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Offshore wind farm optimization

Investigation of unconventional & random layouts

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THESIS

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Investigation of unconventional and random layouts

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Abstract

This project aims at investigating whether or not unconventional and/or random offshore wind farm layouts lead to better performance of the farm. The determination of each solution is based on the estimated value of the Levelized Production Cost, thus the cost per produced unit of energy (i.e., $€_{cents}$/kWh). For the purposes of the current research a previously developed Matlab code is used. Due to some restrictions that had been adopted by the original composer of the code, the tool was updated and extended so that it is able to evaluate more random-shaped offshore wind farms. The optimization of an offshore wind farm layout is a multidisciplinary problem, which includes several design variables. In addition various restrictions should be considered if the purpose of setting the problem on a more realistic basis is desired. In this study due to the limited time as well as narrow computational resources, only some of these parameters are considered. Among others they include, the wake effect, electrical losses and a site specific wind rose. A reference offshore wind farm is set, and in detail is investigated, by a deterministic and stochastic approach, the effect of a) different separation distance for each row and column of the wind farm, b) displacement of individual wind turbine(s), c) discard of specific wind turbine(s).

These alterations try to achieve the increase of the energy production, either by maximizing the energy output of the wind turbines, due to the decrease of the losses caused by the wake effect, or by minimizing the electrical losses. Moreover, a better layout design could be realized by reducing the costs which refer to the overall project. In addition to the aforementioned listed alterations the case of the Horns Rev offshore wind farm is studied. This case is investigated by the deterministic and stochastic approaches, as the previous cases and the results are compared to the ones included in already published bibliography.

Overall, it was shown that the layout design according to the characteristics adopted in this research could lead to a more efficient offshore wind farm. In the majority of the cases it is seen that the decrease of the LPC is mainly a result of the cable cost and losses. When the small test wind farm is considered, it is noticed that the structured approach of unconventional layouts resulted in better values for the LPC in comparison with the more random approach.

Keywords: layout optimization, offshore wind farm design, levelized production cost optimization, unconventional layout design, random layout design

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To all my friends in the Netherlands, thanks for giving me some of the best years of my life. Surely, we went through some live-changing experiences and we acquired some pleasant memories.

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Christos Vezyris

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CHAPTER 1

Introduction

This Chapter acts as an introduction to the research presented in this MSc. Thesis and it tries to outline where motivation to investigate the topic of optimized offshore wind farm layout derives from. Therefore, an overview of the current situation regarding the development of wind energy, especially offshore wind energy, will be given. Moreover, the wind farm layout optimization problem is discussed. Finally, the main research questions that acted as cornerstones of the study are presented.

1.1 General aspects and motivation

Over the past years there has been a significant development of the energy produced from renewable energy sources.Wind energy can be identified as the most significant renewable energy source, as it is this particular sector (i.e., wind energy) that leads the transition to a more sustainable and green future [1]. Indeed, as it can be seen Figure 1.1 the installed wind capacity in Europe was first among all the renewable energy sources. At the moment wind energy has one of the largest installed capacities reaching approximately 200GW, with the future prospects looking promising [2].

In the wind energy sector a trend towards offshore wind application can be witnessed. Figure 1.2 illustrates this trend for the case of European Union. More and more offshore wind farms are constructed [1], [3] in order to benefit from the advantages that sites located in the sea have. Indeed, going offshore can tackle some major disadvantages of the onshore wind energy development, both in terms of technological and social aspect.

In offshore sites can easily being found large continuous areas that wind farms can be placed. This aspect becomes even more significant because wind farms with capacity close to the one of traditional power generation plants need to be constructed. The increased power capacity of an offshore wind farm is clearly supported also from the higher wind speeds blowing. Another important fact is that because the roughness length is lower, less turbulence exists offshore, leading to better wind energy capturing and reduced fatigue damage of the wind turbines. Technologically speaking, there is no need of high towers for the wind turbines since there is lower wind-shear.

Another important constraint of wind energy is the social effect of a wind turbine and a wind farm in general. Offshore wind farms have less impact on people's living conditions in terms of near to zero utilization of land that given the current densely populated areas is a crucial problem. Furthermore, the aesthetic aspect is reduced when positioning wind farms offshore, since they are less or even not seen by anyone. This aspect will be further discussed in section 2.1.3.

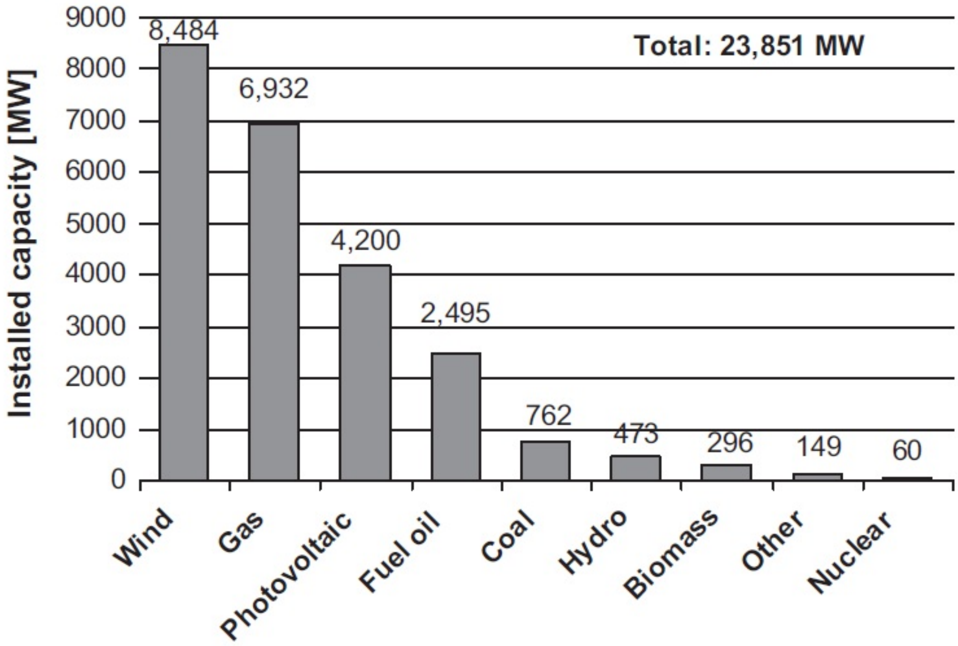


Figure 1.1: *Installed power capacity for all the renewable energy sources in the European Union for the year 2008. The wind energy leads exceeding all other renewable energy sources (e.g., solar energy), while it is found prevailing also some of the more "traditional" energy sources (e.g., gas, coal) [1]*

On the other hand there are also some considerable disadvantages related to the development of wind energy offshore. Most of them result in an increase in the cost of the investment which in turn cause the cost of energy (i.e., the cost per kWh of produced energy) to raise. Such drawbacks would be the more expensive marine foundations and integration into the electrical network. Moreover, due to the worse weather conditions offshore the cost of the installation procedure increases while the operation and maintenance becomes a complicated task. This can lead to reduced turbine availability and hence reduced power output).

In order to minimize the overall effect of the aforementioned disadvantages and thus keep the offshore wind energy industry growing, new techniques and designs should be introduced. Therefore, researches in that direction are performed all over the world in the field of energy management/distribution, material properties and conceptual design, just to mention few. In this category belongs also the investigation of the optimized offshore wind farm layout. By optimizing the arrangement of the wind turbines, the energy production of the wind farm is possible to be increased and thus the overall cost of energy reduces.

1.2 Wind farm layout optimization purpose

As has previously been mentioned, the offshore wind farm layout is a key factor of the viability of a wind energy project. It is related both directly and indirectly to the final cost of energy delivered by the farm. One example of how the layout of an offshore wind farm is directly related to the cost could be that it determines the length of internal electrical cables. From the literature [4], [5] it can be seen that this cost represents 5-10% of the investment cost, thus being a considerable portion of the final cost.

On the other hand, the indirect correlation of the layout with the cost of energy stands for the increased energy losses in the electrical collecting network and also in losses related to the wake effects, just to mention a few examples. The latter are inversely proportional to the separation distance of the wind turbines while the former are proportional to the separation distance.

As can be seen, it is important to have an optimized offshore wind farm layout. In order to do so several other

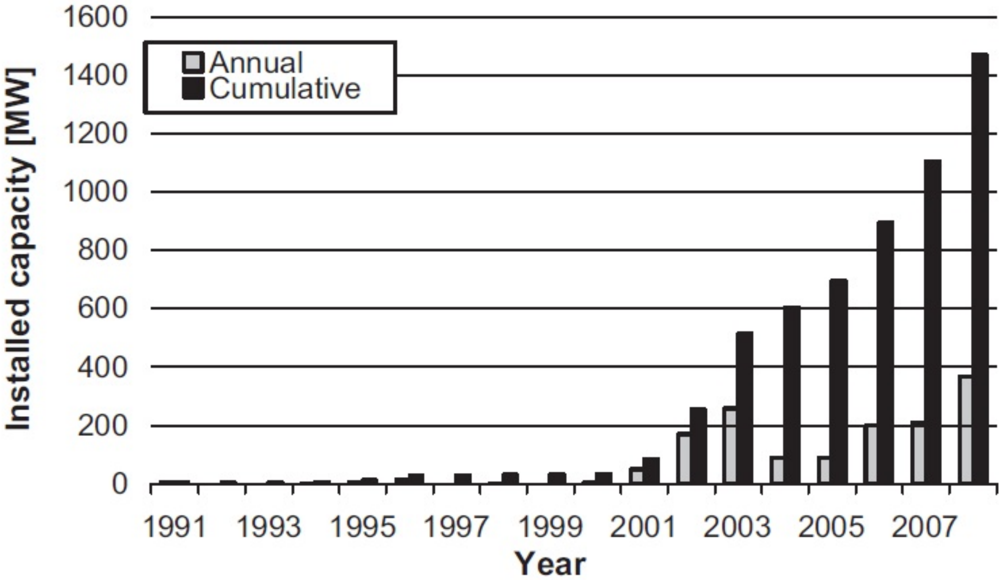


Figure 1.2: *Development of offshore wind energy in European Union up to the year 2007. A rapid increase of the offshore wind energy sector can be observed in this graph. In should be stated that in 2008 have been added more than* $360MW$ *of installed power capacity [1]*

aspects should be reviewed and considered.

G. Moseti et. al. [6] defines the prerequisites that should be determined before estimating the optimized solution for the wind farm layout. Therefore, in order to solve the optimization problem the following issues should be resolved first:

1. To have adequate models so that the behavior of the wind farm can be monitored

2. To have a model which will determine the suitability of each solution

3. To have other parameters, like the wind distribution, the wind turbine properties etc., established

4. To have an optima approached by exploring a small number of possible solutions

Even if the work presented in [6] refers to optimizing an onshore wind farm layout by means of a genetic algorithm, the same principles can be adopted also for the case that an offshore wind farm is subjected to optimization through a different algorithm.

1.3 Research questions

In this section of the MSc. Thesis the research questions that were posed and used as the conceptual framework of the study, will be discussed. The role of the research question as one of the first methodological steps of the investigation is significant, thus this question should be defined accurately and clearly. In order to answer the main research question, several subquestions should be defined priorly. Therefore, first the main research question will be given followed by the essential lower level questions that will lead in answering the main one.

Can a more "random" and unconventional offshore wind farm layout lead to better design ?

This is the main question that the current research will try to answer. Is it possible that braking the grid of the layout, which is the standard practice up until now, will lead to a more efficient design? The construction companies used to consider a rectangular grid as an offshore wind farm layout, since the area percentage of occupation is maximized[1]. Thus, more wind turbines can be placed in a certain area leading to higher installed rated power capacity of the project. However, this may not be the optimum design, hence not providing the highest possible power output.

In order to provide a clear and adequate answer to the main research question other subjects should be addressed first. Therefore, as it is suggested in [6] and is presented in the previous section the following subquestions are formulated.

1. What kind of parameters, which affect the wind farm system, exist?
2. Which is the optimization philosophy that will be used?
3. What are the constrains that should be considered ?
4. What are the models that describe the overall behavior of the wind farm as a system?
5. On what basis the determination of the best solution will be on?
6. What are the alterations that can be done to the grid of the offshore wind farm layout and can lead to more unconventional layouts?

Answering the aforementioned questions can provide for us a more solid ground for drawing conclusions relevant to the main research question. Therefore, in the following chapters of this study by means of literature study, references to previous researches and innovative work, those items will be determined.

In more detail, the answers to the first five questions are given by presenting facts and information found in the literature. Wherever necessary a discussion on this information takes place in order to clarify the relevant subjects. It should be stated that the aforementioned questions are mainly addressed in correspondence with the optimization tool. Hence, the analysis that is given is not very extensive and overall, but rather case specific. The main focus of the present study is on addressing the sixth subquestion. This research question is answered by means of innovative work, performed specifically to provide the appropriate material to treat this subject.

1.4 Overview and structure of the report

Chapter 2 includes a literature study regarding the subjects of the available optimization algorithms and the technical issues which are arisen during the design phases of an offshore wind farm. Indeed, some more general restrictions related to the offshore wind farm design, the wind turbine properties, etc. are presented, while the topic of the optimization methods which have already utilized to solve wind turbines' positioning problem in a wind farm is discussed. Thus, the subquestions number one and two are treated.

The third chapter presents a brief description of the optimization tool which was used to conduct the current research. Chapter 3 provides also an overview of other aspects that have been modeled and describe the behavior of the wind farm, such as the internal electrical collection infrastructure, the wakes developing downwind of the turbines, etc.. This information is essential for addressing subquestions number three to five, regarding the way they are implemented in the tool.

In chapters 4 and 5 the results obtained are presented. These results are used to find an adequate answer to the sixth subquestion. Therefore, chapter 4 includes the corresponding tables and figures to the "mono-variations", whereas the results of "dual-" and "multi-variations" are given in chapter 5.

Chapter 6 includes the conclusions that can be drawn, some recommendations and lessons learned for future work.

[1] This is the case under some restrictions. Such a restriction could be that the minimum separation distance between successive wind turbines cannot be less than 5 times the rotor diameter

CHAPTER 2

Background knowledge

In this chapter some of the fundamentals related to the offshore wind farm design will be explained, along with the available optimization algorithms. Thus, by providing the adequate information the first two subquestions will be addressed. In more detail, some general considerations that are applied in determining the position of the wind turbines will be discussed. The technical issues that can be used as variables in defining the offshore wind farm layout are shown, while the social and environmental issues are briefly introduced. In the last section of the chapter can be found a short discussion about available wind farm layout optimization methods.

2.1 General concerns related to wind turbines' positioning

There are various subjects that should be analyzed prior to developing an offshore wind farm somewhere. All these issues should be considered by the several work groups that focus on different aspects of the wind farm design. In the final designs of many projects, even though a better solution might exist it is not economically or even technologically possible to be implemented in practice. Especially regarding the design of the offshore wind farm layout, it is likely that the calculated optimum separation distance, could not be realized due to constrains imposed by the soil or the increased depth from point to point, just to give two examples.

Even though there are numerous issues similar to the ones aforementioned, researchers [7], [8] consider three different major groups of constrains. Therefore, during the design phase the constrains related to technical, social and environmental issues should be addressed.

Throughout this section an overview of these issues is given. The social and environmental matters are only briefly discussed, since they are more tightly bonded to site selection. However, they do play a role also in determining the final arrangement of the wind turbines. The technological issues are presented in an more elaborated manner, since they are the ones that influence the wind farm layout the most. Moreover, the technological matters can more easily and properly be quantified, which is not the case for the more qualitative social and environmental issues.

2.1.1 Technical issues

There are many things that can be considered as technical issues, thus determining the offshore wind farm design. However, in this section only few of them will be discussed. Hence, a short presentation of two major technical issues follows.

First the technical matters connected with the site characteristics, such as the available area, sea bed soil composition, sea depth, wave height, etc., are discussed. The effect of most of these issues are twofold and are reflected primarily on the wind turbine foundation and in a second level on the wind farm layout. Secondly, a brief presentation of the wind turbine interaction to each other is given. These interactions are refereed as “array losses” and are caused by the energy loss of the downstream wake.

Offshore site imposed issues

Each specific site imposes certain design variables regarding the offshore wind farm layout. Two groups of such design matters are the total area that is available for deploying the wind farm and the climate characteristics that exist in the site under investigation.

Offshore wind farms even though that in general have fewer restrictions related to the total occupied area, in comparison to the onshore wind farms, they still are submitted to some. The area that an offshore wind farm can occupy is not unlimited. Therefore, the design of the layout should include this parameter. The limiting factors to the total offshore wind farm area are, but not limited to:

- Boat routes. Even though small boats, in some cases, are allowed to pass through the wind farm, larger vessels usually cannot, thus the wind farms cannot be constructed in sites that cause vessel traffic disturbance.
- Military restrictions. Because of the cumulative nature of the electromagnetic interference effects that wind turbines can cause on the radar systems, the total area of the wind farm is restricted.
- Underwater cables and pipelines. Normally, the construction of offshore wind farms is permitted in sites that electric/network cables and/or pipelines extend across, if a shift of certain wind turbines’ position occurs. However, if the density of underwater transporting structures is high, the wind farm cannot be deployed at that location.

The first group of factors determines the layout of an offshore wind farm mainly in terms of area allowed to be occupied. The second group of offshore site imposed issues is related to the meteorological conditions of the location and causes micro-positioning changes in the arrangement of the wind turbines.

It is straightforward that each specific site has certain climate characteristics (e.g., annual wind speed, wave height, etc.) that should be interpreted correctly and reflect on the design of the offshore wind farm. Such site specific characteristics could be, but are not limited to, wind characteristics (e.g., mean wind speed, annual distribution of wind direction, etc.), depth of the water, wave conditions, seabed characteristics. Moreover, the proximity to electrical network and the availability of a harbor near by could also perceived as site imposed issues however they will not be analyzed further [9].

Apart from the wind characteristics that will be treated (i.e., how they can be considered as design variables for the layout of the wind farm) in following sections of the present study, the two most important layout-determinant factors are the depth of the water and the seabed characteristics. They both affect the design of the offshore wind farm in a more indirect way. The water depth determines the type of foundation that should be used [10], thus in many cases a compensation should be achieved between the optimum layout design and constrains applied by water depth. This happens since the cost of constructing a specially designed foundation for a certain depth could outbalance the increased power output advantage of placing the wind turbine in that exact spot. Furthermore, similarly to the water depth, constrains could be applied by the seabed compositions as well.

The proper foundation for a wind turbine placed in a specific spot should be engineered regarding also the different layers (e.g., sand, clay, etc.) consisting the seabed, thus their properties. The lateral and axial capacity of the soil is very important parameters, which determine the characteristics of the foundation (e.g., such as the length of the monopile, the base diameter of the gravity base foundation, etc.) [11]. Therefore, it is possible that the positioning of a wind turbine at a spot, with certain soil characteristics, is not merited (i.e., mainly due to economic reasons), thus the optimum wind farm arrangement should be reworked.

Until now the majority of the offshore wind farms have been built in relatively shallow waters (i.e., water depth well under 40m [1], [3], [5]), with few exceptions (e.g., such as Beatrice wind farm), which were built mainly for demonstrative or scientific (e.g., testing of different type foundations) reasons. This was the case both because it was not technologically feasible but mainly because otherwise the complete project would not be economically viable [9], [10].

Array losses

In this paragraph of the MSc. Thesis the array losses will be shortly introduced. Here only the definition of the concept is given, due to the more extensively discussion of this kind of losses throughout the present study. In general it can be said that these losses appear when more than one wind turbines put in close range from each other, thus forming a wind farm. Then it is possible that, for certain wind direction, some of the downwind turbines could be in the wake of the ones being upwind. The wake produced by the upwind turbines has a higher turbulence and a lower wind speed, hence less energy can be captured by the downwind turbines. This is the reason why an efficiency of 100% is impossible to be the case for a wind farm. It is always the case that the power output of individual wind turbines in given weather conditions will be higher than the accumulated power output of an equal rated power wind farm. The array losses are mainly function of [7], [8]:

- Wind turbine spacing
- Wind turbine operating characteristics
- The number of turbines and size of the wind farm
- Turbulence intensity

Let us start with discussing the effect of turbulence on the array losses. As has been mentioned above the wind speed is lower in the wake, however it regains its ambient velocity by momentum and energy exchange [7]. This process is accelerated when there is higher turbulence. At an offshore site turbulence levels of approximately 5% (i.e., which is low, hence larger separation distance is needed) could be expected, while it should be stated that turbulence intensity increases as the wind goes through the wind farm, interacting with the turbine rotor.

As has been discussed previously array losses are the ones affected the most by the offshore wind layout, while they are also the ones that the optimization procedure aims to reduce. Therefore, by assigning values to the aforementioned wind-turbine-related variables (e.g., turbines with different sizes, the overall shape and size of the wind farm turbine, separation distance between the turbines [7]) through an optimization process, an optimized geometry for the wind farm can be found.

To reach such an optimized offshore wind farm layout through estimating the wake effects is part of the current study objectives. In following chapters it is researched the possibility of reducing the array losses (i.e., hence increasing the energy production), which in turn results in lower cost of energy value. These topics are discussed in a much greater extent in section 3.2 of the present study.

2.1.2 Social issues

The construction of an offshore wind farm at a given site may initiate public debate and make unexpected problems come to the surface. Usually the size of a project, mainly in terms of area occupied by the farm, affects and is affected in a direct way by social issues. Therefore, social matters and/or constrains are connected with the offshore wind farm layout design mainly in terms of total area usage rather than specific wind turbines arrangement. For the interested reader a more detailed discussion on the subject of social issues can be found in the Appendix.

2.1.3 Environmental issues

Prior to the construction of an offshore wind farm some environmental issues should be investigated. Especially nowadays that there is an elevated sensitivity of the public opinion towards matters related to the environment, such issues should be treated with the proper caution. It should be stated that as in the case of social matters, also in the case of environmental topics, the effects/impacts are augmented proportionally to the area occupied by the offshore wind farm. Thus, the layout of the farm is important in terms of the total area needed for the offshore wind farm development rather than specific wind turbine positioning. In the Appendix a more elaborated presentation is given.

2.2 Optimization methods

In this section the results of the bibliographic study are presented, regarding the optimization algorithms that have been used so far to solve the problem of wind turbines positioning in a wind farm. First, a general overview of the algorithmic philosophies is given followed by a more detailed discussion of the ones that are more frequently met in the literature.

2.2.1 General overview of the Optimization Algorithms

It is typical when a minimum of an objective function (e.g., minimum of Levelized Production Cost) needs to be found, gradient optimization methods[1] to be utilized. However, an intrinsic weakness of such an algorithm is that it's able to find local minima , but not necessarily the overall minimum. To overcome this issue each possible local minimum should be computed to find the overall minimum but then the optimization problem becomes computationally intensive. In order to address the aforementioned problem scientists and researchers proposed a different optimization philosophy, which is by utilization of algorithms than introduce an element of randomness. Example of such optimization philosophy is the genetic and/or the heuristic algorithm. Indeed, the incorporation of randomness in the algorithm achieves to dislodge the solution from the local minima.

Figure 2.1: *Speed vs. quality spectrum for the gradient search algorithm (GSA), greedy heuristic (GHA), genetic (GA), simulated annealing (SAA), and pattern search (PSA) are shown [12]*

Generally, five different types of optimization algorithms have been found as being the most commonly used for the wind farm layout optimization problem [12]: the gradient search algorithm (GSA), greedy heuristic (GHA), genetic (GA), simulated annealing (SAA), and pattern search (PSA). Through the literature study that was conducted as part of the MSc. Thesis a general trend of researches towards the genetic algorithm was revealed. Currently these algorithms attract the attention of scientists and are undergone ongoing development. A more elaborated description of each different type of algorithm is given in the following sections. In Figure 2.1 a spectrum can be seen which illustrates the trade-off of each algorithm between the time the algorithm takes to reach a solution and how precise this solution is.

[1] Referred also as "hill-climbing" algorithms

2.2.2 Genetic Algorithms

The main concept behind the genetic algorithms is Darwin's law of natural selection combined with the mechanic of survival of the fittest. That said, these algorithms emulate the natural process of reproduction, where the genetic information of two individuals is stored in a chromosomal string and is used to create the genetic code of an offspring [6], [13]. Moreover, similarly to the physical world evolution and adaption are ensured through the highest probability that the fittest individuals have to survive and reproduce [6]. Furthermore, like in the natural process crossover and mutation can occur randomly in the new individuals [6], [13]. In [6] the authors do the following correspondence of terms from biology to optimization algorithm module:

1. *Gene* = design parameter. It is the binary (i.e., one or zero) option that the algorithm has to position a wind turbine in a cell.

2. *Individual* = design configuration. Any solution of the wind farm layout. It expresses all the possible combinations of the cells, thus strings of ones and zeros.

3. *Generation* = evolution stage of the design. Is the pool with all the individuals that have been created in each iteration and from which the best candidates for crossover are selected.

4. *Fitness function* = design quality. Usually either the maximization of the AEP or the minimization of the LPC are used as objective functions.

5. *Social success* = optimality of the design. Is the correspondence that the final solution, proposed from the algorithm, has with the criteria set by the user.

Unlike the traditional gradient based optimization algorithms that start from a single point of the design space, the genetic algorithms processes simultaneously multiple points of the user-defined configuration space [6]. Moreover, genetic algorithms differentiate from traditional optimization methods by the fact that they work with a coding of the parameter set, not the parameters themselves, use objective function information, not derivatives or other auxiliary knowledge and they use probabilistic transition rules, not deterministic rules [13], [14].

In general, a genetic algorithm divides a given area into smaller cells, usually square ones [6], [13], [15], [16], [14], while in some papers [17], [18] cells of different shape are investigated. However, it is straightforward that if an area is divided in a grid of $10X10$ possible wind turbine locations, and there are only two possibilities considered for each grid point , 0 for not having a wind turbine and 1 for having one, an enormous problem of 2^{100} possibilities problem is created. This is the main reason why genetic algorithms are rather slow, requiring a lot of computational time.

After having divided the wind farm terrain in cells, genetic algorithms start with the given population and the fitness of each individual of the population is calculated through the fitness function. Since the fitness values for all the individuals are estimated the next generation of offspring must be constructed. The new population of individuals is obtained through crossover[2] and mutation[3] among the fittest solutions and at random locations. Depending on the composer of the algorithm different probability values are assigned in each operation. Even though the absolute values of these factors are not very important, it is worth underlining that the probability of crossover is usually almost one order of magnitude higher than the mutation probability (e.g., in [6] the author considers $0.6 < P_{cross-over} < 0.9$ and $0.01 < P_{mutation} < 0.1$). The operation of cross-over is responsible for the evolution of the population and the convergence to the optimum. On the other hand, the operation of mutation occurs rarely and exists in order to introduce an element of randomness in the algorithm, by bringing in new characters into the population [6]. It is easily seen that if only the operation of cross-over would happen the population would soon have got "sterilized" and the algorithm could probably converge to a local optima. On the contrary, if only mutation would occur the algorithm would have become more of a random search rather than an optimization algorithm [6].

[2]Parent pairs exchange parts of their string [13]

[3]The random switching of a bit in the individual string to the opposite value [13]

Since 1994 that the concept of wind farm layout optimization by means of a genetic algorithm was initially introduced [6], many other papers have been issued presenting modifications that could solve the intrinsic bottlenecks of simple genetic algorithms (e.g., that genetic algorithms are computationally intense). To address the latter researchers have proposed the Distributed Genetic Algorithms (i.e., DGA) [16], [14]. Thus, these specially modified genetic algorithms have improved overall performance both in terms of time and final solution quality, by dividing the large initial population in smaller groups of subpopulations that occasionally exchange some individuals [14], while in each subpopulation the same principles as in traditional genetic algorithms are applied. Moreover, in [16] it is stated that a hybrid algorithm has been used, which combines the advantages of genetic algorithms for global search with the advantages of hill-climbing algorithms for local optimization.

2.2.3 Heuristic Algorithms

In order to address the problem of the optimum wind farm layout, it has been proposed in [19] a Greedy Heuristic Algorithm. In general, the heuristic algorithm philosophy is synopsized by the fact that three operations are possible and the combination that improves the objective function the most is chosen [19]. These three operations are [19],[20]:

1. *Remove*: Each element (i.e, being for the current problem a wind turbine) is removed consecutively and the algorithm estimates the change in the declared objective function (e.g, the LPC, the AEP etc.).

2. *Move*: Each wind turbine is moved at a different location away from its original position, while the change in the LPC function is monitored.

3. *Add*: If the number of wind turbines, n, in the wind farm is less than a user-defined number, N, then the algorithm assigns $N-n$ wind turbines at random positions of the wind farm, considering some restrictions (e.g., the minimum distance between two wind turbines), and calculates the objective function.

The algorithm starts by applying the aforementioned operations on the offshore wind farm layout. If no improvement in the objective function is seen then in the next iteration only the “add” operation is investigated. The algorithm stops if after a user-defined number of consecutive iterations no improvement is found, thus the algorithm converges [19], [21]. Since the algorithm is “greedy” in nature (i.e., only the best of the potential solutions is chosen), the final solution that is reached after some iterations is highly dependent of the initial solution [19]. Indeed, it is noticed in [19], [21] that the method can easily lead to local optima rather than global ones, thus an element of randomness was added. Therefore, if the algorithm is fully run an adjustment of some of the turbine locations is performed. The solution is considered as final, thus optimal, only after a specified number of unsuccessful (i.e., which result in worse values of the objective function) rearrangements [19], [21].

As has previously been noted the initial state affects extensively the final solution calculated by the algorithm. Therefore, the initial solution should be selected carefully. In [19] three initialization methods are proposed to prevent local minima being found. The first could be a layout with a number of randomly positioned wind turbines. The second is a grid-like layout. Finally, a “constructive heuristic” technique could be utilized. Thus, the algorithm starts with zero wind turbines and adjusts the number and position of them by the three “heuristic” operations [19].

2.2.4 Simulated Annealing Algorithm

As it is aforementioned the main problem of the optimization algorithms is the entrapment that may occur in a local rather than in a global optimum. Initially, the idea of the simulated annealing (SA) algorithm was arisen as a simulation of the cooling that any material was undergone in a heat bath and later this method was proposed as optimization problem solver [20]. SA is characterized in [22] as a metaheuristic (i.e. since it utilizes the operations of *remove, move, add*) for global optimization. Moreover, the algorithm is considered as being a generalization of the Monte Carlo method[4] [22].

[4]Generally, these computational algorithms rely on repeated random sampling to compute their results. In [23] a research is published on optimization of wind farm layout based on Monte Carlo simulation

In the offshore wind farm layout optimization problem, if the cost function is taken as the objective function, the SA moves from a solution to a neighboring one and the objective function is calculated for this new solution. If the objective function has decreased the new solution is readily accepted, on the contrary, the new solution is not discarded but it is still possible to be accepted. The probability that the least fitted solution (i.e., the solution that results in a higher value of the objective function) is taken is given by $P(\delta E) = e^{-|\delta E|}/T$. As δE the difference between the current solution and the new solution is considered and T is the control parameter[5], that is gradually "cooled" (i.e., decreased, thus decreasing the possibility that a worse solution is accepted) to make the system converge [20].

The process starts by defining the space of feasible solutions, which is for the wind farm positioning problem, all the possible combinations of wind farm layouts, under some restrictions and boundary values (e.g., the minimum distance between the wind turbines). Afterwards, the "neighborhoods" of that solution are estimated. The neighboring solutions are the possible solutions that can be found by utilizing the three operations, *remove, move and add*, which are more extensively explained in section 2.2.3. Generally, in SA only tentative solutions exists and the initial tentative solution is created randomly. While a constant number can be taken as a starting annealing temperature [22] it is also possible that different temperatures are considered for each operation, so that a better tuning of the algorithm can be achieved [20]. The iterative process finishes when a stop criterion is reached, therefore it has to be carefully selected.

2.2.5 Particle Swarm Algorithms

Generally, the Particle Swarm Optimization (i.e., PSO) algorithm, similarly to the genetic algorithms, is a population-based, global and stochastic optimization algorithm which was inspired by social behavior of fish schooling and bird flocking [24].

Initially, randomly selected, out of a previously defined search space, positions and velocities are assigned to the starting population of particles. In the study done and presented in [24], a position matrix of the turbines for all the potential solutions in the swarm, the population size and a modification matrix of the positions are defined. In each iteration of the algorithm the velocities and the positions of the particles are updated, thus reaching an optimum layout configuration. With each repetition the search is focused toward promising regions by adjusting particles velocities vector toward both their own historical best positions and swarm's historical best position [24].

PSO has been used to reach a solution of the constrained layout optimization problem (e.g., space constrains regarding the wind farm layout) by an algorithm based on penalty functions. The latter are used so that the constrains, set by the user, can be addressed properly. Thus, the problem transforms into a unconstrained one since the algorithm prohibited (i.e., by penalization, which is based on the number of constrain violations) from reaching an optimum lying in the region of infeasible solutions.

The researchers in [24] state that the results obtained from simulations show that the PSO method performs better for the micro-sitting than the classical genetic algorithms. Moreover, particle swarm algorithms are superior to other approaches because it is easy to implement, converges quickly and is more computational inexpensive. Additionally, the PSO algorithm is better suited in optimization problems that a real number, as solution, is desired [24].

2.3 Addressing the research subquestions

This chapter of the report aims in addressing some of the research subquestions posed in section 1.3. There, it is mentioned that in order to determine whether or not "random" and unconventional offshore wind farm layouts lead to a better optimum of LPC, first the matter of the affecting parameters on the wind farm design should be resolved. As it is discussed in section 2.1, two main categories of issues exist. Firstly, the issues which are related to the specific site that the offshore wind farm is about to be built and secondly, the so called "array losses". Hence, as has been explained in this chapter a specific site may impose some restrictions on the layout design of the offshore wind farm. However, in the current study the first category of issues is only slightly treated, since only a site specific wind rose is determined. The main focus of this thesis is on the "array losses". In following sections various components (e.g., wake induced energy losses, cable losses, etc.) of this category are treated.

[5] Usually this term is referred as "temperature" in order to exist the association with the physical case

In section 1.3 can be found that in order to proceed with answering the main research question of this study, it is important first to determine what are the current optimization philosophies that are used in the relevant scientific field. Indeed, the research revealed currently many different algorithms exist for the optimization of a wind farm layout. Due to reasons that have been discussed in more detail in this chapter, researchers tend to use philosophies that incorporate the element of randomness. Because the development of such an optimization algorithm is a difficult task by itself, it is chosen for the purpose of this research to use an already implemented optimization tool and modify it by adding minor component of the aforementioned optimization algorithms. Therefore, the philosophy discussed in section 2.2.2 regarding the formation of “individuals”, meaning solutions for the layout, is considered. Moreover, the technique of removing wind turbines from the wind farm, introduced by the algorithm described in section 2.2.3, is utilized. Finally, the results obtained by the algorithm presented in section 2.2.4 are compared with results derived in this study.

