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EXECUTIVE SUMMARY OF THE THESIS

Combined Optimization of Layout and Sector Management of Off-Shore Wind Farm

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

Renewable (RE) energy continues to grow unabated today. Despite the pandemic, it was the only energy source that saw an increase in demand in 2020, while demand for all other fuels decreased [1]. Technology advancements in recent years, such as improved forecasts of wind speed, coordinated control, as well as experience gained during the construction and operation of wind farms (WFs), have created new opportunities for developing more innovative and larger wind farms. These advanced and extensive WFs must also be coupled with more sophisticated control systems and larger constructions, resulting in a more challenging development of WFs. Different objectives should be considered simultaneously while mainly they could be contrasting, so there must be a compromise between them, and more design and engineering investigations are needed. Optimization is the tool for helping to investigate these different considerations. Optimization of WFs is one of those crucial tasks that is not trivial and leads to maximizing or minimizing some objectives in the WF, such as Annual Energy Production (AEP), cabling system, wake effect, and so on.

There are several reasons to place WTs as close as possible to each other. One is the necessity to put WTs sufficiently far from all habitation to reduce the visual impact and the noise experienced by locals. In addition, construction costs for access roads and the installation of cables at WF sites are crucial. Based on these economic factors, the optimal WT spacing is between 4 and 8 times the WT's rotor diameter [2], which is small enough to generate significant wake effects.

Wind conditions in the wakes of WTs are described by lower average wind speeds and higher TI than the free stream. These effects are amplified by overlapping the wakes of several WTs. Therefore by decreasing the effective wind speed, power production will be decreased, while increasing turbulence internsity (TI) could boost fatigue load. Therefore it is necessary to define a control strategy to tackle the problem of wake effects in a WF.

Since individual turbines in a WF interact with one another, if each turbine controls itself independently may not provide the optimal performance of the WF. Thus, controlling them at the WF level with set points adjusted according to each WT is desirable to comply with different operating conditions known as sector management. Optimization of a wind farm sector management refers to a trade-off between the energy production and losses resulting from the wake produced by WTs in order to minimize the energy cost. Therefore this strategy aims to minimize energy losses due to wake velocity deficits and fatigue loading caused by additional wake turbulence. This goal is achieved by defining a control strategy through which the operating modes of WTs will be changed according to different wind conditions (wind speeds and wind directions).

Moreover, the general objective for designing a WF is to obtain the highest power output for a chosen site. The placement of WTs inside a specified area means a WF layout. Thus, optimizing the WF layout refers to positioning WTs in a WF to maximize or minimize some objective functions, such as maximizing the energy production or minimizing the cost by considering different constraints that may include WF boundary, initial investment limit, etc. Therefore, it is possible to maximize the power output of WF for a specific design area using the layout optimization strategy.

The thesis aims to develop an algorithm for simultaneous optimization of the layout and sector management of off-shore wind farms. This integrated strategy increases the AEP of the plant (using layout optimization) and reduces the generated wake by the WTs (by sector management optimization). Thus the cost of producing energy could be declined by utilizing this combined optimization. This thesis begins with a study of each optimization scenario individually to validate them and see the benefits they can bring. Ultimately, they will combine to gain the advantages of both approaches.

2. Methodology

AEP is an essential variable when designing wind farms. It represents the energy produced by a wind farm during a given year; therefore, it is imperative to estimate this variable accurately. In addition to affecting electricity production, it also affects the income generated by a power plant. As a result, the AEP has become a popular objective function when solving WF optimization problems, or at least one that needs to be considered during this phase.

2.1. Site Condition

Access to precise wind modeling is vital to investigating a WF properly. This can be achieved by conducting an onsite wind measurement campaign, such as WAsP and WindPRO. It is possible to gain a lot of valuable and accurate data using wind measurement tools, leading to a more detailed analysis of wind farm power generation. The implemented tools can vary depending on WF location and topographic conditions. Generally, linear models, such as the conventional WAsP, work well for flat or moderately complex terrain; however nonlinear models, such as the WAsP CFD, are better suited to complex terrain.

In this thesis, different variables of wind resources that related to locations in the WF were obtained using a wind resource assessment tool. Firstly, an interested area is defined over the WF with a rectangular shape. This area then discretizes into several grids, which defines by a range of x coordinates $[x_1, x_2, \dots, x_N]$ and a range of y coordinates $[y_1, y_2, \dots, y_N]$.

