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WIND FARM LAYOUT OPTIMIZATION WITH NOISE CONSTRAINT

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Abstract. *Wind farm layout optimization consists of setting the best position of the wind turbines to increase the wind farm yield. Usually, power production and investment costs are the main objectives of this problem. However, wind turbines cause some environmental impacts that should be taken into account. One of these environmental issues is noise, which is responsible for annoyance and sleep disorders in residential areas. This study aims to address the layout optimization considering noise propagation and energy production. Different scenarios are analyzed concerning the distance among turbines, wake effect, and sound pressure level constraints. The genetic algorithm is adopted for better performance due to its good results in finding a solution in large search spaces. Firstly, we performed the optimization without noise constraint for a random initial layout. Then, the same layout was optimized, considering conditions to reduce the noise level. According to the results, this optimization process can find reasonable solutions to maximize energy yield and avoid environmental impacts due to the noise of wind farms.*

Keywords: *wind energy, layout optimization, genetic algorithm, noise propagation, environmental impact.*

1. INTRODUCTION

The installation of wind farms has significantly grown in the last decade. In a global context, electricity production through wind currents reached 743 GW of installed capacity at the end of 2020. According to GWEC (2021), in the onshore market it represents an increase of 59% over the previous year.

Typically, a wind farm has some kilometers long and may receive 10 to 100 installed wind turbines (Manwell *et al.*, 2009). Under such circumstances, the proximity among these turbines causes aerodynamic interactions that affect their performance. Thus, the distribution of the wind turbines in space affects the efficiency of the wind farm (Zhang, 2013).

The main objective of a wind farm owner is to produce as much power as possible. Therefore, choosing suitable wind turbines and correctly placing them in a wind farm is a crucial problem. The Wind Farm Layout Optimization (WFLO) becomes even more complex when the land use and the noise level are limited (Kwong *et al.*, 2012).

In large-scale onshore wind farms, the optimization process depends more on the surroundings, such as geographical issues and proximity to residential areas, if compared to offshore wind farms. The complexity of the layout optimization for onshore wind farms is increased by those considerations, requiring more detailed modeling (Cao *et al.*, 2020).

Generally, WFLO is most focused on maximizing energy production and investment costs (Grady *et al.*, 2005). Since wind energy is environmentally correct and clean, a wind farm project must consider environmental impacts such as noise. Wind farm noise has a negative health impact, and it concerns both the developers and the residential areas near wind farms. Noise is an essential factor in the WFLO process.

Another important aspect is the wake effect. In WFLO, wake issues can cause a 15% deficit in energy produced and should not be ignored (Duckworth and Barthelmie, 2008). Besides affecting the power produced, the wake interactions between turbines can also change the noise propagation pattern.

Computational Fluid Dynamics (CFD) methods are known as accurate approaches (Kuo *et al.*, 2016). Although, in terms of WFLO, such simulations that solve Navier-Stokes equations are time-consuming and demand too much computational effort.

Among the optimization algorithms, those gradient-free, like Genetic algorithm (GA), Evolutionary Computation, and Particle Swarm Optimization (PSO), have been widely used in the WFLO problem due to their metaheuristic characteristics (Wu *et al.*, 2020).

Classical optimization methods are not common used in this case because of the multimodality of the space and a large number of design variables in the problem. Our proposal in this work uses a GA formulation due to its robustness and performance. Moreover, GA is a population-based method and has the critical advantage of handle discontinuity issues (Park *et al.*, 2019).

The approach of this work considers both noise minimization and energy maximization as objectives. It aims to quantify the trade-offs in terms of power production and generated noise, verifying situations where these targets are conflicting or not.

The paper is organized as follows. Section 2 describes the numerical models involved in our proposal, including the wake, noise propagation, and energy models. The optimization algorithm is presented in Section 3. Then, in Section 4, we present two test cases followed by the analysis of the results in Section 5. The final section is reserved for conclusions.

2. WIND FARM MODELING

For this work, we followed the ISO-9613-2 (ISO, 2019) noise model to evaluate the noise propagation in the wind farm and the Jensen model (Jensen, 1983) to calculate the implications of the wake effect on the performance of wind turbines.