CHAPTER 3

Optimization Tool

In this chapter of the report is discussed the optimization tool that was used. By doing so the subquestions number three to five, posed in section 1.3, are answered. A general short presentation of the Matlab tool that was used to obtain the initial results is given, combined with a description of some changes that were done. As is discussed later on, the outputs of the Matlab tool include the separation distance of the rows and columns, estimations regarding the annual energy production and energy loss and LPC value, among others. In conjunction with the models shown in section 3.2.1, 3.2.3 and 3.4, about the wake effect, the electrical losses and the various costs respectively, form the basis on which the innovative research, presented in following chapters, relies on.

3.1 General overview of the Matlab tool

In this section the optimization software that was used to obtain the initial optimum layout is described. The tool is implemented in Matlab as part of a MSc. Thesis and it is analyzed thoroughly in [25]. As has been mentioned previously the tool attempts to optimize the layout of an offshore wind farm, by taking into account the energy production of the wind turbines and the energy lost in cables.

The best possible layout is determined then by comparing the LPC of each layout arrangement. Therefore, the tool uses as objective function (i.e., for which tries to find the minimum point) the expression for the LPC (i.e., shown in equation (3.11)). Several inputs are possible to be specified in the tool. Just to give an example of these, the user can determine the number of the wind turbines, the general layout (e.g., whether it will be a single row or a square layout), if a constant wind speed or a variable multi-direction wind speed will be considered etc. On the other hand, the developed tool returns several outputs that apart from the optimal layout include the estimation of the LPC value, the annual energy production, the annual energy losses etc. Some limitation/restrictions are considered in order to facilitate the design of the tool, being the most important one that only square-arranged wind farms can be handled.

Because describing the whole tool is out of the scope of the current project, only the key points of the software, related directly to the investigation of the unconventional layouts, are given. In more detail these key points are:

1. Estimating the “array losses”
2. Wind speed distribution and wind rose
3. Cost models

4. Simulation modes

In the following paragraphs of this sections a brief presentation of these points takes place. Moreover, it should be stated that the models that the tool uses for the determination of the wake effects and the electrical losses, among others, have been verified in a previous study [26].

3.2 Estimating the actual array losses

Section 2.1.1 contains an introduction on the principles and individual aspects that an offshore wind farm optimization procedure should include. In section 2.1.1 the concept of array losses is introduced and a short description of it is given. However, that description is incomplete. Indeed, it explains the origin of the losses, while it provides a hint of how this kind of losses could be mitigated, if not nullified. It implies that one solution to minimize the wake-induced losses would be the increase of the wind turbine separation distance. However, in reality such a solution is inapplicable in most of the cases. The reason lies in the electrical losses which increase proportionally with the separation distance, thus reducing the actually delivered energy.

In this section of the study the interaction and the effects of the wakes on the downwind turbines are discussed. A brief presentation is given about the electrical infrastructure needed and used in the offshore wind farm. The main principles and concepts are shown, while the models used in the present study are introduced. The section starts with a paragraph regarding the wake effects and their relevance to the optimization procedure, and it continues with a paragraph dedicated to the specifics of the electrical infrastructure and how it is tied to the layout optimization.

3.2.1 Wake effects

The wake of a wind turbine is generated due to the movement of the blades and as has been mentioned before, it alters the wind flow characteristics (e.g., wind speed and turbulence intensity). An illustration of the wake can be seen in Figure 3.1. The wake propagating behind a wind turbine causes various effects in the downwind turbines, such as reduced energy harvesting potential and increased fatigue damage. In the present study we will focus solely on the reduced wind speed effect of the wakes. In order to do so also the wake diameter should be estimated, because it is necessary to determine the area of the wake effectiveness.

At the moment there are many models available for the determination of the wind speed and the diameter of the wake. Some of them are based on educated assumptions and are rather simple (e.g., Jensen's model), while others are based on complicated computational fluid dynamics codes. In this section only the description of the Jensen model is given, while some of the most widely used wake models are presented in [26].

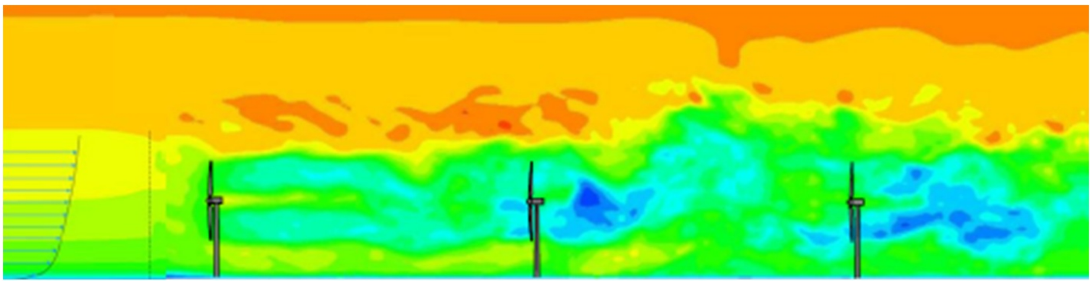


Figure 3.1: *Wake propagating behind rotating wind turbine rotors. The reduced wind speed, indicated by a color tone close to blue, behind each rotor can be observed. Moreover, the increased turbulence intensity experienced by the downwind turbines is shown [26]*

The Jensen model

The Jensen model was initially proposed by N.O. Jensen [27] in 1983. It is based on the description of a single wake, considering the initial velocity reduction and a wake decay coefficient. The main assumption, of the model is that the wind velocity is constant inside the wake and the expansion of the wake and the reduction of the wind speed are linear (i.e., it can be seen in expressions (3.1) and (3.2)). Figure 3.2 illustrates the main assumptions of the model and visualizes a single wake.

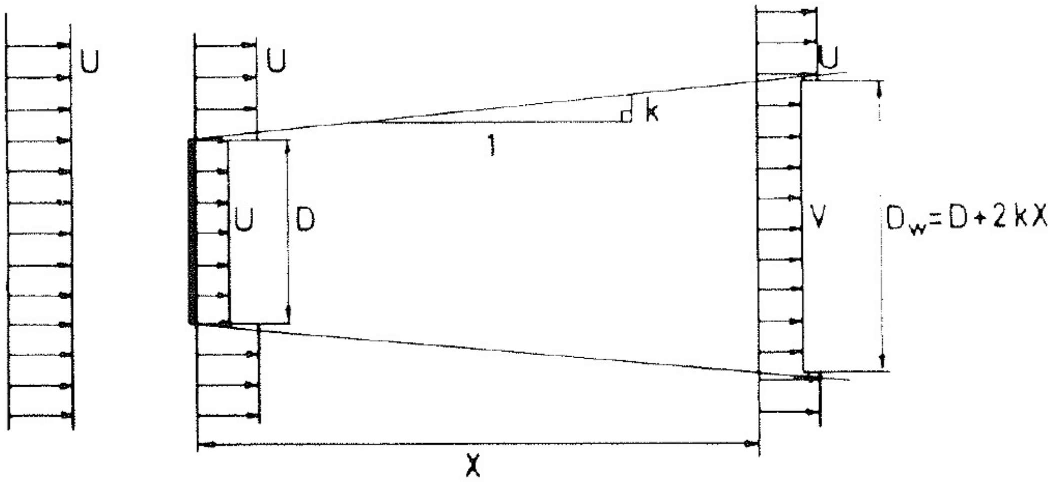


Figure 3.2: *Jensen model. The figure presents the linear expansion of a wake. Moreover, the equation used for the wake diameter after a given distance, depicted as x, is shown [28]*

It can be seen that the model assumes that the initial wake has a diameter equal to the rotor of the wind turbine and it expands linearly downstream. Furthermore, the wind speed in the wake has a lower value, compared with the ambient wind speed velocity. In equation (3.1) and (3.2) the analytical expression for the velocity deficit and the wake diameter expansion can be seen.

$$dV = U - V = U \cdot (1 - \sqrt{1 - C_t}) \cdot \left(\frac{D}{D_w}\right)^2 \tag{3.1}$$

$$D_w = D + 2 \cdot k \cdot x \tag{3.2}$$

where,

dV .... is the velocity deficit of the wake

U .... is the ambient wind speed

V .... is the wind speed of the wake

D .... is the rotor diameter

D_w .... is the rotor diameter at a given distance x

k .... is the decay factor

C_t .... is the thrust coefficient of the wind turbine for a given wind speed

x .... is the distance behind the wind turbine for which the wind speed and the diameter are calculated

The decay factor describes the dissipation of the wake by growth of its width, while the significant variables affecting it are the wind speed, ambient turbulence, turbine induced turbulence and atmospheric stability [25], [29]. Usually it is taken equal to 0.05 for offshore condition, however an analytical expression exists[1].

[1]The decay factor can be calculated as, $k = \frac{A}{ln\left(\frac{h}{z_0}\right)}$, where A is a constant number equal to 0.5, h is the hub height and z_0 is the roughness

Jensen's model, unedited or with small variations, is met frequently in many publications about offshore wind farm optimization [6], [13], [15], [16], [19], [21]. The reason that it is still used in recent researches is due to its simplicity, resulting in a more lean and fast overall optimization algorithm. In the present study Jensen's model is the one implemented for the determination of the wind speed deficit and the wake expansion diameter.

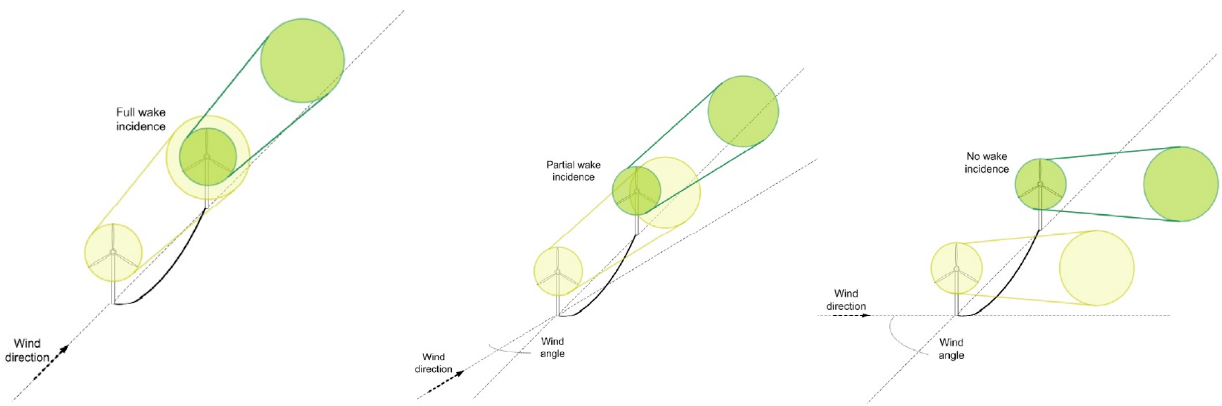
3.2.2 Multiple wakes interaction

Within a wind farm thee different types of wake interaction on the downwind turbines may arise [25]. These interactions are shown in Figure 3.3. Thus, the downwind turbine may be affected fully, partially or not at all by a wake generated by an upwind turbine. Even though that the cases of the full and no wake incidence, shown in Figure 3.3a and 3.3c, are more or less straightforward[2] and no further explanation is given, the case when the downstream wind turbine is affected only partially by the wake is discussed in more detail. Therefore, in order to take into account the partial effect that the wake has on the wind turbine a factor proportional to the rotor area with and without wake incidence is considered. Therefore, the wind speed of a downwind turbine, affected partially by a wake is given as [25]:

$$U_{T2} = (U_{T1} - dV_1) \cdot \frac{A_{T2w}}{A_{T2tot}} + U \cdot \frac{A_{T2f}}{A_{T2tot}} \tag{3.3}$$

where,

U_{T2}	is the average wind speed impacting the downstream turbine
U_{T1}	is the average wind speed impacting the upstream turbine
dV_1	is the average wake wind speed deficit produced by the upstream turbine
U	is the ambient wind speed
A_{T2w}	is the downstream turbine rotor area with incidence from the upstream turbine wake
A_{T2tot}	is the total rotor area of the downstream turbine
A_{T2f}	is the downstream turbine rotor area without incidence from the upstream turbine wake



(a) *Full wake incidence* **(b)** *Partial wake incidence* **(c)** *No wake incidence*

Figure 3.3: *Possible wake incidences [25]*

The fraction $\frac{A_{T2f}}{A_{T2tot}}$ hereafter is called *shadowing coefficient*. Equation (3.3) applies in the case that only one wind turbine is located within the wake of another wind turbine. When there are several wake incidences, which is the most

length which usually equals 0.002m for offshore conditions

[2]When the downwind turbine is in the full wake of an upstream turbine then the wake speed deficit and diameter are calculated using expressions (3.1) and (3.2) respectively. On the other hand when the downstream turbine in outside of the upwind turbine wake, it is considered that it operates at ambient wind speed

frequent case for an offshore wind farm, the mixed wake is equal to the sum of the individual energy deficits wake. Therefore, combined with expression (3.3) returns [25]:

$$U_n = U \cdot \left[1 - \sqrt{\sum_{i=1}^{n} \left(\left(1 - \frac{U_i}{U} \right) \cdot \frac{A_{w-i}}{A_T} \right)^2} \right] \tag{3.4}$$

where,

U_n	is the effective wind speed seen by the current n^{th} turbine
U_i	is the wind speed behind the i wind turbine
U	is the ambient wind speed
$A_{w\text{-}i}$	is the current turbine rotor area with incidence from the i-turbine wake
A_T	is the current turbine total rotor area

3.2.3 Electrical Infrastructure

While understanding the aerodynamic aspects of a wind farm is a very important objective, investigating the electrical infrastructure of a wind farm is of equal importance. There are two main electrical systems in an offshore wind farm, the energy transportation system and the energy collection system.

The former is the one transporting the power produced by the offshore wind farm to the shore. Usually it is comprised by high voltage (i.e., 150kV) alternating current cables which leave the offshore electrical substation[3] and connect to the inland high voltage electrical network. There are two alternatives for the transportation system, the High Voltage Alternating Current (i.e., HVAC) technology and the High Voltage Direct Current (i.e., HVDC) technology, having each advantages and disadvantages [26].

The energy collection system is the internal cable system of the offshore wind farm. This is the one that connects the wind turbines of the wind farm to each other. Moreover, it includes the connection of the entire cluster of wind turbines to the offshore substation. In most cases low to medium voltage (i.e., 33kV) cables are used in the internal grid. Many different topologies for the collection system of an offshore wind farm exist having each different advantages (e.g., increased reliability) [26]. In the current MSc. Thesis the one that is used is the “String layout”. Thus, each column, or “string”, of wind turbines in the offshore wind farm are connected by a single cable.

As it is aforementioned the electrical losses increase as the separation distance becomes larger. The analytical expression for the calculation of the cable losses is:

$$W_{tot}(V) = W_d + W_{tot,\Omega} \cdot \left(\frac{I(V)}{I_{rated}} \right)^2 \cdot \nu_\theta \tag{3.5}$$

$$W_d = n \cdot 2 \cdot \pi \cdot f \cdot C' \cdot L \cdot \frac{V_L^2}{3} \cdot \tan(\delta) \tag{3.6}$$

$$W_{tot,\Omega} = n \cdot R_{total,20} \cdot L \cdot I_{rated}^2 \cdot [1 + \alpha_\theta \cdot (\theta_{max} - 20)] \tag{3.7}$$

where,

[3] The substation hosts the transformer, which increases the potential, hence decreasing the current running through the cables. By doing so the overall electrical losses reduce according to $P_{loss} = I^2 \cdot R$, where I is the current (i.e., in Amps) running through the conductor and R is the resistance of the conductor (i.e., in Ohms)

$W_{tot}(V)$	are the total cable losses at certain wind speed V (W)
W_d	are the total dielectric losses of the cable (W)
$W_{tot,\Omega}$	are the total Ohmic losses of the cable at rated current (W)
$I(V)$	is the current distribution per phase for wind speed V (A)
I_{rated}	is the rated current of the cable per phase (A)
ν_θ	is the temperature coefficient
n	is the number of phases
C'	is the capacitance per phase per unit length (F/km)
L	is the cable length (km)
V_L	is the RMS line voltage (V)
$\tan(\delta)$	is the dielectric loss factor
$R_{total,20}$	is the total AC or DC resistance (including sheath armor losses for AC) at 20 ^{o}C per unit length (Ω/km)
α_θ	is the temperature coefficient of conductor (1/^{o}C)
θ_{max}	is the maximum operating temperature of cable (90 ^{o}C for an XLPE cable) (^{o}C)

As can be observed in equations (3.5), (3.6), (3.7) the benefit of increased separation distance, in terms of reduced wake losses, is compensated by the higher electrical losses of the collecting system. As it is explained in section 3.4.1, another aspect that tends to affect the separation distance between the rows and columns of the wind farm is the cable cost (i.e., which is proportional to the string length). Thus, a balancing of these figures is needed.

3.3 Wind speed distribution and wind rose

In the original code of the optimization tool the considered cases for the wind distribution are two. Thus, the user can select between the options *Holland* and *Horns Rev*. The selection *Holland* corresponds in a wind distribution which has an equal probability per direction and a constant mean wind speed of 7.83m/s. On the other hand, the option *Horns Rev* returns a wind rose, consisted of wind having different probability per direction and different mean wind speed per direction [25]. However, the limitation for the *Horns Rev* option derives from the fact that the user can only select up to 12 wind sectors, whereas the option *Holland* allows up to 40 wind sectors.

The problem with considering few wind rose sector is that the layout optimization cannot be done thoroughly, since the code considers the wake effect (i.e., thus energy production) in the defined number of directions. Moreover, the fewer the wind sectors are the less realistic the inputs are for the optimization process, thus worse estimation for the optimum layout can be found.

For the reasons mentioned previously a new wind rose was set up to be used as an input the current study. The wind rose is illustrated in Figure 3.4. The data were taken from [30] regarding *Station 252-K13* at 53.218^o*North* latitude and 3.220^o*East* longitude. The specific site was selected due to the proximity to the Princess Amalia offshore wind farm (i.e., having 52.588^o latitude and 4.223^o longitude) [31], thus representing a real case. The measurements for the direction and wind speed are comprised of a six-year (i.e., from 1/1/1999 until 1/1/2005) time series with one-hour sampling.

Figure 3.4 depicts the dominant wind direction at 220^o, having a mean wind speed of $\sim$ 9.52m/s. As can be seen in Table 3.1 the accumulated frequency of the South-East quadrant is the higher one.

Analytically, the available energy content of the wind per quadrant for a year can be calculated as [7]:

$$E_w = T \cdot \int_{\theta 1}^{\theta 2} P_\theta \cdot f_\theta \mathrm{d}\theta = T \cdot \int_{\theta 1}^{\theta 2} \frac{1}{2} \cdot \rho \cdot A \cdot U_\theta^3 \cdot f_\theta \mathrm{d}\theta \Leftrightarrow E_{quad} \approx T \cdot \frac{1}{2} \cdot \rho \cdot A \cdot \bar{U}_{quad}^3 \cdot f'_{quad} \tag{3.8}$$

where,

Table 3.1: *Frequency of real data wind direction per quadrant*

Quadrant	Direction $\theta[^o]$	Frequency $f'_{quad}[\%]$	Mean wind speed $\bar{U}_{quad}$[m/s]	Energy E_{quad}[GWh/year]
North-East	(0-90]	16.26	6.73	2.663
East-South	(90-180]	19.25	7.25	3.944
South-West	(180-270]	39.64	8.92	15.119
West-North	(270-360]	24.90	7.73	6.190

T .... is the number of hours per year, thus equal to 8760

$\theta 1, \theta 2$ .... are the lower and upper boundaries of each quadrant

ρ .... is the air density, thus $1.22^{kg}/_{m^3}$

A .... is the rotor area in m^2. Considering the Vestas V80 [32] wind turbine leads to $A = \pi \cdot R^2 \approx 5026.5m^2$

U_θ .... is the wind speed per direction in m/s

f_θ .... is the wind speed frequency per direction

f'_{quad} .... is the cumulative wind speed frequency per quadrant

$\bar{U}_{quad}$ .... is the mean wind speed per quadrant in m/s

Therefore, by using expression (3.8) the wind energy shown in Table 3.1 is calculated. It can be seen that the energy content in the 3^{rd} quadrant (i.e., thus South-West) is by far the highest one. This implies that the optimized layout should has such an wind turbine arrangement that will facilitate/maximize the wind energy harvesting in that direction. Hence, the wind direction and mean wind speed per direction are very important aspects that affect the offshore wind farm layout in a large extent.

3.4 Introducing the cost models

In section 1.3 of this report the research question regarding the determination of a comparison basis which is used in evaluating the fitness of each layout. There are two different solutions used in the literature [6], [13], [15],[19], [20]. Thus, the optimization algorithms try to achieve either the maximization of the Annual Energy Production (i.e., AEP) or the minimization of a cost function.

In the case of the AEP the researchers do not take under consideration the costs deriving from the development of the project. Hence, they only try to reach a solution for the layout which is the most aerodynamically efficient, minimizing the induced by wake effects "array losses". On the other hand in some papers a cost model is implemented. Therefore, some assumptions concerning various costs of the wind farm (e.g., cost of each wind turbine) were done. Although the implemented cost models were rather simple, utilizing educated assumptions and without including many cost factors, could provide an estimation of the cost of energy.

In the current study the solution of an optimization based on a cost model is selected. The model that is chosen to serve as fittest solution comparison basis is the Levelized Production Cost (i.e., LPC) model [25], [33], [34]. The calculation of the LPC is done according to:

$$LPC = \frac{I}{a \cdot AEP_{net}} + \frac{TOM}{AEP_{net}} \tag{3.9}$$

where,

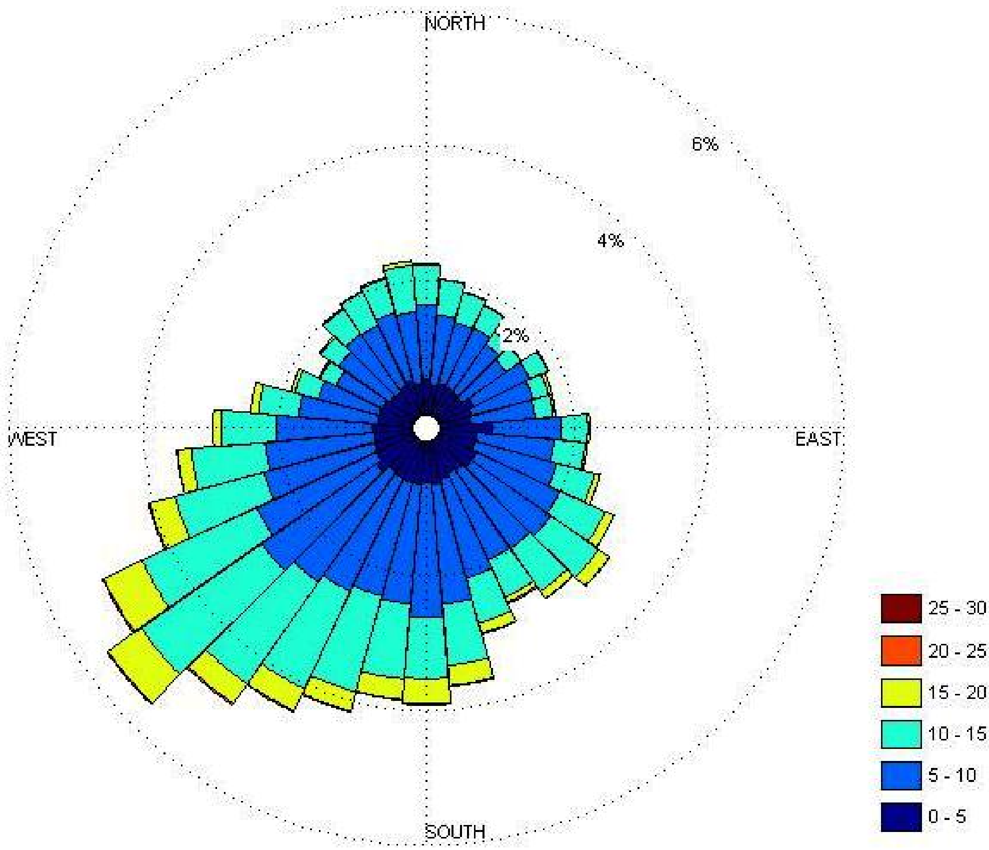


Figure 3.4: *Considered wind rose for the case of a 25-wind-turbine wind farm*

I	is the total capital investment in €
a	is the annuity factor calculated as $a = \frac{1-(1+r)^{-T}}{r}$, where r is the interest rate (i.e. taken as 7%) and T is the lifetime (i.e. taken as 20 years)
AEP_{net}	is the net utilized energy production per year [kWh]
TOM	is the total levelized annual "downline" costs (i.e., all costs other than initial investment, such like the Operation and Maintenance cost) in €

As can be seen in equation (3.9), various factors should be calculated prior to the LPC is found. To begin with, the calculation of AEP_{net}. The energy produced by the wind turbines of the offshore wind farm is calculated, taking into account also the wake effect, while the energy dissipated as electrical losses in the collecting system is estimated as well, as it is described in section 3.2. However, it is evident that in order to have some values for the capital investment and the "downline" costs some assumptions or another model should be considered.

In this section of the report the concept regarding the calculation of Levelized Production Cost which was developed is discussed. As it is aforementioned the model should provide some values for various cost parameters, such as the initial capital cost, the operation and maintenance (i.e., O&M) cost, etc.. The cable cost is considered as part of the initial capital cost and it is calculated separately (i.e., thus, in a more detailed way). Therefore, in subsection 3.4.1 a brief description of the corresponding model is given in advance of the LPC model.

This section is divided in four thematic sections. First, a brief description of the corresponding cable cost model is given. Secondly, the reasons that made the development of a new LPC model attractive are presented, followed by a more detailed analysis of the new model. In the last part of the section a short comparison of the two approaches for the LPC is presented.

3.4.1 Presentation of the cable cost model

The model that is used in the current study for the determination of the corresponding cable costs is discussed in more detail in [25]. In a few words the cable cost model is described by the expression:

$$C_{cables} = \left(N_{strings} \cdot L_{in-cable} + L_{plat-cable}\right) \cdot (C_{Cu} \cdot extra) \tag{3.10}$$

where,

- $N_{strings}$ .... is the number of strings. Thus, it is the number of the offshore wind farm columns, since it is selected the cables to connect the wind turbines of each column
- $L_{in\text{-}cable}$ .... is the length of the string in meters, calculated as $L_{in-cable} = S_{row} \cdot (N_{row} - 1)$, where S_{row} is the separation distance in meters of the wind farm rows and N_{row} is the number of the rows. This is valid when equally spaced rows of wind turbines are considered
- $L_{plat\text{-}cable}$ .... is the length, in meters, of the cable connecting each string to the offshore substation and it is proportional to the separation distance of the wind farm columns
- C_{Cu} .... is the copper cost. It is calculated as, $C_{Cu} = 3 \cdot P_{Cu} \cdot \rho_{Cu} \cdot A$, where P_{Cu} is the market price of the copper [€$_{\text{cents}}$/ton], ρ_{Cu} is the copper density [kg/m^3] and A is the cross section of the of the conductor [mm^2] which is proportional to string's rated current I_{rated}
- $extra$ .... is a weighting factor, which is equal to 1 if a three-core cable per string is used and 1.5 if a three individual single-core cables per string are used

In expression (3.10) it can be noticed that the increased separation distance, which would reduce the wake losses of the wind farm, results in a higher cost for the cables apart from higher electrical losses[4]. Thus, these two parameters restrain the increase of the offshore wind farm separation distance for the rows and columns.

3.4.2 Presentation and analysis of the LPC model

The motivation to investigate and to develop a new model for the Levelized Production Cost (i.e., LPC) stemmed from the fact that the value of LPC is the one that determines the acceptance of a solution as optimal. Moreover, in the tool, which is utilized for the optimization process, the following expression for the LPC is used:

$$LPC = \frac{(C_{FFC} + C_{cables}) \cdot \frac{100}{53} \cdot 10^5}{a \cdot AEP_{net}} \tag{3.11}$$

where,

- C_{FFC} .... is the fixed costs of the farm, calculated as C_{FFC}=$owecs \cdot TP \cdot \frac{100}{80} \cdot \frac{97}{100}$. The assumption here is that the farm fixed costs account for 80% of the initial capital cost, while the cable costs stands for 3% of this number
- $owecs$ .... is the number of wind turbines in the wind farm
- TP .... is the nominal power output of the wind turbines
- C_{cables} .... is the cost of the cables explained in section 3.4.1
- a .... is the annuity factor
- AEP_{net} .... is the annual net energy yield of the offshore wind farm

[4] It is explained also in section 3.2.3 that larger separation distance causes an increase in the electrical losses of the cables,. This can be seen in equations (3.5), (3.6), (3.7)

As it can be seen in equation (3.11) (i.e., a more elaborated approach and derivation of the expression can be found in [25]) a factor equal to 53% is introduced to substitute the second term of expression (3.9). This term is related to various costs applied to the project over its lifetime (e.g., O&M cost, insurance cost, etc.). However, the aforementioned factor results in an overestimation of the cable cost impact. Thus, the proposed separation distance both for the columns and rows of the wind farm was unrealistically tied with the cable cost.

As it can be found in [25] the results of the expression was relatively low in comparison to the data obtained from the literature [35], [36]. Moreover, in [35], [36] it is proposed that when $2MW$ wind turbines are utilized, the resulting LPC is within the range of $6-9$€$_{\text{cents}}$/kWh[36], being for the majority of the projects close to the upper bound of this range. Indeed, in Table 3.2 are presented the data regarding the LPC of already established offshore wind farms.

Table 3.2: *Levelized Production Cost for constructed offshore wind farms [35]*

Name	Commission year	Total power cap.[MW]	OWEC power cap.[MW]	LPC [€$_{\text{cents}}$/kWh]
Scroby Sands	2004	60	2.0	8.7
Kentish Flats	2005	90	3.0	8.7
Lillgrunden	2008	110	2.3	8.7
Horns Rev	2002	160	2.0	6.7
Robin Rigg	2010	180	3.0	9.9

Taking into consideration the aforementioned facts, the development of a new model regarding the cost of energy estimation is attractive. It was chosen as the best solution the model which has been developed by NREL and it is described in [37].

This model is selected due to the fact that many variables are included in it, allowing a better tuning of it in any given case. On the other hand, the introduction of a whole new model instead of a simple function (i.e., such as expression (3.11)) and the calculation of almost 60 variables, have an unwanted effect on the computational time needed.

To quantify this, after some validation runs using various data set combinations (e.g., different size of the wind farm, number of wind rose sectors, etc.), it was noticed that on average a $2-5\%$ increase of the computational time needed can be expected. Even though this increase cannot be considered as minor and hence overlooked, it is opined that this effect is compensated by the better adjustment that the model provides.

To elaborate on that, the model includes a cost estimation for almost all aspects of a wind turbine and an offshore wind farm. The composers of the model have selected to introduce the cost of virtually all the wind turbine components as a function of different variables (e.g., such as the power rating, the mass, the diameter, etc.) in order to allow the convenient use of the model with different inputs. In most of the cases the developers of the model have chosen to express the cost as a function of the wind turbine power rating (e.g., the electrical generator cost, the nacelle cost and the permit acquisition cost). In some other cases the cost of the wind turbine components (e.g., the blades, the shaft, the hub, etc.) is a function of turbine's structural properties, such as the diameter. Finally, the cost of supplementary components like the control and safety equipment is a fixed value.

For the purpose of the current project all the costs introduced in the model were divided in two major categories, the costs that are proportional to the number of wind turbines and the costs that are not. By doing so an approximation for the initial capital investment can be calculated as:

$$I = FC + VC \cdot owecs + C_{cables} \tag{3.12}$$

where,

FC	is the offshore wind farm fixed cost (e.g., permit acquisition cost, etc.)
C_{cables}	is the cable cost as explained in section 3.4.1
VC	is the variable cost per wind turbine of the project (e.g., blade's cost, tower's cost, etc.)

Even though that for the case of an offshore wind farm there are not actually many costs that can be taken as fixed, other costs, like the electrical transmission system cost, which are "insensitive" to the number of turbines, are considered as being fixed. Moreover, it should be noted that the model returns the costs in 2002 U.S.Dollar prices, thus a conversion to 2011 Euro prices is necessary. For this reason an inflation rate of 5% [38] is used and the exchange rate from € to \$ is considered as ~ 0.74, which was the market price on 10/2011 [38].

The new model was incorporated in the optimization tool and the initial results can be seen in Table 3.3. Even though the initial results were promising, the proposed separation distance for the rows and columns was not realistic. Thus, a closer investigation and an analysis of each cost group took place. According to the literature [25], [35], [36], it was concluded that the contribution of the farm fixed and variable cost were relatively accurate, while on the other hand the cable cost was underestimated.

Table 3.3: *Contribution of different cost components expressed as percentages (%) of the initial capital investment. The results obtained for both the original cable cost model (i.e., referred as "old") and the updated one are shown.*

	25 wind turbines		49 wind turbines		81 wind turbines	
Cost Components	Old model	New model	Old model	New model	Old model	New model
Variable Costs	63.7	61.3	76.5	72.8	83.0	78.7
Fixed Cost	34.4	33.2	21.1	20.1	13.1	13.1
Cable Cost	1.9	5.6	2.4	7.1	3.1	8.1

A closer observation to the cable cost estimation model, revealed that the utilized price of the copper (i.e. 2782 €/ton) was outdated, thus a more representative value discovered on the Internet [39] (i.e., 5383.8 €/ton, market price on 10/2011). Moreover , the considered bury cost for the cables (i.e. 100€/km) was too low and as it is suggested in [40] a more appropriate value was chosen (i.e. 100k€/km). These changes resulted in an increase of the cable cost contribution to the initial capital cost from $\sim 1.9\%$ to $\sim 5.6\%$ for a $50MW$ offshore wind farm, as it shown in Table 3.3. It should be mentioned that the updated cable cost model returns cost estimations that are within the range of $5-9\%$ of the initial capital expenditure found in bibliography [35], [36].

After the aforementioned changes in the cable cost model the overall estimation of the initial capital investment was relatively accurate and therefore the component regrading the annual operational costs (e.g., O&M, insurance cost) should be adjusted. However, the lack of information concerning the precise calculation of the different components representing the TOM term in equation (3.9), led to the substitution of the term by an educated estimation. It was found in [34], [35], [36] that the annual operational costs count normally for the $25-30\%$ of the offshore wind farm LPC. Therefore, the expression (3.9) was transformed accordingly into:

$$LPC = \frac{I'}{a \cdot AEP_{net}} \cdot \frac{100}{70} + \frac{C_{cables}}{a \cdot AEP_{net}} \tag{3.13}$$

In equation (3.13) can be noticed that the term I', regarding the initial capital investment does not contain the cable cost. This change is done so that the indirect estimation of the operational cost not being affected by changes in cable cost, and thus not being a function of it. Moreover, a factor of $^{100}/_{70}$ is introduced as a compensation for the elimination of the annual operational costs.

In the following paragraphs of this section a comparison is presented, as a validation process, of the results obtained by the updated LPC model, using expression (3.13), with the results obtained by the original tool expression (3.11). Moreover, the results from the two models are compared with data found in the literature.