Then, for a specific number of wind direction sectors defined by a range of far-field inflow wind directions $[\theta_1^\infty, \theta_2^\infty, \dots, \theta_N^\infty]$ relevant sector-wise values of wind resource variables, such as Weibull-A, Weibull-k, and frequency, could be found. Independent variables of inflow wind direction, such as elevation and overall mean wind speed, are also found. For any arbitrary location (x,y) in the interested area with any far-field inflow wind direction (θ^∞) these dependent and independent variables could be found easily using linear interpolation.

2.2. Wind Modelling

In order to provide realistic wind descriptions, wind measurements need to be used, and continuity of wind speed and direction is essential. After measuring the wind at the reference height, H_{ref}, the data are processed by using bins, In most studies, there is widespread agreement that the Weibull distribution can describe wind scenarios. Therefore, the wind data can be fitted into the Weibull distribution using the following equation:

$$P_{wb}(v, A_k, k_k) = \left(\frac{k_k}{A_k}\right)\left(\frac{v}{A_k}\right)^{c_k-1} \exp\left[-\left(\frac{v}{A_k}\right)^{k_k}\right] \quad (2.1)$$

where P_{wb} is the probability (frequency) density of occurrence for wind speed v, c_k is the scale parameter and A_k is the shape parameter.

By using the Equation (2.1), which is the function of wind speed, it is possible to find the probability of each wind speed and wind direction as follows:

$$\mathrm{P}\,(v_k, \theta_k) = f\,(v_w) \times f\,(\theta_k) \quad (2.2)$$

2.3. Wake Modeling

As mentioned, accurate modeling of wake effects between WTs in the WF is essential to investigate the wind field in WFs.Various wake models are established to investigate the wake effect quantitatively. They could be divided into two general categories: low fidelity model with low computational cost and high fidelity model with high computation cost. They all can predict the wake velocity deficits well; while the high fidelity models better describe the details of the wind flow field, they require much higher computational demands. On the other hand, since low-fidelity wake models are less computationally expensive, they are more suitable for solving wind farm design problems where wind flow characteristics are less critical.

The implemented wake model for this study is Jensen Wake Model. This is one of the earliest engineering models for calculating velocities in the wake of WTs, originating from the work of N. O. Jensen [3]. Using conservation of mass as a basis, the model describes a single wake that expands linearly downstream from the rotor plane. This expansion is a function of the wake decay coefficient, α. In reality, this coefficient depends on different aspects such as ambient turbulence level and atmospheric stability. However, it was empirically calibrated for the far wake based on measurements by Katic et al. (1986) [4]. The typical value of α is 0.04, which is often used for modeling sizeable off-shore wind farms, according to [5].

A WF consists of N_{WT} WTs, the WF layout is characterized by $X = [x_1, x_2, \dots, x_{N_{WT}}]$, $Y = [y_1, y_2, \dots, y_{N_{WT}}]$.Considering WT_i at location (x_i, y_i) and WT_j at location (x_j, y_j) for wind direction θ_k , the original Cartesian coordinates can initially be rotated to θ_k so that wind blows along with the new x' direction. If $x'_i \le x'_j$, WT_j is located the downwind of WT_i or at the same level, and therefore do not influence WT_i. If $x'_i > x'_j$, wind speed and wake zone radius behind WT_j and at the position where WT_i is located, expressed as V_{ij} and R_{ij}, are ruled by the following expressions:

$$V_{ij} = V_0\left[1 - \frac{\left(1 - \sqrt{1 - \mathrm{C_T}(V_0)}\right)}{\left(1 + \alpha\,(\mathrm{x'_{ij}} \,/\, \mathrm{R_r})\right)^2}\right] \quad (2.3)$$

$$R_{ij} = \alpha \cdot x'_{ij} + R_r \quad (2.4)$$

In this equation V_0 is the inflow wind speed, $\mathrm{C_T}(V_0)$ indicates the thrust coefficient of WT at wind speed V_0, α is the wake decay coefficient, $R_r = D/2$ represents the radius of the rotor and $\mathrm{x'_{ij}} = \mathrm{x'_i} - \mathrm{x'_j}$ is the distance between the two WTs along wind direction. Moreover, there is an area in WT_i where affected by generated wake of WT_j which is equal to the overlapping area of two circles with a radius R_r , R_{ij} and center distances $y'_{ij} = |y'_i - y'_j|$ or zero when it is not located downstream of WT_j .