2.1 Wake Model

The Jensen model is chosen as the basis for calculating the wind velocity affected by the wake effect to determine its suitability and effectiveness. This formulation is based on a linear wake expansion and results in a downstream wind speed, a non-linear function of downstream distance. It is the most popular model in this area due to its high simplicity and practicality. Furthermore, the Jensen model is also the standard implementation of much commercial software.

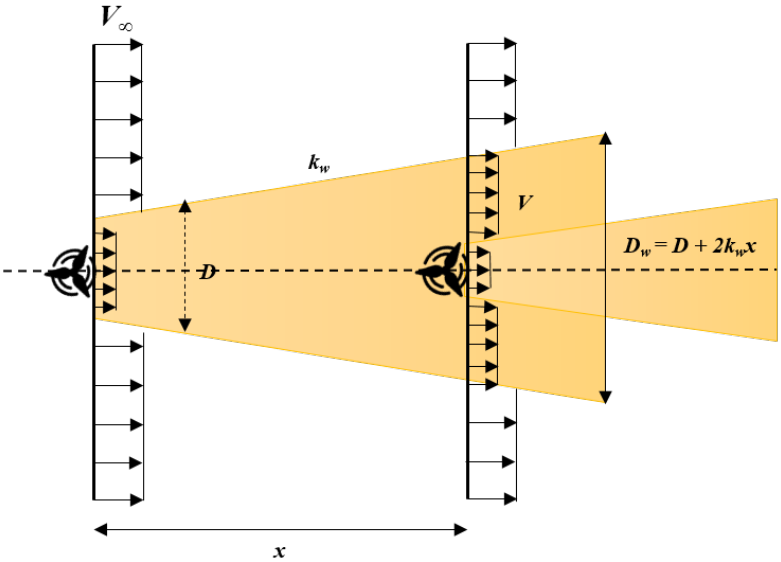


Figure 1. Schematic representation of Jensen wake model.

According to the model, when wind passes the upstream wind turbine, the velocity at the downstream wind turbine can be estimated using the following equation:

$$\frac{\Delta V}{V_\infty} = \left(1 - \sqrt{1 - C_t}\right)\left(\frac{D}{D + 2k_w x}\right)^2, \tag{1}$$

where C_t is the thrust coefficient, and k_w is the wake decay constant, which is 0.07 for an onshore wind farm. $V - V_\infty$ is the reduction in wind speed at a downstream distance x, V_∞ is the free steam wind speed in m/s, x is the distance of a target wind location along free steam, D is the wake-inducing turbine's rotor diameter, and D_w is the wake expansion along the distance x.

In some cases, the downstream wind turbines encounter the phenomenon of mixed and superimposed upstream wind turbine wakes. In this study, if the turbine center of the target wind turbine does not fall within the wake region of the upstream turbine, we do not consider the partial wake and ignore the wake effect. In such a case, using Equation 1, we first calculate the wind speed deficit due to the wake effect from each contributing upstream wind turbine on a target downstream turbine. Then the total speed deficit suffered by this target turbine is calculated by using the square root of the sum of squares of the deficit from each upstream turbine:

$$\left(\frac{\Delta V}{V_\infty}\right)_{total} = \sqrt{\sum_{i=1}^{n}\left(\frac{\Delta V}{V_\infty}\right)_i^2}, \tag{2}$$

where n is the total number of upstream turbines that cause wake, and $\left(\frac{\Delta V}{V_\infty}\right)_i$ is the deficit due to i^{th} turbine among n.

2.2 Noise Model

According to the ISO-9613-2 standard (ISO, 2019), any location where the Sound Pressure Level (SPL) is measured or predicted is a receptor. In WFLO, industrial and residential areas are typically considered receptors for noise calculation purposes.

In this case, the equivalent continuous downwind octave-band sound pressure level (L_f) at each receptor location is calculated for each point source (wind turbines), at each of the eight-octave bands with nominal mid-band frequencies from 63 Hz to 8000 Hz i.e.,

$$L_f = L_w + D_c - A, \tag{3}$$

where L_w is the octave-band sound power emitted by the source. D_c is the directivity correction for not omnidirectional sources. A is the octave-band attenuation, and f is a subscript indicating that this quantity is calculated for each octave band.