The outcomes for both the developed model (i.e., corresponding to equation (3.13)) and the original expression (i.e., corresponding to equation (3.11)) are illustrated in Figure 3.5. Moreover, in this figure are shown the values obtained from the literature [35], [36] and listed in Table 3.2. In the figure it can be noticed that the real-data curve is constant, around 8.7 €$_{cents}$/kWh, for offshore wind farms up to $110MW$, afterwards it decreases to 6.7 €$_{cents}$/kWh for the case of Horn Rev I, finally increases sharply and reaches 9.9 €$_{cents}$/kWh for the Robin Rigg offshore wind farm.

However, a more careful look at the data can reveal that the steep increase in the LPC value for the case of Robin Rigg can be explained partially from the fact that the steel price increased significantly in the year 2008, reaching actually the highest value of the past twelve years [41], [42]. Overall, it should be noted that the LPC value of an offshore wind farm is not by far a function of only the power capacity, but there are many other parameters which affect greatly the final outcome, such as the wind turbine type, the operation and maintenance plan, the sea depth just to mention few.

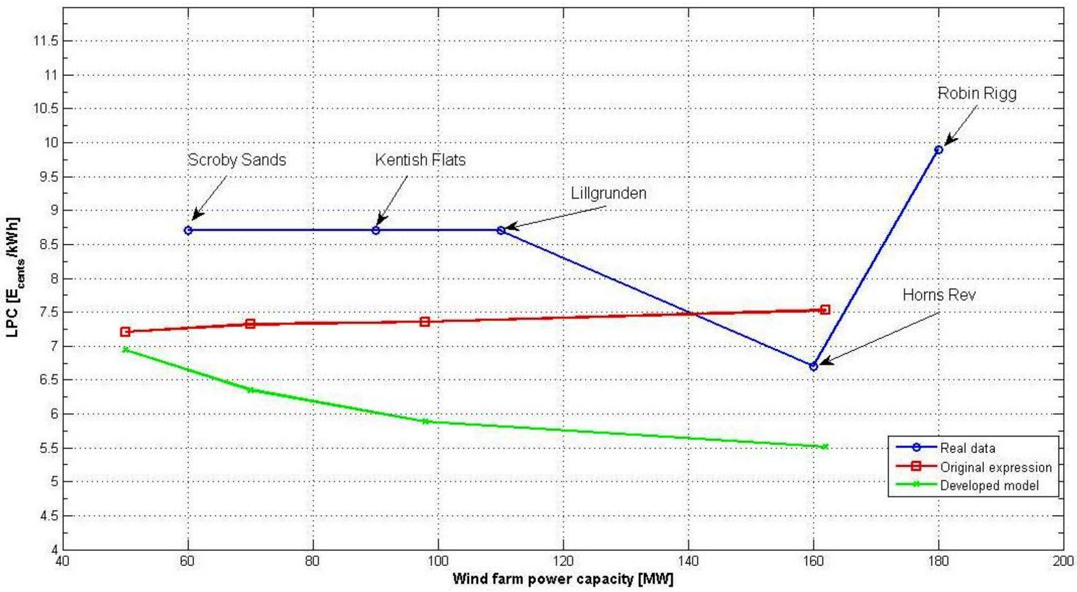


Figure 3.5: *The cost of energy versus the wind farm capacity. The depicted real data correspond in the cases of Scroby Sands, Kentish Flats, Lillgrunden, Horns Rev and Robin Rigg [35]*

In Figure 3.5, it can be noticed that the developed model performs within the reasonable range for a various of offshore wind farm set-ups. Moreover, it can be observed that it predicts the drop in the LPC value as the rated capacity of the wind farm increases. On the contrary the cost of energy calculated by the original model raises linearly with the capacity increase. An objection in this point could be that the original model achieves to predict the increase that is illustrated in Figure 3.5. However, it is considered that this upward movement of the real data curve is explained by the increase that is reported in the steel prices [41], [42] and it is connected in a minor degree with the Robin Rigg wind farm rated capacity.

As has been mentioned before it is not really accurate to derive conclusion of the two models just by judging how they perform in terms of LPC prediction (i.e. illustrated in Figure 3.5). A parameter that a safer conclusion can be drawn from is the initial capital investment estimation, since its behavior is more predictable versus the rated capacity of the wind farm. Indeed, in Figure 3.6 it is shown that the initial capital investment raises almost linearly as the power capacity of the offshore wind farm increases. In Figure 3.6 it can clearly be observed that the estimation of the updated LPC model is closer to the real values, although both the new and old model expand linearly.

As it is also reported previously the objective of the LPC model is not only the absolute number by itself, but also the impact of this value (i.e., through the optimization process) on the suggested separation distance for the columns and rows of the offshore wind farm. In Table 3.4 the resulted separation distance of the tool can be seen, when the original expression and the updated model is used. The comparison with the already established offshore wind farms, listed in Table 3.2, shows that the suggested separation distance is greater in almost every of the actual cases.

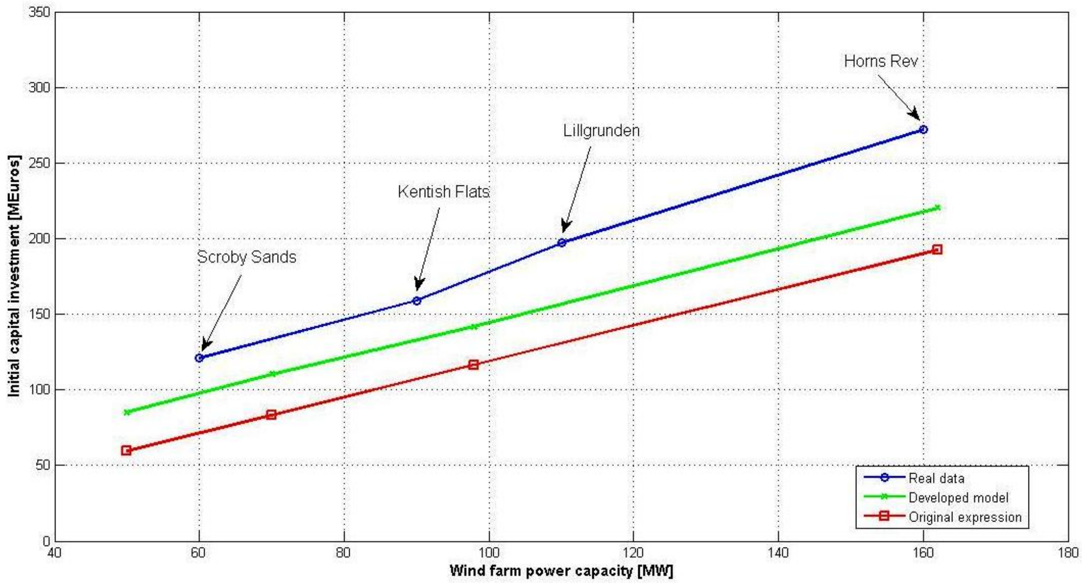


Figure 3.6: *The initial capital investment versus the wind farm capacity. The real data correspond in the cases of Scroby Sands, Kentish Flats, Lillgrunden and Horns Rev are illustrated [35]*

Just to give few examples the actual separation distance in Horns Rev for the columns and the rows is $\sim 7D$ and $\sim 7D$ respectively, while in Kentish Flats is $\sim 7.7D$ and $\sim 7.7D$. However, the declination between the calculated values (i.e., derived after using both the updated LPC model and the original expression) and the actual ones can be explained by the different manner that the internal electrical system has been implemented. Moreover, another explanation could be found in the different kind of particularities and restrictions that each offshore site imposes on the design (i.e., such constrains are presented and discussed in section 2.1).

From the values listed in Table 3.4 can be observed that the resulted separation distances, when the updated model is used, are almost always higher than the actual values. This is promising, since in the optimization tool there is no restriction related to the total area that can be occupied by the offshore wind farm. Thus, if such a constrain is applied the resulted separation distances will be decreased. On the contrary, the separation distances suggested by the tool in the case of the original LPC expression cannot increase, in order to reach the real values.

Table 3.4: *Separation distance for the columns and rows of various size wind farms*

	Original LPC expression		Updated LPC model	
Capacity [MW]	Sep.dist.Columns [D]	Sep.dist.Rows [D]	Sep.dist.Columns [D]	Sep.dist.Rows [D]
50	8	6	11.75	8.25
70	8	6	11.75	8.25
98	9	7	11.75	8.25
162	10	6	10.25	7.25

3.4.3 Conclusions

The LPC function is of high importance in the tool since it operates as the objective function that the tool tries to minimize so that the optimum design is obtained. Therefore, the developed model should be validated according to the already built model but also to published data of existing wind farms.

It was shown that both the models perform relatively well in terms of calculating the LPC value, since both of them are within the range suggested by the literature [36]. In terms of separation distance calculation, it was revealed that when the updated model is used in the toll the results are not very close to real data, compared with the case that the original expression is incorporated in the tool. However, keeping in mind the absence of a restriction of any kind related to the total area occupied by the offshore wind farm, makes the results of the tool, for the case that the updated model is used, more promising.

The developed model achieves to dissociate the estimation of the initial capital cost from the cable cost. That was not possible with the simple fixed cost expression which was originally implemented in the tool. In order to do so, it includes a cost approximation for almost all the components of a wind turbine and an offshore wind farm. Thus, it provides the possibility of better adjustment in the specifics of each case. Moreover, the developed model approximates better the initial capital cost compared to the bibliographic data and it is consistent with the cost contribution of each individual element.

Taken all the above statements under consideration and given the results obtained for both models in this section, it is decided that the updated model (i.e., which is developed according the cost components found in [37]) performs sufficiently well. Hence it is used in the calculations throughout the current study.

3.5 Simulation modes

The developed optimization tool includes two different optimization modes. These two modes are the “separation distance swept mode” and the “optimization mode”. Both of the modes try to minimize the LPC objective function, however they do so in a different way.

In the “sweep mode” the user assigns values to the minimum and the maximum separation distance as well as for the increment step. The tool calculates the LPC value for each point starting at the minimum separation distance and going up to the maximum one by using the predefined step. Therefore, the optimum separation distance for the columns and the rows of the wind farm is estimated. The major advantage of the “sweep mode” is that the demanded computational time is significantly reduced, since only a limited number of calculations (i.e., defined by the user) for the best possible separation distance is needed.

On the other hand, in the “optimization mode” the tool utilizes the *fmincon* function included in Matlab. The *fmincon* function finds the minimum value of a constrained nonlinear multi-variable objective function [43]. The objective and the constrain function definitions are the parameters that are considered by Matlab in order to select the appropriate optimization algorithm(s). The three possible algorithms are: Trust-region-reflective, Active-set or Interior-point [43].

In the current study the initial results for the separation distance of the rows and the columns of the offshore wind farm were taken by utilizing the “swept mode” of the tool. Therefore, when the low and high boundary for the separation distance is set to $5D$ and $12D$ respectively and the searching step equal to $0.25D$, the proposed by the tool dimensions, shown in Table 3.4, were obtained.

CHAPTER 4

Mono-variations results

In this chapter of the study the results of variations that were done to the offshore wind farm layout are presented. These variations are characterized as “mono-variations” due to the fact that only one type of change to the layout occurs. In order to clarify this topic a more detailed discussion takes place on a following section.

Prior to explaining and presenting the results of these variations the reference case that was used throughout this research is discussed, followed by the subjects related to the methodology of the approach. The investigation framework that was considered in the present study is shown. In more detail, the investigation steps are comprised by the introduction of the design variables vector, a manual determination of an improvement possibility and the quantification of the achieved improvement.

Then follows a more detailed description of the random concepts that were considered. The cases that add elements of randomness to the offshore wind farm layout are shown. For each one of them a theoretical background of the reasons supporting the idea that these changes can lead to a more optimized layout is given.

4.1 Reference situation

In order to define the reference situation the topics of the considered wind turbine, wind rose, wake model, size of wind farm, layout of the wind farm should be discussed among others. Thus, the wind turbine that was used in this study is Vestas V80 [32]. The two operating characteristics of the wind turbine that are relevant to the current research are the power output curve, shown in Figure 4.3a and the thrust coefficient curve, shown in Figure 4.3b. As it is argued previously the wind rose is an important parameter when the optimization of an offshore wind farm is sought. Thus, Figure **??** illustrates the wind rose which is taken into account in the present investigation. The positioning of wind turbines in a given area leads to array losses, mainly due to decreased wind speed. The reduction of the wind speed is described by the wake model. In the present research the Jensen model, discussed in section 3.2.1, is used for this purpose. The reference wind farm is consisted of 25 wind turbines arranged in a 5*x*5 layout. The separation distance for the rows and columns of the wind farm are shown in Table 3.4. Hence, given that the separation distances for the rows and columns are calculated by the Matlab tool as 8.25D and 11.75D respectively, a rectangular initial layout is formed. This layout is depicted in Figure 4.1, where also the positions of the wind turbines can be found. Throughout this research the numbering of the rows takes place from South to North. Therefore, position $(0,0)$ is occupied by the first turbine of the first row and in position $(0,2640)$ is located the first turbine of the fifth row. On the other hand the numbering of the columns takes place from West to East. Again position $(0,0)$ is occupied by the first turbine of the first column while the first turbine of the fifth column is placed in position $(3760, 0)$.

4.2 Methodology of approach

In this section the methodology of approach is explained. First, the introduction of the *design variables vector* is presented. The *design variables vector* is a concept that is used throughout the present study to state in each case of "random" layouts which are the considered variables. Secondly, a brief analysis is presented related to the determination of whether an improvement window for further optimization is evident. Thus, this investigation includes the study of the wake propagation, in terms of wind speed and the wake wind speed gradient.

4.2.1 The design variables vector

As has been explained previously the concept of the design variables vector is introduced in order to provide the reader with a condensed idea of which are the considered variables in each "random" layout (i.e., these configurations are presented in section 4.3). Therefore, this section presents the possible variables that may be part of the design variables vector and gives some examples of possible design variables vectors.

In the original optimization tool two overall design variables were considered. Hence, the software could assign different values to the separation distance of the rows and the separation distance of the columns. However, in the present study for a rectangular offshore wind farm layout five major groups of design variables are taken. The design variables consist of the:

1. *Separation distance of the rows*. Each row of the offshore wind farm can be displaced in two ways. Either at the West-East direction, which is taken as the X-axis, or at the North-South direction, which considered to be the Y-axis. The variable which represents the movement along the X-axis is $\mathbf{d_{ri-X}}$, being $\boldsymbol{i}$ the number of the row counting from the South to the North. On the other hand, the variable $\mathbf{d_{ri-Y}}$ signifies the movement of the $\boldsymbol{i^{th}}$ row of wind turbines along the Y-axis. The $\mathbf{d_{ri-Y}}$ stands as the separation distance between the row $\boldsymbol{i}$ and the previous row ***i-1***.

2. *Separation distance of the columns*. There are two different directions of movement that a column can do. First, the movement along the X-axis exists. The variable for the separation distance of each column from the previous one is represented as $\mathbf{d_{cj-X}}$. The $\boldsymbol{j}$ is the number of the column and counts from West to East. Secondly, a column of the wind farm can be repositioned along the Y-axis. In this case the variable is $\mathbf{d_{cj-Y}}$. When a movement of a column along the Y-axis is done the separation distance from the adjacent columns remains the same.

3. *Position of wind turbine along the X-axis*. The variable for the position of a wind turbine along the X-axis is represented as $\mathbf{x_{(i,j)}}$, where ***i, j*** is respectively the row and the column that the wind turbine belongs to.

4. *Position of a wind turbine along the Y-axis*. Similar to the case of the X-axis variable, in the $\mathbf{y_{(i,j)}}$ variable is assigned the position of an individual wind turbine along the Y-axis. Moreover, the ***i, j*** represent the row and the column respectively, that the wind turbine is located at.

5. *Element discard*. In order to create more space inside the wind farm a complete row, column or some individual wind turbines of the wind farm can be taken out of the grid. The variable that is used in this case is represented as $\mathbf{r_{(i,j)}}$. The index $\boldsymbol{i}$ and $\boldsymbol{j}$ signify the row and column, respectively, that the wind turbine belongs to. The variable $\mathbf{r_{(i,j)}}$ is binary. Moreover, in the case that a complete row or column of the wind farm is removed then the variable transforms into $\mathbf{r_{(i,:)}}$, when a row is discarded and $\mathbf{r_{(:,j)}}$ when a column is taken out.

In Figure 4.1 are illustrated all the possible movements, that form the corresponding design variables. Thus, with orange vectors are indicated the initially proposed by the tool separation distance for the rows and the columns (i.e., shown as ***sr*** and ***sc*** respectively). The blue arrows show the movement of a complete row and correspond to the design variable $\mathbf{d_{r3-Y}}$ (i.e., since the displacement of the third row is depicted). The design variable $\mathbf{d_{c2-X}}$, representing the movement of a full column of wind turbines, is also shown in the aforementioned figure. It can be seen with green arrows. Finally, the red arrows illustrate the independent movement of a single wind turbine along the X and Y axis. In the figure the cases of $\mathbf{x}_{(2,3)}$ and $\mathbf{y}_{(1,4)}$ can be found.

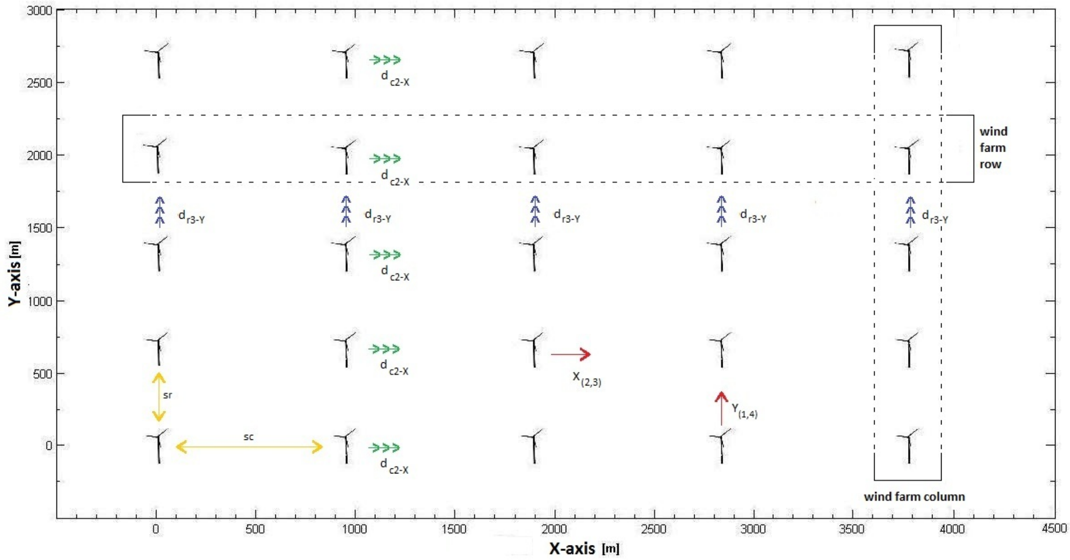


Figure 4.1: *The original wind farm layout for a wind farm, which is consisted of 25 wind turbines is shown. The separation distances are the same as the ones listed in Table 3.4*

According to the aforementioned description of the possible design variables (i.e., also shown in Figure 4.1) some examples follow, which will clarify the function and the morphology of the design variables vector. Let us consider for the first example that the search for a better optimum solution will include the variation of the separation distance of the second row from the neighboring rows (i.e., therefore the displacement is done along the Y-axis) and the repositioning of the fourth and fifth columns along the X- and Y-axis respectively. Hence, the initially proposed position for the rest of the rows is maintained. Thus, the design variables vector becomes:

$$Design\_Vector = [d_{c4-X}, d_{c5-Y}, d_{r2-Y}]$$

Therefore, the corresponding model, which would have been constructed to handle such an optimization case, would assign different values to this three variables. The second example regards the case that the optimization uses as variables the position of wind turbine located at the fourth row and the third column, the position of the turbine positioned at the second row and the second column and the displacement of the third column along the X-axis. The resulted design variables vector becomes:

$$Design\_Vector = \left[(x_{(4,3)}, y_{(4,3)}), (x_{(2,2)}, y_{(2,2)}), d_{c3-X}\right]$$

It can be noticed that because the wind turbines at the position *(4,3)* and *(2,2)* are allowed to move freely, both the $\mathbf{x}_{(\mathbf{i},\mathbf{j})}$ and $\mathbf{y}_{(\mathbf{i},\mathbf{j})}$ variables, of these turbines are used in the design vector. The final example regards the most complex case that can be consider, which is the independent movement of each wind turbine. As it is straightforward the variables which correspond to the separation distance of the rows and columns are out of content, thus only the variables representing the individual movement are used. Therefore, when every wind turbine of the farm can be repositioned independently the design variables matrix contains $N_{owecs} \times 2$ variables. The resulting design variables matrix becomes:

$$Design\_Matrix = \begin{bmatrix} (x_{(1,1)}, y_{(1,1)}) & (x_{(1,2)}, y_{(1,2)}) & \cdots & (x_{(1,nc)}, y_{(1,nc)}) \\ (x_{(2,1)}, y_{(2,1)}) & (x_{(2,2)}, y_{(2,2)}) & \cdots & (x_{(2,nc)}, y_{(2,nc)}) \\ \vdots & \vdots & \ddots & \vdots \\ (x_{(nr,1)}, y_{(nr,1)}) & (x_{(nr,2)}, y_{(nr,2)}) & \cdots & (x_{(nr,nc)}, y_{(nr,nc)}) \end{bmatrix}$$

These are only few examples of possible design variables vectors that may arise during the investigation of different optimization cases. Therefore, prior to the results for each optimization case, the design variables vector/matrix is mentioned in order to facilitate the case-specific rationale.

4.2.2 Determination of improvement possibility

In this section a short analysis takes place regarding the determination of whether an improvement possibility is evident, based on the wake theory. The reason that an optimization window is investigated by reducing the wake effect lies in the fact that this sort of losses are the governing ones in an offshore wind farm. Indeed, the energy losses derived from the wind speed reduction,due to upwind turbines, can be up to 10% [7], whereas the electric energy losses in the cables represent only $0.5-1\%$. Thus, by decreasing the negative effect of wakes, the denominator of equation (3.13) (i.e., corresponding to the annual energy production) can be increased, resulting in a LPC drop.

As it is presented in section 3.2.1 and 3.2.2 the considered wake model is the one introduced by Jensen [27]. In these sections it is also mentioned (i.e., and can be seen from the expressions (3.1) and (3.4)) that in order to reduce the wake effect in an offshore wind farm, there are some modifications that can be made in the layout[1].

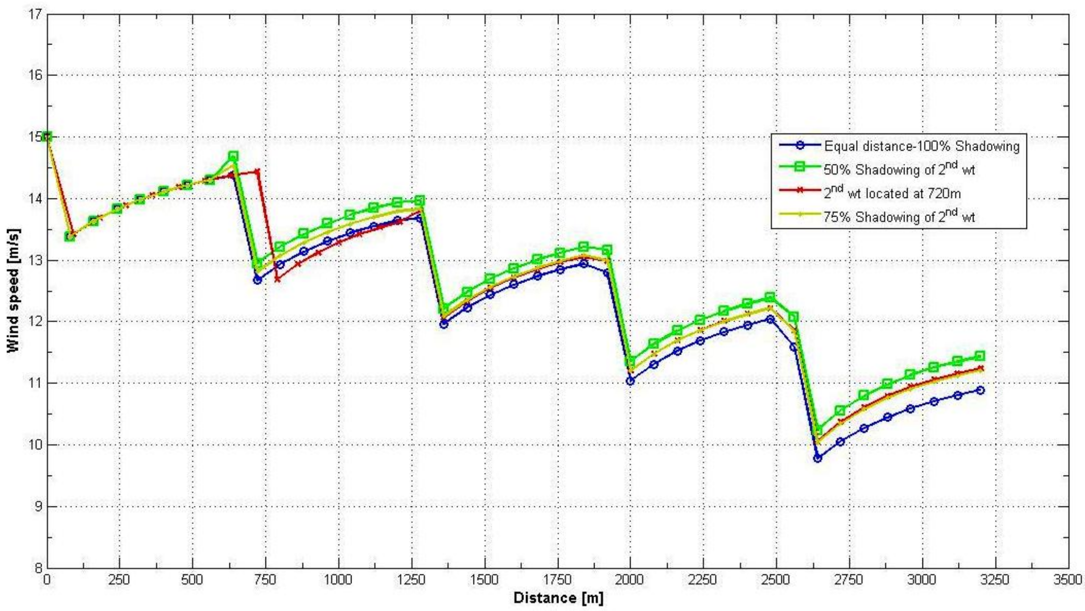
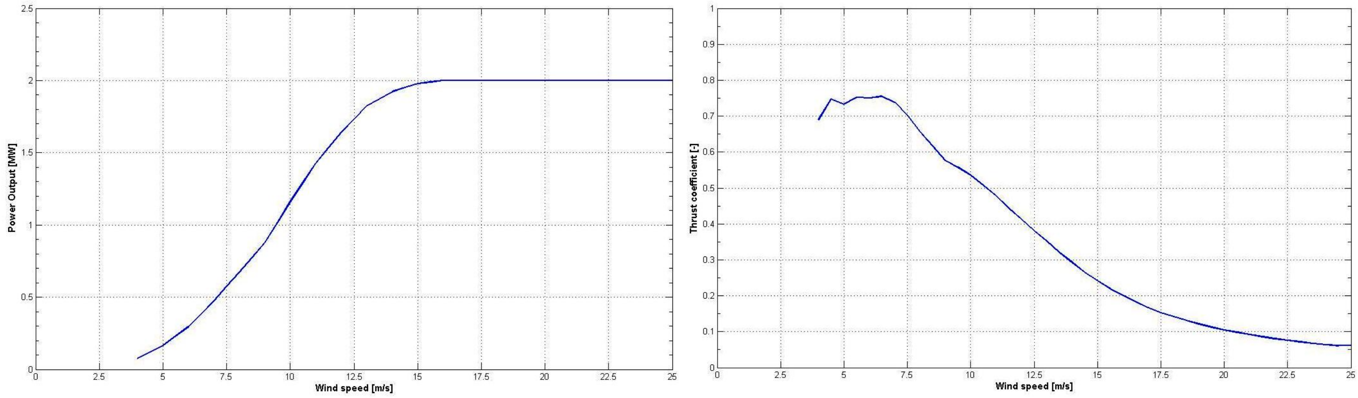


Figure 4.2: *Wake propagation-three cases. The blue curve corresponds to the propagation of the wake when equally spaced (i.e., separation distance of* 640*m) wind turbines and* 100% *shadowing effect on the downwind turbines are considered. The green curve represents the wake propagation when the second wind turbine rotor is only partially affected (i.e.,* 50% *shadowing effect). The red curve shows the case that the second wind turbine is placed at* 720*m behind the first one (i.e., thus the separation distance increased by* 1*D), while the rest wind turbines retain their original position. Finally, the light yellow curve depicts the wake propagation if* 75% *of the rotor is within the upwind turbine induced wake. The wind speed derivation is done by using equation* (3.4)

In Figure 4.2 the cases of a reduced shadowing effect over the second wind turbine and the increased separation distance of the second wind turbine are presented. The graph corresponds to an offshore wind farm consisted of five Vestas V80 wind turbines aligned in a single column, while the ambient wind speed is equal to 15m/s and unidirectional. It can be seen that both the attempt to reduce the second wind turbine shadowing and the increase

[1] Apart from the alterations in the offshore wind farm grid, the operating characteristics of the wind turbines can have a positive effect on the wake induced energy losses. This is clear from equations (3.1) and (3.4), where can be observed that the wind speed deficit predicted by the Jensen wake model is a function of the thrust coefficient, represented as C_t



(a) *Power output* **(b)** *Thrust coefficient*

Figure 4.3: *The characteristic curves of Vestas V80 wind turbine*

of the separation distance have a positive effect compared to the case that the wind turbines are equally spaced and effected fully by upwind turbines' wake. Both the techniques aiming at the reduction of the wake effect, allow the wind speed to recover a better portion of its undistributed velocity. However, it is clearly illustrated that when the second downwind turbine is partially affected, the wind speed "seen" by the consecutive turbines (i.e., in this case the third, fourth and fifth wind turbine) is higher. Thus, an offshore wind farm layout that incorporates the aforementioned design philosophy for the minimization of the shadowing coefficient of the upwind turbines is expected to have reduced "array losses" and thus reduced LPC value.

By using equation (3.2) and considering $k \approx 0.048$, $x = 640$m, $D = 80$m, it can be calculated that the wake expansion diameter equals approximately 141m at the position of the second wind turbine. Hence, if a 50% shadowing of the second wind turbine rotor is desired, it should be placed $\sim \pm 71$m along the X-axis with respect to its initial position. Therefore if the initial position of the wind turbine is (x, y) meters, the new position should be either $(x - 71, y)$ or $(x + 71, y)$. This displacement of the wind turbine(s) indicates that a longer underwater cable should be used for the interconnection, resulting in increased values of the electrical losses and the electrical cable cost. If a ~ 71m move of a wind turbine is considered, then a cable approximately 15m longer is need (i.e., per string), thus resulting in a $\sim 2\%$ increase of the electrical losses per year (i.e., calculated by equation (3.5)). With respect to the cable cost, the maximum increase is again $\sim 2\%$ per cable string (i.e., the expression (3.10) is used for the calculation).

On the other hand, if it is considered a mean yearly wind speed lower than the rated wind speed then the energy production per string can be estimated as around 6.5% increased (i.e., a mean increase of $\sim 2\%$ for the wind speed is considered, as can be seen in Figure 4.2, and expression (3.8) is used) due to the repositioning of the second wind turbine. It can be seen that there might be an opportunity window for obtaining lower LPC value by such a rearrangement.

Another topic that should be discussed is how sensitive is the resulted wake wind speed to the "shadowing" coefficient. In Figure 4.2 it can be noticed that when the aforementioned coefficient becomes 0.75 (i.e., thus 75% of the rotor is affected by the wake, while 25% is within the undistributed ambient wind flow) the resulted wind speed is lower. It can be observed that the light yellow curve is over the red curve, representing the case with increased separation distance between the first two wind turbines, until the third wind turbine. However, the red curve is slightly over the yellow one for the fourth and fifth wind turbines. Moreover, is more clearly noticed that behind the last rotor the wind speed shown by the red curve is higher. Hence, it can be concluded that if a string of more than five wind turbines is realized then the technique which increases the separation distance between the first and the second wind turbines may return higher wind energy capturing compared to the one that a shadowing effect of around 75% is accomplished.

In the analysis that takes place in the following chapters of the present study, it is useful to include also the gradient of the wind speed over the distance. First the analytical calculation of the representative expression is derived. Thus, by manipulating equation (3.1) it can be found that the wake wind speed gradient equals:

$$
\begin{aligned}
V = U - U\cdot\left(1-\sqrt{1-C_t}\right)\cdot\left(\frac{D}{D_w}\right)^2 \Leftrightarrow \frac{\mathrm{d}V}{\mathrm{d}x} &= \left[U - U\cdot\left(1-\sqrt{1-C_t}\right)\cdot\left(\frac{D}{D_w}\right)^2\right]' \\
&= \left(U\cdot\sqrt{1-C_t}\cdot D^2 - U\cdot D^2\right)\cdot\left(\frac{1}{(D+2\cdot k\cdot x)^2}\right)' \\
\Leftrightarrow \frac{\mathrm{d}V}{\mathrm{d}x} &= -\left(U\cdot\sqrt{1-C_t}\cdot D^2 - U\cdot D^2\right)\cdot\left(\frac{4\cdot k}{(D+2\cdot k\cdot x)^3}\right)
\end{aligned}
\tag{4.1}
$$

Figure 4.4 illustrates the results obtained by using expression (4.1). In the graph can be observed that the rate (i.e., blue curve) of the wake wind speed recovery is not constant over the downwind distance. It is higher the shorter the distance is, afterwards it steeply decreases until the first 650m, while it continues to reduce more smoothly until the end of the plot (i.e., thus when the distance is approximately 3250m).

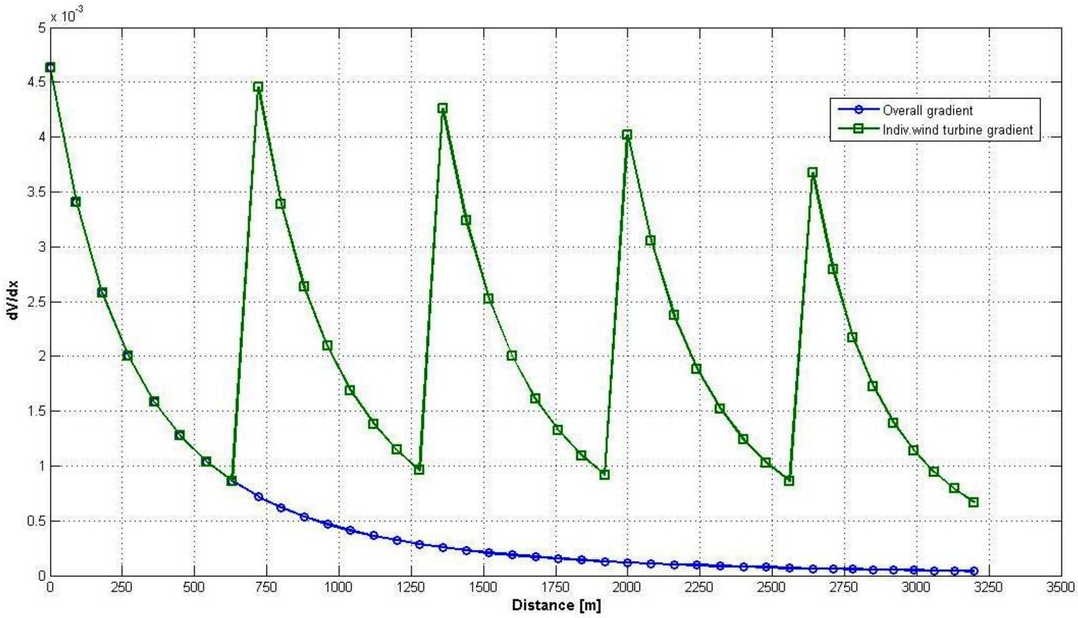


Figure 4.4: *Wake wind speed gradient for the Jensen model. The curve resulted from the expression* (4.1) *and it steeply decreases for the first* $\sim$ 650*m while afterwards the rate drops. The gradient for the consecutive wind turbines is represented with the green curve*

4.3 Creating unconventional layout

In this section are discussed the different types of the investigated "random" configurations. These changes led to more unconventional offshore wind farm layouts, aiming in the LPC value minimization. Here, a short description of the unconventional layouts is given and more specifically the reasoning and motivation behind each "scenario" is presented. The order of the considered cases is based on their complexity, thus the number of variables that each design variables vector contains.

1. *Row/Column movement*. Two subcategories exist:

- A row or a column of the wind farm is allowed to positioned along the X- or the Y-axis axis respectively. In this case the design variables $\mathbf{d_{ri-X}}$ and $\mathbf{d_{cj-Y}}$ are utilized. This manipulation on the layout is done in an attempt to position some of the wind turbines outside of the upwind turbine wakes. As it is explained in section 4.2.2 and illustrated in Figure 4.2, such a modification shows the largest potential and thus it can be proved beneficial for the resulting LPC.
- A row or a column of the wind farm is allowed to positioned in a different location along the Y- or X-axis respectively. Therefore, the design variable $\mathbf{d_{ri-Y}}$ or $\mathbf{d_{cj-X}}$ is used depending the situation. This modification aims at increasing the separation distance between consecutive rows/columns (i.e., for details see section 4.2.2 and Figure 4.2), thus reducing the wake effect. Similarly to the previous case, the research presented in previous sections indicate that such a movement can have a positive effect on the LPC value.