$$A_{ij} = \begin{cases} A_{ol}(R_r, R_{ij}, |y'_{ij}|)\,, & \mathrm{x'_i} > \mathrm{x'_j}\,, \\ 0, & \mathrm{x'_i} \le \mathrm{x'_j} \end{cases} \quad (2.5)$$

According to the transversal distance between two circles, $d_{ij} = |y_i - y_j|$, the rotor of WT_i might be placed in the full wake, partial wake, or out of the wake of WT_j.

Based on the wake effects of two WTs described in these equations, the effective wind speed WT_i experienced can be derived based on the kinetic energy deficit balance assumption, as:

$$\bar{V}_i = V_0\left[1 - \sqrt{\sum_{j=1}^{N_{wt}} \left(\frac{A_{ij}}{A_r}\right)^2 \cdot \left(1 - \frac{V_{ij}}{V_0}\right)^2}\,\right] \quad (2.6)$$

Where $A_r = \pi R_r^2$.

It is noteworthy to mention that due to adding wake generated by running WTs, the effective wind velocity $\bar{V}_i$ could be lower than the upstream wind speed, which reduces the power production by WTs.

2.4. Turbulence Intensity

The turbulence intensity is one of the main characteristics of this study since it can regulate the sector management optimization defined in it. Thus this variable must be calculated accurately.

The turbulence intensity is composed of the ambient turbulence intensity, TI^{∞}, and the added turbulence intensity caused by the generated wakes of neighboring wind turbines, TI_{add}. The obtained wake turbulence intensity, TI, is then calculated as:

$$TI = \sqrt{(TI^{\infty})^2 + (TI_{add})^2} \tag{2.7}$$

The ambient turbulence intensities are the variable that the measurement campaign will assess in the chosen site, and it is formulated as :

$$TI^{\infty} = \frac{u'}{V_{hub}} \tag{2.8}$$

Where V_{hub} represents the incoming wind velocity at hub height and u' or σ_u is the standard deviation and defined by:

$$\sigma_u = \sqrt{\frac{1}{N}\int_0^T (u_x(t) - \bar{U}_x)^2\, dt} \tag{2.9}$$

In this equation, N reveals the number of samples at a particular measurement position $u_x(t)$ represents the streamwise velocity at the time t, T stands for the length of time and $\bar{U}_x$ represents the average streamwise velocity over time.

The additional turbulence in the wake is described empirically [6] as:

$$TI_{add} = \frac{1}{C_1 + C_2 \frac{x/D}{\sqrt{C_T(V_{IN})}}} \tag{2.10}$$

The two constants $C_1 = 1.5$ and $C_2 = 0.8$ are given in [7] and x/D is the ratio of two WTs distances to the rotor diameter. The combined turbulence intensity (TI) asymptotically approaches the ambient atmospheric turbulence intensity with increasing downstream distance.

2.5. Power Production

In reality, each wind condition has a different probability, obtained using onsite measurement and Weibull distribution, as mentioned before. Using previous equations and considering the obtained wake is derived for a given wind direction θ_k, it can conclude that V_i in (2.6) is a function of reference wind speed v_w, wind direction θ_k and WF layout (X,Y), i.e., $\bar{V}_i = \bar{V}_i(X, Y, v_w, \theta_k)$. Using the frequency of occurrence of wind speed v_w in direction θ_k, $F_{wk} = f_{occ}(v_w, \theta_k)$ the expected power production by WF is :

$$P_{tot} = \sum_{i=1}^{N_{wt}} \sum_{k=1}^{N_{wd}} \sum_{w=1}^{N_{ws}} P\,(\bar{V}_i(X, Y, v_w, \theta_k)) \cdot F_{wk} \tag{2.11}$$

Correspondingly the AEP of WF is formulated as :

$$AEP_{Net} = \sum_{i=1}^{N_{wt}} 8760 \cdot \eta_i \cdot \iint P\,(\bar{V}_i(v^{\infty}, \theta^{\infty})) \cdot \mathrm{P_i}\,(v^{\infty}, \theta^{\infty})\; dv^{\infty}\theta^{\infty} \tag{2.12}$$

In these equations, 8760 is the total number of hours in one year, η_i denotes the availability factor of WT_i, which is equal to one here for simplicity of the equation. Moreover, dv^{∞} and $d\theta^{\infty}$ are the range of each bin of wind speed and wind directions, so firstly, it is needed to discretize them and then integrate the equations in these ranges.

