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Optimizing the layout of onshore wind farms to minimize noise

Xiawei Wu[a], Weihao Hu[a,*], Qi Huang[a], Cong Chen[b], Mark Z. Jacobson[c], Zhe Chen[d]

[a] School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
[b] Public Health England/Health Data Insight Community Interest Company, Capital Park, Fulbourn, Cambridge CB21 5XE, United Kingdom
[c] Department of Civil and Environmental Engineering, Stanford University, USA
[d] Department of Energy Technology, Aalborg University, Pontoppidanstraede 101, Aalborg DK-9220, Denmark

HIGHLIGHTS

- It represents the layout optimization considering noise problem with wake effect.
- The wake effect is considered with power production as priority and WT noise.
- Two strategies are analyzed due to different economic and regulatory requirements.

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ABSTRACT

As wind farm numbers and areas increase worldwide, it has become increasingly important to examine the impact of wind energy on the surrounding environment. One effect in some scenarios is noise, which depends on the type and age of the wind turbines and the distances between them and the residential buildings. Previous research on wind farm layout optimization has been generally aimed at achieving the minimum investment cost or maximum captured energy. This approach does not entirely align with minimizing noise. This paper focuses on an optimal layout for a wind farm considering its noise, without sacrificing power production. By optimizing the wind farm layout, the minimum noise is set as the basic objective, and both the wake effect and distances among wind turbines are considered. The basic particle swarm optimization algorithm and its evolutionary version are adopted and compared for better performance of calculation cost. Two strategies are presented to address the problems in various scenarios and to demonstrate the applicability of the proposed method and its effectiveness in designing layouts that minimize noise. Compared to a reference layout, a stringent noise control strategy could reduce the noise by 11%, even if minor, and increase the power production by 3.1%. A flexible strategy could reduce the noise by 5.7% and increase the power production by 3.1%.

1. Introduction

Wind energy generation capacity has increased substantially worldwide owing to the abundance of wind energy resources, decreasing cost of wind energy, and establishment of policies that favor clean, renewable energy sources. According to the Global Wind Energy Council, wind energy added 51.3 GW in new capacity in 2018 [1]. The newly installed capacities of wind energy in China and the United States rank first and second, respectively, in the world in terms of rapid development.

Because of the high productivity of offshore wind farms, research efforts have focused on them. However, in addition to the high initial investments required, the operation and maintenance costs of offshore wind farms are high. Therefore, additional large onshore wind farms are also being developed. Compared to offshore wind farms, the optimization of large-scale onshore wind farms is more dependent on the surroundings, such as the topography of the construction area and presence of neighboring residential areas. Such considerations have increased the practical difficulty of the layout optimization for onshore wind farms, requiring more detailed and well-considered designs.

Recently, some reports and research studies have observed that wind farm noise can, in some cases, cause negative emotions, insomnia, and various other symptoms [2,3]. Some of these studies have led to controversial discussions about the impacts of wind farm noise on human sleep and psychological distress [4,5]. [5] indicates that if residents have a negative attitude toward the wind farm noise or are

* Corresponding author.
E-mail addresses: xiaweiwu@hotmail.com (X. Wu), whu@uestc.edu.cn (W. Hu), hwong@uestc.edu.cn (Q. Huang), cchen12@googlemail.com (C. Chen), jacobson@stanford.edu (M.Z. Jacobson), zch@et.aau.dk (Z. Chen).

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Nomenclature

B	Number of blades
f	Band center frequency
R	Rotor radius
Î¡	Air density
V_0	Initial wind speed at the upstream wind turbine
$S_{overlap}$	Actual overlap area between the wake area and the downstream blade-sweeping area
S_0	Rotor-sweeping area of the wind turbines
X	Distance between the upstream and downstream wind turbines
N	Total number of wind turbines in the wind farm
C_p	Power coefficient
Β	Blade pitch angle
Λ	Tip speed ratio
SPL_1	First part of the wind turbine noise model
SPL_2	Second part of the wind turbine noise model
Φ	Angle between the rotor-hub-to-receiver line and its vertical projection in the rotor plane
$V_{0.7}$	Blade forward speed at 0.7 radius
$C_{0.7}$	Rotor blade chord at 0.7 radius
$σ^2$	Mean square of the turbulence
K_a	Frequency-dependent scaling factor
S	Constant Strouhal number, 16.6
H	Hub height
V_r	Resultant velocity at the blade element (m/s)
D	Directivity factor
Δ	Boundary layer thickness
S	Strouhal number
S_{max}	Maximum value of the Strouhal number, 0.1
K_b	Constant scaling factor, 5.5 dB
x_i	Position of a particle
v_i	Velocity of a particle

concerned about its effect on their property value, their sleep is expected to be affected. Although some related studies have depicted that personal attitudes, and not wind turbines (WTs), have a significant impact on wind farm noise perceptions, other evidence indicates that wind farm noise itself, in some cases, may cause some sleep disturbance [3]. Another study [6] found a relationship between the sound pressure level and the noise annoyance. With the increasing growth of wind energy and the potential effects of noise in a few instances, minimizing noise is a useful objective.

According to the recommended environmental noise standard proposed by the International Organization for Standardization (ISO), the allowable level in a residential area is approximately 35–45 dB(A), which in an industrial area can be appropriately increased to up to 50 dB(A) [7]. Such recommended values can be appropriately adjusted where the local standards are different. Regarding the prevention and control of noise in wind farms, considering the problem during the early layout design can effectively reduce it in a subsequent stage. In previous research on WT location selection, wind farm layout optimization generally focused on maximizing the energy production or minimizing the investment costs [8–10], and the noise problem was rarely considered. In addition, based on the varying actual conditions of wind farms, numerous practical problems have been integrated into the trade-off issues of wind farm productivity and revenue for improving the comprehensive optimization [11,12]. Considering the carrying capacity of the land, status of the seabed, and other factors, wind farm layout optimization was implemented in several scenarios in [11]. According to [12], because of the area restrictions caused by natural gas pipelines, oil wells, and traffic, the WT layouts must be updated to suit the actual conditions. The optimization of actual wind farms was further analyzed in [13]. However, there is currently no detailed research on wind farm layout optimization with focus on the WT noise problem. Given the demand for the effective use of land resources and the increasing scale of wind farms, onshore wind farms are inevitably constructed near residential areas, labor-intensive industrial areas, and even schools. Although wind energy is an environmentally friendly and clean energy, wind farm layout planning should consider the noise problem, instead of exclusively focusing on power generation or investment costs.

In wind farm layout optimization, wake issues must not be ignored. In addition, not all the WTs on wind farms can achieve the ideal wind velocity to capture the wind energy because of the wake effect; specifically, only a downstream WT can capture the wind, which initially decreases and then gradually increases to a specific value passed by the upstream WTs. The wake effect can cause up to a 15% gap between the actual energy production and the ideal value for typical-sized wind farms [14]. Separating the wind farms from each other reduces the wake effects [15]. Additionally, the WT noise is subjected to similar conditions, because the inaccurate estimation of wind velocities without considering the wake effect impacts the rotor rotational speed, and thus, the WT noise. The working principle of WTs is the mechanical rotation by turbine blades to generate energy. However, during the WT operation process, substantial noise is generated [16]. WTs have numerous potential noise sources, including gear, mechanical, tip, inflow, and airfoil self-noise [17]. Thus, the wake effect affects both the power generation and WT noise on wind farms.