2. *Wind turbine movement*. Similar to the case that a complete row and/or column is moved along X- and/or Y-axis, individual wind turbines can be placed on a different location. The reason is identical to the event that a cluster of wind turbines repositions. By having individual wind turbines move in the internal space of the wind farm, the wind speed in the wakes regains a value closer to the undisturbed value, thus the power production increases. Moreover, by assigning different variables for the exact position to each wind turbine the undesirable effect of downwind turbines' shadowing can be eliminated, or at least minimized.

3. *Wind turbine(s) discard*. In this group of layout variation the variable $\mathbf{r_{(i,j)}}$ is used to represent the wind turbine which is taken out of the farm. Apart from individual wind turbines a complete row and/or column can be removed. The elimination of certain elements of the farm is done in order to create more space in the internal, thus allowing the wind speed in the wakes to repossess a value close to its ambient one. It is shown in Figure 4.2 that the increased separation distance between downwind turbines act positively on the power production.

4.4 Movement in the West-East direction

In this section of the report the different arrangements of the wind turbines that derived after movements of complete rows and columns of the wind farm along the X-axis (i.e., as can be seen in Figure 4.1) are presented. The resulted LPC estimations for these new layouts are discussed. First the case that a row is moved along the X-axis is shown followed by the case that a columns executes a X-axis movement.

4.4.1 Row movement

As it is discussed in section 4.3 and illustrated in Figure 4.2 the most efficient way to obtain higher operating wind speed is by trying to position the wind turbine outside of the upwind turbine's wake. Therefore, the simultaneous movement of all the wind turbines, which belong in the same wind farm row, along the X-axis attempts to accomplish the aforementioned effect. As it is pointed before, a shadowing factor of 0.5 of the upwind turbines can influence significantly the potential wind energy produced by the downwind turbines. In Table 3.4, can be found that for a 50MW-power-capacity wind farm the proposed by the tool row and column separation distances are 660m and 940m respectively.

According to the expression (3.2), if it is assumed that $D = 80m$, $k \approx 0.048$ and $x = 660m$, the wake diameter would be approximately equal to 143m at the position of the second wind turbine. However, this estimation is valid for the case that the wind blows from the North or South (i.e., thus the angle of the incoming wind is equal to 180^o). It is discussed in section 3.3 that the predominant wind direction is from 180^o to 270^o. Figure 4.5 illustrates what would be the area that the wake affects, for the case that the wind blows from the predominant direction (i.e., the third quadrant has a mean wind direction of $\bar{\theta} = 225^o$). It should be noted that the diameter of the wake, D_eff, is larger than the one estimated by equation (3.2) for that distance, due to the angle of the incoming wind. The results for the wake diameter on the projection of the next row are listed in Table 4.1.

From the data presented in Table 4.1 can be seen that the induced by the wind turbines of one row shadowing effects on the wind turbines of the following row are limited. For example when the wind direction is 180^o the wind turbines of the first row have an effect on all the wind turbines located in the downwind rows and in the same column, when the wind direction is 230^o the $T_{(1,1)}$ (i.e., the turbine located at the first row, first column, thus in position (0m,0m)) affects the $T_{(2,2)}$[2]. Even though that the movement of the subsequent downwind row may not have a direct positive effect on the energy output of this specific row, a displacement along the X-axis could favor the power production of the wind farm as the wind turbines located further downwind can increase their power output. This speculation leads us to the assumption that the movement of the first row would have the best output, since its wake interacts with the majority of downwind turbines.

Figure 4.6 depicts the resulted curves of the LPC estimation when each row of the wind farm is moved along the X-axis. The design variables vectors that were used are:

$$Design\_Vector = \begin{bmatrix} d_{r1-X} \\ d_{r2-X} \\ d_{r3-X} \\ d_{r4-X} \\ d_{r5-X} \end{bmatrix}$$

Overall, in Figure 4.6 can be observed that the movement of any of the wind farm rows do not result in a LPC value that is lower than the original one. The most significant results stems from the relocation of the first and fifth rows, reaching a LPC value of $\sim$ 6.96€$_{\text{cents}}$/kWh. Moving these two rows along the X-axis causes a reduced shadowing effect on the downwind turbines for specific incoming wind angles. However, from the figure can be concluded that overall the shadowing effect is enhanced by the independent relocation of each wind farm's row. This phenomenon takes place due to the initially proposed large separation distance. Indeed, the wake impact analysis reveals that for the predominant wind direction the wind turbines on the first row do not affect the turbines located on the second, third and fifth rows, while they induce only a shadowing factor on the third wind turbine of the fourth row. During the analysis a non-ideal wind farm, having row and column separation distances of $6D$, was examined. The results in this case revealed that the movement of the second and fourth row along the X-axis would have influenced positively the wind farm energy production, leading consequently to a lower LPC value.

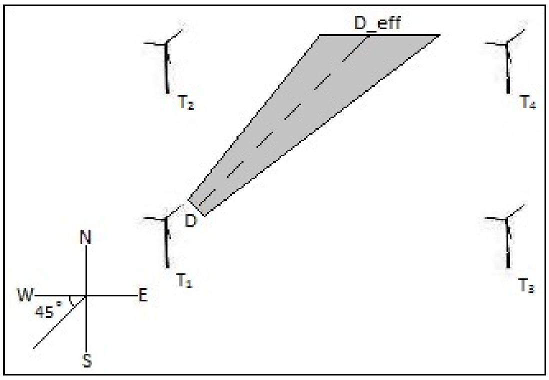


Figure 4.5: *The expansion of the wake at the downwind row. The wake generated by the upwind turbines affects a larger area when the wind farm rows are not perpendicular to the incoming wind*

4.4.2 Column movement

Similarly to the case of a row movement along the X-axis the case that a column moves along the same axis exists. Such a displacement could result in an offshore wind farm layout that would minimize the shadowing effect of upwind

[2]This is also valid for the $T_{(1,2)}$ which affects the $T_{(2,3)}$ etc.

Table 4.1: *The central point of the wake impact when the wind blows from the* 3^{rd} *quadrant. The wake y coordinate is always the same and equal to the solution given by the tool. Therefore, when the second row is considered the y-coordinate is equal to* 660*m, for the third row is* 1320*m, etc. The x coordinate is given with respect to the wind turbine placed on the left (i.e., thus closer to* $x = 0$*)*

Incoming wind angle [°]	Downwind distance [m]	Wake's center x coordinate	D_eff [m]
180	660.0	0.0	143.08
190	670.18	116.99	146.28
200	702.36	241.58	156.62
210	762.10	383.49	176.62
220	861.60	558.06	212.27
230	1026.80	794.47	278.03
240	1320.00	1160.33	415.16
250	1929.70	1864.98	786.70
260	3800.80	4116.36	2754.96

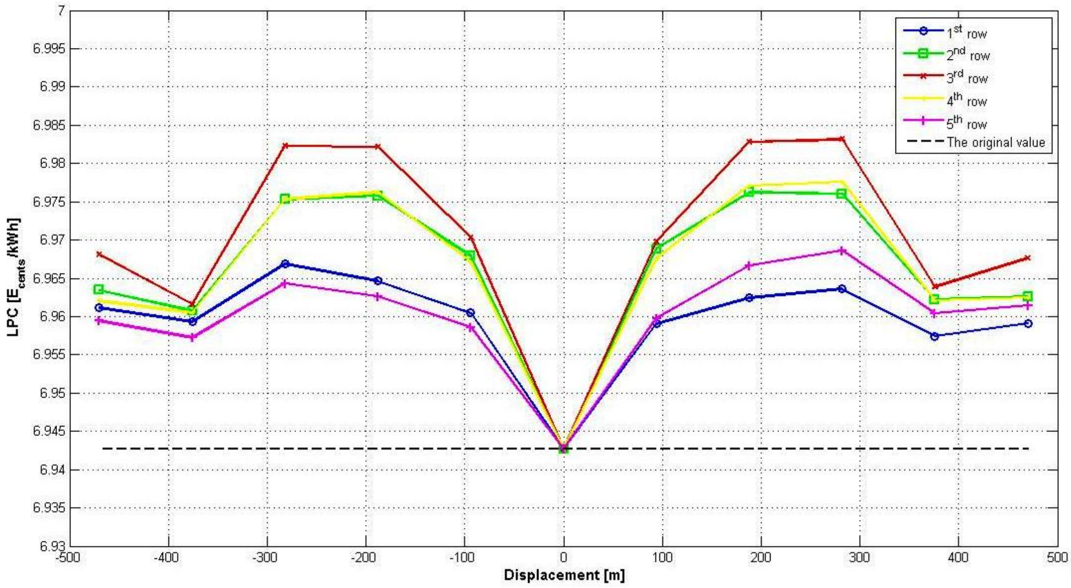


Figure 4.6: *25wts-LPC for a row movement along the X-axis. The resulted LPC is illustrated when the original position for all the wind turbines located in the same row is changed. The figure derived after using separately each design variable row of the design vector. To give an example the red line corresponds to Design_Vector(3)*

turbines on the downwind turbines. However, a column displacement would not only result in reduced shadowing factors for the downwind turbines, but it would increase the separation distance between two consecutive wind farm columns.

The design variables vector that is used in the current analysis is set up as:

$$Design\_Vector = \begin{bmatrix} d_{c1-X} \\ d_{c2-X} \\ d_{c3-X} \\ d_{c4-X} \\ d_{c5-X} \end{bmatrix}$$

In Figure 4.7 the outcomes can be found regarding the column movement investigation. The research reveals that the movement of the first and fifth wind farm columns result in a lower value for the LPC. A closer look on the energy production calculation shows that when the first or the fifth column moves to ~ -450m and ~ 450m (i.e., with respect to the original position) respectively the energy generated by the wind turbines on these columns increases. In particular when the wind blows from 220^o the energy production of the fifth column raises by approximately 1%.

However, Figure 4.8 depicts that the highest gain in terms of energy production occurs when the wind direction is 90^o and 270^o. In this case the augmented energy production is a result of the increased separation distance between the wind turbines. Thus, when the wind turbines of the first row move to the aforementioned location, the separation distance between them and the turbines placed in the second row becomes 1390m. In Figure 4.4, where the gradient of the wind speed in the wake versus the downwind distance is illustrated, can be seen that the wind speed for such a distance is close to the undisturbed value. The increased wind speed results in higher power output and consequently to higher energy production.

Overall, the repositioning of the wind farm columns at the West-East direction results in lower LPC values in comparison with the outcomes of a row movement, seen in Figure 4.6. The most significant result derives from the movement of the wind turbines forming the first and fifth columns. However, the difference between the original LPC value and the one obtained from the modified layout is approximately -0.1%, although the larger separation distance between the columns allow the wake wind speed to reach a higher value, thus increasing the energy production of the wind farm. In this point it should be mentioned that the increased separation distance of the first and fifth column has also a counter-effect which is no other than the increased length of the cables need for the connection to the offshore platform. The longer cables lead to higher cable costs alongside with increased electrical energy losses.

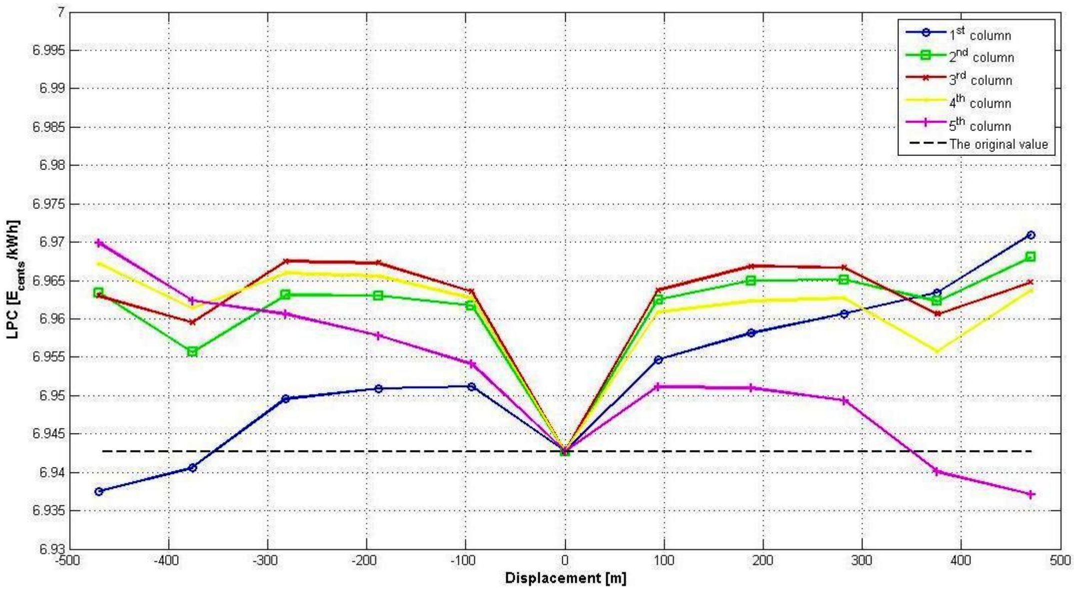


Figure 4.7: *25wts-LPC for a column movement along the X-axis. The resulted LPC is illustrated when the original position for all the wind turbines located in the same column is changed. The figure derived after using separately each design variable column of the design vector. To give an example the blue line corresponds to Design_Vector(1)*

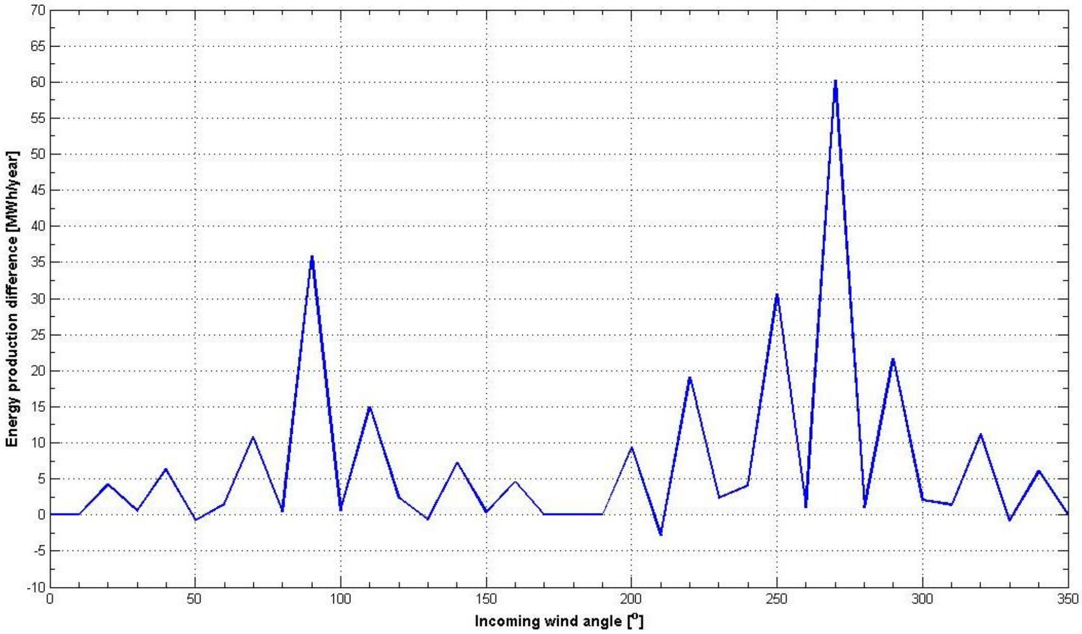


Figure 4.8: *25wts-Energy production difference. X-axis movement. The energy produced per wind direction by the modified layout is subtracted from the energy produced per wind direction by the original layout. The original layout corresponds to a separation distance for the rows and columns of* $8.25D$ *and* $11.75D$ *respectively. The modified layout has the first column of the wind farm relocated to* $-450m$ *from its initial position*

4.5 Movement in the North-South direction

This section of the study presents and explains the different arrangements of the wind turbines that derived after movements of complete rows and columns of the wind farm at the North-South direction, thus along the Y-axis. These arrangements result in different LPC estimations which are discussed. First the case that a row is moved along the Y-axis is shown, while the case that a columns executes a Y-axis movement follows.

4.5.1 Row movement

As has also been explained in section 4.3 the purpose of a row repositioning along the Y-axis is to increase the separation distance between neighboring rows, thus creating more free space in the internal of the wind. Moreover, due to the multi-directional wind, certain cases may arisen where reduced shadowing effects might imposed on downwind turbines. The outcome is that the wake wind speed regains a value closer to the ambient wind velocity.

When a row movement along the Y-axis takes place, the partial energy production for some directions is expected to increase. For specific incoming wind directions the separation distance raises, thus the energy production inclines. As it is mentioned in Table 3.4 the separation distance of the wind farm rows is calculated as 660m. Hence, each row of wind turbines moves in the range [-330m 330m], which acts in a preventive manner so that two wind turbines are not positioned in an unrealistically close distance.

The design variables vector that is used becomes:

$$Design\_Vector = \begin{bmatrix} d_{r1-Y} \\ d_{r2-Y} \\ d_{r3-Y} \\ d_{r4-Y} \\ d_{r5-Y} \end{bmatrix}$$

The LPC values of the different arrangements can be found in Figure 4.9. As can be seen there, none of the new layouts performs better in comparison with the original one. In the first look some peculiar conclusions may be drawn from the figure. It is shown that the placement of the first row of wind turbines to -330m have a smaller impact on the LPC value compared to the case that the first row is positioned at 330m. Although the energy production is favored by the wider separation distance, as it is aforementioned in section 4.2.2, the cable cost and the energy loss in the cables increase due to the longer length of the conductor. In particular, when the first row is positioned at 330m, thus closer to the second row, the energy production decreases by $\sim 5.2\%$, while the cable cost and the energy losses in the cables reduce by $\sim 13.6\%$ and $\sim 27.6\%$ respectively. From equation (3.13) can be noticed that these two factors also determine the final LPC estimation.

A similar explanation can be given for the case of the fifth row. In Figure 4.9 it is shown that the displacement of the fifth row towards the fourth row (i.e., thus moving it -330m from its original position) results in lower LPC values, in comparison to the case that an increase of the separation distance between these two rows takes place. However, this is the result of the reduced cable cost and cable electric loss.

As it has been mentioned a highly determinant factor is the performance in terms of cable cost and net energy production when the wind blows from the 220^o. Therefore, under this condition it can be found that the movement of the first wind farm row to -330m, causes a $\sim -1\%$ drop in the net energy production as well as a $\sim 6.8\%$ increase in the cable cost. The net energy production is decreased primarily due the longer cables needed for the wind turbines' interconnection. However, the analysis revealed that due to the larger separation distance created by the row displacement for -330m, a shadowing effect is induced on the downwind turbines. To give an example, the wake of $T_{(1,1)}$ affects partially $T_{(2,2)}$ and $T_{(5,4)}$ and fully $T_{(4,3)}$[3].

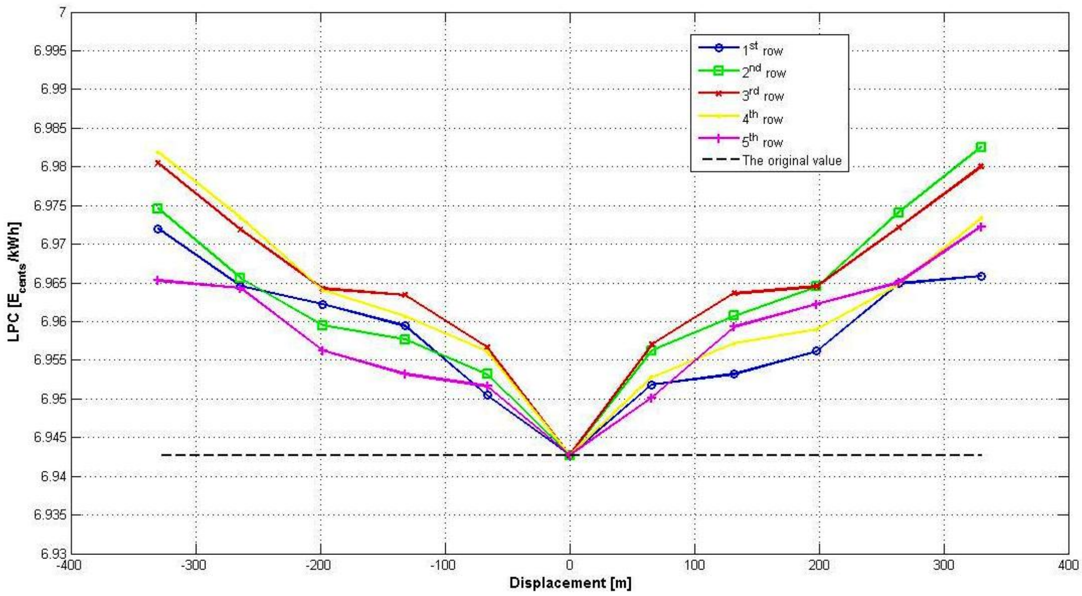


Figure 4.9: *25wts-LPC for a row movement along the Y-axis. The resulted LPC is illustrated when the original position for all the wind turbines located in the same row is changed. The figure derived after using separately each design variable row of the design vector*

4.5.2 Column movement

The purpose of a column repositioning along the Y-axis, as in the case of a row movement, is to increase the separation distance between subsequent columns and to reduce the shadowing effects on downwind turbines. The corresponding design variables vector is:

[3] If no repositioning of the first row is considered the wake of $T_{(1,1)}$ affects partially $T_{(3,2)}$ and $T_{(4,3)}$

$$Design\_Vector = \begin{bmatrix} d_{c1-Y} \\ d_{c2-Y} \\ d_{c3-Y} \\ d_{c4-Y} \\ d_{c5-Y} \end{bmatrix}$$

The range for the movement of each column set as [-330m,330m]. In Figure 4.10 can be observed that the results obtained after using each row of the design variables vector separately, are higher than the initial suggestion of the tool. Moreover, should be noted that the LPC estimations for a column movement are lower than the ones for the row movement. This can be explained by the lack of other affecting parameters, such as the cable cost and the cable electrical losses. Therefore, the result of each case is determined solely by the wake effect.

The movement of an offshore wind farm column along the Y-axis is expected to reduce the shadowing effects. From equation (3.2), if the downwind distance is taken equal to 940m, it is found that the wake diameter is approximately 170m. Thus, by repositioning the wind turbines of the first column by 125m[4] causes a zero shadowing coefficient, for certain wind directions, on the wind turbines of the second column, increasing the energy production of the wind farm, as it is explained in more detail in section 4.2.2.

The zero shadowing coefficient on the second downstream column is the case for a 90^o incoming wind direction (i.e, provided that the 0^o is assigned to South) and 270^o, although reduced shadowing coefficients can be witnessed for other wind directions. In Figure 4.11 is illustrated the energy difference between the original and modified layout. As it is expected the energy production for incoming wind direction of 90^o and 270^o is increased. However, the total energy production is reduced by approximately 0.1%. In Figure 4.10 can be noticed that when the first column of the wind farm moves to -150m, the LPC estimation is roughly 6.95€$_{\text{cents}}$/kWh which represents an increase of around 0.1%. Due to the absence of cable cost and cable losses increase, the result of the LPC expression (i.e., equation (3.13)) is only affected by the relative net energy production difference between the original and the modified layout.

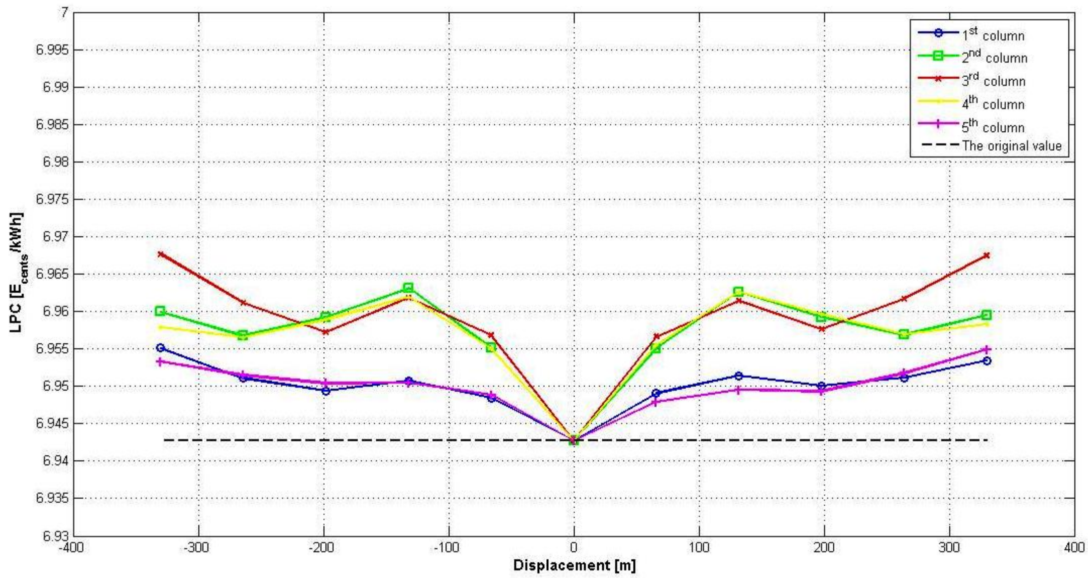


Figure 4.10: *25wts-LPC for a column movement along the Y-axis. The resulted LPC is illustrated when the original position for all the wind turbines located in the same column is changed. The figure derived after using separately each design variable row of the design vector*

[4]The wake radius is approximately equal to 85m, therefore the wind turbine has to be displaced additional 40m, which is the radius of the rotor, in order to not be affected at all by the wake of the upwind turbine

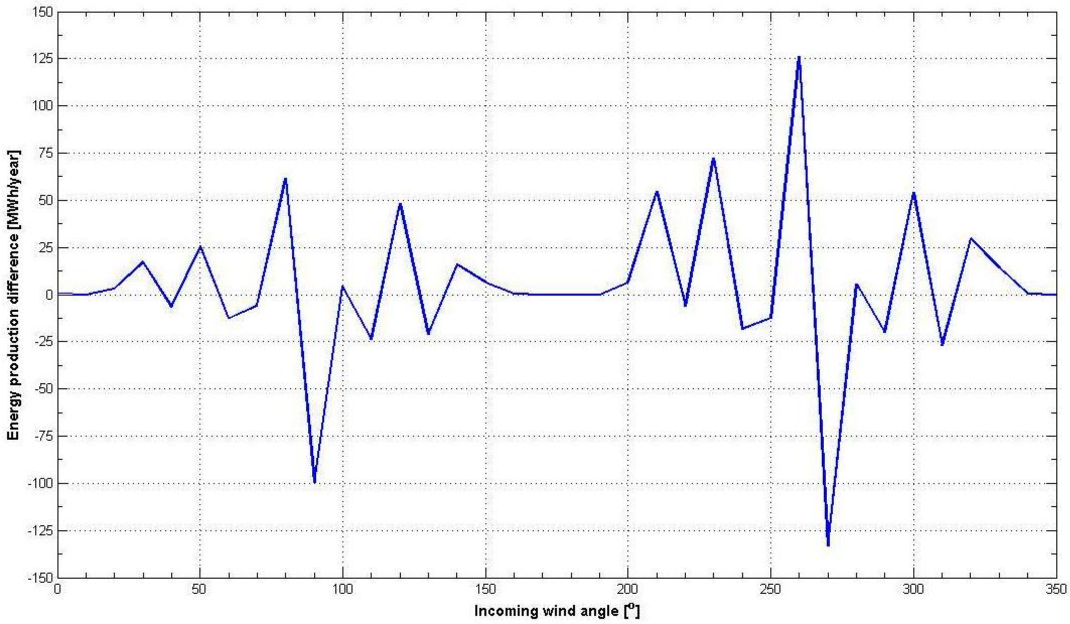


Figure 4.11: *25wts-Energy production difference. Y-axis movement. The energy produced per wind direction by the modified layout is subtracted from the energy produced per wind direction by the original layout. The original layout corresponds to a separation distance for the rows and columns of* $8.25D$ *and* $11.75D$ *respectively. The modified layout has the first column of the wind farm relocated to* $-150m$ *from its initial position*

4.6 Cluster removal

Until this point the cases that are shown, mainly aimed at reducing the shadowing coefficients on the downwind turbines. However, from the results can be observed that only the movement of the first and fifth column along the X-axis has a positive effect on the LPC value (i.e., Figure 4.7). As has been explained through the analysis in section 4.2.2, an increase of the wind turbines separation distance is beneficial for the wind speed rebound.

In the previous section is investigated the case that the separation distance is increased by movement of either rows or columns of the wind farm. Another mechanism which could result in a larger separation distance is the removal of certain elements of the wind farm.

Additionally, to the wider separation distance which is created by the extraction of a row and/or a column from the wind farm, the LPC estimation is further affected by the reduction of the term I' (i.e., equation (3.13)). Thus, the initial capital investment, being mainly proportional to the number of wind turbines, reduces. However, it is expected that also the Annual Energy Production of the offshore wind farm will decline.

In the following sections, first the case that a row is removed from the offshore wind farm grid is investigated, followed by the column discard case.

4.6.1 Row removal

The removal of a complete row of the offshore wind farm can be beneficial for the LPC estimation. Due to the larger separation distance between rows of the wind farm the wake wind speed has a value closer to the ambient one, resulting in higher energy output of the wind turbine, while the initial investment costs are reduced by $\sim 12.5\%$. Despite the increase of the energy production of specific wind turbines, under some wind directions, the overall annual energy production production of the wind farm will drop. Moreover, due to the “string” topology of the cables the removal of a row does not reduce the electrical infrastructure cost.

In Figure 4.12 can be seen that when the second wind turbine is removed from the column the wake wind speed at the third, fourth and fifth wind turbine is increased by 7.07%, 8.28% and 10.11% respectively. Thus, the energy production of the corresponding wind turbines is higher. The design variables vector which corresponds to the removal of certain rows becomes:

$$Design\_Vector = \begin{bmatrix} r_{(2,:)} \\ r_{(3,:)} \\ r_{(4,:)} \end{bmatrix}$$

In Table 4.2 the results for the LPC calculation are listed, when the second, third and fourth row of the offshore wind farm are discarded, thus when Design_Vector(1:3) is used. It is straightforward that the removal of the first and fifth row would not have a positive effect on the total energy production since the wind turbines of these two rows operate at ambient wind speed under certain wind speed directions.

In the table can be seen that the removal of any offshore wind farm row does not result in an improved LPC value. In particular the LPC value is increased by approximately 8.73% compared to the original value, while it should be noted that the smaller difference (i.e., 8.71%) for the LPC arises when the third row is discarded. This is expected because the wind turbines on the second and fourth row have for many wind directions energy output equal to the undistributed production, which is a consequence of the wide separation distance. A closer look to the energy production per incoming wind direction can shed some light on the reasons that no improvement of the LPC value is noticed.

When the second row of the wind farm is removed, it is expected according to Figure 4.12, that the energy production would increase for wind coming from 0^o and 180^o. Even though that this is the case for each individual downwind turbine the surplus of energy, created by the row removal, does not exceed the energy production of the turbines that were discarded. In more detail, when the wind direction is 0^o the energy production of the offshore wind farm decreases by approximately 15.8%, when the second row is removed. For the case of 220^o wind direction the total energy production drops by approximately 20%. Overall, it is estimated that the energy production is reduced by 19.5%. The main reason that no significant increase in the energy production of the downwind turbines is noticed by a row removal, lies in the initial large separation distance.

As has been explained the original separation distance for the rows and columns allows the wake wind speed to regain the better portion of its undistributed velocity, while the shadowing effects on downwind turbines are minor. Thus, no optimization of these aspects can be achieved by the removing a complete row of the offshore wind farm.

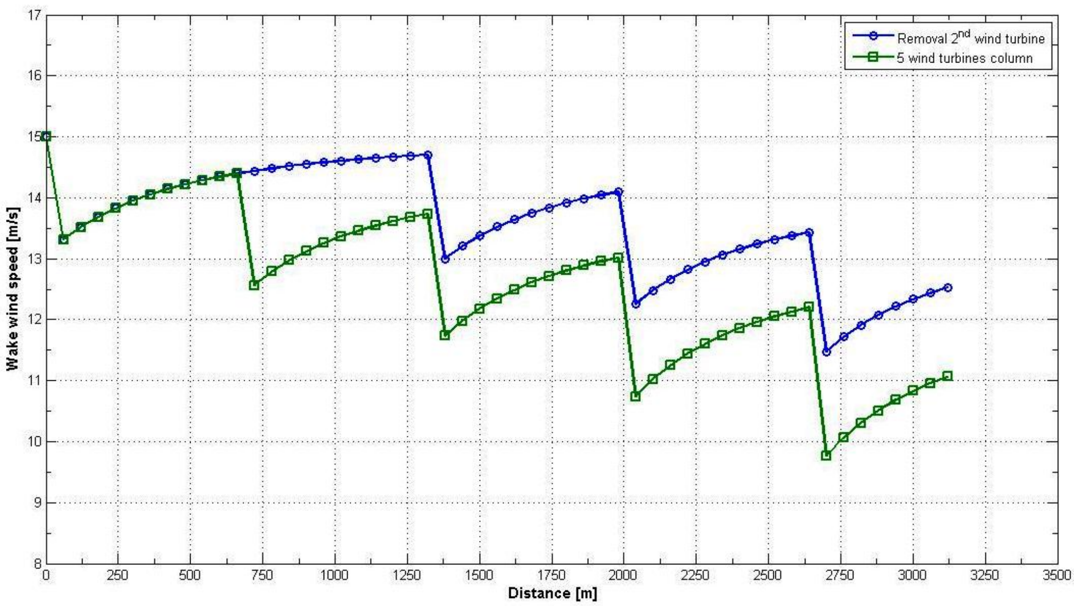


Figure 4.12: *Wake wind speed vs Distance. Second wind turbine removal*

Table 4.2: *LPC estimations for a row/column removal-25 wind turbine farm. The original wind farm resulted in an LPC estimation of* 6.94€$_{cents}$/kWh

Row/Column removed	Row removal LPC [€$_{cents}$/kWh]	Column removal LPC [€$_{cents}$/kWh]
2	7.549	7.458
3	7.547	7.455
4	7.548	7.458

4.6.2 Column removal

The column removal behaves in the same manner as the row removal. Thus, it creates more space in the internal of the offshore wind farm, allowing the wake wind speed to regain a value closer to the ambient one, while it decreases the initial investment costs. Additionally, to the decrease of the wind turbine variable costs, the removal of a complete column reduces the number of cable strings, hence causing further costs reduction.

