Collection System Cable Routing and Wake Losses Optimization in Offshore Wind Farms

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SUMMARY

Offshore wind farms with high installed capacities and located further from the shore are starting to be built by northern European countries. Furthermore, it is expected that by 2020, several dozens of large offshore wind farms will be built in the Baltic, Irish and North seas. These wind farms will be constituted of a considerable number of turbines packed together. Due to shadowing effects between turbines, the power production is reduced, resulting in a decreased wind farm efficiency. Moreover, the collection system length and complexity rapidly increase with the number of wind turbines installed, resulting in higher investment costs and power losses. Hence, when large wind farms are considered, wake losses and collection system total length are important aspects that need to be optimized. Nonetheless, designing a large offshore wind project is a very complex task. In the development phase, an enormous amount of time is used to generate feasible wind farm designs. For example, the manual layout optimization and cable routing are highly time consuming. Amongst others, this drawback leads to offshore wind projects with very high investments costs. In fact, electricity generated offshore is, up to today, substantially more expensive when compared to onshore wind or combined cycle gas turbines.

Wind farm layout optimization is a possible solution to further increase the efficiency of wind projects leading to lower prices of energy generated offshore. Moreover, investment costs would be reduced if the collection system could be automatically designed via optimization tools.

The aim of this work is to obtain optimized offshore wind farm layouts with enhanced energy production while considering the seabed constraints, e.g. maximum sea depth, inappropriate soil types and large seabed gradients. Through the use of optimization tools it is also desired to alleviate the designer teams of mundane manual layout optimization and cable routing.

The optimized wind farm layout obtained presents higher energy yield. Although, the collection system total length is higher than for the standard case, the overall system efficiency is improved. Moreover, installation costs of the collection system were reduced through the avoidance of challenging areas of the wind farm. The wind turbine support structures costs were also reduced since deep areas of the seabed were avoided.

In this work it is presented a novel optimization tool to obtain optimized offshore wind farm layouts while taking into consideration the seabed profile. Due to the increased offshore activity in recent years, as well as the expected installation in the coming years, this tool becomes very important and relevant for the offshore field.

1. Introduction

According to the European Commission, offshore wind will have a substantial contribution in helping the European Union to meet its energy policy objectives. Hence, a substantial increase in the offshore wind installed capacity is expected in the coming years. This growth, when compared to the installed capacity at the end of 2007, is believed to be approximately 30 to 40 times higher, by 2020, and 100 times in 2030 [1]. Together with the wind farms rated power (see Figure 1), also the number of installed turbines per project is rapidly increasing. Furthermore, it is believed that this trend will continue [2].
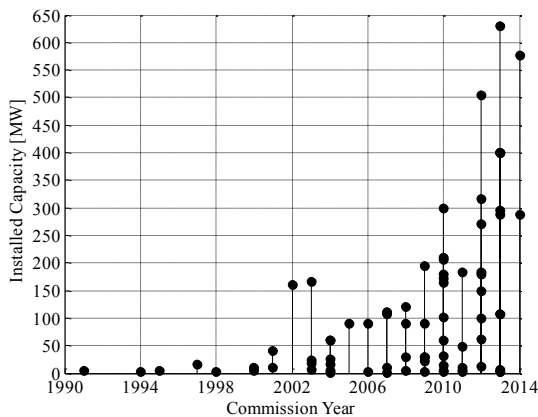

Figure 1 - Commission year and installed capacity for commissioned and under construction offshore farms [3]
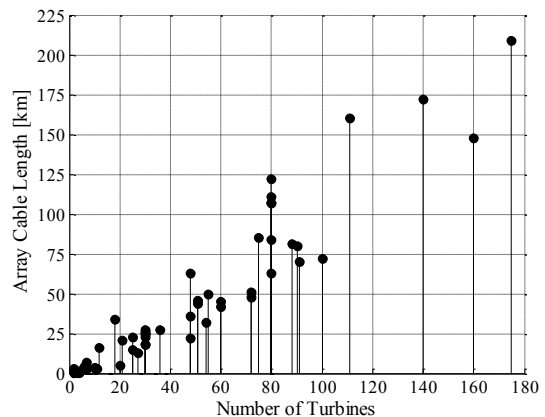
Figure 2 - Number of turbines and array cable length for commissioned and under construction offshore farms [3]