The wake effect has a reduction impact on wind velocities. Moreover, some environmental facts, such as terrain change and restricted area, also have a remarkable influence on wind velocities and wind farm optimization [18,12]. [18] focused on the wind velocity and power production in complex terrain and subsequently performed wind farm optimization. [12] considered several restricted areas, such as oil wells and gas pipelines, to observe wind farm layouts. In recent years, some studies have also considered different objectives to deal with different actual concerns and scenarios for wind farms. In [19], the objective was to make the wake effect uniform, instead of only increasing the power production, and the results exhibited that this was a more comprehensive consideration. [20] estimated the influence of neighboring wind farms on the annual energy outputs of a new planned wind farm. Furthermore, a novel algorithm was developed for such scenarios to achieve an effective performance. The research in [21] modified the combination of wind farm design and electrical system design to reduce the total wind farm costs. Furthermore, a gradient approach has been used to formulate a multi-objective problem that includes the land problem, energy output, and electrical system [22]. In addition, turbine noise is an objective worth considering. For example, [23] explored the influence of wind farm noise limitation on the energy output. However, it was based on a semi-empirical turbine noise, and not a mathematical turbine noise calculation.

Remarkably, wind farm noise is an important environmental factor, and minimizing it can be the main objective of wind farm optimization. In residential areas, it is necessary to ensure that the relevant requirements of zero noise pollution and increased power generation are satisfied. Specifically, considering the wake effect will have a significant impact on the productivity calculation and WT noise in designing the layout for onshore wind farms. Recently, several wind farm optimization studies considered noise [24–27]. [25] was a relatively early study on wind farm layout that considered turbine noise. Furthermore, there are several very early studies that prospectively investigated the layouts of wind farms and their impact on wind farm noise [28–30].

Subsequently, [24] developed and proposed a complete framework to perform optimization considering energy and noise. However, the wake model was simplified without considering the actual wake area change with different wind directions, and only an approximate value of this factor was used to evaluate the wake effect [24]. This reduces the accuracy of the wake assessment but improves the calculation time. [26] proposed a novel hybrid method based on genetic algorithm and probabilistic gradient to deal with the trade-off between energy and noise. [27] considers various constraints such as land use to re-examine similar problem. Regarding turbine noise, WT noise is assigned a fixed value, and then the wind farm noise is calculated using a noise propagation model to different distances, which is called a semi-empirical model [26,27]. This semi-empirical model has obvious advantages in calculation cost, but it ignores the interaction effects of noise, wake and WT distances. In fact, the wind farm noise is related to the wind velocity change caused at the WTs. Thus, the turbine noise problem should appropriately consider the wind velocity under a specific wake effect. In general, the wake model in this paper considers a specific overlap wake area, owing to the wind direction and wake deficit. Moreover, the turbine noise model considers the wind velocity change due to the wake effect. The wake effect (wind speed and wind direction must be considered), noise issue, and power production should be considered comprehensively with some models containing wind velocities.

This study makes the following contributions. 1) It presents wind farm layout optimization considering the noise problem with both wind velocity changes and noise propagation. 2) The wake effect is considered along with power production and WT noise, with the power production given priority. 3) Two practical strategies are analyzed according to different economic and regulatory requirements, which are compared and validated by an actual reference wind farm.

The paper is organized as follows. The development of the relevant models is presented in Section 2. In Section 3, the problem formulation and constraints are described. The optimization methods and framework are presented in Section 4. A case study is discussed in Section 5. Finally, the conclusions and directions for future research are offered in Section 6.

2. Wind farm model

In this section, the Hubbard model is presented as a basis for evaluating the noise of wind farm layout designs. Moreover, the Jensen model is used to calculate the wind velocities in WTs. WT noise and power generation are considered in terms of a trade-off in the subsequent layout optimization.

2.1. Wind turbine noise model

A noise model for WTs based on the aerodynamics noise model was proposed by Hubbard et al. in the 1980s and verified by the National Aeronautics and Space Administration of US [16]. Based on the sounding principle of a WT, the model consists of three parts: the noise generated when the inflow turbulence and blades meet, the noise generated by the encounter between the turbulent boundary layer and the trailing edge of the blade, and the noise caused by the airflow separating from the trailing edge of the blade.

Because the trailing edge of a modern WT blade is mostly pointed, the noise in the third part is smaller than those of the first two parts and can be ignored [31]. Therefore, the first two parts of the Hubbard model are used in evaluating the noise generated by WTs. The equations are as follows:

$$SPL_1 = 10\lg\left[\frac{B\sin^2\varphi\rho^2 C_{0.7}(\omega)R\sigma^2 V_{0.7}^4}{r_0^2 c_0^2}\right] + K_a(f) \tag{1}$$

$$f_{peak} = SV_{0.7}(\omega)/(h - 0.7R) \tag{2}$$

$$SPL_2 = 10\lg\left\{\frac{V_r^5 BD\delta l}{r_0^2}\left(\frac{S}{S_{\max}}\right)^4\left[\left(\frac{S}{S_{\max}}\right)^{1.5} + \frac{1}{2}\right]^4\right\} + K_b \tag{3}$$

2.2. Multiple noise sources

Remarkably, a noise observation site is not only affected by one WT sound source in a wind farm but also by the multiple noise sources presented by the multiple WTs of an entire wind farm. Each WT is regarded as a noise source and can be accumulated in a logarithmic form [32]. The formula for calculating two noise sources can be written as follows:

$$L_2 = 10\lg(10 \wedge (L_i/10) + 10 \wedge (L_j/10)) \tag{4}$$

where L_i is the noise of one WT, and L_j is the noise of another WT. The noise of the entire wind farm can be accumulated using this method.

2.3. Sound level

Sound evaluation must consider the sound level and make certain corrections to the acquired sound parameters based on different sound levels. Among these levels, the A sound level is the closest to that perceived by a human ear and is chosen to evaluate the impact of wind farm noise. Moreover, in the noise spectrum analysis, the octave or 1/3 octave noise calculation formula is used to obtain the octave or 1/3 octave band sound pressure level [33]. This study adopts the octave band sound pressure level as an example. The sound pressure level of each octave band is assumed to be L_{pi}. Thus, the accumulated wind farm noise value, L_A, for A sound level can be rewritten as follows:

$$L_A = 10\ln\left[\sum_{i=1}^{n} 10^{0.1(L_{pi}-\Delta L_i)}\right] \tag{5}$$

where ΔL_i is the A-frequency weighting correction value of the ith octave band (the correction value can be found in the sound level meter international standard IEC 61672-1 [33]), and n is the total octave band number.

2.4. Statistical sound level LN

WT noise is typically irregular, and its severity varies according to the wind conditions and the wake effect. In addition, regarding the wind farm location selection, the impact of WT noise on the surrounding environment is a long-term process and not an issue of a single instance. Therefore, in the layout design of wind farms, the statistical method of LN is adopted for evaluating the annual profile of a wind farm noise. The statistical sound level indicates that the probability of occurrence of noise greater than this noise value is N%. For example, L50 = 45 dB (A) signifies that the probability of noise exceeding 45 dB (A) over a period is 50%.

To ensure that the entire wind farm noise level does not exceed the standard recommended by the environmental noise regulations, L10 is chosen as the evaluation standard in this study. Satisfying this evaluation standard implies that the wind farm satisfies the standard in 90% of the annual wind conditions.

2.5. Wake velocity 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. When wind passes the upstream WT, the wind velocity at the downstream WT can be estimated using the following equation [34]:

$$V_i = V_0 - V_0(1 - \sqrt{1 - C_t})\left(\frac{R_0}{R_0 + kx}\right)^2\left(\frac{S_{overlap}}{S_0}\right) \tag{6}$$

where C_t is the thrust coefficient and k is the wake decay constant, which is 0.07 for an onshore wind farm [35].