The design variables vector which corresponds to the removal of certain columns becomes:

$$Design\_Vector = \begin{bmatrix} r_{(:,2)} \\ r_{(:,3)} \\ r_{(:,4)} \end{bmatrix}$$

As can be seen in Table 4.2 the results for the LPC calculation when the Design_Vector(1:3) is used individually, are higher than the original LPC value. Specifically the LPC has increased by approximately 7.42%, 7.38% and 7.43% by the removal of the second, third and fourth columns respectively. From these results can be noticed that the increase in the LPC value is lower, compared to the row-removal case, which can be mainly attributed to the cable cost reduction. The initial investment costs decreases around 1.8% due to the smaller number of cable string demanded for the modified arrangement of the wind turbines.

The new offshore wind farm layout is expected to favor the energy production especially for the wind direction of 90^o and 270^o. Indeed, when the wind blows from 90^o and the second column is discarded the energy production of the downwind columns is increased by 4.1% on average, however the overall energy production of the wind farm is reduced by $\sim$ 17%. From the analysis has concluded that the energy production for the predominant wind direction is reduced by 19.8% when the second or the fourth columns are removed. When the complete wind rose is considered the energy produced by the offshore wind farm is approximately 19.6% smaller in comparison with the original wind farm.

All in all, can be said that the layouts resulted by the removal of an offshore wind farm column does not return a LPC value lower than the original one. This can be explained, similar to the case of a row removal, by the large separation distances for the rows and columns that the original layout suggests.

4.7 Individual wind turbine movement

Until this point of the study have been presented the modified offshore wind farm layouts resulted from either movement or removal of wind turbine clusters. Thus, a complete row or column of the original layout was displaced along the X- or Y-axis or fully discarded. In this section of the report is investigated the case that only a single wind turbine is move along X- and Y- axis, in order to benefit from reduced shadowing effects and/or increased separation distance.

When a complete row or a column is displaced, the new arrangement can turn out to increase the energy production of some wind turbines of the clusters while it is possible that can reduce the energy output of certain wind turbines at the same time. To give an example, when an incoming wind from 220^o is considered and the wind turbines of the first column move by -100m with respect to their original position along the Y-axis (i.e., for a more detailed discussion refer to section 4.5.2), the energy output of $T_{(4,1)}$ and $T_{(5,1)}$ drops by $\sim 1\%$ while $T_{(3,1)}$ delivers 2% more energy, matching the energy output of wind turbines operating in free flow. Although the differences are minor they provide some rough numbers and indications of nonidentical behavior of wind turbines in changes to the layout when the latter is a result of a cluster movement.

The movement of each wind turbine individually attempts to address the aforementioned problem. Therefore, when each wind turbine is allowed to repositioned in a predefined space around its original position the LPC value is possible to decline as a result of higher energy production of wind turbines due to higher wind speed. The design variables matrix reflecting the movement of individual wind turbines becomes:

$$Design\_Matrix = \begin{bmatrix} (x_{(1,1)}, y_{(1,1)}) & (x_{(1,2)}, y_{(1,2)}) & (x_{(1,3)}, y_{(1,3)}) & (x_{(1,4)}, y_{(1,4)}) & (x_{(1,5)}, y_{(1,5)}) \\ (x_{(2,1)}, y_{(2,1)}) & (x_{(2,2)}, y_{(2,2)}) & (x_{(2,3)}, y_{(2,3)}) & (x_{(2,4)}, y_{(2,4)}) & (x_{(2,5)}, y_{(2,5)}) \\ (x_{(3,1)}, y_{(3,1)}) & (x_{(3,2)}, y_{(3,2)}) & (x_{(3,3)}, y_{(3,3)}) & (x_{(3,4)}, y_{(3,4)}) & (x_{(3,5)}, y_{(3,5)}) \\ (x_{(4,1)}, y_{(4,1)}) & (x_{(4,2)}, y_{(4,2)}) & (x_{(4,3)}, y_{(4,3)}) & (x_{(4,4)}, y_{(4,4)}) & (x_{(4,5)}, y_{(4,5)}) \\ (x_{(5,1)}, y_{(5,1)}) & (x_{(5,2)}, y_{(5,2)}) & (x_{(5,3)}, y_{(5,3)}) & (x_{(5,4)}, y_{(5,4)}) & (x_{(5,5)}, y_{(5,5)}) \end{bmatrix}$$

The range that each wind turbine of the offshore wind farm is allowed to repositioned is:

$$x_T - \frac{1}{2}sd_{col} < x < x_T + \frac{1}{2}sd_{col}$$

$$y_T - \frac{1}{2}sd_{row} < y < y_T + \frac{1}{2}sd_{row}$$

where x_T, y_T are the initial x and y coordinates of T wind turbine. For instance if $T_{(4,3)}$ with initial position of $(1880, 1980)$m is considered, the range which can be placed within is $1410 < x_{(4,3)} < 2350$, $1650 < y_{(4,3)} < 2310$. In Figure 4.13 can be seen the possibilities for the position of $T_{(4,3)}$ as an example. The option of a deterministic[5] instead of stochastic[6] approach in order to designate the turbines' position is selected. Thus, the step along the X-axis is set as $0.1 \cdot 0.5 \cdot sd_{col} = 47$m while along the Y-axis is $0.1 \cdot 0.5 \cdot sd_{row} = 33$m and in total 8 possible directions are formed. Therefore, the overall number of possible positions for each turbine of the offshore wind farm is 40, as can be seen in Figure 4.13. This number of possibilities was selected mainly due to the elevated computational time required if the number of positions raises.

In Figure 4.14 are illustrated the minimum LPC values resulted by the procedure, while it should be mentioned that each variable of the design matrix is used independently. The matrix containing the solutions which generate the minimum LPC for each wind turbine is:

$$Positioning\_Matrix = \begin{bmatrix} (-470, 330) & (470, 330) & (1410, 0) & (3290, 330) & (4230, 330) \\ (-470, 330) & (470, 660) & (1880, 660) & (3290, 660) & (4230, 330) \\ (-470, 1650) & (470, 1320) & (1410, 1320) & (3290, 1320) & (4230, 990) \\ (-470, 2310) & (470, 1980) & (1410, 1980) & (3290, 1980) & (4230, 2310) \\ (-470, 2310) & (470, 2310) & (1410, 2640) & (3290, 2640) & (4230, 2310) \end{bmatrix}$$

[5] A deterministic algorithm is an algorithm which has a predictable behavior. Therefore, for a particular input, it always produces the same output, while it always processes the same sequence of states

[6] A stochastic algorithm utilizes random variables. For an optimization problem these random variables might include random constrains, random iterates, etc.

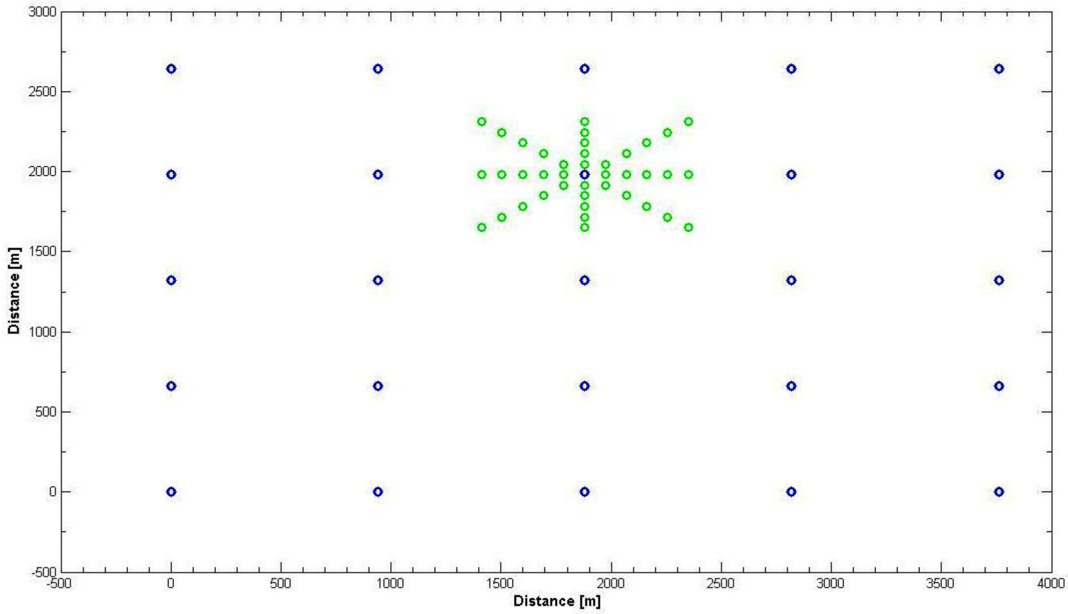


Figure 4.13: *Possible positions for $T_{(4,3)}$ when the individual movement of each wind turbines is considered*

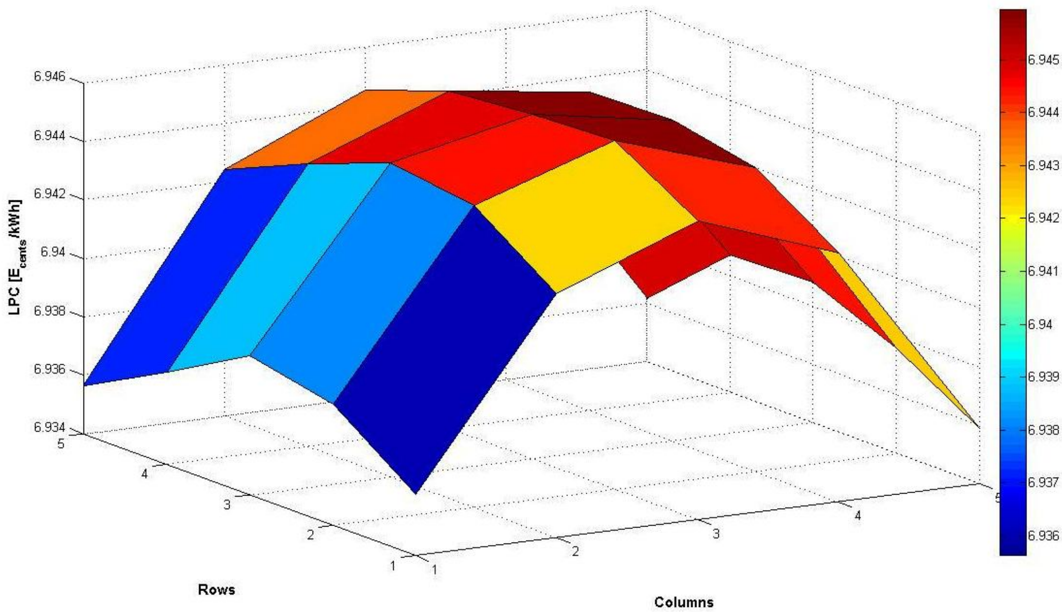


Figure 4.14: *LPC results for the individual movement of each wind turbine of the offshore wind farm*

It should be mentioned that the positioning matrix includes the position of each wind turbine which leads to the lower LPC, however the estimated LPC is not necessarily lower than the initial value. In Figure 4.14 can be noticed that the movement of the wind turbines located in the outer rows and columns cause a decrease in the LPC value. On the other hand, the wind farm having layouts generated by the individual movement of centrally positioned wind turbines do not have a LPC value lower than the original one. In particular, the repositioning of $T_{(1:4,2)}$, $T_{(:,3)}$ and $T_{(2:5,4)}$ does not deliver a layout which leads to lower LPC value by either increasing the energy production or decreasing the cable cost and electrical losses. Therefore, the displacement of $T_{(:,1)}$, $T_{(:,5)}$ alongside with $T_{(1,2)}$, $T_{(5,2)}$ and $T_{(1,4)}$ results in layouts which minimize the LPC value. Moreover, the movement of the aforementioned wind turbines return more than one LPC value that are lower than the initial one. All the possible positions for a given wind turbine which improve the original LPC can be seen in Figure 4.15.

A closer look at the values of the positioning matrix reveals that the wind turbines of the first and fifth column tend to move towards the outskirts of the wind farm, thus increasing the separation distance. As has been discussed in section 4.4.2 the same behavior is noticed when the first and the fifth columns of the offshore wind farm treated as clusters.

Furthermore, the positioning matrix contains values for the position of the first and fifth row of the wind farm which optimize further the LPC. In general it is suggested that the distance between the first and last row of the farm should reduce leading in decreased length of the cable connecting the wind turbines, and thus lower cost and electrical losses. However, such suggestion is not similar to the one presented in section 4.5.1. There, in Figure 4.9 can be seen that the displacement of a complete row of the wind farm along the Y-axis does not return better LPC values. This difference can be explained by the simultaneous movement of individual wind turbines along both axes and not only along the Y-axis which is the case in the cluster movement. Moreover, the repositioning of a single wind turbine does not induce shadowing effects in many of the downwind turbines of the farm whereas when more wind turbines move simultaneously shadowing effects are caused in more wind turbines.

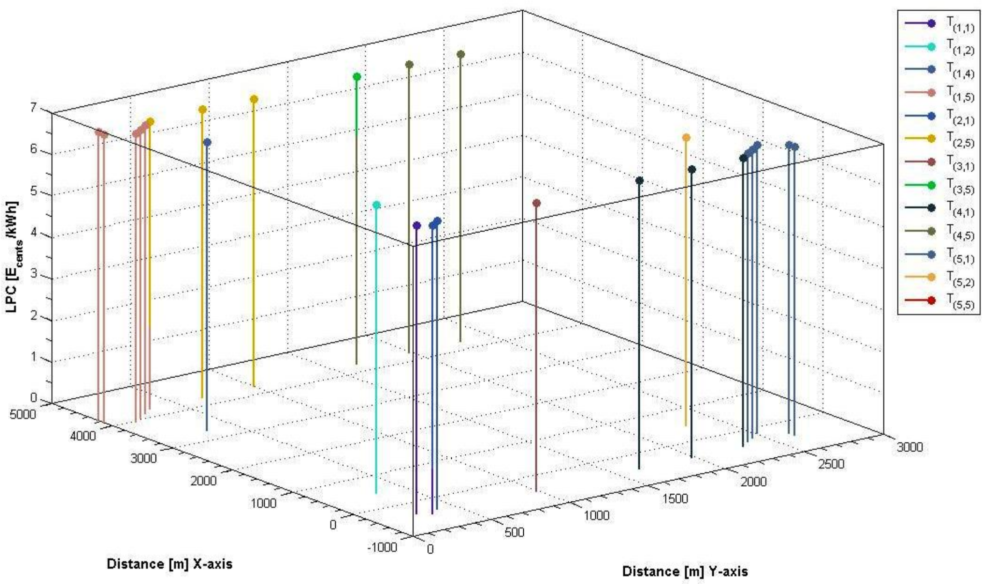


Figure 4.15: *Position of the wind turbines that improve the LPC. The X- and Y-coordinate of* $T_{(:,1)}$, $T_{(:,5)}$, $T_{(1,2)}$, $T_{(5,2)}$ *and* $T_{(1,4)}$ *are shown*

As can be noticed the positioning matrix is composed of many duplicate suggestions for the position of specific wind turbines. For example $T_{(1,1)}$ and $T_{(2,1)}$ reach an optimum, thus lower, value for the LPC when the design variable becomes $(-470, 330)$m. Another example might be $T_{(1,5)}$ and $T_{(2,5)}$ for which the best solution is found to be $(4230, 330)$m. However, in the analysis conducted here this is not an issue since the movement of each wind turbine generates a different layout. A problem regarding the duplicate values emerge when all the suggested positions are considered at the same time as in section 5.1.1.

Overall, the layouts which are concluded from the movement of individual wind turbines have a positive effect on the LPC value, since it reduces the initial value. However, it should be mentioned that the difference between the old LPC value and the new estimation is small, being in some cases 0.1%. Although, this number is low, keeping in mind primarily the fact that this difference is the outcome of a single wind turbine's movement and secondly the limited number of predetermined positions that each wind turbine could be placed to, it is safe to accept these results for further investigation.

4.8 Individual wind turbine removal

As it is explained in section 4.6, the removal of a wind turbine from the layout accomplishes to create more space in the interior of the wind farm allowing the wake wind speed to reach a higher velocity, alongside with reducing the number of wakes inflicting the downwind turbines. Moreover, the initial costs of the wind farm reduce since the number of the wind turbines is smaller. However, in the present study it is not taken into account any decrease in the cable costs when a wind turbine of the fifth row is removed. On the other hand, the drawback of a turbine removal is quite straightforward. Thus, the total energy production of the wind farm is possible to decline. In sections 4.6.1 and 4.6.2 it has been shown that by taking out of the initial layout a cluster of wind turbines, either a row or a column, the LPC value does not improve.

For the case that a single wind turbine is discarded from the offshore wind farm layout, the corresponding design variables vector becomes:

$$Design\_Matrix = \begin{bmatrix} r_{(1,1)} & r_{(1,2)} & r_{(1,3)} & r_{(1,4)} & r_{(1,5)} \\ r_{(2,1)} & r_{(2,2)} & r_{(2,3)} & r_{(2,4)} & r_{(2,5)} \\ r_{(3,1)} & r_{(3,2)} & r_{(3,3)} & r_{(3,4)} & r_{(3,5)} \\ r_{(4,1)} & r_{(4,2)} & r_{(4,3)} & r_{(4,4)} & r_{(4,5)} \\ r_{(5,1)} & r_{(5,2)} & r_{(5,3)} & r_{(5,4)} & r_{(5,5)} \end{bmatrix}$$

The obtained solution matrix when the simulation is executed for removing each wind turbine independently is null. Thus, similarly to the case that a cluster of wind turbines is considered, taking out of the offshore wind farm any wind turbine does not improve further the LPC value. In Figure 4.16 can be found the resulted LPC values. Can be noticed that regardless of which specific wind turbine is discarded the LPC value is rather constant at around 7.045$€_{cents}$/kWh. Furthermore, the removal of the wind turbines located at the center of the offshore wind farm returns the lowest value of the LPC. The wind turbines positioned in the interior of the wind farm have on average the lowest energy production, being a result of the multiple wakes effect as can be seen in Figure 4.17. These wind turbines experience the lowest wind velocities since they are affected by the wake of the wind turbines on the outskirts. Therefore, the total energy production of the wind farm does not reduce as much as in the case of a wind turbine removal positioned on the perimeter of the farm.

Overall, can be said that due to the initially large separation distance for the rows and columns of the offshore wind farm the removal of a single wind turbine does not improve the LPC value. The wide space that is created in the wind farm as a result of the big separation distance allows the wake wind speed to reach a value close to the ambient velocity while it restrains the negative shadowing effect on downwind turbines.

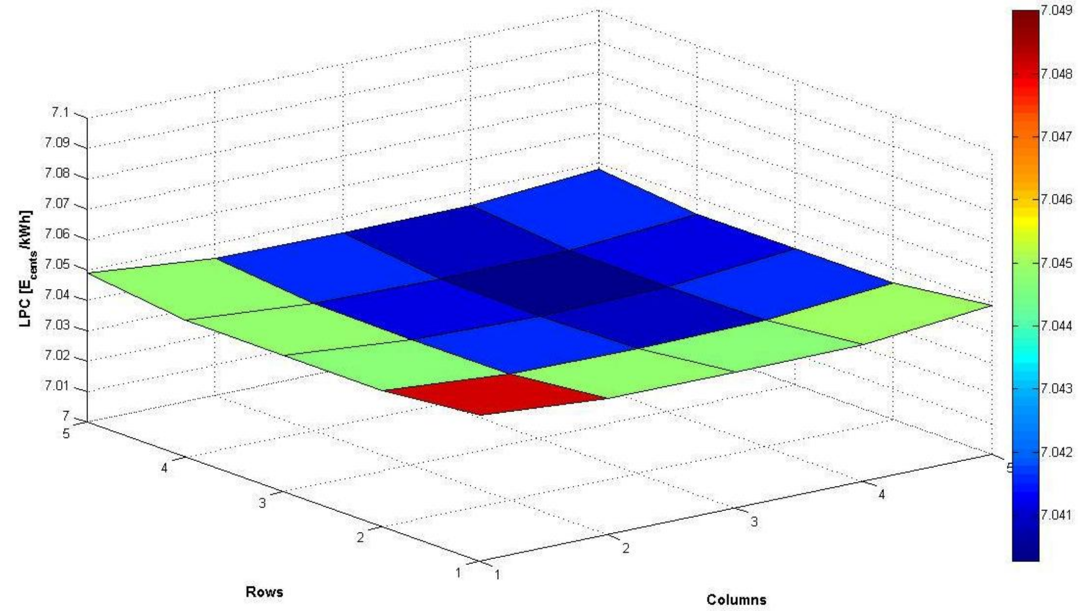


Figure 4.16: *LPC estimation for the removal of individual wind turbines*

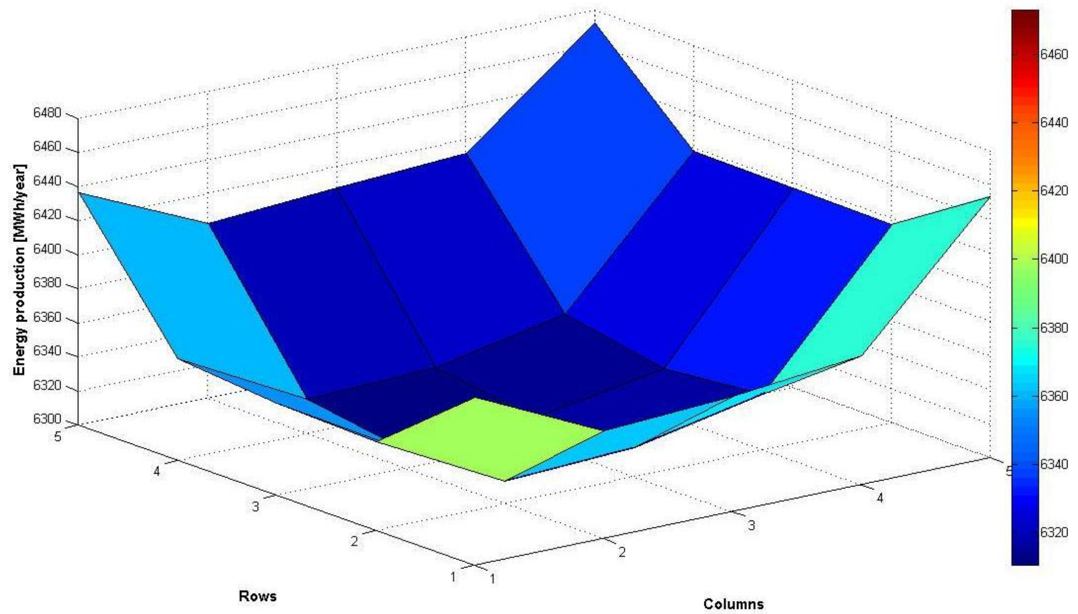


Figure 4.17: *Annual energy production per turbine in a 25 wind turbines farm*

CHAPTER 5

Dual- and Multi-combinations results

In this chapter of the report the results obtained regarding the LPC of the offshore wind farm when more than one type of alterations occur simultaneously. In the previous chapter were presented the effects that single variations have on the wind farm performance, both in terms of energy generation and production cost. Thus, has been shown that the movement of the first and fifth columns of the wind farm reduce the estimated LPC value while the individual displacement of certain wind turbines can have a positive effect, yet a minor one.

The description of the chapter outline follows. First, the results relevant to the individual movements of the wind turbines of the farm are discussed. Later on in this chapter are presented the results obtained by combinations of individual wind turbine movements and relocations of wind farm's columns. Finally, the case of the Horns Rev offshore wind farm is researched.

5.1 Individual wind turbines movement

In section 4.7 it was shown that several solutions for the corresponding design variables matrix exist, leading to reduced LPC values. Even though the improvement on the LPC is low an optimization window is evident. In this section first a deterministic approach is investigated in order to improve the LPC. Aiming to research whether or not the positive effects of individual turbines' movement are added, the positions suggested as best solutions in section 4.7 are combined and used simultaneously.

The second paragraph of the section includes the results obtained by a stochastic approach that was followed. This specific analysis is based on random movements of the wind turbines and investigates the possibility that totally random offshore wind farm layouts may be more effective in terms of produced energy cost.

5.1.1 Deterministic approach

In the deterministic approach is attempted to reach a lower LPC value for the offshore wind farm by creating a layout which combines the best solution for each individual wind turbine. The optimum positions for the turbines are included in the solution matrix in section 4.7. As it is discussed there, the proposed solution matrix contains some double-listed values. In particular $T_{(1,1)}$ coincides with $T_{(2,1)}$, $T_{(1,5)}$ coincides with $T_{(2,5)}$, $T_{(4,1)}$ coincides with $T_{(5,1)}$ and $T_{(4,5)}$ coincides with $T_{(5,5)}$. Therefore, for each pair of wind turbines placed in the same position an alternative location should be found for one of them. The wind turbine that changes proposed solution is selected on an estimated LPC basis. Thus, from Figure 4.15 the positions for each pair of turbines, having the same proposed by the code coordinates, are selected which lead to the arrangement with the lowest LPC. This procedure generates the following positioning matrix for the turbines of the offshore wind farm:

$$Positioning\_Matrix = \begin{bmatrix} (-470,330) & (470,330) & (1880,0) & (3290,330) & (4230,330) \\ (-470,990) & (940,660) & (1880,660) & (2820,660) & (4230,660) \\ (-470,1650) & (940,1320) & (1880,1320) & (2820,1320) & (4230,990) \\ (-470,1980) & (940,1980) & (1880,1980) & (2820,1980) & (4230,1650) \\ (-470,2310) & (470,2310) & (1880,2640) & (2820,2640) & (4230,2310) \end{bmatrix}$$

I can be seen that $T_{(2,1)}$ is relocated at $(-470,990)$m, $T_{(2,5)}$ is now placed at $(4230,660)$m, $T_{(4,1)}$ is moved at $(-470,1980)$m and $T_{(4,5)}$ is positioned at $(4230,1650)$m. Figure 5.1 illustrates the layout that corresponds to the aforementioned positioning matrix.

The differences between the original layout and the modified layout are not limited to the wind turbines that were mentioned previously. As it is discussed also in section 4.7, some more general trends can be noticed. Thus, the wind turbines located at the first and fifth column of the wind farm (i.e, $T_{(:,1)}$, $T_{(:,5)}$) tend to increase their separation distance while the turbines positioned at the first and fifth row (i.e, $T_{(1,:)}$, $T_{(5,:)}$) move towards the second and fourth row respectively. The latter is a consequence of the reduced cable cost and electric energy losses which result by the decrease in the separation distance while the former influence positively the energy production without a significant effect in the cable cost.

The LPC which result from the modified layout is 6.92€$_{\text{cents}}$/kWh while the original layout has a value of 6.94€$_{\text{cents}}$/kWh. Hence, a decrease of close to -0.4% can be noticed. Although, this drop in the LPC is minor, it is better than the mean decrease which is obtained by the individual movement of wind turbines. From Figure 4.14 can be seen that on average the movement of single wind turbines optimize the LPC by only $\sim -0.06\%$[1]. Even though the comparison of the resulted LPC with the mean value of the results obtained in section 4.7 provides some useful information, it is more helpful to compare the result with the summation of the LPC changes presented in the aforementioned section. Hence, it can be found whether or not the positive effects on the LPC of individual turbine movement have a cumulative behavior. Therefore, the summation of the new LPC reductions (i.e., the LPC values are shown in Figure 4.14) is subtracted from the original LPC. Thereby, the estimated LPC value is approximately 6.89€$_{\text{cents}}$/kWh, being -0.8% decreased. It is aforementioned that the new arrangement of wind turbines does not return such a low value. Therefore, can be said that the effect on the LPC of individual wind turbines' movement is not fully accumulative.

In order to explain the decrease in the LPC value of the modified layout the energy production should be investigated. Thus, Figure 5.2 illustrates the comparison between the energy production of the offshore wind farm when the original layout and the modified layout are considered. It can be seen that for certain wind directions (e.g., 260^o, 280^o) the original layout leads to higher energy production whereas the modified layout supports the energy production from other wind directions (e.g., 270^o, 90^o). However, the remark that can be made from the figure is that both the layouts have similar overall energy production (i.e., the modified layout leads to $\sim -0.03\%$ reduced energy generation) while in the third quadrant (i.e., from 180^o to 270^o which is the predominant one) a small increase in the energy delivered by the offshore wind farm with the modified layout can be noticed (i.e., $\sim 0.25\%$). As has been explained previously the main reason that no difference in the energy generation outcome is recorded lies on the wide initial separation distance for both the rows and columns of the wind farm. Therefore, when the wind turbines are positioned according to the original layout, they induce minimum wake effects on each other and no significant improvement is possible.

Following the aforementioned reasoning, the reduction on the LPC value for the modified offshore wind farm has different origin. Indeed, the analysis revealed that the cable cost and the electrical losses are decreased by -6.1% and -10.5% respectively. Before going into analyzing how these numbers stem from, it should be discussed why they differ, since both cable cost and cable losses are proportional to cable length. This can be explained by the fact that

[1]This percentage refers only to the layouts that are generated by individual movement of wind turbines and result in LPC values lower than 6.94€$_{\text{cents}}$/kWh which is the original estimation for the LPC

the electrical losses generated in the cables connecting the wind turbines strings to the offshore platform are not taken into consideration. However, in the determination of the electrical losses of the modified layout has been considered the difference of the variable $L_{plat-cable}$ with respect to the initial value. Therefore, approximately 0.94km more cable for the connection to the offshore station is used in the modified layout which in conjunction with the decrease in the length of the strings connecting the wind turbines affect the electrical losses as can be seen in equations (3.6) and (3.7). Overall, the total length of cables results in reduced electrical energy lost, and thus, the net energy generation of the wind farm is slightly increased by $\sim 0.02\%$.

As can be seen in equation (3.10), describing the cable cost, two variables exist that are connected to the separation distance of the rows and columns of the wind farm. Hence, in the modified layout the variable $L_{in-cable}$ is on average equal to 2.178km since the wind turbines on the first and fifth rows have moved towards the center of the wind farm, while the variable $L_{plat-cable}$ becomes 10.34km as the movement of the first and fifth columns further away from center of the farm is reflected in that value. The comparison and the variation of some key figures between the modified layout and the original layout can be found in Table 5.1.

Table 5.1: *Comparison of some key figures between the original layout and the modified layout*

	Original Layout	Modified Layout	Variation [%]
$L_{in-cable}$ [km]	2.64	2.178	-17.50
$L_{plat-cable}$ [km]	9.4	10.34	10.00
C_{cables} [M€]	4.7579	4.4695	-6.06
Energy production [$^{MWh}/_{year}$]	159301.0	159258.0	-0.03
Cable losses [$^{MWh}/_{year}$]	753.6882	674.8847	-10.46
Net energy production [$^{MWh}/_{year}$]	158547.8	158583.1	0.02

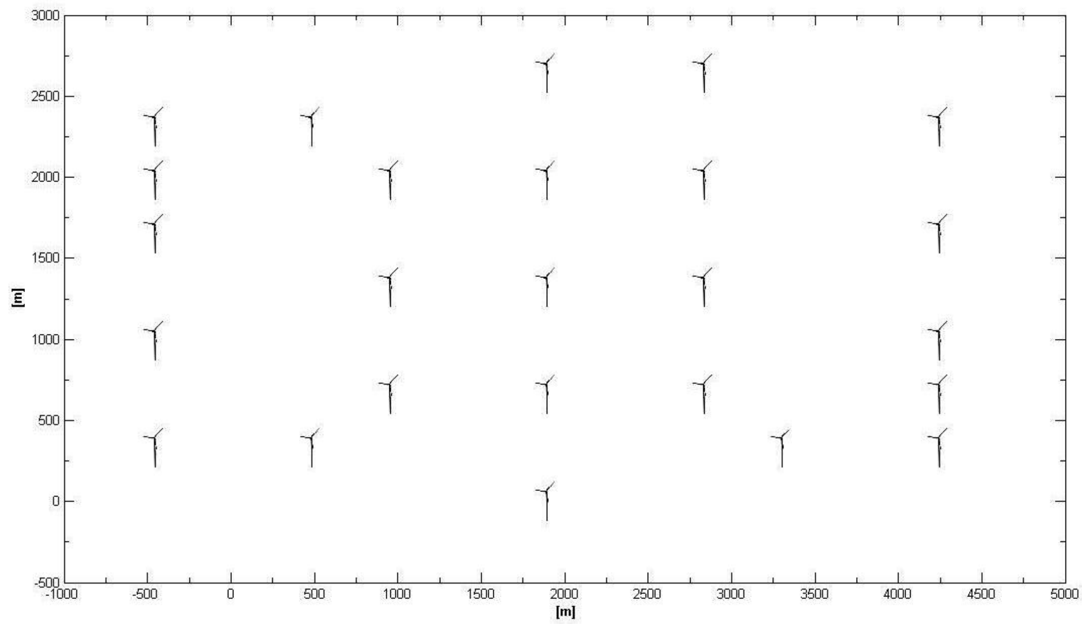


Figure 5.1: *Individual turbine optimum position-Layout of 25 wind turbines. The layout results when the optimum position for each individual wind turbine is considered as it is explained thoroughly in section 4.7 the original layout can be found in Figure 4.1*

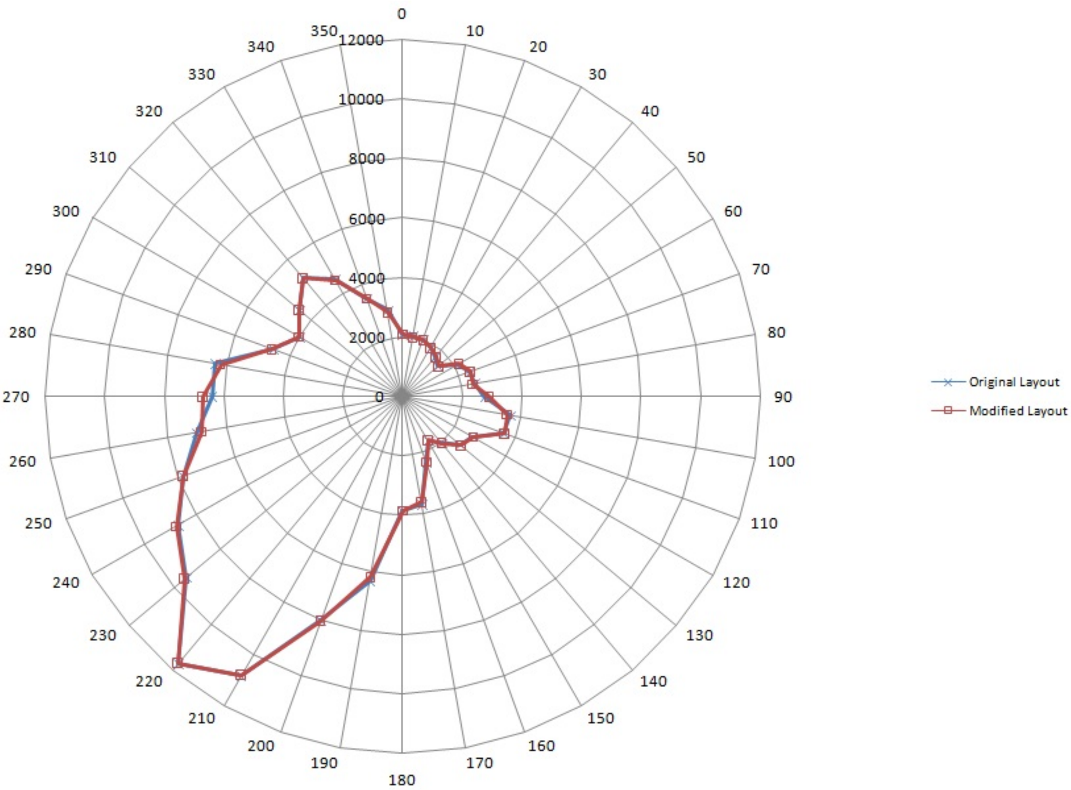


Figure 5.2: *Energy production comparison when the original and the modified layout are considered. The original layout is formed having $8.25D$ as separation distance for the rows and $11.75D$ as separation distance for the columns. The modified layout resulted from the best, in terms of LPC estimation, possible combinations of the individual wind turbine movement. The locations of the wind turbines can be found in the Positioning_Matrix. The energy production is shown in* $^{MWh}/_{year}$

5.1.2 Stochastic approach

As it is explained previously the stochastic approach aims in discovering the possibility that a better optimum LPC exists and can be reached through a random procedure. The introduction of the element of randomness intends to generate offshore wind farm layouts, similar to the ones proposed by the various algorithms described in section 2.2. Moreover, it looks for solutions that were not investigated by the deterministic approach since they are not included in the area of possible solutions (i.e., a graphical representation of a possible solution area can be seen in Figure 4.13). Furthermore, the combination of various variables simultaneously increases the complexity of the problem and makes the beforehand estimation of the LPC a difficult task. The stochastic approach tries to address this very issue by combining variables that otherwise might have been overlooked and would have slipped the attention. Therefore, in this section of the study the methodology that was adopted to deliver "random" wind farm layouts is explained followed by a statistical analysis and discussion of the research outcomes.