Several octave weightings can convert the sound pressure level in Eq. (3) to a valid SPL. For wind farm layout applications, it is usual to use A-weighted SPL (Maia *et al.*, 2010). The equivalent continuous A-weighted downwind sound pressure level (L_{avg}) at a specific location can be calculated from the sum of the contributions of each point source in each octave band,

$$L_{avg} = 10 \log \left\{ \sum_{i=1}^{n} \left[\sum_{j=1}^{8} 10^{0.1[L_f(i,j)+A_f(j)]} \right] \right\}, \tag{4}$$

where n is the number of wind turbines, j is the index representing one of the eight standard octave mid-band frequencies, and the $A_f(j)$ is the standard A-weighting coefficients.

The attenuation term (A) in Eq. (3), is the sum of different attenuation effects due to geometrical divergence (A_{div}), atmospheric absorption (A_{atm}), ground effects (A_{gr}), sound barriers (A_{bar}), and miscellaneous effects (A_{misc}), i.e.,

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc}. \tag{5}$$

In this model, we assumed attenuation due to sound barriers and miscellaneous effects as insignificant. The detailed calculation procedure can be followed in the ISO 9613-2 standard document (ISO, 2019).

2.3 Energy Model

To calculate the wind farm's energy, we first need to divide the entire wind resource data into small wind instances. It helps us estimate the probability of these wind instances, which we do by dividing the number of data points inside the current wind instance by the total number of data points. We denote the probability of occurrence of j^{th} wind instance by p_j.

Using the wind turbine power curve data and the effective wind speed determined by the wake model, we can estimate the power produced by each turbine (P_j) and obtain their sum to calculate the wind farm power produced (P_{total}), i.e.,

$$P_{total} = \frac{8760}{10^3} \left(\sum_{j=1}^{72} p_j P_j \right). \tag{6}$$

According to the sizes of the intervals, we have 72 wind instances in total. Multiplying P_j with the corresponding frequency of occurrence of the wind instance (p_j) and, then, by a factor of 8760, the total number of hours in a year, we have the Annual Energy Produced (AEP). A factor of 10^3 in the denominator converts the power to gigawatts-hour (GWh).

3. OPTIMIZATION ALGORITHM

As we mentioned before, Genetic Algorithm (GA) for the WFLO was applied. GA is a metaheuristic search algorithm inspired by the concept of natural selection and is good at finding a global optimum in large search spaces. GAs search the optimum solution through the solution space by keeping a population of solutions selected according to their fitness to solve the optimization problem. An essential advantage of GAs is that they are gradient-free and avoid problems with the non-continuity of the solution or objective function, converging to the neighborhood of the global optima (Hou *et al.*, 2016).

As defined in the previous section, our goal is to maximize AEP following the constraints of wind farm perimeter ($x_{min}, y_{min}, x_{max}, y_{max}$), distance among the wind turbines (d_{min}), and noise pressure level of the wind turbines (L_{avg}), that should be less than a certain limit ($Noise_{max}$). The optimization problem is formulated as follows:

$$\begin{cases} maximize & P_{total} \\ subject \;\; to & x_{min} \leq x_i \leq x_{max} \\ & y_{min} \leq y_i \leq y_{max} \\ & \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq d_{min} \\ & max\left[L_{avg}\right] \leq Noise_{max} \end{cases} \tag{7}$$

The initial layout is generated randomly in this formulation, and the corresponding objective values (energy generation, noise level) are evaluated. The main steps were compiled in a flowchart (Figure 2) for better visualization.