2.6. Combination of wake

As in the superposition of WT noise as described above, one downstream WT cannot be affected by one upstream WT in the wind farm. A downstream WT is affected by several upstream WTs, and the wind velocity at a downstream WT generated by N WTs can be derived as follows [34]:

$$V_m = V_0\left[1 - \sqrt{\sum_{m=i}^{N}[1-(V_i/V_0)]}\right] \tag{7}$$

2.7. Energy model

The maximum power point tracking (MPPT) is assumed to be adopted in calculating the wind energy production of each WT as a control strategy [36]. Therefore, the energy production of each WT can be calculated as follows [37]:

$$P_m = \begin{cases} 0 & 0 \leqslant V_m \leqslant V_{cut\_in} \\ 0.5C_{p,opt}(\beta,\lambda)\rho\pi R^2 V_m^3 & V_{cut\_in} \leqslant V_m \leqslant V_{rated} \\ P_{rated} & V_{rated} \leqslant V_m \leqslant V_{cut\_out} \\ 0 & V_{cut\_out} \leqslant V_m \end{cases} \tag{8}$$

The specific values of the parameters in (8) depend on the specific model selection for WTs. Moreover, the total power production can be expressed as follows:

$$P_{\text{tol}} = \sum_{m=1}^{N} P_m \tag{9}$$

3. Problem formulation

Depending on whether an inhabitant of a residential area selected as a noise observation site receives economic compensation for a slight noise interference, there are two scenarios, and the corresponding problems are considered here. The objectives and constraints are analyzed subsequently.

3.1. Strict noise control

The WTs are designed to be constructed in a predefined area S1 with a residential area S2 (Fig. 1). Area S2 is assumed to be a strict noise control zone as a noise observation site. Specifically, the owner of this area does not receive any economic compensation to endure the excessive wind farm noise. The evaluation value for noise can be selected from the ISO standard to determine if the wind farm noise is excessive for the different area types considered as noise observation sites [7].

As displayed in Fig. 1, it is assumed there are three white WTs in area S1, and the orange circle around each WT represents the noise range and the value generated by this WT. The darker its color, the larger the noise. The outermost part indicates that the WT noise value of the position is less than the specified evaluation value. It is worth mentioning that the noise value range may not be a regular circle in the wind farm because of the noise superposition of different WTs, and it will be considered according to Eq. (4). This figure is only intended to illustrate the concept of a strict noise control zone.

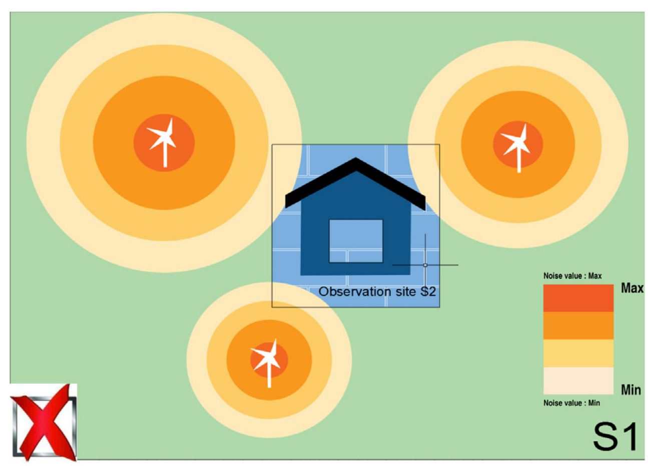
For different wind farms, the coordinate system can be used to represent the different locations of all the WTs and the surrounding residential properties. Wind farms worldwide may have different characteristics, including their locations, number of WTs, planned area of wind farms, and distribution of the surrounding properties. The scenarios in this study are differentiated for different strategies. Once a strategy is selected, such as the strict noise control strategy in this part, the basic characteristics of the wind farm and the distribution of the surrounding residents should be adjusted; following which the next optimization steps are begun. Therefore, the results in this study can be extended to other wind farms and provide a technique that can be applied to any wind farm.

Although the noise superposition in the WTs is difficult to represent in Fig. 1, it is fully considered in the mathematical models and cases. As displayed in Fig. 1(a) and (b), noise interference is not permitted in the strict control noise scenario. Therefore, the maximum noise value generated by the WTs in the entire area S2 cannot exceed a specified value, regardless of the amount of financial compensation.

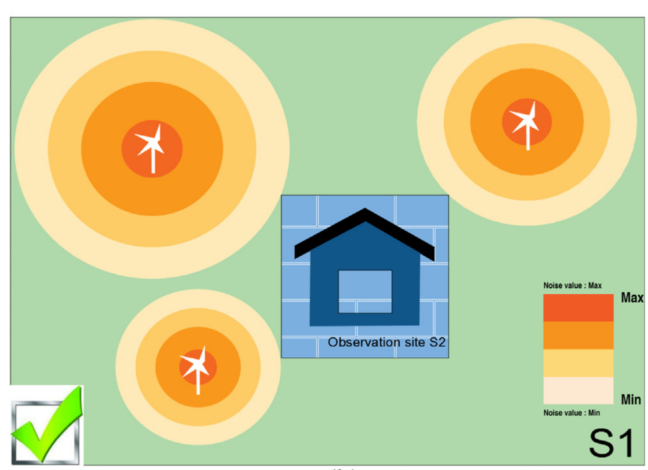
In the optimization process of a wind farm layout, the power production can also be optimized to a maximum, thereby satisfying the noise requirements. The power production depends on the WT location selection, which affects the obtained wind velocity considering the wake effect. The locations of the WTs on a wind farm are represented by a coordinate system (x_j, y_j). Thus, the total power production of this wind farm considering the wake effect can be expressed as follows:

$$P_{total} = \sum_{j=1}^{N}[P_j(x_j, y_j)] \tag{10}$$

The wind farm noise of WTs in a residential area acting as a noise observation site is determined using the rotational speed, ω, of each WT and the WT layout, (x_j, y_j), and this observation site is fixed according to Eqs. (1)–(5). Based on the traditional MPPT control strategy, the rotational speed of each WT is related to the optimal tip-speed ratio, λ, and the wind velocity can be written as follows:



(a)



(b)

Fig. 1. Strict noise control zone as a noise observation site. (a) Slight noise interference. (b) No noise interference.

$$\omega_c = \frac{\lambda_{opt} v_j}{R} \tag{11}$$

$$\omega_{\min} \leqslant \omega \leqslant \omega_{rated} \tag{12}$$

where the rotational speed is subjected to the rated rotational speed, and the specific value depends on the specific WTs adopted for the cases.