The element of randomness in the stochastic approach is introduced both in the specific wind turbine(s) that is/are about to be repositioned and what the coordinates of the exact position might be. On the other hand, the number of wind turbines that can be relocated and the range within the wind turbines can be positioned are defined. Therefore, the range within which each wind turbine can be placed is assigned as:

$$x_T - \frac{1}{2}sd_{col} + \frac{D}{2} < x < x_T + \frac{1}{2}sd_{col} - \frac{D}{2}$$

$$y_T - \frac{1}{2}sd_{row} + \frac{D}{2} < y < y_T + \frac{1}{2}sd_{row} - \frac{D}{2}$$

The position of the T^{th} wind turbines along the X- and Y-axis are represented as x_T and y_T respectively, while the sd_{col} stands for the separation distance between the columns and the sd_{row} stands for the separation distance between the rows. It should be noticed that the a term equal to $\frac{D}{2}$ is introduced in order to prevent the occasion that neighboring wind turbines coincide to each other. As it is straightforward the number of wind turbines that can change position goes from one up to the number of wind turbines that constitute the offshore wind farm. Figure 5.3 depicts an example of random movement of 25 wind turbines.

The stochastic process is described by the combination of the following design variable vector and design matrix:

$$Design\_Vector = \begin{bmatrix} R_{T1} \\ \vdots \\ R_{Nwt} \end{bmatrix}$$

$$Design\_Matrix = \begin{bmatrix} (x_{(1,1)}, y_{(1,1)}) & (x_{(1,2)}, y_{(1,2)}) & (x_{(1,3)}, y_{(1,3)}) & (x_{(1,4)}, y_{(1,4)}) & (x_{(1,5)}, y_{(1,5)}) \\ (x_{(2,1)}, y_{(2,1)}) & (x_{(2,2)}, y_{(2,2)}) & (x_{(2,3)}, y_{(2,3)}) & (x_{(2,4)}, y_{(2,4)}) & (x_{(2,5)}, y_{(2,5)}) \\ (x_{(3,1)}, y_{(3,1)}) & (x_{(3,2)}, y_{(3,2)}) & (x_{(3,3)}, y_{(3,3)}) & (x_{(3,4)}, y_{(3,4)}) & (x_{(3,5)}, y_{(3,5)}) \\ (x_{(4,1)}, y_{(4,1)}) & (x_{(4,2)}, y_{(4,2)}) & (x_{(4,3)}, y_{(4,3)}) & (x_{(4,4)}, y_{(4,4)}) & (x_{(4,5)}, y_{(4,5)}) \\ (x_{(5,1)}, y_{(5,1)}) & (x_{(5,2)}, y_{(5,2)}) & (x_{(5,3)}, y_{(5,3)}) & (x_{(5,4)}, y_{(5,4)}) & (x_{(5,5)}, y_{(5,5)}) \end{bmatrix}$$

Where, N_{wt} is the number of wind turbines that can change their initial position within the range that previously mentioned and $R_{T1}...R_{Nwt}$ are randomly selected wind turbine(s). Moreover, as N_{rep} is considered the number of repetitions that the process goes through. The analysis held regards a 25 wind farm, which is the one used for demonstrative purposes throughout this study, and $N_{rep_1} = 100$ and $N_{rep_2} = 1000$. Figure 5.4 shows the cumulative distribution function exported from the data obtained for $N_{rep_2} = 1000$. It can be observed that the smaller the N_{wt} is the steeper the curve is. Hence, when the number of wind turbines which change their positions randomly is relatively small the range of the LPC variation is narrow and close to the initial value. On the other hand, when the number of wind turbines repositioned is large the resulting LPC reaches higher values as the considered layout affects more drastically the energy production and the cable cost.

Figure 5.5 illustrates the lowest values per number of wind turbines moved when the process is executed for 10^2 and 10^3 repetitions. It can be noticed that both curves follow a similar trend. Until N_{wt} becomes 15 the increment rate is higher, whereas after this threshold both curves have a steady behavior. In general can be observed that the curve corresponding to the case that the process is repeated for 10^3 has lower values except for $N_{wt} = 21$. Moreover, should be mentioned that the line representing the outcomes of the stochastic process for $N_{rep_1} = 10^2$ and $N_{wt} = 2$ has a LPC value which is lower than the original one, while when $N_{rep_2} = 10^3$ similar outcomes are witnessed both for $N_{wt} = 1$ and $N_{wt} = 2$.

Finally, Figures 5.6 and 5.7 show the corresponding histograms for the two cases of N_{rep}. Figure 5.6 depicts the case that $N_{rep_2} = 1000$. As can be seen from the graph the most expected value of the LPC raises as the number of wind turbines which are relocated raises. The same trend can be observed also in Figure 5.7 which concerns the case that $N_{rep_1} = 100$. Thus, it can be said that when the number of wind turbines that change positions is small, then the LPC has a value close to the original one, if not lower. Overall, the mean value for the two processes is approximately 6.98$€_{\text{cents}}$/kWh, whereas, the median holds a value of 6.99$€_{\text{cents}}$/kWh.

Taking into consideration all the data presented previously in the section can be concluded that the stochastic process is likely to result in LPC values which are higher than the original one. As it has argued before the initial wide separation distance for the rows and columns of the offshore wind farm do not provide an optimization window since the array losses are already close to the minimum ones.

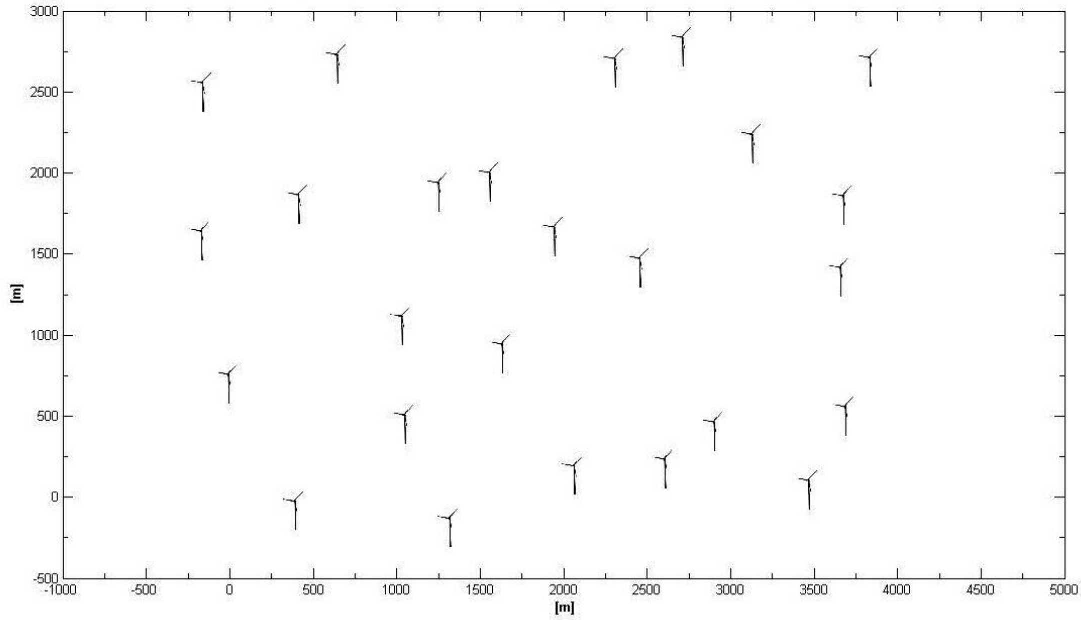


Figure 5.3: *Example for the layout when 25 wind turbines are randomly placed within the predefined range*

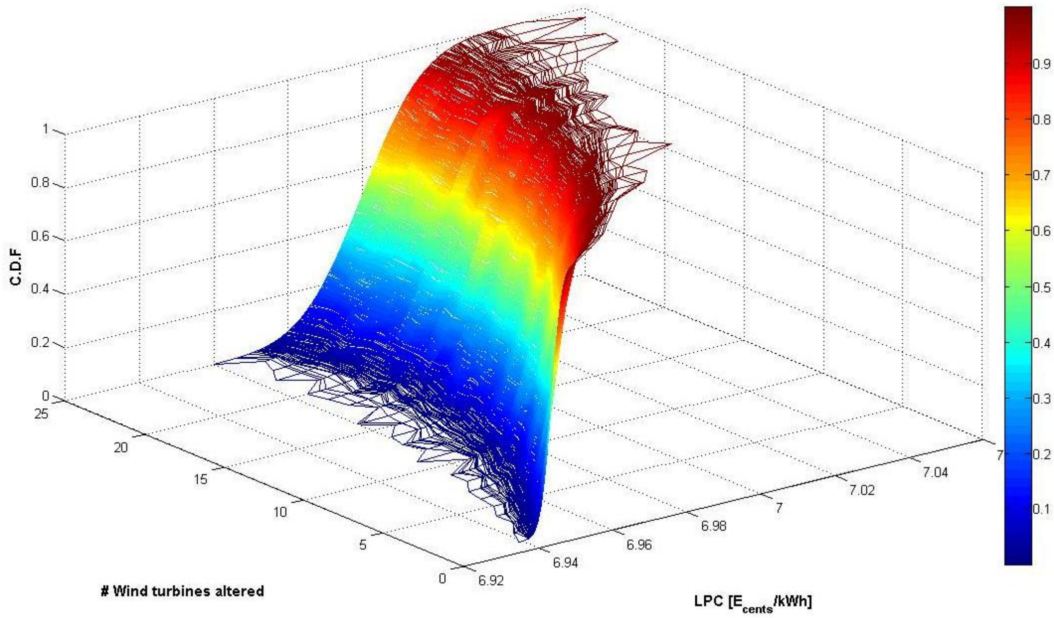


Figure 5.4: *Cumulative density function of the results obtained for the LPC of an offshore wind farm when the number of wind turbines that are allowed to reposition randomly increases from 1 up to 25*

5.2 Column movement and individual wind turbines movement

In section 4.4.2 is discussed that the movement of specific offshore wind farm columns create a layout which in turn results in better optima for the LPC value. Moreover, the repositioning of some wind turbines individually has similar effect. Therefore, in this section two approaches are presented focusing on researching the possibility for LPC improvement. The first paragraph is dedicated in the deterministic approach of the problem, since the layouts which

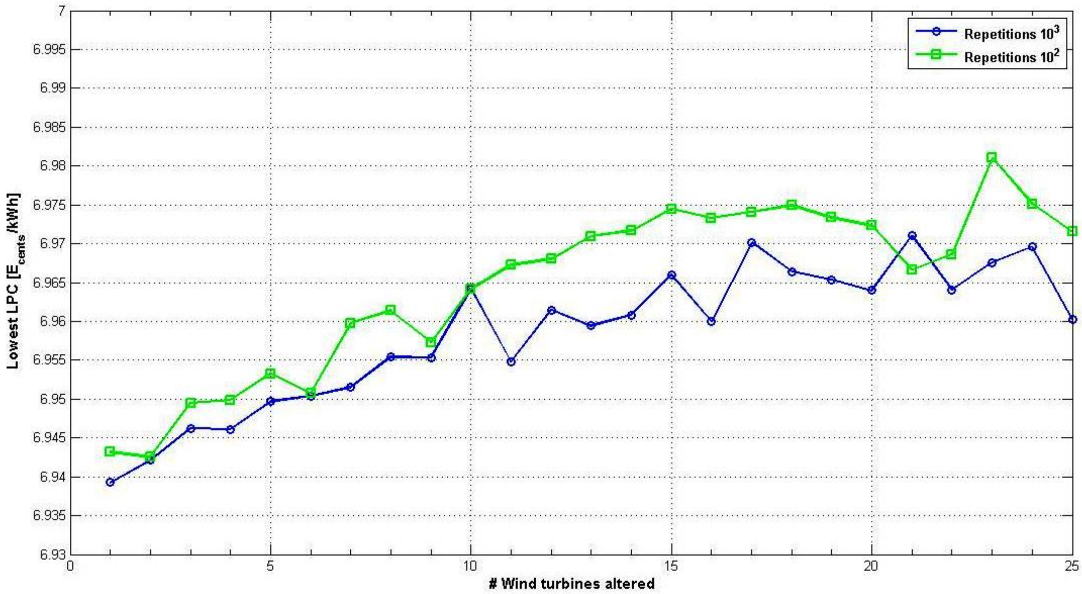


Figure 5.5: *Lowest LPC values generated by the stochastic process. It is illustrated the cases when a 25 wind turbines wind farm is used and the number of repetitions is set equal to 100 and 1000*

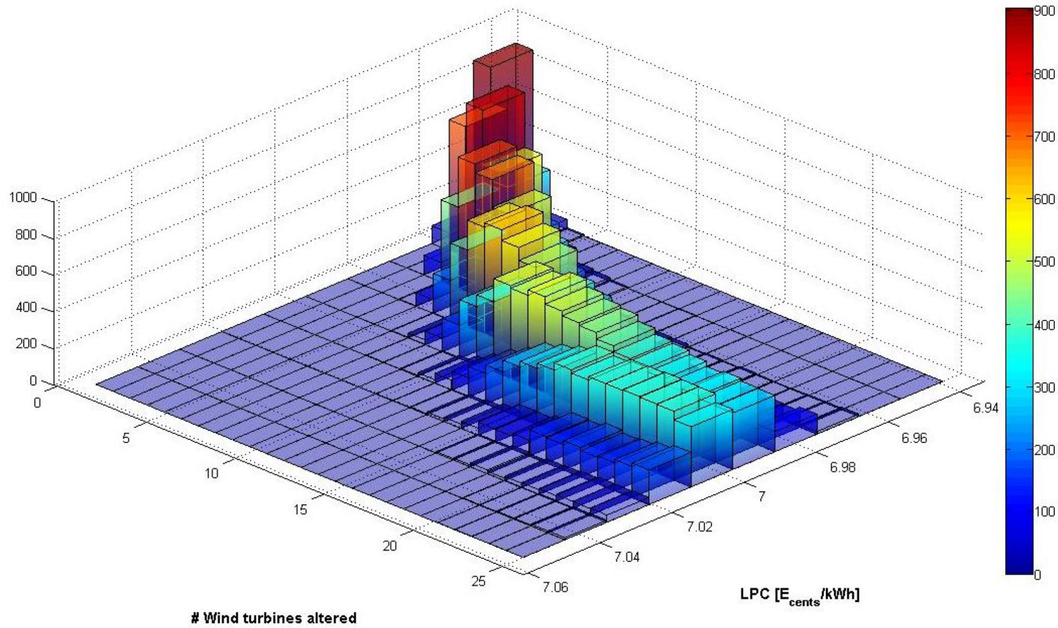


Figure 5.6: *Histogram per # wind turbines repositioned and LPC for 1000 repetitions generated by the stochastic process*

combine the best solutions for the column movement and the individual turbine movement are considered.

In the second part of the section is presented the analysis which has been done regarding the investigation of a better LPC optima by stochastically combining the movement of random columns and the movement of single wind turbines.

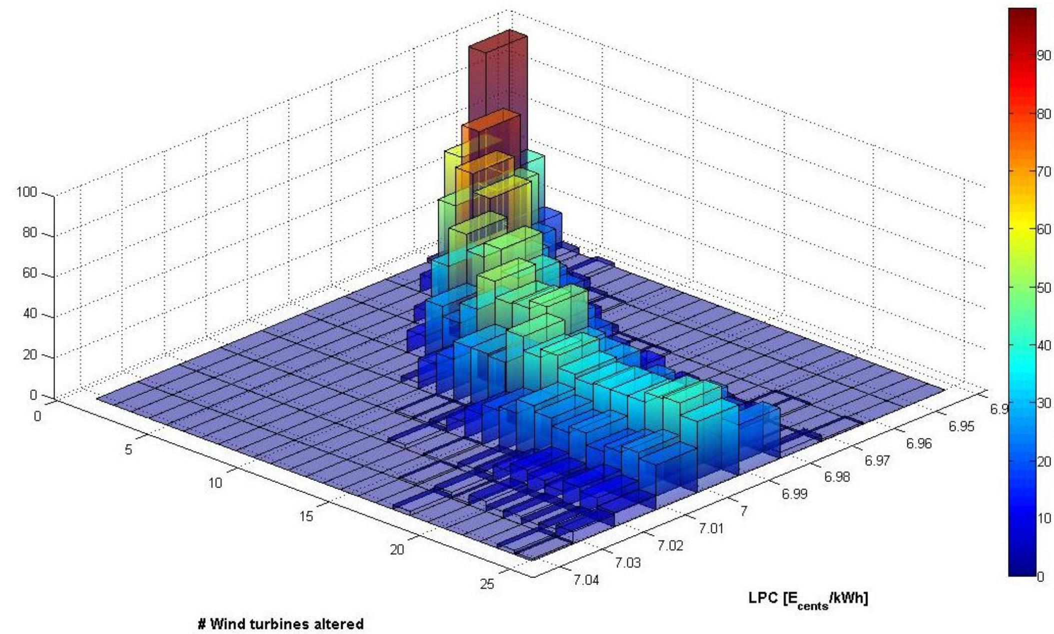


Figure 5.7: *Histogram per # wind turbines repositioned and LPC for 100 repetitions generated by the stochastic process*

5.2.1 Deterministic approach

The deterministic approach aims to combine the solutions obtained by the repositioning of complete columns and the movement of single wind turbines which result in improved LPC. In section 4.4.2 is shown that the layouts which have the first or the fifth column located 470m away from their initial position and thus, having a larger separation distance from their neighboring columns, achieve to increase the offshore wind farm energy production and consequently the LPC. Although, the displacement of the first and fifth column by 380m has a positive effect on the LPC, as it can be seen in Figure 4.7, it is minor than the one of the 470m-displacement and therefore it is not investigated further.

In section 4.7 is discussed that the movement of wind turbines can result in layouts that promote the improvement of the LPC. A closer look in the outcomes of the positioning matrix reveals that the positions proposed “incorporate” the displacement of the first and fifth column. However, it is proposed different than the original Y-axis coordinates for the turbines of these two columns. In the analysis that follows the wind turbines in the first and fifth columns have moved only along the X-axis, while they maintain their original y-coordinates. Finally, the combination of the solutions for the first and fifth columns movement and the individual wind turbine movement leads to the following positioning matrix:

$$Positioning\_Matrix = \begin{bmatrix} (-470,0) & (470,330) & (1880,0) & (3290,330) & (4230,0) \\ (-470,660) & (940,660) & (1880,660) & (2820,660) & (4230,660) \\ (-470,1320) & (940,1320) & (1880,1320) & (2820,1320) & (4230,1320) \\ (-470,1980) & (940,1980) & (1880,1980) & (2820,1980) & (4230,1980) \\ (-470,2640) & (470,2310) & (1880,2640) & (2820,2640) & (4230,2640) \end{bmatrix}$$

In Figure 5.8 can be seen the graphical representation of the offshore wind farm layout. The layout that is formed is very similar to the one that has been discussed in section 5.1 and is illustrated in Figure 5.1. This attribute is also reflected in the final estimation of the LPC which is 6.92€$_{cents}$/kWh. Therefore, this layout results in an approximately -0.5% reduced LPC value. In contrast with the previous case (i.e., presented in section 5.1) where the decrease is an effect primarily of the reduction in the cable costs, here an increase in the energy generation of the wind farm can be observed. A comparison of some key figures between the offshore wind farm with the original layout and the modified layout can be found in Table 5.2.

Given the displacement of the first and fifth column of the wind farm the energy production when the wind blows from 90^o and 270^o is favored. Therefore, according to Figures 4.2 and 4.4 the larger separation distance allows the wake wind speed to rebound, consequently resulting in increased energy generation. The higher energy production of the modified layout against the original layout can be observed in Figure 5.9. In addition, in the figure an elevated energy output for the cases of 0^o and 180^o is seen. The displacement along the X-axis of $T_{(1,2)}$, $T_{(1,4)}$ and $T_{(5,2)}$ is the reason for this energy step up. Hence, the movement of $T_{(1,2)}$ allows $T_{(2,2)}$ to operate in ambient wind speed condition, while $T_{(5,2)}$ is only affected by the wake of $T_{(1,2)}$[2]. Finally, it should be noted that for 220^o the energy delivered by the modified layout is approximately equal to the one of the original layout.

The aforementioned energy increase of the modified offshore wind farm layout in conjunction with the decrease in the cable costs, resulting by the shorter cables needed for each string, explain the overall drop in the LPC. As it is previously justified, the decrease of the LPC is minor due to the already very well optimized original layout, which by proposing wide separation distances for the the rows and columns, achieves to minimize the offshore wind farm "array losses".

Table 5.2: *Comparison of some key figures between the original layout and the modified layout which results by the movement of the first and fifth columns alongside with the relocation of certain wind turbines*

	Original Layout	Modified Layout	Variation [%]
$L_{in-cable}$ [km]	2.64	2.44	-7.50
$L_{plat-cable}$ [km]	9.4	10.34	10.00
C_{cables} [M€]	4.7579	4.7473	-0.22
Energy production [$^{MWh}/_{year}$]	159301.0	159733.25	0.3
Cable losses [$^{MWh}/_{year}$]	753.6882	753.1886	-0.1
Net energy production [$^{MWh}/_{year}$]	158547.8	158980.1	0.27

5.2.2 Stochastic approach

The purpose of the stochastic process regarding the movement of individual wind turbines alongside with the repositioning of complete columns of the wind farm is to search for better optima of the LPC, apart of the ones found by previously explained methods. It has been shown that both the movement of the first and fifth columns of the wind farm in conjunction with the relocation of specific wind turbines lead to improved LPC values. However, it is possible that a more effective combination of these two different types of movement might exist. Therefore, the stochastic process with the introduction of the element of randomness aims to check over this possibility. In order to investigate this possibility the appropriate design variables vector becomes:

$$Design\_Vector = \begin{bmatrix} R_{C1} \\ \vdots \\ R_{N_c} \\ R_{T1} \\ \vdots \\ R_{N'_{wt}} \end{bmatrix}$$

[2]This analysis is valid for the case that 0^o. However, similar behavior is observed for 180^o

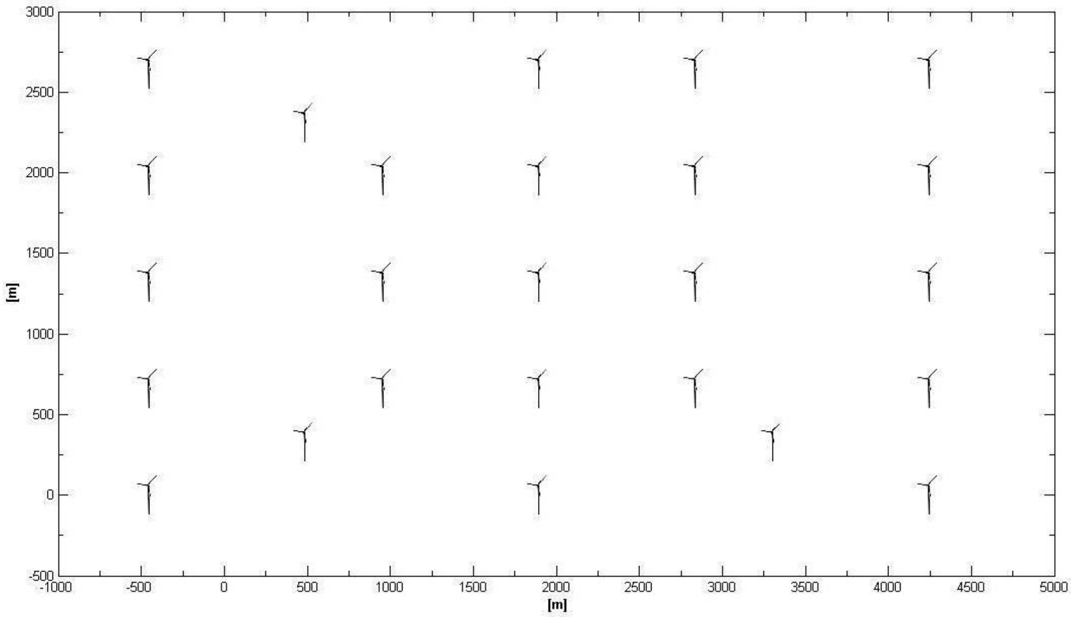


Figure 5.8: *The layout of the offshore wind farm when the first and fifth columns of the farm are relocated according to the solution found in section 4.4.2 while, $T_{1,2}$, $T_{1,4}$ and $T_{5,2}$ change positions as proposed by the positioning matrix in section 4.7. Mind the same, as the original, y-coordinates of the turbines in the first and fifth columns*

Where, N_c is the number of columns that can be moved along X-axis and can have values in the range of $[1, nc]$, being nc the total columns of the wind farm, N'_{wt} is the number of wind turbines that can change their initial position, being limited by $N_{wt} - N_c \cdot T_{string}$, while T_{string} is the wind turbines per sting of the wind farm. Moreover, $R_{C1}...R_{Nc}$ is/are randomly chosen column(s) of the wind farm and $R_{T1}...R_{N'_{wt}}$ is/are randomly selected wind turbine(s). The restriction set in the selection of wind turbines regards that any wind turbine belonging in a column that is about to be repositioned is not an eligible candidate. This restriction is considered because it is desired that the columns of the wind farm move as clusters along X-axis, while the initial separation distance between the rows is maintained. The range within which can a wind turbine move maintains the same as the one mentioned in section 5.1.2. The range for the column movement is $[a, b]$ while the a, b are defined as:

$$a = \begin{cases} X_{(1,R_{Nc})} - \frac{1}{2}sd_{col} + \frac{D}{2} & \text{for} \quad N_c = 1 \\ X_{(1,R_{Nc})} - \frac{1}{2}\left(X_{(1,R_{Nc})} - X_{(1,R_{Nc}-1)}\right) + \frac{D}{2} & \text{for} \quad N_c \neq 1 \end{cases}$$

$$b = \begin{cases} X_{(1,R_{Nc})} + \frac{1}{2}sd_{col} - \frac{D}{2} & \text{for} \quad N_c = 5 \\ X_{(1,R_{Nc})} + \frac{1}{2}\left(X_{(1,R_{Nc}+1)} - X_{(1,R_{Nc})}\right) - \frac{D}{2} & \text{for} \quad N_c \neq 5 \end{cases}$$

The number of repetitions that the process repeats is $N_{rep} = 1000$. Under the aforementioned specifications the lowest LPC value obtained by the stochastic process is 6.94€$_{\text{cents}}$/kWh. Thus, the minimum value resulted from the procedure is equal to the original estimation for the LPC. However, as can be seen in Figure 5.10 the possibility that such a value is obtained is very low. Moreover, Figure 5.11 illustrates the corresponding histogram obtained for the procedure. There, it is noticed that a value close to 6.99€$_{\text{cents}}$/kWh is more likely to result by simultaneous random displacement of random column(s) and random repositioning of random individual wind turbine(s).

5.3 Case: Horns Rev offshore wind farm

This section of the report is dedicated to the investigation of the case of the Horns Rev offshore wind farm. Horns Rev wind farm is built in the eastern North Sea, approximately 15km from the Danish shore. It was erected in 2002 and

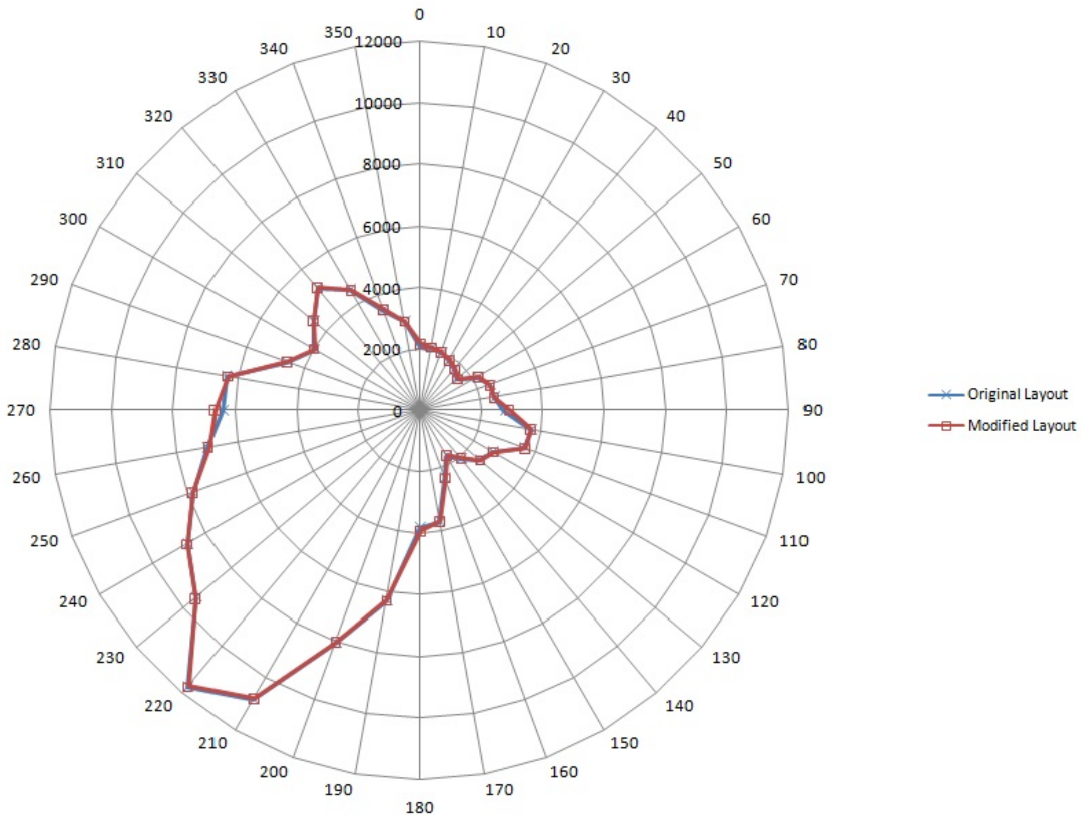


Figure 5.9: *Energy production comparison when the original and the modified layout are considered. The original layout is formed having* $8.25D$ *as separation distance for the rows and* $11.75D$ *as separation distance for the columns. The modified layout resulted from the best, in terms of LPC estimation, possible combinations of the individual wind turbine movement and column movement. The locations of the wind turbines can be found in the Positioning_Matrix. The energy production is shown in* $^{MWh}/_{year}$

at that time it was the offshore wind farm with the highest power capacity in the world. It is composed by 80 Vestas V80 2MW wind turbines which leads to a total capacity of 160MW and to around $600^{GWh}/_{year}$ of energy production [44]. Horns Rev offshore wind farm has 8 rows and 10 columns while the separation distance for both the rows and columns is $7D$. Figure 5.12 provides a graphical representation of the layout. In [20] it is discussed the subject of the Horn Rev offshore wind farm layout optimization by means of the Simulated Annealing algorithm, which is presented in section 2.2.4 of the present study. The resulting layout can be seen in Figure 5.13.

This section aims in exploring the possibility that a layout for the Horn Rev offshore wind farm exists, leading to improved LPC value. Moreover, the concluded optimized layout is compared to the one that is proposed in [20] and shown in Figure 5.13. In order to obtain an improved layout two different methodologies are investigated. First, a deterministic approach is presented in section 5.3.1. Hence, each wind turbine in the grid is relocated in several predetermined positions and afterwards it is evaluated whether or not an improvement in the LPC occurred. The stochastic approach, presented in 5.3.2, utilizes the element of randomness in order to look for layouts that perform better in terms of LPC. Thus, random wind turbines are randomly repositioned within a given range.