Due to the increasing number of turbines per offshore wind project, the collection system length is also growing. In Figure 2 it is shown the total number of turbines and the collection system length for commissioned or under construction offshore wind projects. A wind farm currently under construction is the British offshore wind farm, Gwynt y Môr, which will have a total installed capacity of 576 MW [3]. It will be composed of 160 wind turbines of 3.6 MW each. A 33-kV collection system with a total cable length of 148 km will be installed. The wind farm layout, including the wind turbines and substation locations as well as the collection system layout is shown in Figure 3.
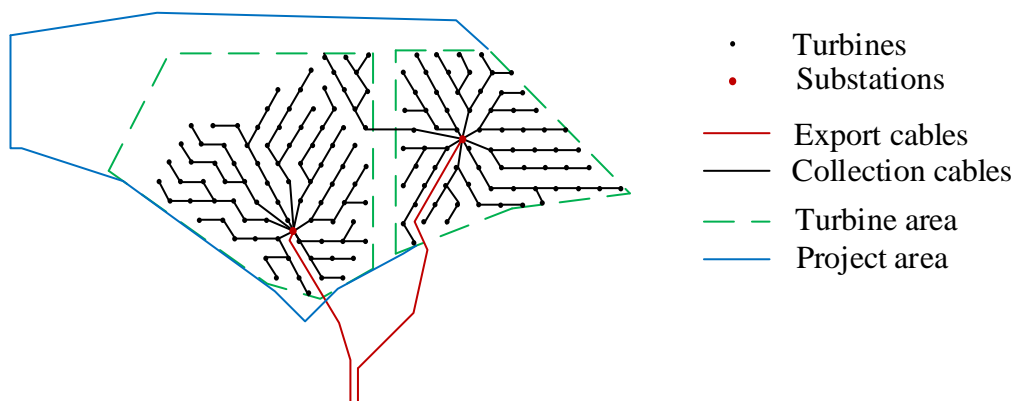

Figure 3 - Gwynt y Môr offshore wind farm [3]

In the initial offshore wind projects the collection system layout was predominantly set by a straightforward trade-off between investments costs and turbine separation. Larger turbine separations lead to lower wake losses and higher energy production per turbine. On the other hand, higher initial investments and operational costs and lower energy production per unit of seabed were obtained. Future wind projects will require a more sophisticated set of trade-offs between, for example, wake losses, collection system costs, support structure costs and installation costs. Implementing these trade-offs will involve the development and use of fast and reliable software tools that optimize the collection system for the lowest cost of energy or other parameters depending on the targets of the wind farm designers [8]. Feedback from industry is that greater investment in wind farm design and optimization at the development stage will lead to cost savings in later stages of the project [8].

In order to reduce costs, e.g. collection system cost, turbines tend to be packed in wind farms. However, the installation of wind turbines close to each other causes interferences such as shadowing effects. For example, the efficiency of the Danish Horns Rev offshore wind farm is 11% lower when compared to what the same turbines would produce if installed alone [3].

Optimizing the turbines micro siting is one possible strategy to reduce wake losses. However, due to the high nonlinearity nature and amount of design variables of the problem, the search space becomes too complex to be solved through deterministic algorithms. A possible solution is the use of stochastic algorithms, where randomness is included in the process [5]. The use of optimization methods inspired by biological processes in the turbine micro siting problem is not novel. For instance, an evolutive algorithm set to optimize the wind farm profits was used in [6]. In order to do so, it was required the minimization of the investment costs while maximizing the net cash flows, through energy generation optimization and power losses reduction. A modular and parallelizable evolutionary optimization strategy set to optimize the layout of a wind project with thousand turbines was presented in [7].

Work regarding the optimization of the collector system of offshore wind farms may be found in the literature. For instance, in [11] it is addressed the design of a collector system for a large wind farm. The objective was the minimization of total trenching time via the reduction of the collector system total length. An approach which makes use of decomposition strategies to solve the optimal collector layout problem while considering redundant elements and asymmetrical patterns was presented in [12]. In [13] a modified genetic algorithm was used to find optimal layouts for collection systems composed of cables with different cross sections. However, in any of the literature works the seabed profile was taken into consideration for the collection system design.