In addition, the wind velocity that arrives at a WT considering the wake effect based on Eqs. (6) and (7) can be expressed as follows:

$$v_j = F(x_j, y_j) \tag{13}$$

Therefore, the noise generated by a single WT and all the WTs at one observation point can be established, respectively, as follows:

$$L_j = 10\lg\left[\sum_{i=1}^{2} 10^{0.1SPL_i(f)}\right] \tag{14}$$

$$L_{farm} = 10\lg\left[\sum_{j=1}^{N} 10^{0.1L_j(x_j,y_j)}\right] \tag{15}$$

Therefore, if the local wind condition is obtained and L10 is chosen as the evaluation standard, the noise of the entire wind farm depends on the location of each WT (x_j, y_j), and must be limited to a certain value to construct a more environmentally friendly wind farm. The global noise of the wind farm evaluated by L10 can be rewritten as follows:

$$L10_{farm}(x_j, y_j) \leqslant \text{Noise}_{\max} \tag{16}$$

Because the observation point is evaluated as a region, rather than as a point, the observation point coincides with the actual residential area, e.g., an industrial area or animal sanctuary. Thus, this area is quantized into m points, and $L10_{farm,\ m}$ is the noise value of each point position evaluated by L10 in this area. Therefore, it is necessary to ensure that the maximum noise value of all the points in the area satisfies the noise requirements as

$$\max[L10_{farm,m}(x_j, y_j)] \leqslant Noise_{\max} \tag{17}$$

This study selected 45 dB(A) as the evaluation value to determine if a noise was excessive [7]. Therefore, the maximum noise value in this noise strict control zone must not exceed 45 dB(A) according to the ISO noise standard. Then, the objective can be rewritten as

$$\max[P_{total}(x_j, y_j)] = \max\left(\sum_{j=1}^{N} P_i(x_j, y_j)\right) \tag{18}$$

$$\max[L10_{farm,m}(x_j, y_j)] \leqslant 45dB(A) \tag{19}$$

Additionally, the interval between any two WTs must not be less than a certain distance for excessive turbulence.

$$S_1(x_j, y_j) = \sqrt{(x_j - x_j') + \left(y_j - y_j'\right)} - d_{\min} \geqslant 0 \tag{20}$$

3.2. Economically compensated noise control

The strict noise control zone becomes an economically compensated noise control zone if the owner of zone S2 is willing to accept a certain degree of economic compensation for slight noise interference. As displayed in Fig. 2, the compensation can be accepted regardless of the layout being (a) or (b), depending on the actual target requirements. Specifically, the owner of the wind farm pays an economic benefit to the surrounding area, and there is a trade-off between the economic losses for noise and the more optimized choice of the wind farm layout design. The same is true for the noise control zone, which includes a trade-off between the obtained economic gains and the slight noise disturbance. In fact, this outcome could be a win–win situation if both accepted and required.

The amount of economic compensation for the wind farm noise problem is converted into energy yields to make the optimized layout intuitive, and the price for the energy yield is assessed by the market electricity prices. Here, it is assumed that each 1 dB(A) of excess noise must be compensated by up to 10,000 kWh/dB(A). It is worth noting that this example is only an estimate provided to illustrate this method. Depending on the level of economic development and the relevant regulations in various regions, the actual compensation gap may be larger, even reaching sufficiently high compensation, leading to the abandonment of the wind farm. In addition, this value can be adjusted based on any actual scenario.

Most of the derivations are the same as the derivation for the strict noise control described above. Thus, the mathematical relations for the excess noise and the amount paid for compensation can be derived as follows:

$$P_{cps} = 10000 \text{ kWh/dB}^*(L10 \text{ - } 45 \text{ dB}) \tag{21}$$

$$\max[L10_{farm,m}(x_j, y_j)] \leqslant \left(45 + \frac{P_{cps}}{10000}\right)\text{dB(A)} \tag{22}$$

Compared to the strict noise control zone, the economic compensation for a noise problem is considered here. The problem is transformed into a method for selecting a certain degree of economic compensation under the condition that the economic compensation can be accepted, and then for designing a wind farm layout to maximize the

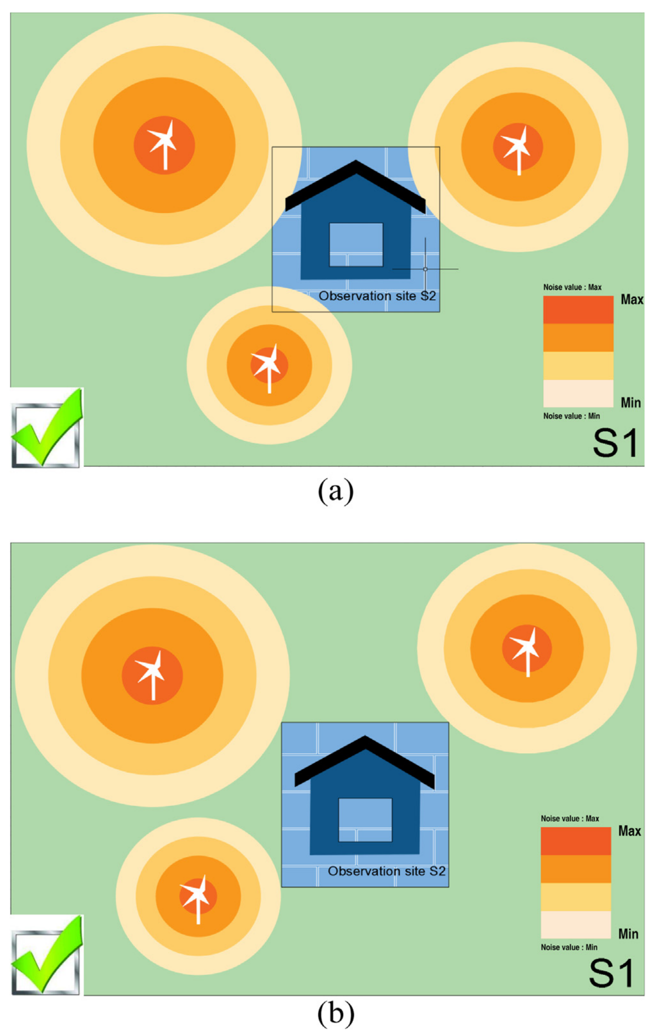


Fig. 2. Economically compensated noise control. (a) Slight noise interference permitted. (b) No noise interference.

benefits.

Notably, if the wind power company pays excessive economic compensation for the noise problem, the costs will be significantly increased, and the power generation gain from the improved layout may not be substantial. If WT noise is not allowed to occur in the residential zone, energy production may be reduced because of the wake effect or the wind condition, and optimal placement may not be obtained. Even if the choice of the WT location around noise control zone S2 is acceptable for economic compensation, there is a problem in weighing the cost and obtaining the compensation amounts.

The objective can be expressed as follows:

$$\max[P_{total}(x_j, y_j)] = \max\left(\sum_{j=1}^{N} P_i(x_j, y_j) - P_{cps}\right) \tag{23}$$

Similarly, the minimum distance between any two WTs remains limited by the following:

$$S_1(x_j, y_j) = \sqrt{(x_j - x_j') + \left(y_j - y_j'\right)} - d_{\min} \geqslant 0 \tag{24}$$

4. Methods

Considering the wake effect and the wind farm noise issue, the wind farm layout optimizations require a substantial number of calculations, and there are a series of constraints. In this section, the penalty function method and the heuristic particle swarm optimization (PSO) algorithm are introduced. Following this, the framework for the optimization process is provided.

