsje, “Cable route optimization for offshore wind farms in morphodynamic areas,” in *The 27th International Ocean and Polar Engineering Conference*, San Francisco, 2017.

[5] Y. Qi, P. Hou, R. Jin, Z. Yang, G. Yang and Z. Dong, “Cable Connection Optimization for Heterogeneous Offshore Wind Farms via a Voronoi Diagram Based Adaptive Particle Swarm Optimization with Local Search,” *Energies,* no. 14, pp. 644-665, 2021.

[6] A. Klein and D. Haugland, “Obstacle-aware optimization of offshore wind farm cable layouts,” *Annals of Operations Research,* no. 272, p. 373–388, 2019.

[7] S. Wei, L. Zhang, Y. Fu and F. Li, “Hierarchical Optimization for the Double-Sided Ring Structure of the Collector System Planning of Large Offshore Wind Farms,” *IEEE TRANSACTIONS ON SUSTAINABLE ENERGY,* vol. 8, no. 3, pp. 1029-1039, 2017.

[8] M. Lerch, M. De-Prada-Gil and C. Molins, “A metaheuristic optimization model for the inter-array layout planning of floating offshore wind farms,” *Electrical Power and Energy Systems,* vol. 131, no. 107128, 2021.

[9] D. Cazzaro, M. Fischetti and M. Fischetti, “Heuristic algorithms for the Wind Farm Cable Routing problem,” *Applied Energy,* vol. 278, 2020.

[10] T. Zuo, Z. H. Dong, Z. Tong, Y. Tang and K. Meng, “Offshore wind farm collector system layout optimization based on self-tracking minimum spanning tree,” *International Transactions on Electrical Energy Systems,* vol. 29, no. 2, 2018.

[11] X. Gong, S. Kuenzel and B. C. Pal, “Optimal Wind Farm Cabling,” *IEEE TRANSACTIONS ON SUSTAINABLE ENERGY,* vol. 9, no. 3, pp. 1126-1136, 2018.

[12] J.-S. Shin and J.-O. Kim, “Optimal Design for Offshore Wind Farm considering Inner Grid Layout and Offshore Substation Location,” *IEEE TRANSACTIONS ON POWER SYSTEMS,* vol. 32, no. 3, pp. 2041-2048, 2017.

[13] C. El Mokhi and A. Addaim, “Optimization of Wind Turbine Interconnections in an Offshore Wind Farm Using Metaheuristic Algorithms,” *Sustainability,* vol. 12, no. 14, 2020.

[14] J. Serrano González, Á. L. Trigo García, M. Burgos Payán, J. Riquelme Santos and A. G. González Rodríguez, "Optimal wind-turbine micro-siting of offshore wind farms: A grid-like layout approach," *Applied Energy,* vol. 200, pp. 28-38, 2017.

[15] P. Hou, W. Hu, M. Soltani, C. Chen and Z. Chen, "Combined optimization for offshore wind turbine micro siting," *Applied Science,* vol. 189, p. 271–282, 2017.

[16] A. C. Pillai, J. Chick, L. Johanning and M. Khorasanchi, "Offshore wind farm layout optimization using particle swarm optimization," *Journal of Ocean Engineering and Marine Energy,* vol. 4, pp. 73-88, 2018.

[17] P. Hou, G. Yang, W. Hu, C. Chen, M. Soltani and Z. Chen, "Cable Connection Scheme Optimization for Offshore Wind Farm Considering Wake Effect," in *2018 IEEE Congress on Evolutionary Computation, CEC 2018*, Rio de Janeiro, 2018.

[18] J. Serrano Gonzalez, M. Burgos Payán, J. M. Riquelme Santos and F. González-Longatt, "A review and recent developments in the optimal wind-turbine micro-siting problem," *Renewable and Sustainable Energy Reviews 30,* pp. 133-144, 2014.

[19] J. H. Holland, "Genetic Algorithms," *Scientific American, Vol. 267,* pp. 66-73, 1992.

[20] W. Hu, Z. Chen and P. Hou, "Optimisation for offshore wind farm cable connection layout using adaptive particle swarm optimisation minimum spanning tree method," *Renewable Power Generation IET 10(5),* pp. 694-702, 2016.