Prior to presenting the modifications to the offshore wind farm layout that might lead to a better LPC, some important aspects and properties, are discussed. Figure 5.14 shows the wind rose which is taken into account. It is comprised of 12 sectors opposed to the wind rose (i.e., it can be seen in Figure3.4) used in the simulation cases presented until this point of the report. The reason that less sectors are taken is due to the much higher computational time needed in any other case. As it is explained in section 3.3 the original optimization tool provides an option to use a 12-sector wind rose based on real data for the Horns Rev offshore wind farm. However, in order to maintain a relevance to the results presented so far it is chosen to use the data obtained from *Station 252-K13* [30]. An other

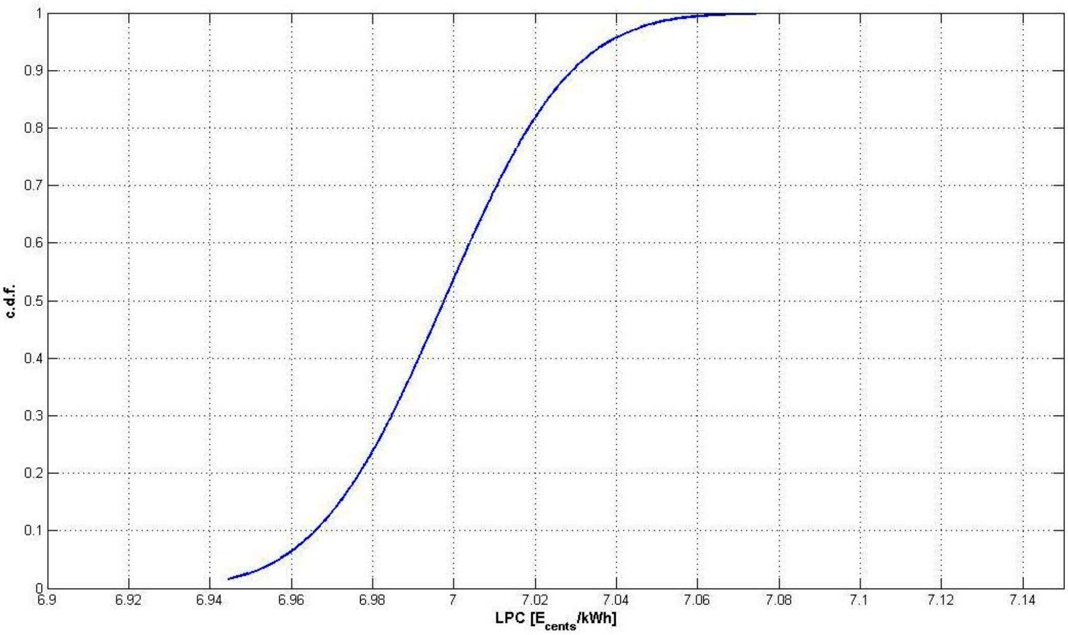


Figure 5.10: *Cumulative density function for individual turbine movements combined with column movements*

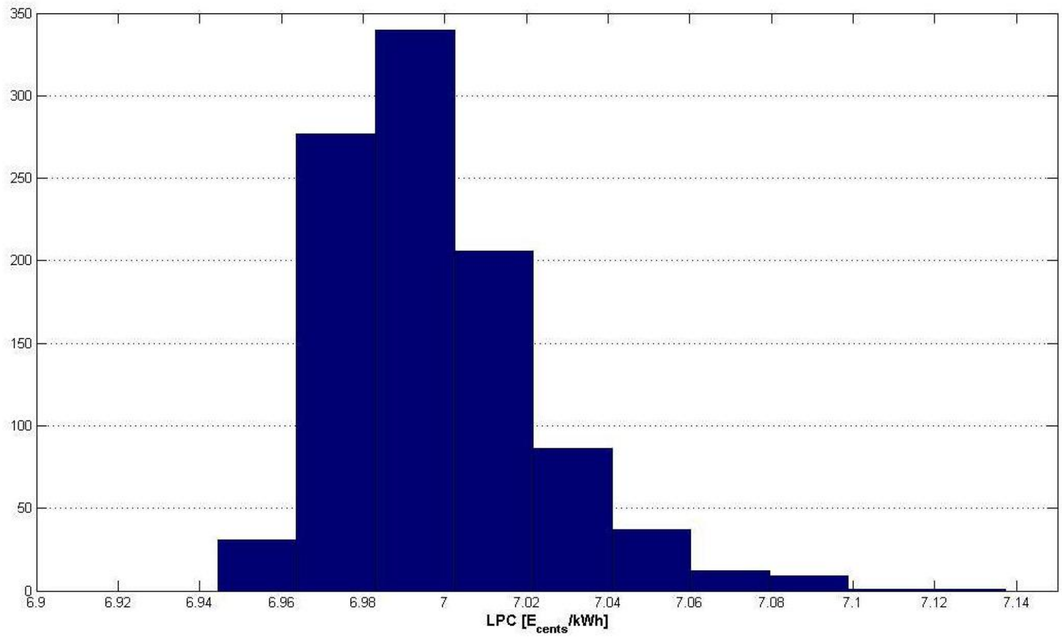


Figure 5.11: *Histogram for the stochastic process when individual wind turbines movement and column movement is considered*

compromise that is made is related to the cable pattern. In [44] can be seen that in reality, for every two strings of cables connecting the wind turbines there is only one cable connecting these string to the offshore platform. Although the same number of cables for the wind turbines interconnection is considered (i.e., there are 10 strings connecting the wind turbines to each other) there are 10 cables used to connect each string to the platform instead to 5 which is the real case in Horns Rev offshore wind farm.

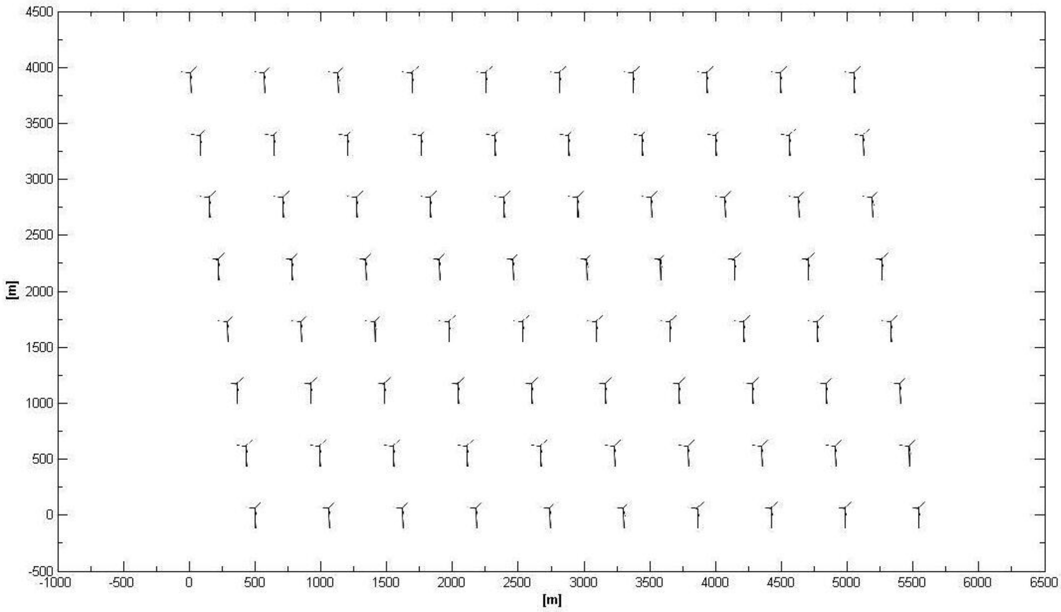


Figure 5.12: *The Horns Rev offshore wind farm layout*

5.3.1 Deterministic approach

The deterministic approach in the Horns Rev offshore wind farm layout optimization concerns the repositioning of each wind turbine to a predefined location. The positions that led to the lowest LPC values form the positioning matrix. The procedure is similar to the one described in the previous sections of the report having as main difference that the predefined positioning vector contains 32 locations instead of 40. This is the case in order to decrease the computation time needed for the simulations.Thus, the range which is divided in 32 positions, arranged similarly to the ones seen in Figure 4.13, equals to:

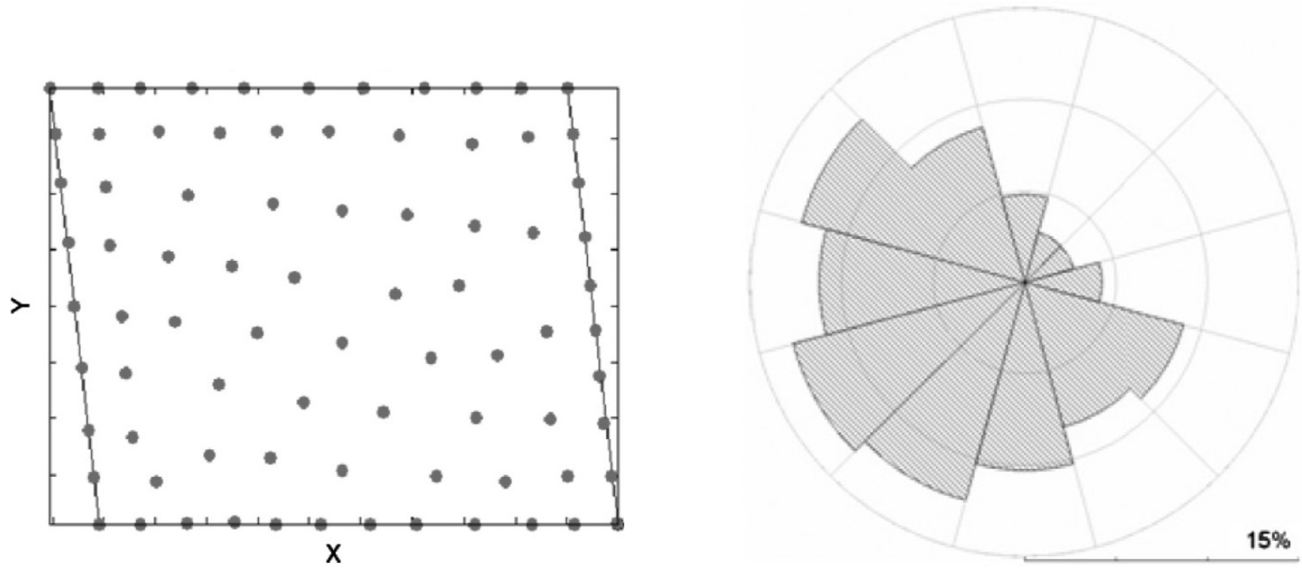
$$x_T - \frac{1}{2}sd_{col} + \frac{D}{2} < x < x_T + \frac{1}{2}sd_{col} - \frac{D}{2}$$

$$y_T - \frac{1}{2}sd_{row} + \frac{D}{2} < y < y_T + \frac{1}{2}sd_{row} - \frac{D}{2}$$

The design variables matrix becomes:

$$Design\_Matrix = \begin{bmatrix} (x_{(1,1)}, y_{(1,1)}) & (x_{(1,2)}, y_{(1,2)}) & \cdots & (x_{(1,10)}, y_{(1,10)}) \\ (x_{(2,1)}, y_{(2,1)}) & (x_{(2,2)}, y_{(2,2)}) & \cdots & (x_{(2,10)}, y_{(2,10)}) \\ \vdots & \vdots & \ddots & \vdots \\ (x_{(8,1)}, y_{(8,1)}) & (x_{(8,2)}, y_{(8,2)}) & \cdots & (x_{(8,10)}, y_{(8,10)}) \end{bmatrix}$$

In Figure 5.15 the best solutions for the individual movement of the wind turbines can be found. Moreover, Figure 5.16 illustrates the lowest LPC values which result by the individual movement of the Horns Rev wind turbines. As can be observed in Figure 5.16 the movement of a single wind turbine to its corresponding position, illustrated in Figure 5.15, has a positive effect on the LPC value. Thus, when the position with the most significant effect is considered, the initial LPC, listed in Table 5.3, drops to approximately 5.66€$_{cents}$/kWh from 5.67€$_{cents}$/kWh. Despite



(a) *Optimized Horns Rev layout* **(b)** *Considered wind rose*

Figure 5.13: *Optimized layout and considered wind rose for the Simulated Annealing algorithm [20]*

the decrease is small it is possible a better final result will be found when the optimum positions for all the wind turbines are considered simultaneously. In Figure 5.16 can be found that the lowest value for the LPC results by the repositioning of $T_{(1,8)}$ and $T_{(8,1)}$. In section 5.1.1 it is shown that when the best solutions for the movement of individual wind turbines are gathered in a positioning matrix, the generated layout performs better in terms of LPC in comparison with the original layout. Nevertheless, the individual positive effects on the LPC value do not have a fully cumulative behavior.

The best solutions obtained in the previous step form the positioning matrix for the wind turbines of the Horns Rev offshore wind farm. Some general trends are evident, which are noticed also in the case of the 25-wind-turbines farm. To begin with, the first and tenth columns of the wind farm are swifted outwards, creating more space between them and the neighboring columns. Secondly, the first and eighth row are located more closely to the following and previous row respectively, reducing the cable length. Furthermore, a free space is created in the center of the optimized layout while a tendency of certain wind turbines towards specific locations is also noticeable, resulting on closely positioned wind turbines. However, when the layout is composed by the wind turbines arranged as they are presented in Figure 5.15 the estimated LPC is higher than the original one. Some key figures between the original layout and the modified layout are listed in Table 5.3. It can be seen there that an increase of $\sim 2\%$ in the LPC is evident for the modified layout. The reason for that is due to the $\sim -2\%$ net energy production delivered by the modified Horns Rev offshore wind farm arrangement. Even though, the cable costs are decreased by approximately -6.5% and the cable losses are reduced by around -12%, as an output of the shorter cables needed for the interconnection of each string of wind turbines, their effect cannot overbalance the negative effect of the lower annual energy production.

A more close look in the annual energy production, which can be found in Figure 5.17, reveals that the modified layout leads to about $5^{GWh}/_{year}$ less energy generation when the wind blows from 180^o and 210^o. On the other hand, when the wind direction is 90^o and 270^o due to the displacement in the North-South direction of various wind turbines (e.g., $T_{(1,4)}$-$T_{(1,7)}$ and/or $T_{(8,1)}$, $T_{(8,2)}$, $T_{(8,8)}$) the separation distance between downwind turbines is larger, and thus, according to Figure 4.4 the wind speed regains a value closer to the ambient one and consequently the energy generation raises.

Figure 5.18 shows the annual energy production estimation for each wind turbine. The wind turbines when the original layout is considered generate energy which is depicted in Figure 5.18a and as can be observed have values that expand in a smaller range. Thus, the wind turbines located in the center of the Horns Rev wind farm produce approximately $5800^{MWh}/_{year}$ while the wind turbines positioned closer to the perimeter of the farm have

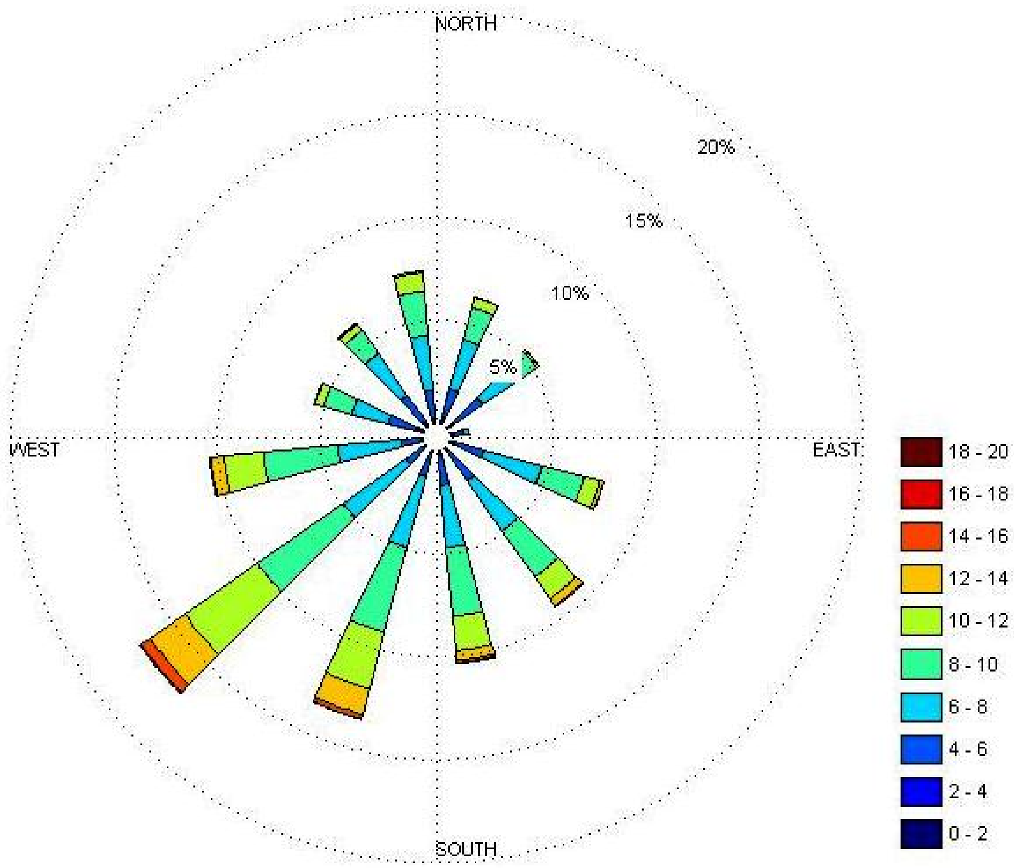


Figure 5.14: *Wind rose with 12 sectors which is used in the calculations of Horns Rev offshore wind farm*

higher energy outputs which reach $\sim 6300^{MWh}/_{year}$. On the contrary the energy production, seen in Figure 5.18b, of the wind turbines positioned accordingly to the modified layout do not follow the same trend. Therefore, the range of the energy outputs is larger, expanding from $\sim 5300^{MWh}/_{year}$ up to $\sim 6300^{MWh}/_{year}$. The wind turbines at the center of the farm have increased their energy output, contrariwise in the original layout case they produce the lowest energy. Due to the minor separation distance between certain wind turbines of the first and second row, seventh and eighth row, second and third column and ninth and tenth column they have a shadowing effect on each other, not allowing the wake wind speed to rebound, thus producing low energy.

As it is discussed previously, unlike the case when a 25-wind-turbine farm is investigated, the deterministic approach for the optimization of the Horns Rev offshore wind farm layout does not result in an improvement for the LPC. Even though the individual movement of each wind turbine has a positive effect on the LPC, when all the wind turbines of the farm are repositioned simultaneously the estimated LPC is higher than the original one. In order to assess whether or not further optimization of the wind farm layout is possible a stochastic approach is adopted. Therefore, the approach attempts by introducing the element of randomness to address this specific question.

5.3.2 Stochastic approach

It is explained previously in the report that the stochastic process utilizes random wind turbines at random positions in order to search for a better offshore wind farm layout. This approach is referred to as *fully-stochastic approach*. In addition to the fully-stochastic approach in this section is introduced one more type of stochastic approach. Therefore, the *semi-stochastic approach* generates layouts for the Horns Rev offshore wind farm by combining solutions for the positioning of individual wind turbines which have been found by the deterministic approach. It is aforementioned

Table 5.3: *Comparison of some key figures between the original layout and the modified layout for the case of Horns Rev offshore wind farm. The modified layout results from the individual movement of wind turbines*

	Original Layout	Modified Layout	Variation [%]
$L_{in-cable}$ [km]	3.89	3.5953	-7.56
$L_{plat-cable}$ [km]	25.45	25.69	0.93
C_{cables} [M€]	13.5963	12.7373	-6.32
Energy production [$^{MWh}/_{year}$]	480370	469810	-2.20
Cable losses [$^{MWh}/_{year}$]	5247.1	4624.1	-11.87
Net energy production [$^{MWh}/_{year}$]	475122.9	465186.4	-2.09
LPC[€/kWh]	5.67	5.77	1.82

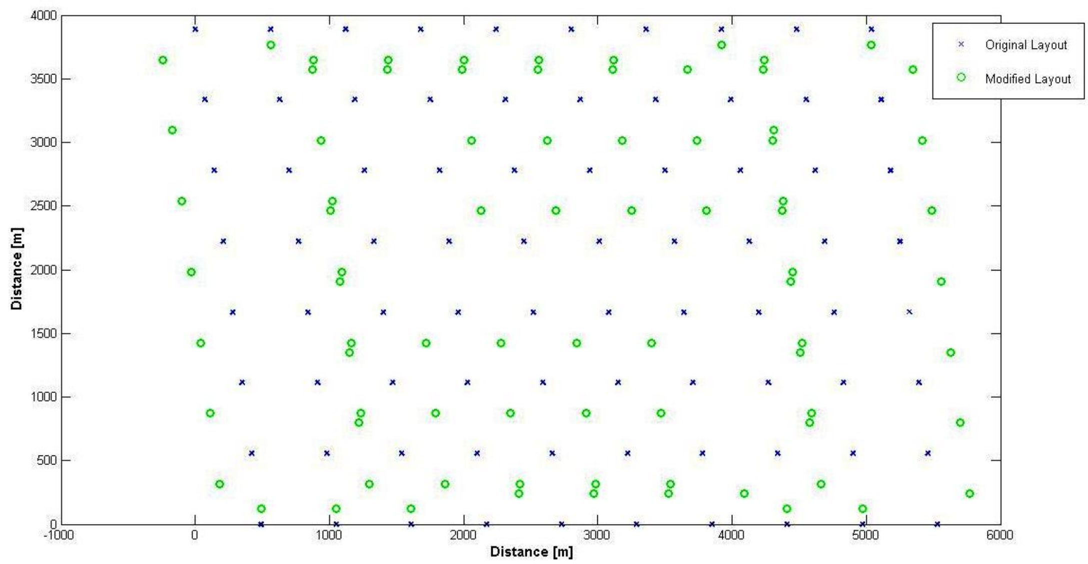


Figure 5.15: *The Horns Rev offshore wind farm modified layout. The figure depicts the suppositions of the best layout when one turbine at the time is repositioned while it also shows the modified layout. This layout results by the deterministic approach and stems from the combination of the best solutions obtained for each turbine individually*

that it is possible the deterministic approach to conclude in more than one solutions which result in an improvement of the LPC. This can be seen in Figure 4.15 where these solutions are illustrated for the case of a 25-wind-turbines offshore wind farm. In this section of the present study first the semi-stochastic approach is discussed, followed by the fully-stochastic approach.

Semi-stochastic approach

In order to compose the modified layout of the Horns Rev offshore wind farm which is discussed in section 5.3.1 the position of each wind turbine is based on the solution that individually returns the lowest LPC. However, the simulations revealed that this approach does not result in an improvement of the LPC. Therefore, the semi-stochastic approach creates layouts out of the solutions that were found in the deterministic approach but they are not the lowest ones. The process selects randomly a position for each wind turbine out of the "pool" of positions found by the deterministic process which return a lower than the original LPC.

It is chosen the semi-stochastic process to generate 100 layouts. In Figure 5.19 can be seen the corresponding

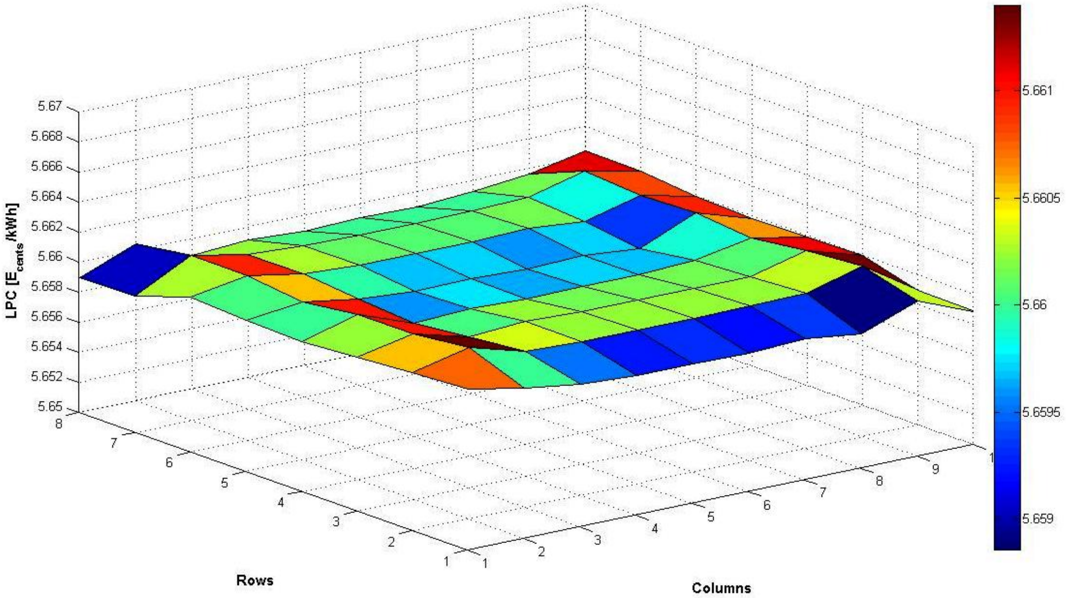


Figure 5.16: *LPC for the individual movement of Horns Rev offshore wind farm*

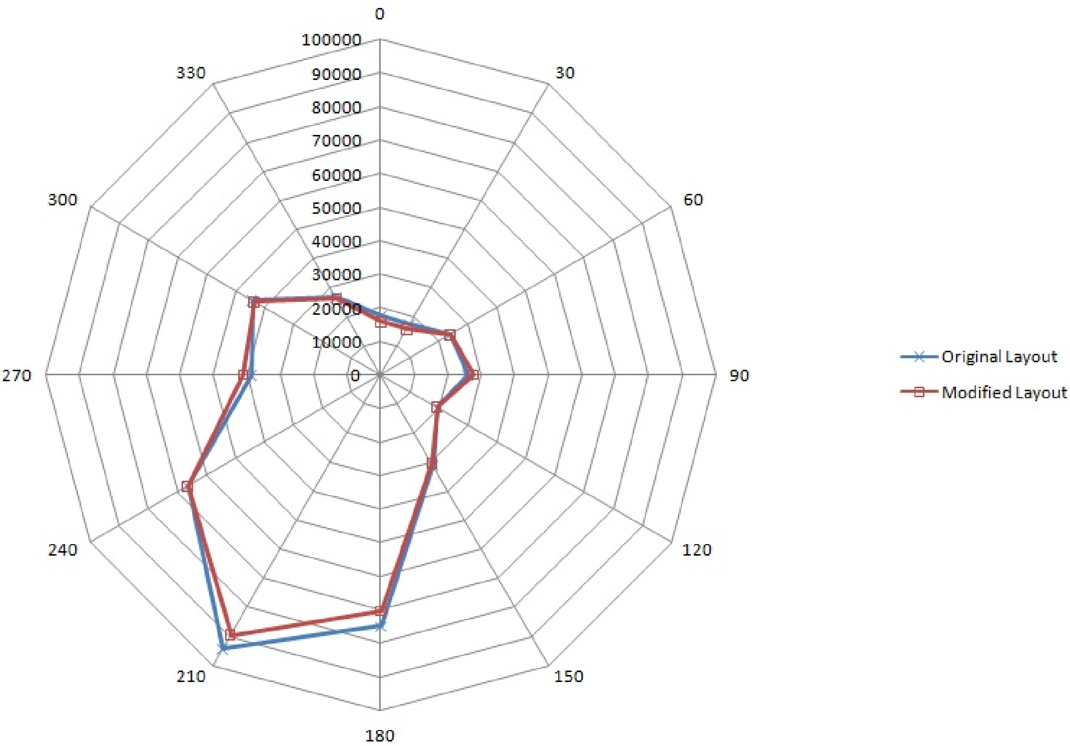
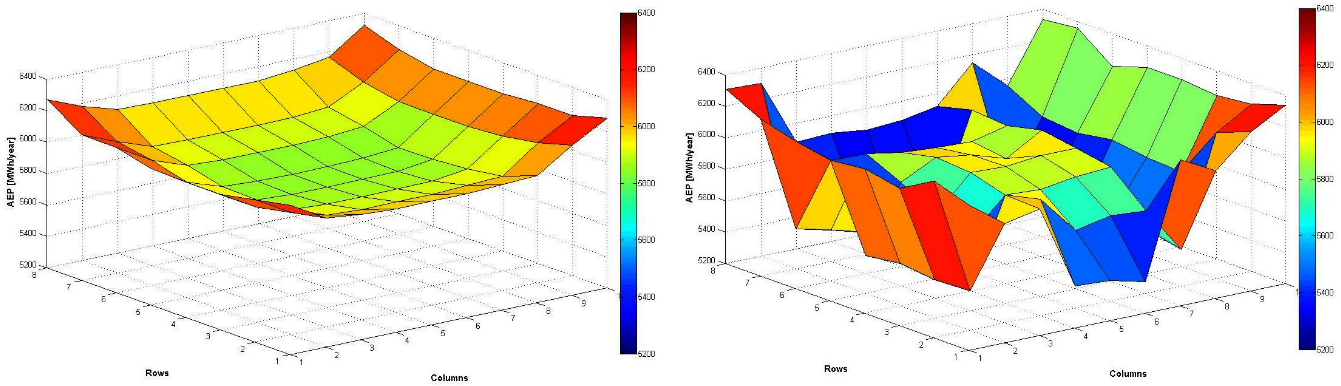


Figure 5.17: *Energy production comparison when the original and the modified layout are considered. The original layout is formed having 7D as separation distance for the rows and columns. The modified layout resulted from the best, in terms of LPC estimation, possible combinations of the individual wind turbine movement. The locations of the wind turbines can be seen in Figure 5.15. The energy production is shown in* $^{MWh}/_{year}$

histogram for the LPC calculation. It can be observed that 89% of the layouts derived by the semi-stochastic approach led to LPC estimations which are lower than the one generated by the original Horns Rev layout. As can be seen in



(a) *AEP per wind turbine-original Horns Rev layout* **(b)** *AEP per wind turbine-modified Horn Rev layout*

Figure 5.18: *The Annual Energy Production of each wind turbine for the original and the modified layout-Horns Rev case*

Figure 5.19 the lowest calculated LPC value obtained by the procedure is $\sim 5.62€_{\text{cents}}$/kWh. Figure 5.20 depicts the layout which corresponds to the aforementioned LPC value. Thus, the optimized, by means of the semi-stochastic approach, layout of the Horns Rev offshore wind farm appears to retain some general characteristics that are observed in the cases of the 25-wind-turbine farm as well as the modified, according to the deterministic approach, Horns Rev wind farm. Therefore, half of the turbines consisting the first and tenth columns of the wind farm have an increased separation distance from the wind turbines on the neighboring columns. Moreover, the majority of the first row wind turbines are moved towards the center of the wind farm. However, this trend is not evident in the wind turbines of the eighth row, which seem not to follow any specific pattern of movement.

Table 5.4: *Comparison of some key figures between the original layout and the optimized by the semi-stochastic approach layout for the case of Horns Rev offshore wind farm*

	Original Layout	Modified Layout	Variation [%]
$L_{in-cable}$ [km]	3.89	4.08	4.90
$L_{plat-cable}$ [km]	25.45	25.45	0.00
C_{cables} [M€]	13.5963	13.9473	2.58
Energy production [$^{MWh}/_{year}$]	480370.0	485399.2	1.05
Cable losses [$^{MWh}/_{year}$]	5247.1	5569.2	6.14
Net energy production [$^{MWh}/_{year}$]	475122.9	479830.0	0.99
LPC[€/kWh]	5.67	5.62	-0.86

The authors in [20] argue that the layout, shown in Figure 5.13, achieves a 0.33% increased annual energy production when a simplified model is used, while the increase reaches $\sim 1\%$ when *WAsP* software package is used for the calculations. However, it should be said that the authors in [20] have chosen to maintain fixed the boundaries of the wind farm. Therefore, it can be seen in Figure 5.13a that the wind turbines at the wind farm periphery are not allowed to relocate. In Table 5.4 are listed some key figures of the semi-stochastically optimized layout. As can be seen the net annual energy production derived by the optimized layout is higher, by approximately 1%, in comparison to the one produced when the original layout is considered. Moreover, the gross energy generation when the optimized layout is considered is augmented also by $\sim 1\%$, which is a value close to the one found in [20]. The difference noticed between the results regarding energy generation of this research and the one presented in [20] could be partially explained by the area constrain considered in the aforementioned research. Figure 5.21 shows the gross energy generation per wind direction. It can be observed that the optimized layout, likewise the modified by the deterministic approach layout presented in section 5.3.1, performs worse than the original Horns Rev layout in the predominant wind direction. However, for 90^o and 270^o due to the more scattered pattern of wind turbines' positioning, which leads to the "braking" of the rows formation, the optimized layout allows the wind turbines to operate in more favorable wind speed conditions. Therefore, despite the raise of the cable cost and cable losses, as a result of the longer cables utilized, the final estimation of the LPC is reduced by approximately 1%.