The design of the wind farm layout is determined by amongst others, physical constraints, component design limitations, environmental considerations, optimum use of the wind resource considering wake effects, economies of scale and collection system economics and physical limitations [10]. Detailed analysis of wake modelling, cable costs and cable layout is necessary in order to achieve an optimal layout. The wake effects have usually a stronger driver of economics than the increased costs of extra collection system cabling needed to allow an increased turbine spacing [10].

The aim of this work is to obtain optimized offshore wind farm layouts with optimized energy production and collection system design while considering the seabed constraints, e.g. maximum depth, inappropriate soil types and large seabed gradients. It is also desired to alleviate the designer teams of repetitive manual required for layout optimization and cable routing.

The remainder of the paper is organized as follows: in the next section an introduction to wake losses modelling is given. Thereafter, the evolutionary algorithm employed is presented. In the following section it is described the proposed optimization method for the collection system routing. Thereafter, a case study is presented, followed by the results and discussions sections. At the end conclusions are drawn.

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2. Wake losses

The wake growth model used, so-called Jensen model, was originally proposed in [14]. The wind speed deficit model employed was presented in [15]. These models have been widely adopted in wind farm layout optimization [16]. For the interested reader, more information regarding different analytical models for wake losses may be found in [17] [18] [19].

Differently from a solitary turbine, the wind speed seen by a $j-th$ turbine, positioned in the wake of one or more turbines, is given by:

$$U_j = U_0 \left(1 - deficit \right)$$

where U_0 is the ambient wind speed and *deficit* is the velocity decrease caused by shadowing effects.

The wake expansion is considered to be linear, hence:

$$R_k^w = R_k + \alpha d_{kj}$$

where R_k^w is the wake front radius, R_k is the turbine rotor radius, α is the decay factor (in offshore conditions, a value of 0.05 is normally used [18]) and d_{kj} is the distance between the turbines being considered.

The interference caused by an upstream $k-th$ turbine to a $j-th$ turbine may be calculated as:

$$U_{kj} = \frac{1 - \sqrt{1 - C_{T_k}}}{\left(1 + \dfrac{\alpha d_{kj}}{R_j} \right)^2} \frac{A_{kj}}{A_j}$$

where C_{T_k} is the $k-th$ turbine thrust coefficient at a given speed, A_j is the $j-th$ turbine rotor area and A_{kj} is the $j-th$ turbine rotor area influenced by the upstream turbine k.

If the wake front affects entirely the $j-th$ turbine, $A_{kj} = A_j = \pi R_j^2$. If the wake fronts affects partially the turbine rotor sweep area (see Figure 4), A_{kj} is given by:

$$A_{kj} = \frac{1}{2} \left(R_k^{w2} \left(2\arccos\left(\frac{R_k^{w2} + c_{kj}^2 - R_j^2}{2R_k^w c_{kj}} \right) - \sin\left(2\arccos\left(\frac{R_k^{w2} + c_{kj}^2 - R_j^2}{2R_k^w c_{kj}} \right) \right) \right) + R_j^2 \left(2\arccos\left(\frac{R_j^2 + c_{kj}^2 - R_k^{w2}}{2R_j c_{kj}} \right) - \sin\left(2\arccos\left(\frac{R_j^2 + c_{kj}^2 - R_k^{w2}}{2R_j c_{kj}} \right) \right) \right) \right)$$

Finally, if the wake front does not impact the $j-th$ turbine, $A_{kj} = 0$.

The wake losses model takes into consideration multiple interferences from upstream turbines. Hence, the deficit term is calculated as:
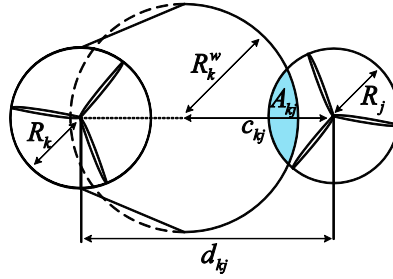
$$deficit = \sqrt{\sum_{k=1}^{n} U_{kj}^2}$$

Figure 4 - Turbine partially affected by an upstream turbine wake front

Assumptions

Several assumptions were made in the wake speed deficit modeling [15]. These assumptions may lead to innacure results. A Computational Fluid Dynamics (CFD) model is likely to achieve more accurate estimations of the wake velocities [20]. However, such high fidelity CFD simulations is the excessive computational complexity and processing time. Hence, such models are not suitable for optimization purposes where multiple model evaluations are made. The assumptions are:

- The wind speed in the wake front is axi-symmetric;
- The wake front starts to expand immedialty after the turbine rotor;
- The wind speed reduction inside the wake front is considerd to be linear;
- Turbine loads were not considered;
- The turbines are identical, i.e. similar physical and performance characteristics;
- Wind turbulence was not considered;
- The freestream wind speed is homogenous.