2.6. Constraints

The design of wind farms involves meeting several factors, such as technical, economic, legal, and so forth. This study evaluated both optimization approaches by considering two constraints: (1) inclusive and exclusive boundaries; (2) minimal distance requirements. In addition, another limit to optimizing sector management is the Penalty function, which will be detailed in the next chapter.

Exclusive and inclusive boundaries refer to possible and infeasible areas for turbine placement, which could be a result of the ability to lease land, existing roads, properties, or soil conditions. This study assumes that the boundary is a rectangular area seven times the diameter of WT.

Secondly, the minimal distance between two wind turbines in a wind farm is another limit in engineering which signifies that the distance between both turbines must exceed a particular value. It is essential to impose this restriction since the shorter the distance between turbines, the more significant the wake loss and the higher the level of turbulence, resulting in higher fatigue loads and maintenance costs and even a shorter turbine lifespan. Additionally, there must be a small distance between two turbines to prevent their blades from coming into contact and prevent one turbine from falling on the other. A constraint can be provided by WT manufacturers and is also determined by specific terrain features and wind resource characteristics at the specific location.

In this study, a minimum distance has been imposed for layout optimization, which is fixed and formulated by:

$$\sqrt{\left(x_i^2 - x_j^2\right) + \left(y_i^2 - y_j^2\right)} \geq Dist_{\min}\ , \quad for\ \ i,j = 1,2,\cdots,N_{wt}\ (i \neq j) \tag{2.13}$$

$\mathrm{Dist}_{\min}$ is the minimum acceptable distance between WTs. For the sake of this study, it is equal to 5 times the diameter of WT's rotor (5D).

2.7. Wind Farm Case

The chosen WF for this study is Horns Rev1, which is an off-shore wind farm with a 160 MW capacity for power production. This farm comprises 80 Vestas V80 wind turbines, generating 2.0 MW each. Generally, optimization is time-consuming and requires high computational cost; Moreover, this study combined two optimization approaches that increase even more this time. Thus, instead of investigating the whole WF with 80 WTs, here, a new WF is considered on this site (Hornsrev1) with 9 WTs. It must add that the wind condition characteristics will not change by location since the WF is off-shore and there is no complex terrain, so because of having the same geographical area, they remain the same. This new WF is shown in Figure 2-1.

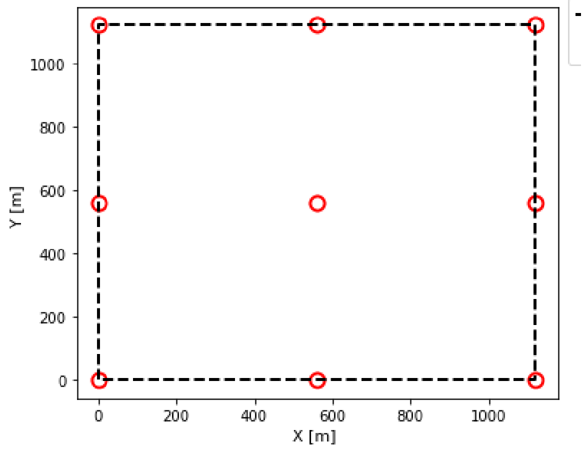

Figure 2-1: New defined wind farm layout.

Then, for further analysis and optimization, the WF and its wind data are simulated in the Pywake [8], a Python library developed by DTU University and an open-source tool for simulating the wind farms and calculations of its AEP. After simulating the WF in pyWake, it is possible to define the optimization scenarios explained before.

3. Sector Management

The main goal of this optimization strategy is to reduce wakes generated by WTs and their detrimental effects. While keeping the power output of WF higher is another objective. WF's power production will inevitably decrease by utilizing sector management since some WTs must be stopped in some wind conditions, and therefore power production will decline. These goals combine and create a unique objective function aiming to obtain the best compromise between these targets, which could be met by changing operational modes of different WTs in the WF.