4.1. Penalty function

To solve the objective described above, the wind farm noise problem is transformed into a constraint. In addition, a penalty function is used to obtain a trade-off between maximizing the power production and minimizing the noise problem of each wind farm layout design during the optimization process. Moreover, the constraint problem is transformed into an unconstrained problem using the penalty function, and thus, becomes a single-objective one. Therefore, the rule that any noise value within zone S2 cannot exceed 45 dB(A) can be explained as follows. The maximum noise value of this area must satisfy the following equation:

$$S_2(x_j, y_j) = \{45\text{dB(A)} - \max[L10_{farm,m}(x_j, y_j)] \geqslant 0\} \tag{25}$$

Particularly, for noise pollution, the limitation of the wind farm construction area and the minimum distance between any two WTs, the penalty function is integrated into the object function to obtain a feasible solution based on the two scenarios. Thus, the penalty function for the strict noise control zone is constructed as follows:

$$p_1(x_j, y_j) = |\min\{0, S_2(x_j, y_j)\}| \tag{26}$$

In addition, the problem for strict noise control can be rewritten as follows:

$$\textit{Objective}: \max(P_{total}(x_j, y_j)) \tag{27}$$

Subject to:

$$\begin{cases} \phi(x_j, y_j) = |\min\{0, S_1(x_j, y_j)\}| \\ p_1(x_j, y_j) = |\min\{0, S_2(x_j, y_j)\}| \end{cases} \tag{28}$$

Therefore, the object function can be written as follows:

$$\max\left(P_{total}(x_j, y_j) - PF\left(p_1(x_j, y_j) + \sum_{j=1}^{N} \phi(x_j, y_j)\right)\right) \tag{29}$$

In (28), $p_1(x_j, y_j)$ signifies that the noise value at any position in strict noise control zone S2 is not allowed to exceed 45 dB(A). Remarkably, the noise value of each position is superimposed by all the WTs of the entire wind farm. In the strict noise control zone, the penalty term PF in (29) is assigned a considerable value to ensure the satisfaction of the no-noise interference requirement. If the penalty is not sufficiently large, a feasible solution will not be obtained. Therefore, the penalty must be close to infinity. Moreover, Φ (x_j, y_j) indicates that the minimum distance between any two WTs must be greater than a certain distance. Here, 4D (four times the diameter of a WT) is selected as an evaluation distance; otherwise, the penalty will be insufficient, as in (29).

For economically compensated noise control, Eq. (24) is used to limit the distance between the WTs, so that the minimum value is greater than 4D. This approach is the same as that for the strict noise

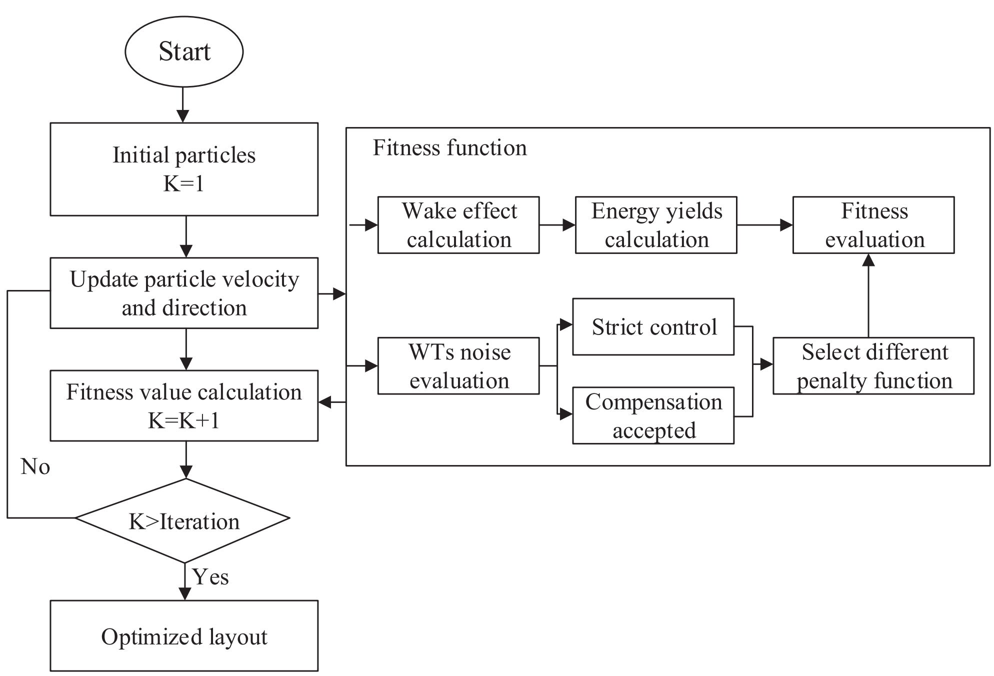


Fig. 3. Optimization framework for the whole process.

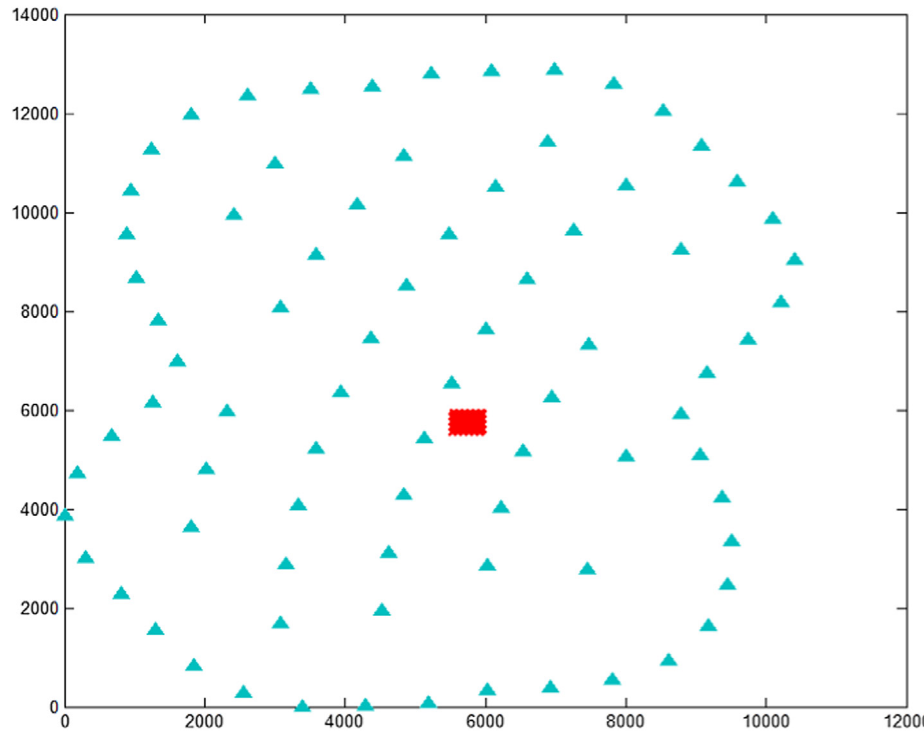


Fig. 4. Reference wind farm layout.

Table 1
Parameters for scenario analysis.

Item	Parameter	Value
10 MW DTU wind turbine	Cut-in wind speed	4 m/s
	Rated wind speed	11.4 m/s
	Cut-out wind speed	25 m/s
	Rotor diameter	178.3 m
	Rated Power	10 MW
Reference wind farm size	Length	12864 m
	Width	10401 m
Observation point	Center point	(5750, 5750)
	Length	500 m
	Width	500 m

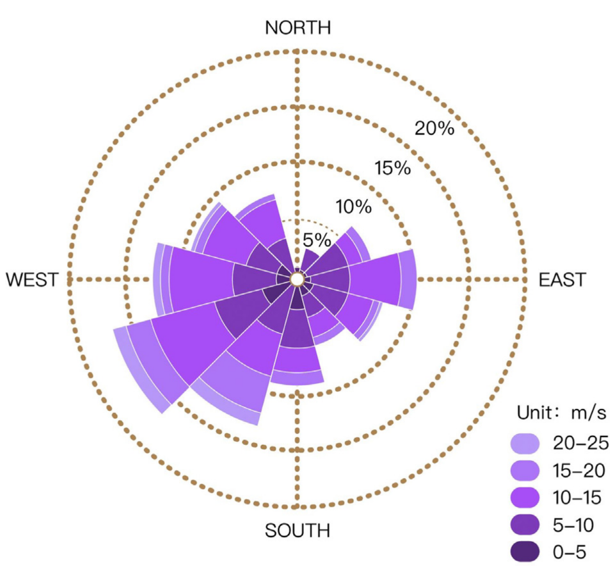


Fig. 5. Wind rose.