3. CMA-ES Algorithm

The Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) is one of the most powerful evolutionary algorithms for real-valued single-objective optimization of non-linear and non-convex functions, especially in black-box settings [21]. The CMA-ES self-adapts the covariance matrix of a multivariate normal distribution, which is used to sample new solutions from the multidimensional search space, where each variate is a search variable [22]. The correlations between variables are respected due to the covariance matrix, making it a powerful evolutionary optimization algorithm. It efficiently minimizes unimodal functions and in particular is superior on ill-conditioned and non-separable problems [23]. The CMA-ES algorithm has been applied in different fields of engineering [24]. Next, the different steps of the algorithm, shown in Figure 5, are described.
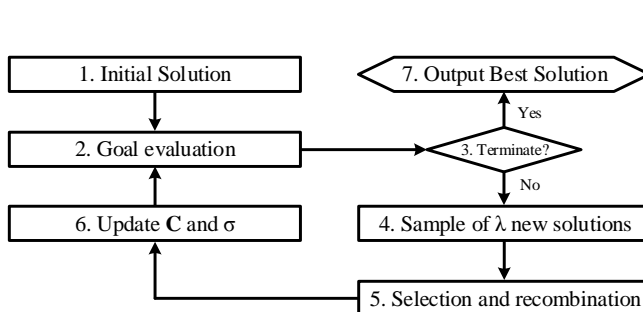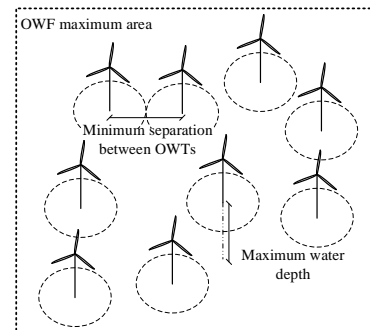

Figure 5 - Flowchart of the CMA-ES algorithm

Figure 6 - Constraints taken into consideration for the turbines sitting problem

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3.1. Initial solution

At the initialization (step 1 of Figure 5) an initial wind farm layout is created. The wind turbine coordinates, which have as boundaries the wind farm area limit, are encoded in the solution. All the encoded variables are real valued. The composition of a solution is given by:

$$\mathbf{X} = \begin{bmatrix} x_1 & \cdots & x_k & y_1 & \cdots & y_k \end{bmatrix}$$

where (x_1, y_1) and (x_k, y_k) correspond to the coordinates of the first and $k-th$ turbines, respectively.

3.2. Optimization goal

The optimization goal is to increase the wind farm efficiency through a reduction of the wake losses. This is expressed as:

$$\eta_{WF} = \frac{P_{WF}}{\sum_{i=1}^{n} P_{WT_i}}$$

where η_{WF} is the wind farm efficiency, P_{WF} is the wind farm total power production and $\sum_{i=1}^{n} P_{WT_i}$ represents the power produced by the turbines without shadowing effects.

3.2.1. Constraints

In order to obtain feasible wind farm layouts, the following constraints (displayed in Figure 6) were implemented [24]:

- A minimum distance of four turbine rotor diameters is required for neighbouring turbines;
- The turbines have to be placed inside the allowed wind farm area;
- A maximum water depth of 30 m is applied to the wind turbine locations.

3.3. Stopping Criterion

When the maximum number of optimization iterations is reached, the optimization ends and returns the best solution found during the optimization.

3.4. Sampling of new solutions

In the CMA-ES, a population of λ new individuals is generated by sampling a multivariate normal distribution:

$$\mathbf{x}_h^{(g+1)} \sim \mathbf{m}^{(g)} + \sigma^{(g)} \mathcal{N}\left(0, \mathbf{C}^{(g)}\right) \text{ for } k = 1, ..., \lambda$$

where $\mathbf{m}^{(g)}$ is the mean value of the search distribution at generation g, $\sigma^{(g)}$ is the standard deviation, $\mathcal{N}\left(0, \mathbf{C}^{(g)}\right)$ is a multivariate normal distribution with zero mean and covariance matrix $\mathbf{C}^{(g)}$.