Therefore this approach aims to define a control strategy (sector management) for different WTs in different wind conditions so that the operational modes of WTs will be modified according to different wd and ws. There are two possible scenarios for WTs in this strategy stopping or working with full loading each wind condition. Finally, it is needed to optimize this control strategy since much consideration must be fulfilled to give good sector management. The ultimate result of this optimization is a matrix with the size

of WTs number, wd, and ws, to counter the WTs to different wind conditions.
Since all parts of wind farm modeling have been programmed using the programming language Python (PyWake), thus, using an efficient library in Python can make the optimization algorithm easier. For this reason, the Python package Scipy.optimize.minimize has been chosen to optimize sector management strategy [9]. The flowchart of this optimization strategy is revealed in Figure 3-1.

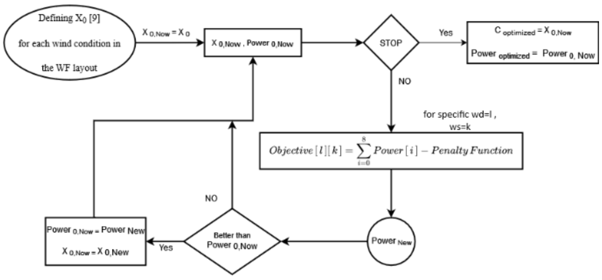

Figure 3-1: Optimization algorithm for sector management

The defined objective function for this sector management that must be optimized is as follows:

$$Objective = Power\ production - Penalty\ Function$$
$$= \sum_{i=1}^{N_{wt}} \sum_{k=1}^{N_{wd}} \sum_{w=1}^{N_{ws}} P_{ikw} - \sigma_k \times \max\left(0, TI_{ikw} - TI^{\ max}\right)^2 \tag{3.1}$$

Where Scipy library maximizes this objective function considering the limits and with the help of Pywake. It must be noted that the penalty function is defined to regulate the optimization strategy and demonstrates the effect of generated wake by WTs. Thus when the turbulence intensity, TI_{ikw} , will be higher than the limit, $TI^{\ max}$, the wake effect affects the power production, and this function is deducted from power production (in the objective function) to include the impact of the generated wake. Otherwise, the penalty function would be zero, meaning that generated wake is unimportant.

Indeed if the objective function is negative for a specific wt, wd, and ws (power production will be lower than the penalty function), the WT must be stopped since, in this condition, WTs are producing more wake compared to produced power, and it is not rational to work the WT. Moreover, there is another condition in which, although $wt = i$ has a positive objective, stopping this WT can reduce the generated wake highly on the other WTs; therefore, in this situation, it is feasible to stop that WT to increase the AEP of WF. Since the generated wake will diminish on the other WTs so the experienced velocity by the other WTs will be improved. However, for $wt = i$ the effect of wake does not outweigh power output, but it can affect a lot other WTs. Therefore, sector management needs optimization to find a suitable control strategy that considers all these conditions.

Furthermore, this penalty function should not be less strict since it causes stopping a few numbers of WTs. Inversely having a harsh penalty function stopped a lot of WTs, so the AEP of the wind farm may decrease dramatically. Therefore a compromise between them is needed to define the penalty function.

This optimization needs to consider many configurations as mentioned above; hence reducing the number of wind directions and wind speeds investigations could help decrease the CPU time; however, it can diminish the accuracy of the strategy. To do this, wd is discretized into 36 bins with 10° length, so instead of investigating 360 different wd, only 36 ones are analyzed. While for the ws, since the chosen WT's cut-in and cut-off velocity are 4m/s and 25m/s, respectively, ws is discretized into 22 different bins. Therefore the sector management optimization is analyzed in 36 wd and 22 ws bins, and the final matrix for operating modes of WT, called “C” (in Figure 3-1), has the size of [9,36,22]. This matrix consists of 0 and 1 values, which means that the WT is stopped or working, respectively. Hence each WT in this matrix, according to different wind conditions, has a specific operating mode to stop or work.