control, and the penalty is also infinite. For the noise problem, the market price of electricity is selected as a reference for the penalty function. Specifically, in the case of such a cost, this part of the economic benefit can be beneficial to the wind farm owners, and the noise control of the wind farm can be relatively weakened. Therefore, the wind farm can achieve high benefits while providing the other side economic compensation, which is also common and reasonable in an actual scenario. In addition, the penalty value for the noise issue is chosen based on Eqs. (21) and (22). Therefore, the objective can be rewritten as follows:

$$\max\left(P_{total}(x_j, y_j) - 10000^* p_1(x_j, y_j) + PF^* \sum_{j=1}^{N} \phi(x_j, y_j)\right) \tag{30}$$

4.2. PSO

The PSO algorithm has been widely used in the wind farm layout optimization problem with good performances [38,39]. Heuristic algorithms including PSO and genetic algorithm have been proven suitable to deal with nonlinear optimization problems [40]. In [41], the grid-like regular layout for commercial wind farms is studied, and the authors evaluates the comparison between PSO and genetic algorithm in multiple cases of layout optimization. It can be validated that PSO performs better [41]. Particularly, PSO has more remarkable performances in problems with continuous variables to find a feasible solution [42]. Recently, a comprehensive research is implemented in [43], which compares the advantages and disadvantages of eight algorithms in the layout optimization problem. Though it is possible for some state-of-the-art optimization algorithms to provide better computing efficiency, it has been proven that the PSO has small differences even compared with the best one of eight algorithms [43]. Since this paper does not emphatically focus on a more in-depth exploration of algorithms, it just applies an algorithm with a middle-to-top performance in the layout optimization problem to deal with specified layout optimization and explore the acceptable calculation cost. So, the PSO algorithm is employed for layout optimization in this paper. In order to discuss the specific calculation time, an evolutionary version of PSO is

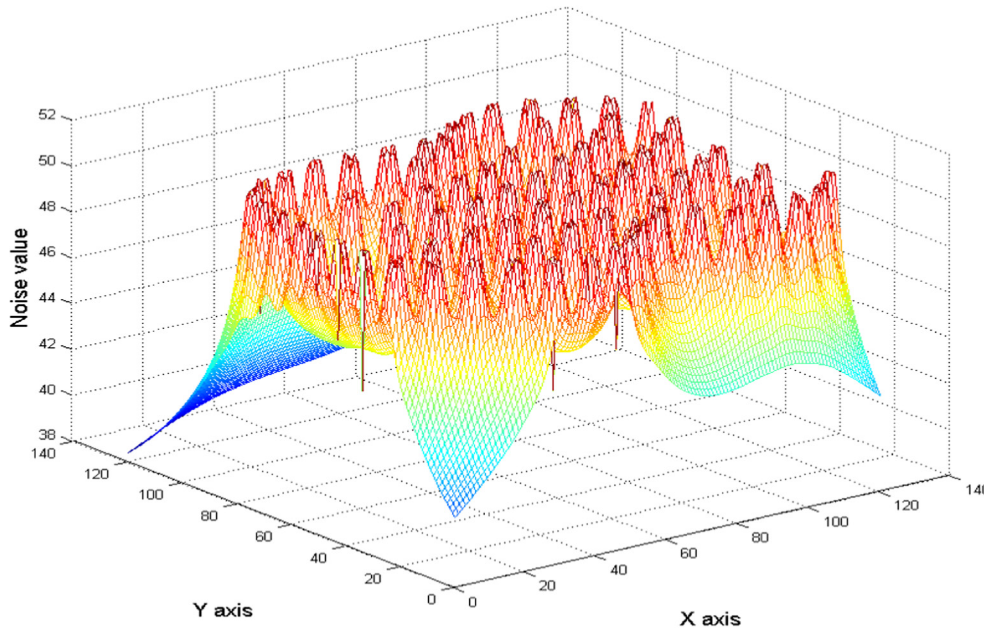


Fig. 6. Noise distribution of the entire wind farm (Unit: dBA).

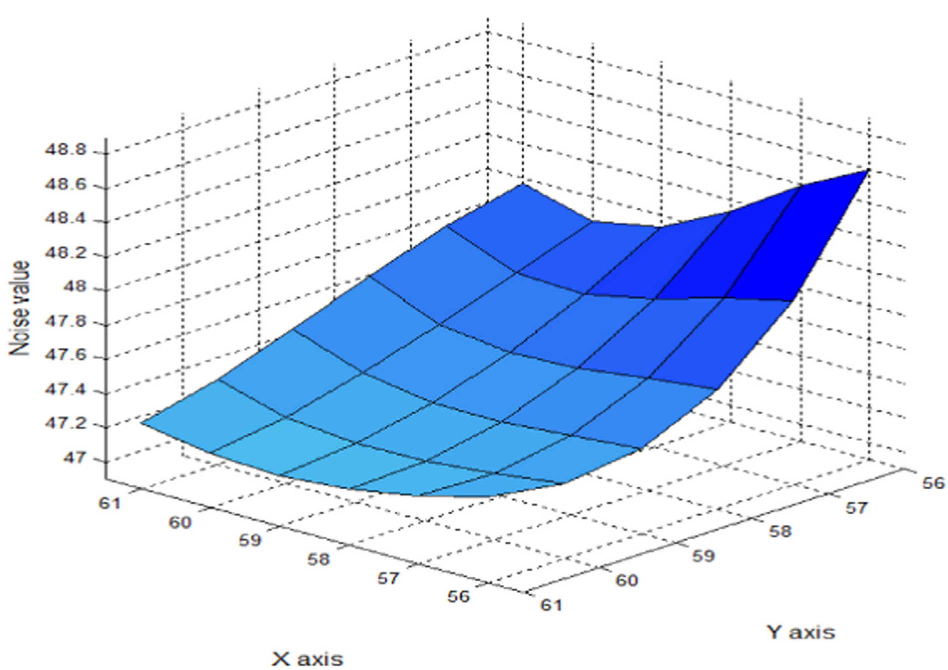


Fig. 7. Noise distribution of the observation area (Unit: dBA).

Table 2
Original layout and optimized layout without considering noise.

Names	Energy production (GWh)	Noise evaluation (dBA)	Noise exceed value (dBA)
Reference wind farm	4015.17	48.60	3.60
Optimization without considering noise	4212.01	50.69	5.69

used for comparison with regular PSO [44,45].

The PSO algorithm is a global random search algorithm based on swarm intelligence proposed by Kennedy and Eberhart, who were motivated by the artificial life research to simulate migration and clustering behavior during the foraging of birds [44]. In PSO, the potential solution to each optimization problem is a bird in the search space, termed a particle. All the particles have fitness values determined by the function being optimized, and each particle has a velocity that determines the direction and the distance it flies.