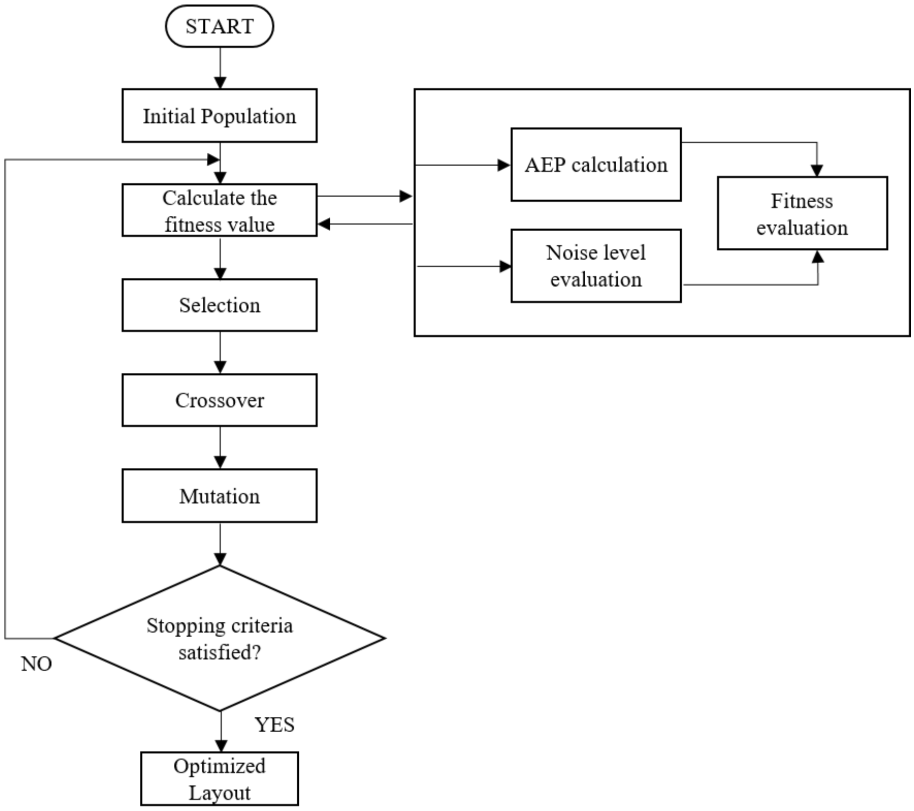


Figure 2. Flowchart of the optimization framework.

The first step is to create a *population*, which consists of a random set of solutions. Each solution is a *chromosome*, and these chromosomes are made of smaller parts called *genes*.

In GA, each completed iteration is considered a *generation*. After each created generation, the *fitness function* must be evaluated. The fitness function determines how far the next-generation chromosomes are from the optimal solution. The best solutions of each generation are defined by their fitness value.

The evaluation of the fitness function occurs by calculating the annual energy production considering the noise constraints. The most suitable solutions are established, and the value of their fitness functions is used as a parameter for the next step.

To the next step, the classic GA operators are defined: *selection*, *crossover*, and *mutation*. The creation of a new generation occurs through *reproduction*, where the selection operator chooses pairs of parents from the population. This selection occurs based on the fitness values of the individuals.

During the reproduction process, the crossover is performed. Crossover is considered the most important GA operator. It is responsible for the genetic recombination of individuals, generating new ones. After that, the chromosomes created from the crossover are subjected to the mutation process. Mutation consists of changing the position of some genes to increase the diversity of the population.

Finally, after creating a new generation, the best solution (chromosome) of that generation is selected and compared with the previous solution. This process is repeated until the algorithm reaches the stopping criteria.

4. TEST CASES

In our test cases, the wind farm is a piece of flat terrain, with dimensions of 4.0 km by 4.0 km, subject to the wind regime presented in Figure 3, described by the wind rose diagram. The wind turbines are identical, and their characteristics are shown in Tab. 1. Figure 4 represents the power curve and the thrust coefficient behavior of a wind turbine.

Table 1. Characteristics of the wind turbines.

Parameter	**Value**
Cut-in wind speed	4 m/s
Cut-out wind speed	26 m/s
Rated power	3 MW
Rotor diameter	50 m
Turbine height	100 m

The ISO 9613-2 standard determines the maximum sound pressure level permitted in residential areas as 45 dB(A). Consequently, this is the value we adopted for the $Noise_{max}$ parameter. Other important parameter is the minimum distance among wind turbines and, for this problem, d_{min} is 400 m.

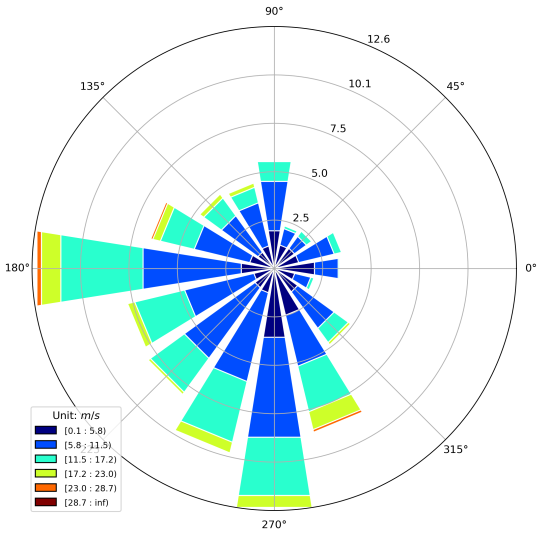


Figure 3. Characteristics of the wind data (velocity and direction).