There are two unknown values in the Equation (3.1) that designers must set according to their targets, experience, and some try and errors, σ_k and TI^{max}. The multiplication factor, σ_k should not be either too small or large since it causes less strict or harsh penalty function, respectively. In this study, three different values have been applied, 10^8 , 10^9 and 10^{10}. After investigating the obtained results with these coefficients, the best σ_k is chosen, which is 10^9. Optimization results with 10^8 would give less effective penalty charging since, in some wind conditions, the AEP of WT is negative, meaning that the penalty charging outweighs power production (effect of the generated wake is high) while the WT is working; in this condition, it is not rational that the WT is working, and it must be stopped while the obtained result after optimization shows that WT is working, so optimization is not working properly in this condition. Moreover for 10^{10} the number of stopped WTs is too high, so the penalty function is too strict, and power output will decline dramatically, and again, this value is not suitable to use.

Regarding the TI^{max} some experiments are needed, as the chosen value is larger, the penalty function will be minor, and the effect of the penalty is less strict; therefore, defining the function is useless in this condition. Inversely smaller values cause a more severe penalty, resulting in switching off the majority of the WTs in most wind conditions, which is not a logical control strategy. Hence it is better to have a different value of TI^{max} according to different wind conditions. The number of wd and ws bins are 36 and 22, respectively, so it is possible to define a matrix for TI^{max} with this size.

The final strategy for defining TI^{max} is discretizing wind conditions into different bins so that the TI^{max} is a function of wd and ws, whose value changes according to them. Each element of this matrix is the average value of TI for different WTs in each specific wd and ws bin. Indeed the average value of experience turbulence intensity by WTs for a specific wind condition is taken as the TI^{max} in that wd and ws. In this approach, the size of TI^{max} matrix is $[36,22]$ where wind directions are discretized into 36 bins (each 10-degree one bin), and wind speeds are discretized into different bins (22 groups).

Moreover, turbulence intensity is composed of two components according to Equation (2.7) , ambient turbulence and the one generated by WT's wake. Since the imported wind data in the Pywake regarding the Horsnerv1 WF does not include the ambient turbulence intensity, it simply assumed that the ambient turbulence is 0.1, which is incorrect since WS will change this value. This lack of information is due to using a cup anemometer to find the wind data only gives information regarding wind velocity. In order to obtain results about turbulence intensity, measurements like LIDAR are needed.

So it is needed to define an approach to calculate this turbulence intensity by changing the WS. To do this, the NTM modified approach is used, which is an approach to guess the value of turbulence intensity when the real turbulence intensity of wind data is unavailable. This approach is formulated as follows:

$$\sigma_1 = I_{ref}(0.75\ V_{hub} + 5.6) \qquad (3.2)$$

$$TI(V) = \frac{(\sigma_1\ /\ V_{hub}) + 0.1}{2} \qquad (3.3)$$

In this equation I_{ref} is chosen according to the wind turbine classes; since the V80-2MW is known as class I, $I_{ref} = 0.16$. Moreover V_{hub} is the experienced velocity by WTs.

The final result of this optimization strategy is mentioned in Table 3-1. Results regarding the WF case demonstrate the AEP of WF when all WTs are working and no sector management strategy is implemented.

	AEP [GWh]	Operating=0
WF Case	80.962	0 %
Modified NTM	80.937	1.12 %

Table 3-1: AEP of sector management

4. Layout Optimization

This strategy optimizes the chosen wind farm layout to achieve the highest possible AEP. This process is done by modifying the initial WF layout while the defined constraints are respected.

The first step is to check whether the stop condition is met, which determines the number of runs for this optimization procedure. In better explanation, steps 2 to 5 will be done in every run of the optimization algorithm to find the best layout in that specific iteration. So there must be a maximum number for evaluating these steps, known as the Evaluation number.

The pseudo-code of this algorithm is as follows:

Algorithm 1 Pseudo code of RS algorithm for layout optimization

1: Initialize

Select initial layout $\boldsymbol{S_0}$ (obtained from experiments or other optimization algorithms)

Evaluate the objective function: $\boldsymbol{f_0} = \boldsymbol{f}(\boldsymbol{S_0})$; set **Improve_flag = .Fasle**.