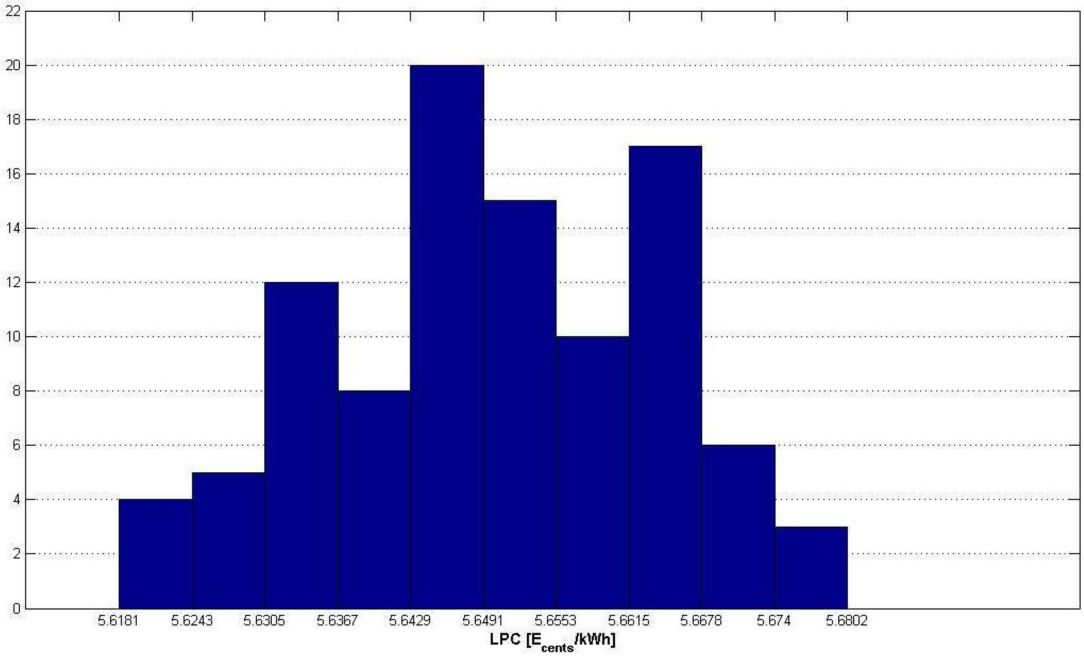


Figure 5.19: *Histogram for the semi-stochastic process-Horns Rev case*

Fully-stochastic approach

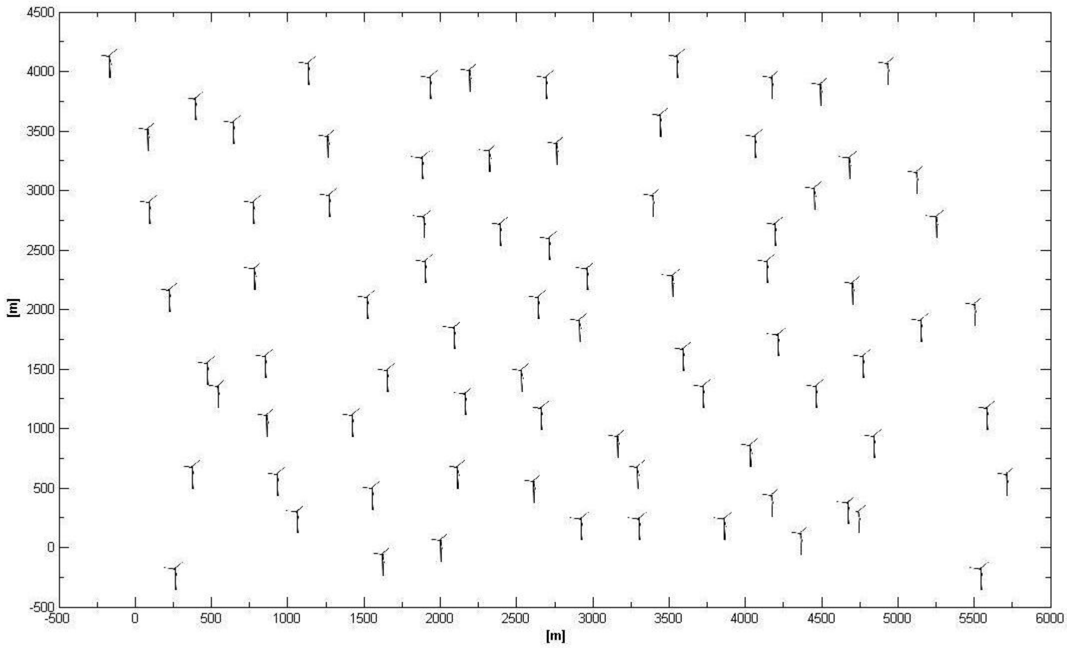
The fully-stochastic approach is similar to the stochastic approaches which are explained in previous sections of the report. In short, it utilizes random wind turbines, based on a predefined number, and repositions them in random locations. The difference to the semi-stochastic approach rests on that there is no "sampling pool" for the positions of the wind turbines. Thus, every wind turbine, which is selected randomly, can be assigned to a position within the range:

$$x_T - \frac{1}{2}sd_{col} + \frac{D}{2} < x < x_T + \frac{1}{2}sd_{col} - \frac{D}{2}$$

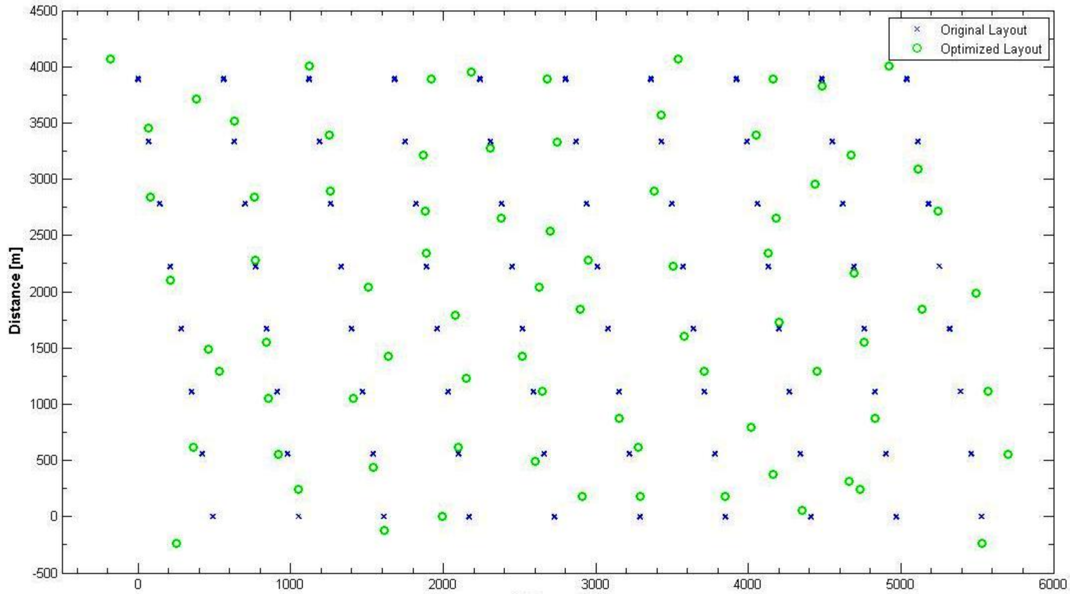
$$y_T - \frac{1}{2}sd_{row} + \frac{D}{2} < y < y_T + \frac{1}{2}sd_{row} - \frac{D}{2}$$

The fully stochastic process is described by the following design variable vectors and design matrix:

$$Design\_Vector = \begin{bmatrix} R_{T1} \\ \vdots \\ R_{N_{wt}} \end{bmatrix}$$



(a) *Optimized Horns Rev layout*



(b) *Original and optimized Horn Rev layout*

Figure 5.20: *Optimized layout obtained by the semi-stochastic approach-Horns Rev case*

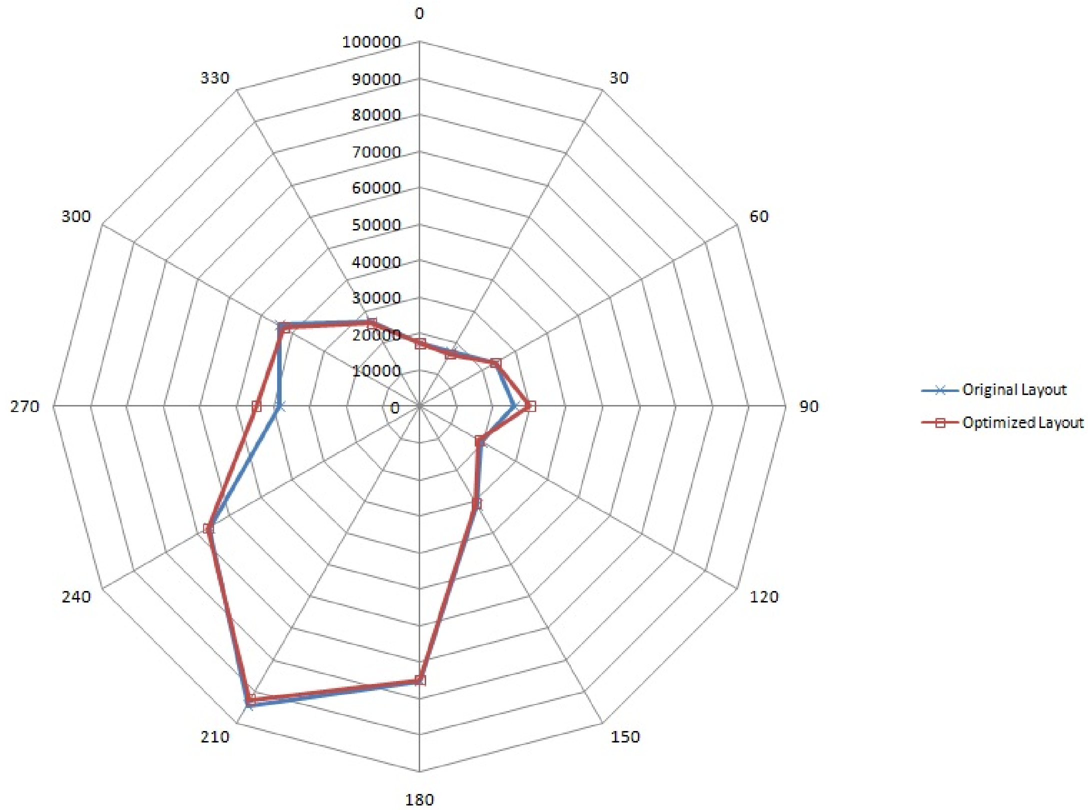


Figure 5.21: *Energy production comparison when the original and the optimized layout are considered for the case of Horns Rev offshore wind farm. The optimized layout resulted from the best sample, in terms of LPC estimation, of the semi-stochastic approach. The energy production is shown in* $^{MWh}/_{year}$

$$Design\_Matrix = \begin{bmatrix} (x_{(1,1)}, y_{(1,1)}) & (x_{(1,2)}, y_{(1,2)}) & \cdots & (x_{(1,10)}, y_{(1,10)}) \\ (x_{(2,1)}, y_{(2,1)}) & (x_{(2,2)}, y_{(2,2)}) & \cdots & (x_{(2,10)}, y_{(2,10)}) \\ \vdots & \vdots & \ddots & \vdots \\ (x_{(8,1)}, y_{(8,1)}) & (x_{(8,2)}, y_{(8,2)}) & \cdots & (x_{(8,10)}, y_{(8,10)}) \end{bmatrix}$$

The process was executed for $N_{wt} = [5, 80]$ with a step of 5, while $R_{T1}...R_{N_{wt}}$ are randomly selected wind turbine(s). Figure 5.22 shows the resulting histogram. The difference with the ones presented in section 5.1.2 can be observed. There, it is noticed that the more wind turbines that are repositioned the bigger the mean value and the spread of values become, whereas the fully-stochastic approach for the case of the Horns Rev wind farm shows a reverse relation between the number of wind turbines relocated and the expected LPC value. Thus, when 5 wind turbines are displaced the most expected value of the distribution is ~ 5.67€$_{\text{cents}}$/kWh, while when the number of wind turbines increases to 80 the most expected value returned by the process is ~ 5.62€$_{\text{cents}}$/kWh.

Figure 5.23 illustrates the cumulative density function per number of wind turbines allowed randomly repositioned. The results shown in Figure5.4 suggested that the probability to obtain a better LPC value from the movement of few wind turbines is higher than the one of more wind turbines. However, here the movement of 5 wind turbines returns a probability of $\sim 1\%$ that the LPC will be lower than the original one. On the other hand, when 80 wind turbines are relocated the probability increases to $\sim 76.4\%$. Since the effect of fewer wind turbines' movement on the LPC is less noticeable the cumulative density function is steeper for this case.

Finally, Figure 5.24 illustrates the minimum values for the LPC obtained for each execution of the fully-stochastic approach, having different number of wind turbines repositioned. The corresponding curve declines whereas in Figure

5.5 it is observed a rather ascendant trend. Moreover, could be added that all the LPC values plotted in the figure are lower than the original LPC value of Horns Rev offshore wind farm.

Overall, these differences seen in the aforementioned Figures might be explained by the unoptimized initial layout of the Horns Rev offshore wind farm. The layout of the 25-wind-turbines farm is optimized for the given wind conditions (i.e., the wind rose is depicted in Figure 3.4), prior to be researched for a LPC improvement possibility, having initial dimensions listed in Table 3.4. Hence, the more the initial layout is changed, by increasing the number of wind turbines moving randomly, the worse is the performance of the wind farm in terms of LPC. On the other hand, the separation distance for the rows and columns of the Horns Rev offshore wind farm are taken as they are in reality, thus equal to 7*D*. Therefore, the optimization process "sees" inherent conceptual issues in the design of the layout, and as a consequence the repositioning of more wind turbines leads to better LPC optima. However, it should be stated that the results of the fully-stochastic approach might vary if the models for the wind conditions and/or the net energy production change.

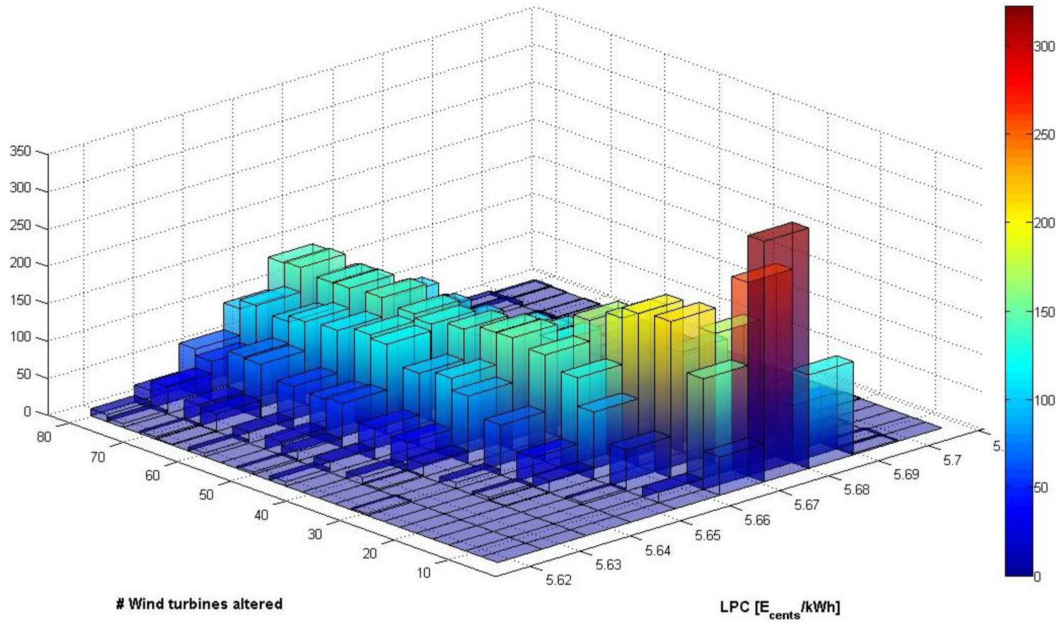


Figure 5.22: *Histogram per # wind turbines repositioned and LPC for 500 iterations generated by the fully stochastic approach-Horns Rev case*

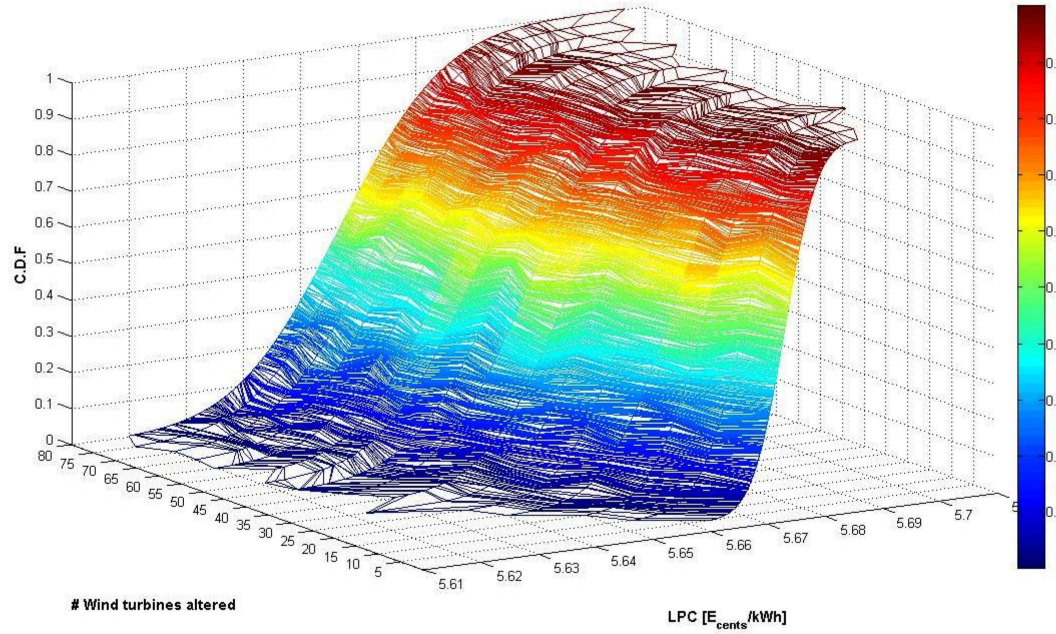


Figure 5.23: *Cumulative density function for the fully stochastic approach-Horns Rev case*

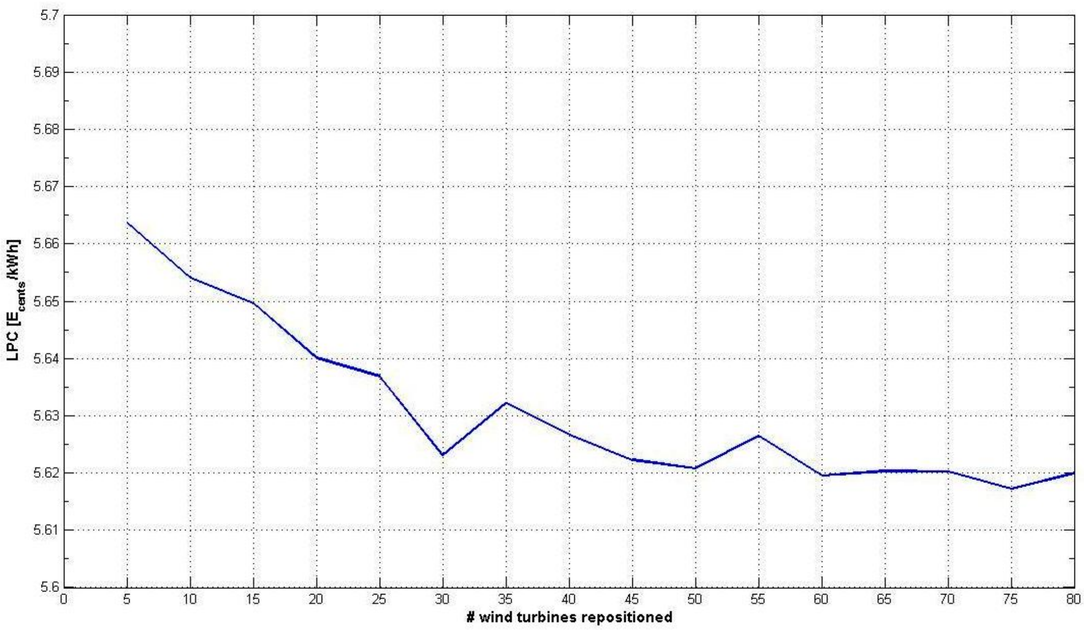


Figure 5.24: *Lower LPC values obtained by the fully stochastic approach per # of wind turbines relocated-Horns Rev case*

CHAPTER 6

Conclusions

This chapter of the report concerns the conclusions that can be drawn from the work derived from the research. Therefore, the main research question which asks whether or not "*more random and unconventional offshore wind farm layouts lead to better design*" is addressed. Prior to, answering this the research subquestions should be treated.

The first subquestion refers to the parameters which affect the design of a wind farm. The parameters that were identified in this study concern the technical issues. Therefore, such parameters might be the water depth, wave conditions, seabed characteristics and wind parameters, such as mean wind speed and/or annual distribution of wind direction. From the listed parameters in the current research a site specific wind rose is used.

The second subquestion concerns the possible optimization philosophies which exist and might be utilized. Such optimization algorithms are among others, the genetic, heuristic, simulated annealing and particle swarm algorithms. Due to the difficulties arisen by the development of such an algorithm, a different solution was adopted. Thus, some core elements of these algorithms were used. Therefore, the concept of "individuals", introduced by the genetic algorithms, was used, while the technique of removing wind turbines from the wind farm, utilized by the heuristic algorithms, was integrated into the optimization process.

The constrains that were identified are related with the minimum, maximum separation distance, as well as the step that is used in the optimization tool. Even though a possible limitation on the used area could provide a more realistic approach, such a restriction has not been considered. This was done so that the results after the optimization would be directly comparable to the initial ones and find out the magnitude of the improvement in the LPC value that could be achieved.

The fourth subquestion asks which models describe the behavior of the wind farm system. The models that were recognized as such, were firstly the array losses. They include the wake losses and the electrical infrastructure losses. Alongside with the aforementioned models, the cable costs and the LPC estimation, are modeled.

The model of the LPC estimation serves as the basis upon which the determination of the best solution is made. In the existing bibliography which concerns the topic of the wind farm layout optimization, either the energy production maximization or the cost of energy minimization is used. In the current study the solution of the LPC minimization was selected, primarily in order the comparison of the results to be possible before and after the optimization, and secondly because such a solution represents a more realistic case.

The sixth subquestion refers to the alteration possibilities that can be done to the grid of the offshore wind farm layout and lead to more unconventional layouts. In this study the categorization of layout rearrangements was conducted in two main groups. Thus, depending on the number of the existing variables, mono or multi variations may exist. Even though various results were obtained by the corresponding simulations, in this section only the most promising of them are discussed. Thus, looking at the case that a column of the offshore wind farm is repositioned, it can be seen that the displacement of the first and last columns resulted in a lower LPC. The minimum LPC value that was noticed is approximately -0.1%, compared with the original value. The reduction of the LPC stems from the higher energy production which results from the increased separation distance. The second case that led to a reduced LPC value was the test case of individual wind turbine movement. Overall, the repositioning of wind turbines located in the wind farm boundaries is recommended. Thus, the wind turbines forming the first and last columns it is suggested that should move further from the center of the farm, while some wind turbines located in the first and last row it is suggested that should reduce the separation distance from the neighboring rows. The movement of a single wind turbine revealed that a decrease of around 0.1% in the LPC value can be expected. The reduction of the LPC is produced by the increased separation distance when turbines of the first and last columns are moved. On the other hand, when turbines of the first and last rows are displaced, the source of the LPC reduction can be found in the decreased electrical losses in conjunction with the reduced cable cost.

Keeping in mind that the test wind farm is rather small and with big separation distances, the conclusions that can be drawn from the mono-variations might be that a minor LPC improvement can be achieved when the grid with equal spacings breaks. The more unconventional layout created by the movement of a wind turbines cluster or individual wind turbines increases the energy output by suggesting larger separation distances for the outer columns. Moreover, the net energy production increases when the separation distances for the outer rows reduce while such a design philosophy imposes lower cable costs. It could be said that the magnitude of the aforementioned LPC improvement would be bigger if an offshore wind farm with more wind turbines was considered. In such a case the larger space created between the outer columns, leading to higher wind speed, would be beneficial for more downwind turbines.

The second stage in the research was about determining how layouts generated by multi-variations perform. In order to investigate this, the combinations of the most promising mono-variations were considered.

When several wind turbines are relocated simultaneously a LPC which is approximately reduced by -0.4% can be obtained. It was noticed that this result does not demonstrate that the reduced LPC values suggested by individual wind turbines' movement add up. Moreover, it was argued that this result is mainly originated by the drop in the electrical losses and electrical cost of the new layout rather than the better performance in terms of energy production. The stochastic approach showed that the movement of more than two wind turbines simultaneously does not improve the wind farm LPC. Moreover, the stochastic approach proved to be sensitive to the number of times that goes through. It was shown that if the process is allowed to run more times, the resulted LPC values would be lower from the ones already obtained.

When a simultaneous displacement of the outer wind farm columns and individual wind turbines is considered, similar LPC results were obtained as the ones described previously. Thus, a drop of the LPC value close to -0.5% can be expected. On the contrary to the previous case that the reduction of the LPC was mainly a result of the cable cost and losses, in this case a minor increase of the energy production of the wind farm can be found. When a more random procedure was considered, it was revealed that there is a small possibility of generating a layout, which has a LPC value lower than the original one.

Based on the results mentioned for each case, some general conclusions can be drawn. Therefore, it might be concluded that the initial optimization of the tool made the further optimization of the layout a rather difficult task. The separation distances for the rows and columns of the offshore wind farm proposed by the tool were large. Thus, the original layout induced minimum energy losses by the wake effects. This might explain why in many of the test cases no improvement in the LPC value was seen. In the majority of the cases it was noticed that the decrease of the LPC was mainly a result of the cable cost and losses. Thus, the new layout suggested the use of shorter cables, reducing the corresponding cost and losses. Overall, when the small test wind farm is considered, it was noticed that the structured approach of unconventional layouts resulted in better values for the LPC in comparison with the more random approach.

The last case which was studied was the Horns Rev offshore wind farm. The Horns Rev case was investigated by applying a simultaneous movement of several wind turbines. It was shown that there are many possible layouts that lead to an improved LPC value. The best LPC result was approximately 0.9% lower than the original value. This reduction stemmed from the increased energy production of the optimized layout. Moreover, it was argued that the larger the number of wind turbines that move is, the bigger the probability that the LPC improve is. This comes in conflict with what was noticed in the small wind farm case study. The different behavior might be explained by the unoptimized initial layout of the Horns Rev offshore wind farm. The investigation revealed that further improvement of the LPC could be achieved if the process was executed more times.

The study of the Horns Rev wind farm showed that the optimization of a large wind farm with unoptimized initial layout can return a LPC which is reduced in a greater extent than the small wind farm case. The movement of most of the turbines of the first row towards the second one, thus, reducing the spacing, can be noticed. Moreover, in the optimized layout it is also suggested the displacement of wind turbines in the first and last columns further away from the farm's center.

These remarks, in conjunction with what was noticed in the previous cases, can be generalized with relative safety. A more unconventionally designed offshore wind farm layout, having the outer columns outward displaced and the outer rows inward repositioned, could result in a better LPC value. The reduced cable costs and the increased net energy production reflect in an approximately $0.5 - 1\%$ reduced LPC value.

In this study various assumptions were considered. Therefore, future research on this topic could try to withdraw these assumptions and uncertainties. Such recommendations for future work may include:

1. Review of the cable cost model. As it was revealed by the research the cable cost model in many cases defined the solution. Hence, it is an important layout optimization sub-function. Although as part of the current study some changes were done in order to update the values of the model, further investigation could provide more confidence in the model.

2. Review of the cable electrical loss model. Similarly to the cable cost function, the model simulating the energy dissipated as heat in the cables is of high importance. Therefore, a closer look on the model should be taken. In particular it would be helpful a sensitivity study regarding the specific characteristics of the cable, as well as the environmental conditions, such as soil temperature and/or burial depth.

3. Different wake model. In the present study only the Jensen wake model was used. Even though for the majority of the cases simulated here a different wake model is not expected to generate significantly altered results, it could provide better estimations for the energy production of the wind farm.

4. Implementation of a different optimization philosophy. The first chapter includes a discussion regarding the layout optimization algorithms. The implementation of one of them and the comparison of the results with the current results, would allow to draw better conclusions about the wind farm layout optimization problem.

5. Wind rose. The optimization of an offshore wind farm layout needs to take into account the meteorological conditions of the specific site. In this research a particular wind rose was used. Thus, all the results were based on these data. A sensitivity study for different weather conditions, would provide better insight into the layout optimization.

6. More realistic wind farms. Apart from the Horns Rev case, a 5x5 reference wind farm was used. The main reason was that the computational time increases significantly otherwise. However, the investigation of a larger, and thus more realistic, wind farm would provide a more sound answer to the main research question.

7. Introduction of some restrictions. These would aim at making the case studies more realistic. Such restriction might be a total area constrain for example. Therefore, the unrealistically large separation distances of the rows and columns may be avoided.

8. Different wind turbines. In most already built offshore wind farms the same type of wind turbines has been used in each farm. This was the case also in the current research. However, it would be interesting the investigation of the layout optimization for a wind farm consisted of different types of wind turbines.

9. Different operational characteristics. The optimization of a wind farm layout is based on the wake effect. However, the wake effect is a function of the upwind turbines thrust coefficient. In this study it was considered that each wind turbine has optimum operational characteristics. However, if the wind farm is considered as a system, the overall wake loss might be minimized by having each wind turbine operate in other than the individually optimum state.

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APPENDIX

This Appendix includes a more elaborated discussion regarding the social and environmental issues that should be taken under consideration during the design phase of an offshore wind farm.

Social Issues

In many researches the issue of the ”Not In My Back Yard” (i.e., NIMBY) is discussed extensively and considered as the main social constrain of the offshore wind farm development [7], [8], [45]. NIMBY has been defined as ”an attitude ascribed to persons who object to the siting of something they regard as detrimental or hazardous in their own neighborhood, while by implication raising no such objections to similar developments elsewhere”[46]. This constrain is augmented by the several issues for which the public acceptance wavers whether can affect positively or negatively the community. Some of these issues are [5], [47], [48]:

1. *Fisheries*. Erection of an offshore wind farm may raise potential concerns related to the fishing industry of the near communities since it can impose certain restrictions. Mainly such restrictions are applied so that the inner cabling and the transportation submarines cables be protected. Thus, it is possible that the fishing activity could be prevented inside the wind farm. However, if the cables are buried in a certain depth this effect can be minimized and the fishing activity can continue unhindered. Moreover, the separation distance of the wind turbines can affect the fishing activity, since the fishing vessels may be obligated to make certain maneuvers to avoid collision of the fishing equipment on the wind turbines [48].

2. *Maritime traffic*. There are minimal temporary impacts to navigation in the immediate vicinity of ongoing construction operations. If a grid pattern is about to be considered as a layout then the maritime traffic is facilitated compared with the case that the wind turbines are randomly scattered. In an offshore wind farm that is designed in a more ”conventional” way, the mariners can use the the straight courses, created by the design itself. Therefore, only the depth restriction applies in that case. Moreover, an offshore wind farm can provide additional aids for navigation, since the mariners can use the emitted sound to orientate themselves, while the wind farm can also be used as a point of reference [48].

3. *Recreation/Tourism*. It is possible that the construction of an offshore wind farm could harm the tourism of a local community. In [46] it is mentioned that there is some people, who stated that they are willing to switch to another beach in the case of an offshore wind farm construction on their casual beach. However, the percentage of people that express their interest to go and see themselves an offshore wind farm is much greater [46]. Moreover, there is a possibility of creating new services, such as recreational boat tours, visitor center, etc. that will push forward tourism in the area. Thus, it could be said that the construction of an offshore wind farm will

not affect negatively, if not positively, tourism in a community, keeping in mind that the expressed intentions are not as reliable as the actual behavior [46]. Finally, it should be mentioned that it is hard to quantify and assess the effect of visual and noise impacts on tourism (i.e., these issues are further discussed in section 2.1.3).

4. *Telecommunications*. People are mainly concerned of how and in what extent an offshore wind farm could case interferences in their electromagnetic appliances, such as TVs, mobile phones, etc.. Even though interferences are common in the case of onshore wind parks, they are relatively unusual in the case of offshore wind farms. In order a microwave transmission (e.g., cellular networks: 1-2GHz, TV: 50MHz-1GHz and radio broadcast transmissions: 100MHz (FM) [7]) to be interfered, a wind farm should be positioned between the transmitting tower and the receiving tower, which is hardly the case for any offshore wind farm. The reason for that is due to the line-of sight and point-to-point nature of the transmission. Especially, for the case of TV and radio a small interference may occur because of signal scattering [8]. Besides the aforementioned interferences wind farms can cause signal disturbances of radar.

5. *Electromagnetic interference effects of wind turbines*. By developing an offshore wind farm at a certain area, there is a possibility of obstruction to the microwave signals coming from telecommunication towers due to the existence of wind turbines. These signals could be coming from multi-purpose radars. Radars can serve weather monitoring, air-traffic control and navigation but also defensive functions (e.g., tracking down hostile forces, detecting missiles, etc.) [7], [8]. There are two main interferences, which are related to radar signals and caused by the rotation of wind turbines blades. Hence, this movement can create clutter interference and Doppler interference [7], [8]. Some examples of impacts of wind farms on radar systems follow, even thought there could be several implications [8]:

   - In some cases a signal can be confused as a storm due to the wind turbine reflection of energy.
   - The characteristics of the received data (e.g., velocity and spectrum width) can be contaminated, resulting in detection of meteorological phenomena such as tornadoes, storm motion and turbulence.
   - The distance that wind farm lies within is critical. When the distance is in the range of few kilometers the turbines can block a significant portion of the microwave radiation, thus causing “blindness” to the radar for objects behind the farm.
   - Air traffic control could be affected by the presence of wind turbines. Thus, airplanes flying over the wind farm can be “invisible” by the vertical “cone of silence” created by the turbines.
   - The Doppler shifts caused by the blade rotation can be perceived by the radar systems as moving airplanes, hence confusing the operators.

All the constrains mentioned previously are considered as some of the social issues that an offshore wind farm may cause to emerge. However, these are not the only ones since in [47] can be found that a remote wind farm can be considered as a subject of national defense.

Environmental Issues

Even though there is quite a substantial number of published researches investigating the environmental effects of wind farms, they are mainly orientated towards onshore wind farms. However, some of the constrains applied in that case (i.e., onshore wind farms) remain, in a different sense though (e.g., noise, visual impact), while others are suitable only in the offshore environment (e.g., impact on fish population). In [5], [7],[8], [47] the main issues identified as environmental constrains are:

1. *Fish*. Fish in the area is the kind of fauna which is affected in the most straightway manner. Fish population can suffer direct and indirect effects as a consequence of a wind farm construction [48]:

   - Habitat loss due to the preparatory work on the sea bed

- Mortality/Displacement from various reasons during commission phase of the project (e.g., increased vessel traffic)
- Elevated total suspended solids (i.e., short-term effect, mainly witnessed during the construction phase)
- Acoustical impacts due to several reasons (e.g., from the sledgehammers during installation of the wind turbines, while during operation from the vibration and sound emitted by them)
- Electromagnetic/Thermal emissions from the submarine cables
- Shading
- Alternations in currents/waves (i.e., a more detailed discussion of this topic can be found in a latter paragraph where the effects on *Hydrology* are discussed)

It is important for an offshore wind farm design group to account for all the issues listed above so that the impact of the project to the fish is minimized as possible.

2. *Birds*. The development of wind energy can affect birds in direct and in indirect ways. The directly induced effects on the bird population in a given site can be the following ones [5], [7]:

- Bird electrocution and collision mortality
- Changes to bird foraging habits
- Alteration of migration habits
- Disturbance to breeding, nesting, and foraging

The indirect effects that the offshore wind farms have on avifauna might be [48]:

- Disturbance, displacement or exclusion of fish from suitable habitat, thereby causing disturbance and psychological stress
- Long-term alteration of ocean currents, leading to changes in food distribution and availability
- Reduction in the visibility of the prey and or inhibition/cessation of photosynthesis caused by suspend sediments (i.e., this is mainly evident during construction)

Once again it should be stated that these are not the only effects that many suffer the birds from the offshore wind energy deployment in an area. However, the list provides an idea of parameters related to bird harassment.

3. *Benthos/Seabed life*. The total area occupied by the wind farm is a critical parameter for many different issues, which are analyzed in previous sections. When the impact of a given project to the seabed life is investigated then the area is maybe the only parameter that should be taken into consideration. Negative effects on benthic and selfish resources are directly related to the total area of sea floor needed for the project.

4. *Visual Impact*. Determining the visual impact of an offshore wind farm in not an easy task. The assessment of the visual effect is based on several factors. Some of these factors are [8], [49]:

- Distance of viewers from the project
- View duration
- Angle of view
- Panoramic versus narrow view
- Scenic quality of view
- Focal point within view
- Number of observers
- Viewer expectations,

- Visibility
- Weather conditions

The aforementioned factors are more site related ones. Additionally, visual impact can be outcome of factors related to specific characteristics of the project. Such factors could be [7], [49]:

- The number and design of turbines
- Layout of the offshore wind farm
- The color of the wind turbines
- The number of blades

It should be pointed that not all the factors have the same influence on the level of visual impact, being the distance of the project from shore and the contrast (i.e., induced by weather conditions and color) the most significant ones [49].

5. *Noise/Vibration*. The impact of noise is limited in a close range from the base of a turbine and thus it is hardly noticeable from people being on shore. However, it affects the mammals and fishes [50], not always in a clear way. There is a distinction based on the source of the sound [7], [8]:

   - Aerodynamically induced noise, due to the aerodynamic interactions between the blades and wind.
   - Mechanically induced noise, due to the movement of wind turbine's parts (e.g., gearbox, generator, etc.)

   Moreover, there are different levels of noise emissions depending on the project phase (e.g., construction, operation etc.) [50].

6. *Sediment soil*. This constrains is mainly encountered during the commissioning phase of the wind farm and it affected by [48]:

   - Installation of wind turbine foundations (e.g., monopiles, gravity based foundation, etc.)
   - Anchoring and positioning of construction vessels
   - Sediment coverage of cables, both for the collection system (i.e., inner cables of the wind farm) and the transportation system (i.e., medium voltage submarine cables to shore)
   - Scour protection applied to wind turbines and by vortices created around the wind turbine foundations

7. *Hydrology*. An offshore wind farm can affect also hydrology. The observed effects extend in a local scale and are mainly associated with the currents and waves [48].

   - Currents: The separation distance has an impact on tidal and wind-driven currents. However, the relatively small cross-section of the foundations over the wide separation distance does not have large-scale effects, since small eddies are dissipated shortly after the wind turbines.
   - Waves: Densely positioned wind turbines can cause significant large-scale impacts to wave conditions. Moreover, the foundation/pile diameter is crucial in the wave-impact assessment. If the diameter exceeds a certain limit then small-scale reflection and diffraction of waves is expected to occur.

   As it can be seen the layout of the wind farm has a major role on hydrology, since the separation distance between the rows and columns affects both the locally induced currents and waves.