In this work, we examined two optimization cases. In the first case, we solved the maximum energy problem by finding the optimal location of 16, 20 and 36 wind turbines in the wind farm. Initially, we evaluated the noise level but not considering it as a constraint. These simulations guarantee the scalability of our proposal and can handle any number of wind turbines.

Then, in the second case, we solved the problem for the optimal location of 16 and 20 wind turbines limited by the noise level constraint. The goal is to maximize energy generation and minimize noise at the receptor inside the wind farm to illustrate the performance trade-off between these two aspects. The receptor was positioned in the center point of the perimeter, x=2000 m and y=2000 m.

5. RESULTS

At first, we performed simulations with turbines of predefined initial positions in equally spaced rows. However, it showed greater demand for iterations to achieve the same result of a random initial scenario. This behavior shows that initial random layouts converge faster to the optimal solution. Then, for the first simulations with a initial random layout, the WFLO was implemented without considering the noise constraint. Even so, the noise pressure level was estimated. In this way, we can compare to the noise limited case. The relevant optimized results for the AEP and noise evaluation are provided in Table 2.

Table 2 indicates that, if the noise constraint is not considered, the noise values at the observation point exceed the limit of 45 dB(A) in all scenarios. Although, power production improves by 1.21%, 2.77%, and 3.25% for 16, 20, and 36

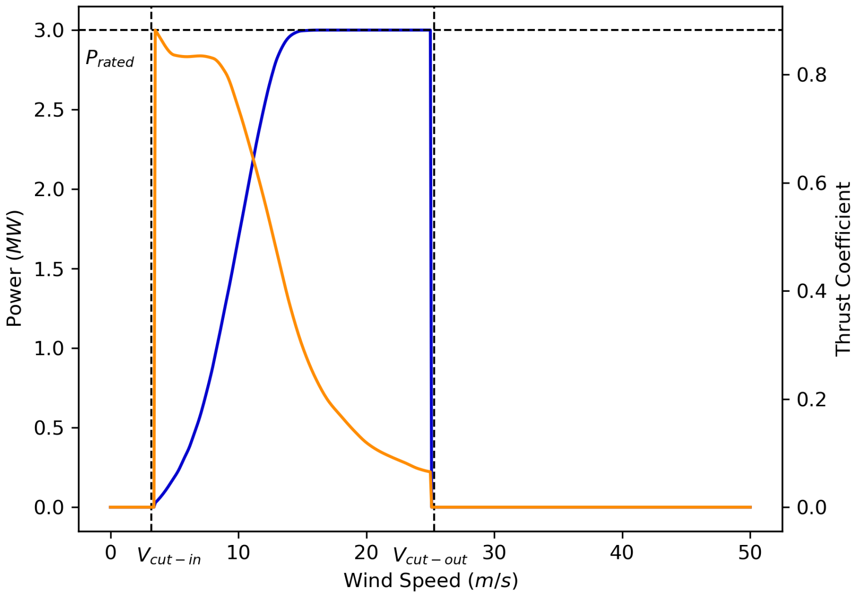


Figure 4. Power curve (blue line) and Thrust coefficient (yellow line) of a wind turbine.

Table 2. Scenario of optimized wind farms without noise constraint.

AEP (GWh)	SPL (dB(A))	Wind Turbines	Noise exceeded (dB(A))
174.85	49.2	16	4.2
226.04	54.9	20	9.9
385.07	52.6	36	7.6

wind turbines, respectively, after optimization.

For the second case, noise constraint was adopted. The WFLO can be followed in Fig. 5 where the initial and optimized layouts are compared. The AEP values with the iterations are displayed in Fig. 6 and show the behavior of the optimization process. The solution is improved at each iteration until it reaches the stopping criterion of constant value for 50 iterations.