2: **while** the stop condition is not True:

Random Move

if (Improve_flag == .Fasle.) :

Pick a WT randomly and modifying its location randomly

$\boldsymbol{S} = \boldsymbol{S_0} + \boldsymbol{\Delta S}$ (ΔS is limited with the long edge of WF)

else:

Select the moved WT last time, and relocate it in the old direction with a randomly step size

end if

3: Feasibility Check

Checking the feasibility of $\boldsymbol{S}$ regarding constraints

if S is not feasible:

Repeat the **Random Move (Step 2)**

end if

4: Layout Evaluation

Compute the objective function of feasible layout $\boldsymbol{S}$: $\boldsymbol{f} = \boldsymbol{f}(\boldsymbol{S})$

(Note: Since only one WT is moved, updating the wake matrix and then calculating the power output of WF saves a high computational cost

5: Optimal Layout Update

if ($\boldsymbol{f} > \boldsymbol{f_0}$):

set $\boldsymbol{S_0} = \boldsymbol{S}$, $\boldsymbol{f_o} = \boldsymbol{f}$,

set Improve_flag = .True.

else:

set Improve_flag = .False.

end if

6: end while

7: $\boldsymbol{S_0}$ is the optimized layout

Another value determines the number of runs in this algorithm, indicating the number of times the optimization process starts from zero to obtain the final layout. Since this strategy is utilized random moves, each run could result in different results; because of this, the number of runs and evaluations should be a reasonable value to find the best outcomes. According to different experiments, 40 is a suitable value for iterations (runs), and evaluation numbers up to 100,000 could lead to better results. So here, the stop condition means that the number of iterations must be lower than 40 in this study, while 100,000 evaluations would be done in each iteration to get the optimized layout.

The feasibility step (step 3) is regarding evaluating the new obtained layout, where it should be checked according to the defined constraints for the optimization strategy. As mentioned before, the minimum distance between WTs is 5D, so each new layout must fulfill these limits. Moreover, new positions of WTs must be inside the feasible area defined by the designer (inclusive and exclusive boundaries)

This algorithm is needed again to determine the number of wd and ws bins for evaluation. These values should be chosen to decrease the computational time while keeping the accuracy of results as high as possible. This optimization is performed 40 times from scratch to evaluate the different results because the WT choosing and modifying its location is random, so it can give a different layout after optimization. For this reason, the number of wd and ws bins is 12 and 22, respectively. For instance, wd is divided into 12 bins with 36° length.

The results of this layout optimization for 40 different runs, each consisting of 100,000 evaluations, are shown in Table 4-1.

	AEP [GWh]
Maximum	82.353
Minimum	81.758
Mean	82.131
Std	0.134

Table 4-1: different results of layout optimization

The maximum value of AEP obtained from different 40 runs is taken as the final result of this optimization strategy. Moreover, the Std between outcomes is not significant, meaning that the difference in results of different runs is shallow, so it shows that although this algorithm is intrinsically random final findings are nearly the same.

5. Combined Optimization

After validating two distinct optimization algorithms, they are combined to benefit from both, increasing the AEP of WF by Layout optimization while decreasing the wake effects by sector management. The flowchart of this integrated optimization process is demonstrated in Figure 5-1 with the following steps :

1. Choosing the initial layout either randomly or by another consideration;
2. Optimizing the sector management of WF and calculating its AEP, known as $\widehat{AEP}$;
3. Optimization of the WF layout by selecting a WT randomly and moving its position considering different constraints mentioned before;
4. This random movement is acceptable if it leads to increasing the AEP; otherwise, repeat step 2;
5. Optimizing sector management for this new layout and obtaining the new AEP, known as $\widehat{AEP_{New}}$;
6. If $\widehat{AEP_{New}} \geq \widehat{AEP}$ the new one replaces the previous control strategy

This procedure continues until meeting the maximum iteration numbers.