In each iteration, the particle updates itself by tracking two extremes. The first is the optimal solution found by the particle itself, and the solution is termed as the individual extremum solution. The other extreme is the most current finding of the entire population. The particle updates the position by tracking the individual extrema, $pbest_i$ and

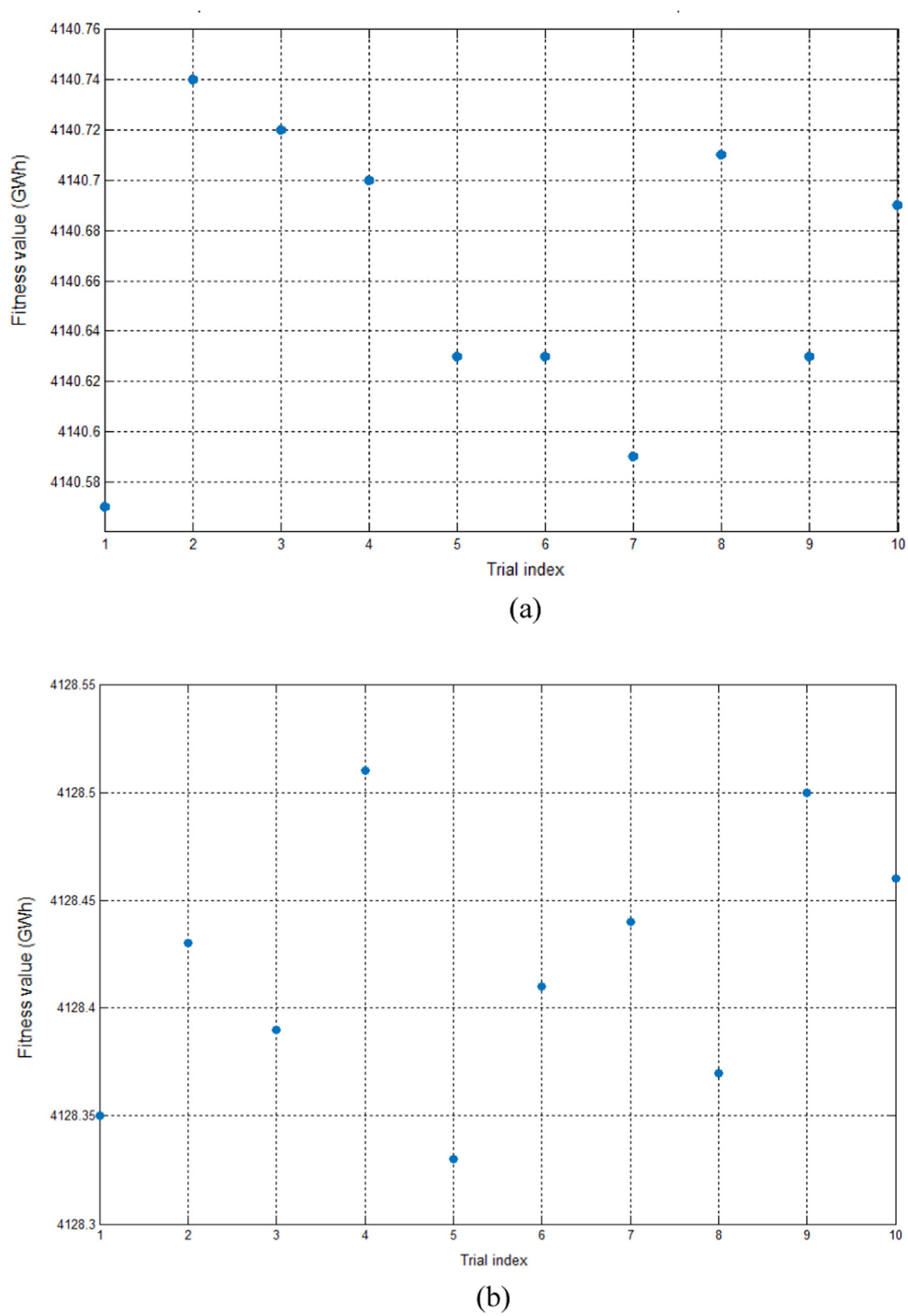


Fig. 8. Fitness values for several trials (a) IA-PSO [41]. (b) Traditional PSO [40].

Table 3
Average efficiency of algorithms for Case A.

Types	Average Fitness value (GWh)	Average Calculation Time (s)
Traditional PSO	4128.42	176,915
IA-PSO	4140.66	61,532

global extrema, $gbest_i$. In addition, the particles update their speeds and positions by the following formula:

$$v_i = v_i + c_1 * rand * (pbest_i - x_i) + c_2 * rand * (gbest_i - x_i) \tag{31}$$

$$x_i = x_i + v_i \tag{32}$$

where c_1 and c_2 are typically adopted as the learning factors of the particle. An improved PSO called intelligent augmentation of particle swarm optimization (IA-PSO) has been proposed and proved to perform well in optimization problems [45].

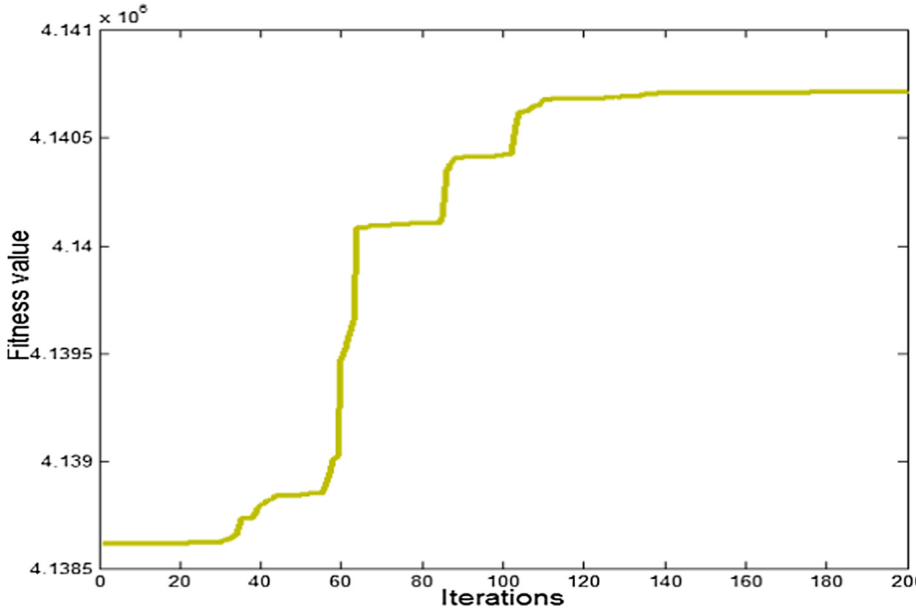


Fig. 9. Fitness value with iterations.

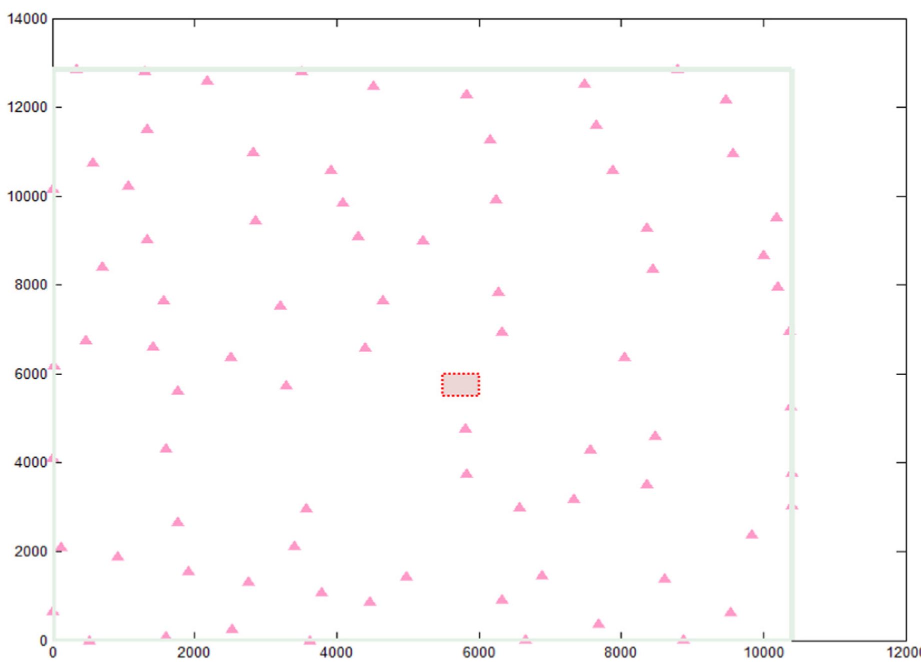


Fig. 10. Optimized layout for strict noise control.