[21] M. Banzo and A. Ramos, "Stochastic Optimization Model for Electric Power System Planning of Offshore Wind Farms," *IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 26, NO. 3,* pp. 1338-1348, 2011.

[22] B. E. Gillet and L. R. Miller, "A Heuristic Algorithm for the Vehicle-Dispatch Problem," *Operations Research, Mar. - Apr., 1974, Vol. 22, No. 2 ,* pp. 340-349, 1974.

[23] J. Lysgaard, A. Letchford and R. Eglese, "A new branch-and-cut algorithm for the capacitated vehicle routing problem," *Mathematical Programming; Volume 100,* pp. 423-445, 2004.

[24] R. Fukasawa, . H. Longo, J. Lysgaard, M. Poggi de Aragão, M. Reis, E. Uchoa and R. Werneck, "Robust Branch-and-Cut-and-Price for the Capacitated Vehicle Routing Problem," *Mathematical Programming; Volume 106,* p. 491–511, 2006.

[25] S. Dutta and T. J. Overbye, "A clustering based wind farm collector system cable layout design," in *2011 IEEE Power and Energy Conference at Illinois*, Urbana, IL, USA, 2011.

[26] S. Dutta and T. J. Overbye, "Optimal Wind Farm Collector System Topology Design Considering Total Trenching Length," *IEEE Transactions on Sustainable Energy ( Volume: 3, Issue: 3),* pp. 339 - 348, 2012.

[27] A. C. Pillai, J. Chick, M. Khorasanchi, S. Barbouchi and L. Johanning, "Application of an offshore wind farm layout optimization methodology at Middelgrunden wind farm," *Ocean Engineering 139,* pp. 287-297, 2017.

[28] R. Hassan, B. Cohanim, O. de Weck and G. Venter, "A comparison of particle swamr optimization and the genetic algorithm," in *46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Austin, Texas, 2005.

[29] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory," in *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, Nagoya, Japan, 1995.

[30] M.-A. Schwarzkopf, F. Borisade, D. Matha, M. D. Kallinger, M. Y. Mahfouz, R. Durán Vicente and S. Muñoz, "D4.1 Identification of floating wind-specific O&M requirements and monitoring technologies," H2020 COREWIND project, 2020.

[31] N. Srinil, "13 - Cabling to connect offshore wind turbines to onshore facilities," in *Offshore Wind Farms - Technologies, Design and Operation*, Woodhead Publishing, 2016, pp. 419-440.

[32] C. Kost, S. Shammugam, V. Jülch, H.-T. Nguyen and T. Schlegl, "Levelized cost of electricity Renewable energy technologies," Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, 2018.

[33] N. O. Jensen, "A note on wind generator interaction," *Risø-M, No.2411,* 1983.

[34] R. D. Zimmerman, C. E. Murillo-Sanchez and R. J. Thomas, "MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education," *Power Systems, IEEE Transactions on,* vol. 26, no. 1, pp. 12-19, 2011.

[35] V. J. Ferreira, J. I. Rapha, J. Verma and J. L. Domínguez, "D6.1 General frame of the analysis and description of the new FOW assessment app," 2020.

[36] General Bathymetric Chart of the Oceans, "Gridded bathymetry data," 2021. [Online]. Available: https://www.gebco.net/.

[37] V. J. Ferreira, G. Benveniste, J. I. Rapha, J. Verma and J. L. Domínguez, "D6.2 Initial LCA and LCOE," COREWIND, 2021.

[38] "lifes50plus," [Online]. Available: https://lifes50plus.eu/. [Accessed 10 09 2021].

[39] M. Srinivas and L. M. Patnaik, "Adaptive probabilities of crossover and mutation in genetic algorithms," *IEEE Transactions on Systems, Man, and Cybernetics ( Volume: 24, Issue: 4),* pp. 656 - 667, 1994.

[40] S.-H. Yang, J. Ringsberg and E. Johnson, "Parametric study of the dynamic motions and mechanical characteristics of power cables for wave energy converters," *Journal of Marine Science and Technology,* 2018.

[41] S. Li and C. Nguyen, "Dynamic response of deepwater lazy-wave catenary riser," *Deep Offshore Technology International 147,* 2010.