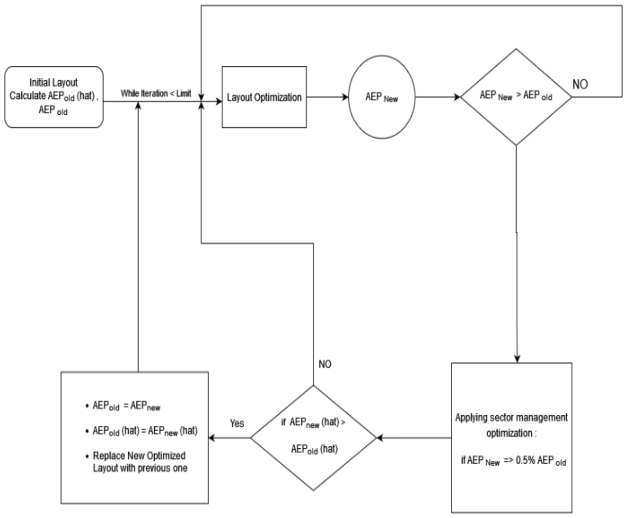

Figure 5-1: A combined optimization algorithm

Since sector management optimization is time-consuming, it takes much time to use this optimization algorithm for all the new configurations from layout optimizations. Therefore in this integrated optimization, sector management optimization will be performed just when the AEP increase from layout optimization is greater than a threshold which is 0.5%. Moreover, the number of bins for wd and ws in the sector management optimization performed in the combined algorithm has been decreased to 12 (wd) and 3 (ws) to accelerate the process. (while when sector management evaluated individually, they were 36 and 22, respectively). Each 30° is established one bin for wd. At the same time, ws is discretized into three different velocities, low medium, and high wind speed, and during the optimization, only these three values will be investigated for different wds, which are 5,12, 19 m/s. The number of bins for layout optimization is the same as before in combined optimization (12 bins for wd and 22 bins for ws). The reason for having a higher bins number for ws in the layout optimization compared to the sector management is that this strategy takes lower time, so it is possible to increase the number of evaluations to keep the accuracy of results higher.

6. Conclusions

After implementing both algorithms, the results will be as follows :

	AEP [GWh]
Maximum	82.114
Minimum	81.616
Mean	82.833
Std	0.113

Table 6-1:Different results of combined optimization

As previously, the maximum AEP in the table is considered the final result of this strategy. So by implementing both sector management and layout optimization, the wind farm can generate 82.114 Gwh. The obtained value for Std also shows that the difference between results of various runs is insignificant, so although this algorithm has a random nature, its outcomes are reliable.

The final layout achieved for the best result of this optimization strategy is demonstrated in Figure 6-1. The original WF layout also shown with the feasible boundary (dashed line) is for the optimization. Like the layout optimization, there is no general trend for placing the WTs in the WF, only that they tend to be near the boundary area. Moreover, as it is evident, the location of some WTs is the same in the original and optimized WF layout.

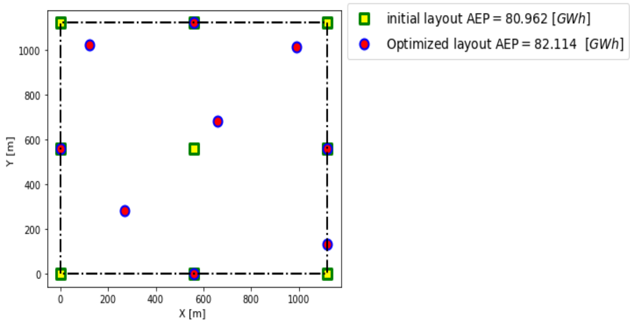

Figure 6-1: New optimized layout and original one

In order to evaluate the effectiveness of the final layout, it is essential to compare the results of different strategies to see how much benefit they can bring. The obtained AEP from different methods is expressed in Table 6-2. Using the integrated combined optimization could achieve the best result since the AEP of the original wind farm has been increased from 82.962 GWh to 82.114 GWh, which experienced a nearly 1.5% improvement in power generation. Additionally, this benefit could be doubled since the combined optimization decreases the wake effects and fatigue load on the WTs. Thus, the final AEP output is increased while the cost of WF may decline due to diminishing the detrimental effects of the generated wake.

	AEP [GWh]
Original Layout	80.962
Sector Management Optimization	80.937
Optimized Layout	82.353
Combined optimized Layout	82.114

Table 6-2:Comparison of different strategies

Moreover, The CPU time for different optimization strategies introduced in this thesis is shown in Table 6-3, obtained by implementing optimization algorithms in Python on DTU Cluster with an Intel® i5-3210M CPU @ 2.50 GHz.

	CPU Time [h]
Sector Management Optimization	3.00
Layout Optimization	1.39
Combined Optimization	1.46

Table 6-3: CPU Time for different optimization algorithms.

It should be mentioned that since the layout and combined optimizations run 40 different times, mentioned CPU time in the table is the average time for these different runs. S it is evident from the table that by decreasing the number of bins in layout and combined optimizations, CPU time has been decreased. However, this can reduce the accuracy of results and accelerate the optimization process.

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