Figure 7 displays the noise map for each wind farm configuration. The distribution is obtained by calculating the sound pressure level of each noise source and applying the spherical wave propagation method, where the intensity of the sound level increases according to the sphere equation i.e.,

$$I = \frac{E}{4\pi r^2}, \tag{8}$$

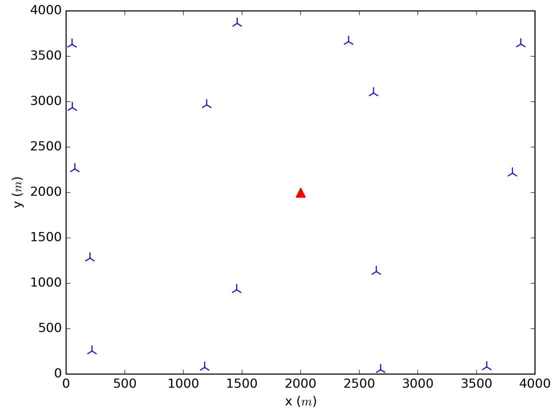
where I is the propagation intensity, E is the noise source power and r is the distance between source and receiver.

The optimized results for the WFLO considering noise constraint are provided in Table. 3 for AEP and noise evaluation.

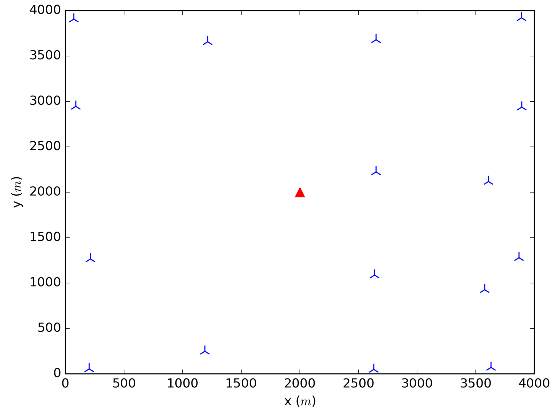
Table 3. Scenario of optimized wind farms with noise constraint.

AEP (GWh)	SPL (dB(A))	Wind Turbines	Noise exceeded (dB(A))
174.28	44.9	16	-0.1
225.11	44.7	20	-0.3

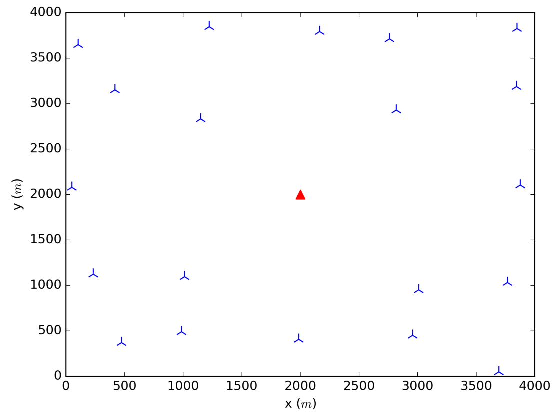
Case 2 indicates that when sound pressure level is limited, power production is slightly smaller compared to the first case, a difference about 0.32% for 16 WT and about 0.41% for 20 WT. However, the optimization considering noise improved AEP by 1.03% and 2.35% for 16, 20 wind turbines, respectively. Moreover, these results are crucial to constructing a more environmentally friendly wind farm and avoiding problems due to noise disturbance. Therefore, the proposed method can further reduce the wind farm noise and increase the power production in the WFLO process.