3.5. Selection and Recombination

In step 5, the best $\mu = \left\lfloor \dfrac{\lambda}{2} \right\rfloor$ solutions are selected for recombination to obtain the new mean value of the search distribution. The CMA-ES performs a comma-selection, meaning that no elitism is performed, which enhances the escape from local minima of the problem [23].

3.6. Update C and σ

In the last step, the covariance matrix and the standard deviation are updated according to the newly sampled solutions. For a more detailed explanation the reader is referred to [22] [23].

4. Collection system routing

Dijkstra's algorithm was used to find the shortest path between wind turbines. The wind farm seabed was discretize in a 3D grid (see Figure 7). The grid step was set to 5 m since it is the average monopile size of an offshore wind turbine [3]. In order to account for unfeasible areas (as shown in Figure 8) a large penalization was attributed. In this way, Dijkstra's algorithm prefers to avoid such cells and only crosses them if there are no other possible paths. The following constraints were implemented in the collection system cable routing (displayed in Figure 8):

- A maximum water depth of 30 m is applied to the cable routing to prevent the need of different machines to perform the installation of the collection system;
- A minimum water depth of 10 m is applied to the cable routing in order to minimize the possibility of accidents made by human activity, e.g. cable damage through a boat anchor.
- The areas of the seabed composed by rocks were avoided to prevent the need for special cable laying machinery;
- Large seabed gradients were avoided in order to facilitate the cable installation procedure.

The turbines that are interconnected with the same cable were pre-established. Moreover, also the number of turbines per cable is set beforehand.
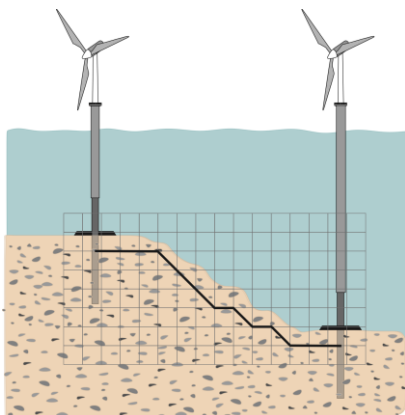

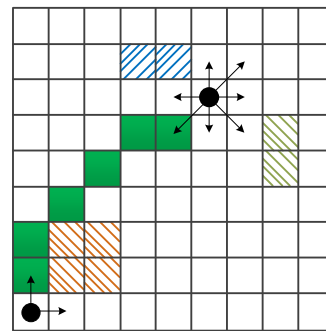*Figure 7 - Seabed discretization for the cable routing problem*

Figure 8 - Graph used by the Dijkstra's algorithm. Unfeasible areas shown in stripped colors (blue: deep areas, yellow represent undesired seabed soils and brown are areas with large seabed gradients) and a possible path between two turbines is shown in green.

5. Case study

The wind farm area has a square shape, with 5 km per side. The seabed profile is shown in Figure 9, while the restricted areas are shown in Figure 10.
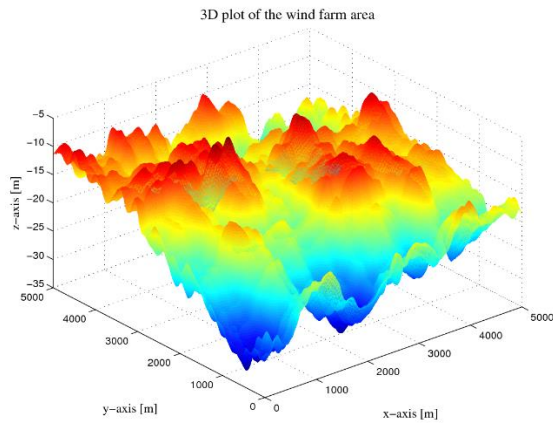