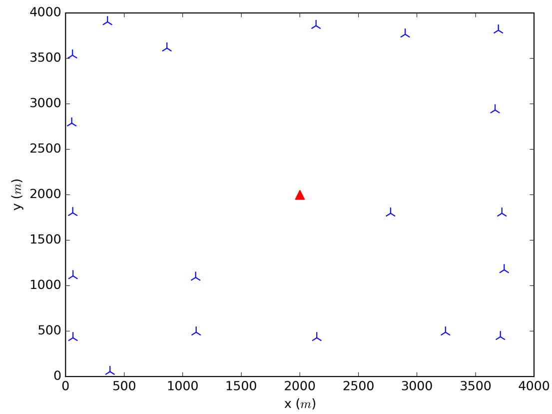
(a) Initial layout - 16 WT



(b) Optimized layout - 16 WT

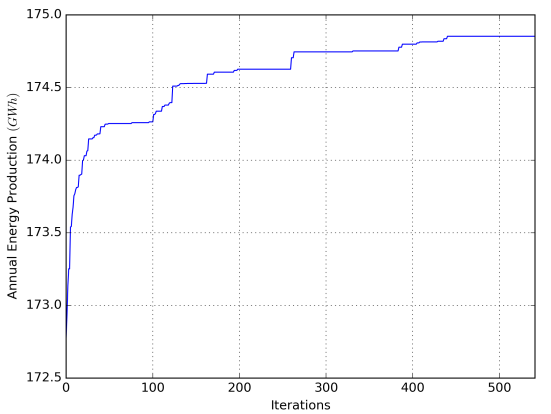


(c) Initial layout - 20 WT

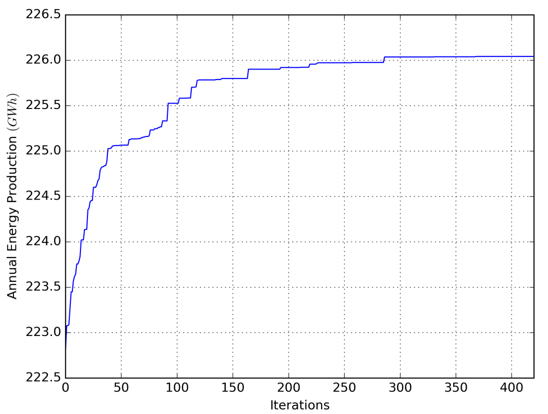


(d) Optimized layout - 20 WT

Figure 5. Layout optimization for Case 2.



(a) 16 WT

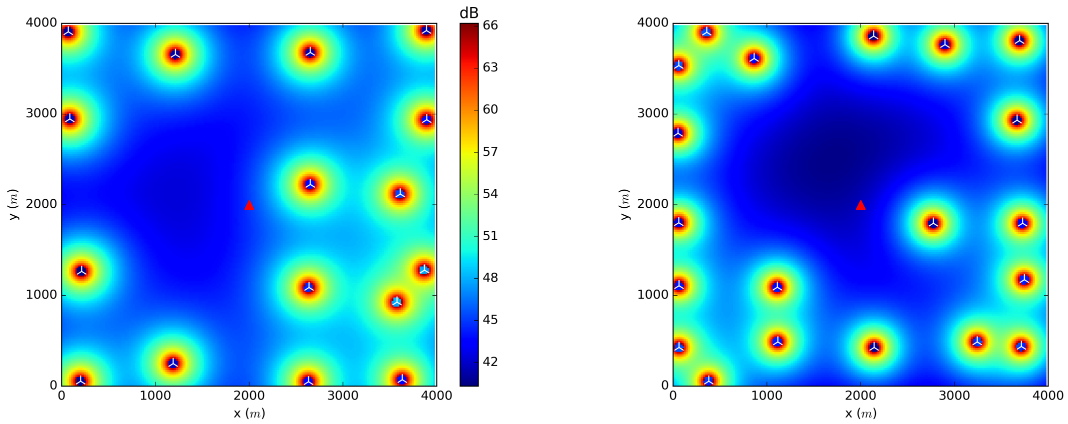


(b) 20 WT

Figure 6. Optimization behavior for Case 2.

6. CONCLUSION

In this work, we have proposed an approach to the Wind Farm Layout Optimization problem considering noise constraints. Two cases are presented to quantify the trade-offs in terms of power production and generated noise. In the first case, we simulated three different wind farm configurations to evaluate these in terms of power production only. Then, in the second case, we evaluated the same configurations in terms of noise level. The Genetic Algorithm was used in the optimization process and returned good results. The cases described here indicate that this formulation has a relevant effect



(a) Noise Map - 16 WT (b) Noise Map - 20 WT

Figure 7. Sound Pressure Level distribution for case 2.

on reducing noise when keeping or increasing the produced power and can be extended to any wind farm. This approach can reduce noise by 22.7% and increase power production by 2.35% for a wind farm with 20 wind turbines compared to an initial random layout. Thus, this technique can effectively reduce wind farm noise and increase energy production. Further work may consider investment costs for a complete model and evaluation of a whole wind farm project.

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