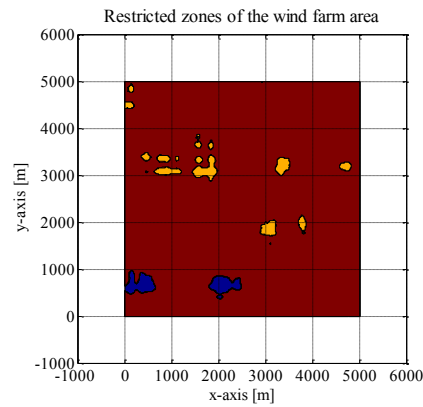*Figure 9 - 3D plot of the wind farm seabed*

Figure 10 - Restricted areas of the wind farm area. In blue it is shown the areas that are too deep while yellow represents places made of rocks

To evaluate the wake losses due to turbine shadowing it is necessary to have information about the wind profile of the wind farm area. Figure 11 shows the wind rose with the average wind speeds and respective frequencies.

The wind farm is composed of 36 identical turbines with a total installed capacity of 221.4 MW. The turbines have a hub height of 100 m and a 126 m rotor diameter. Figure 12 and Figure 13 show the turbines power and thrust curves, respectively. Initially the wind turbines are placed in a grid with 1 km distance between them.

In this work a 33 kV cable with 400 mm^2 cross section and a rated power of 37 MVA was used for the collection system [9]. This results in six collection system cables each one interconnecting six wind turbines leading to a total of 36.9 MVA per cable.
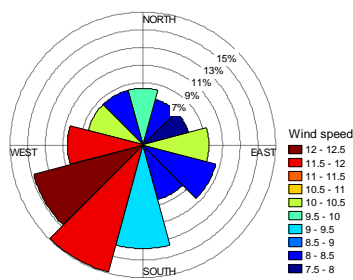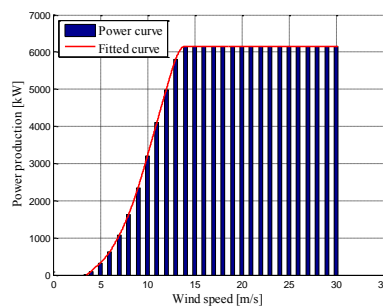

Figure 11 - Wind rose
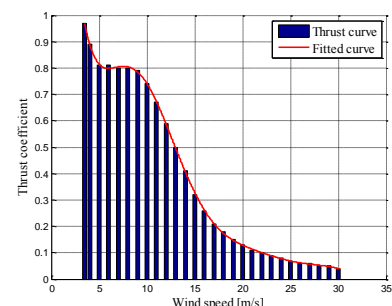

Figure 12 - Wind turbine power curve

Figure 13 - Wind turbine thrust curve

6. Results

The results for the wind farm efficiency and collection system total length for 4 different cases are presented in Table I.

In the first case, the wind turbines are kept in their initial standard grid. The wind farm efficiency in this case is 80.77%. If the seabed of the wind farm is considered to be completely feasible, a collection system with a total length of 30 km is obtained. Figure 14 shows that with such assumptions the Dijkstra algorithm gave straight lines between the wind turbines as the shortest possible routes (black lines).

In the second case, the same standard layout was used. However, only the wind farm area given as feasible in Figure 10 is used for the cable routing. Figure 14 shows the shortest collection system cable (dark green lines) for this case. Five cables were altered from their initial routings, since unfeasible areas were situated in the initial cable routing. With this cable rerouting a 4.6% increase is obtained for the total cable length (see Table I).

In Figure 15 it is shown the optimized wind farm layout given by the CMA-ES algorithm. Once again, the cables plotted in black do not take into consideration the unfeasible areas of the wind farm, while in green the cable routing avoids the unfeasible zones. It can be seen that 4 cables were altered from their original route. By altering these cable routes a 5.5% increase is obtained when compared to the base case. The optimized wind farm layout and the feasible cable routing are shown in 3D in Figure 16. It can be easily observed that the cable routing avoids the deep areas of the seabed.

Table I - Wind farm efficiency and total collection system length for standard and optimized wind farm layouts

Wind farm layout	Standard		Optimized	
Cable routing	Unconstrained	Constrained	Unconstrained	Constrained
Wind farm efficiency	80.77%		+13.46%	
Collection system length	30 km	+4.6%	+3.4%	+5.5%

7. Discussion

Improved collection system designs combined with optimized wind farm layouts were obtained with the optimization tool introduced in this work. The designs present lower investments costs, due to the avoidance of non-desired areas of the seabed. For example, deep areas were neglected, leading to costs savings of the turbine support structures. Undesired seabed soil types, e.g. rocky areas, of the wind farm were dodged, leading to faster cable laydown times. Moreover, special machinery required to install cables through rocks were avoided.

Lower installation and maintenance costs and higher wind farm efficiencies are obtained through the design tool here presented. Furthermore, the designs are obtained through optimizations algorithms, alleviating in this way, the standard manual labour required nowadays.
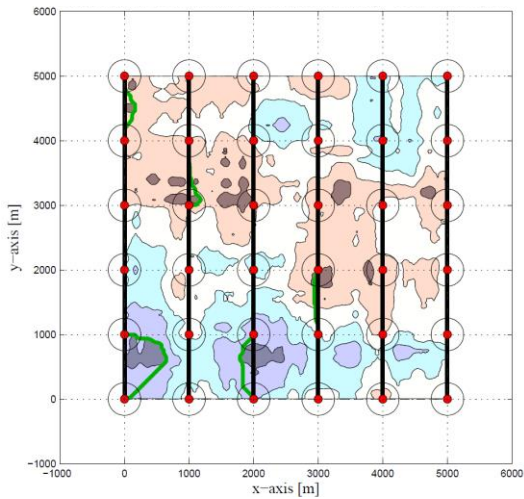
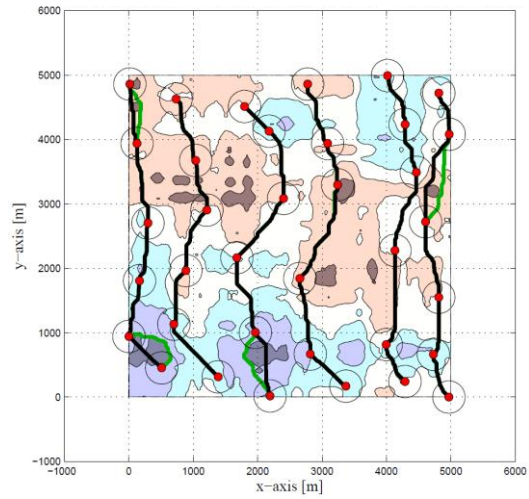*Figure 14 - Constrained and unconstrained cable routing for the standard layout*

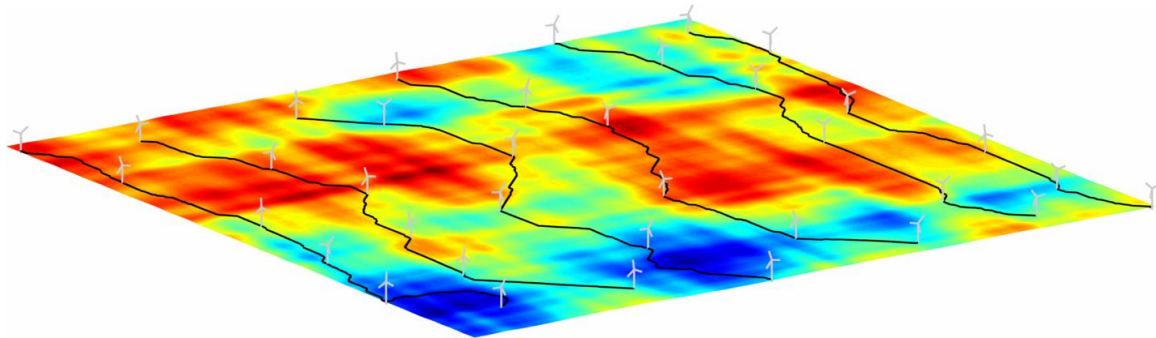*Figure 15 - Constrained and unconstrained cable routing for the optimized layout*

Figure 16 - 3D plot with the optimized wind farm layout and constrained collection system routing

8. Conclusions

Future offshore wind farms will be built with a higher number of turbines packed in a constricted area. Thus, wake losses and collection system will play an important role in the overall offshore wind farm efficiency. The optimization method proposed in this work, provides wind farm developers with optimized wind farm layouts and respective improved collection system cable layouts which take into consideration specific features from the site, e.g. wind rose and seabed profile.

This tool may be used by offshore wind farm design teams. Due to increased offshore activity in recent years, as well as the expected installation in the coming years, this wind farm design tool becomes very important and relevant for the offshore wind field.

Acknowledgement

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