4.3. Optimization framework

As represented in Fig. 3, after initializing the particle group of the PSO, power production is used to evaluate the WT layout. Each particle update indicates a new WT layout. Then, the noise value of the corresponding WT is calculated, and the current wake effect is evaluated. Based on the two types of strict noise control and economical compensation, different penalty functions are constructed to obtain the capacity of the wind farm. When a certain number of iterations is reached, the optimized fitness value is obtained.

5. Case study

The cases are analyzed on MATLAB R2014a platform and run by a Dell six-core computer model T7820. Two cases are implemented for verifying the effectiveness and practicality of the method and to optimize the WT siting selection for the noise problem as well as the power production corresponding to the two scenarios. The PSO algorithm is implemented 200 times to obtain a relatively fully optimized result for each trial.

Designed in Germany, FINO3 is chosen as the reference wind farm with 80 10 MW DTU WTs as the reference WTs, and the original layout is displayed in Fig. 4 [46,47]. It should be noted that the reference wind farm is considered an industrial standard layout of this size and will be compared to its layout and the power production with optimized ones. The observation area is a red square with a center of (5750, 5750) and a side length of 500 m on the coordinate axis, which represents a small part of a residential area, a small industrial area, or a bird sanctuary in the wind farm. In Fig. 4, each triangle represents a WT, and the red rectangle represents the observation area. It can also be noted that the

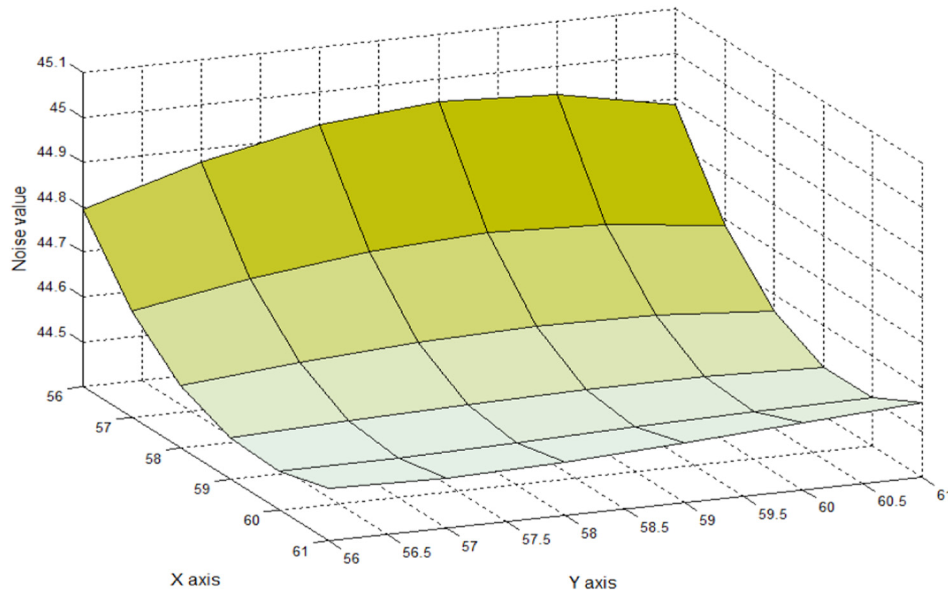


Fig. 11. Noise evaluation of the optimized layout for strict control (Unit: dBA).

Table 4
Reference wind farm and two scenarios of the optimized wind farms.

Names	Energy production (GWh)	Noise evaluation (dBA)	Noise exceed value (dBA)
Optimization without considering noise	4212.01	50.69	5.69
Strict noise control	4140.74	44.95	0

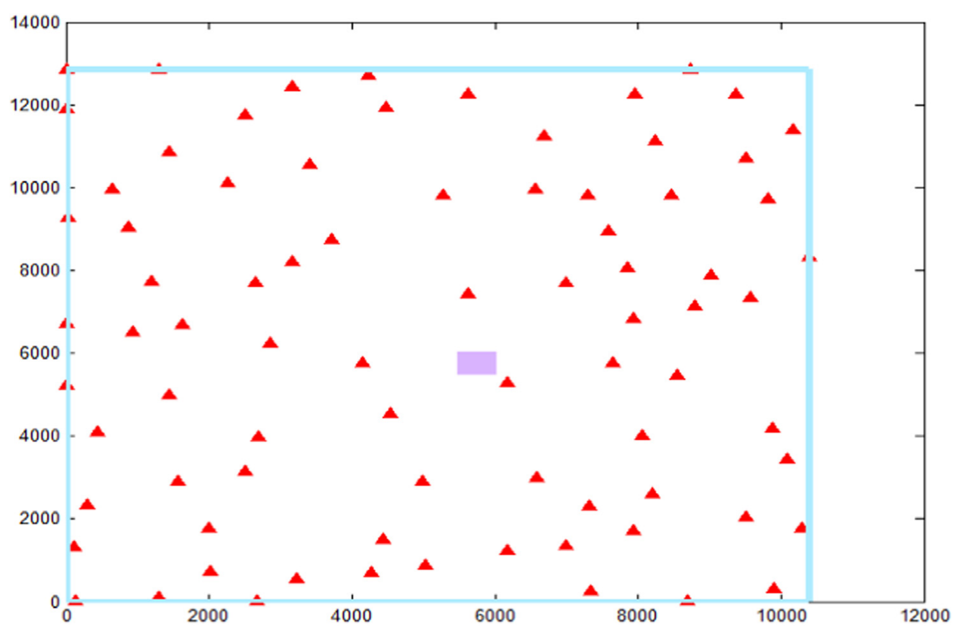


Fig. 12. Optimized layout for Case B.

shapes are the same in the other layouts presented below, although different colors are used to distinguish. Parameters for scenario analysis are given in Table 1.

The input time series wind speed and the distribution of direction for the calculation are obtained from the Norwegian Meteorological Institute, and the raw data were formulated into a wind rose for illustration purposes (Fig. 5) [48].

To better compare with the subsequently discussed two cases corresponding to strict noise control and compensated noise control, the noise distribution of the original wind farm layout based on the wind rose is presented in Figs. 6 and 7. All the units of the noise values are dB (A). Fig. 6 displays the noise distribution of the entire wind farm, and Fig. 7 presents the noise distribution of the observation area. Figs. 6 and 7 indicate that the wind farm noise is not background noise. Moreover, the wind farm noise originates from the reference WTs layout, as displayed in Fig. 4. The ratio of the noise map x-y coordinates, such as in Figs. 6 and 7, and the layout map, such as in Fig. 4, is 1:100, and all the WT positions on the wind farm are represented.

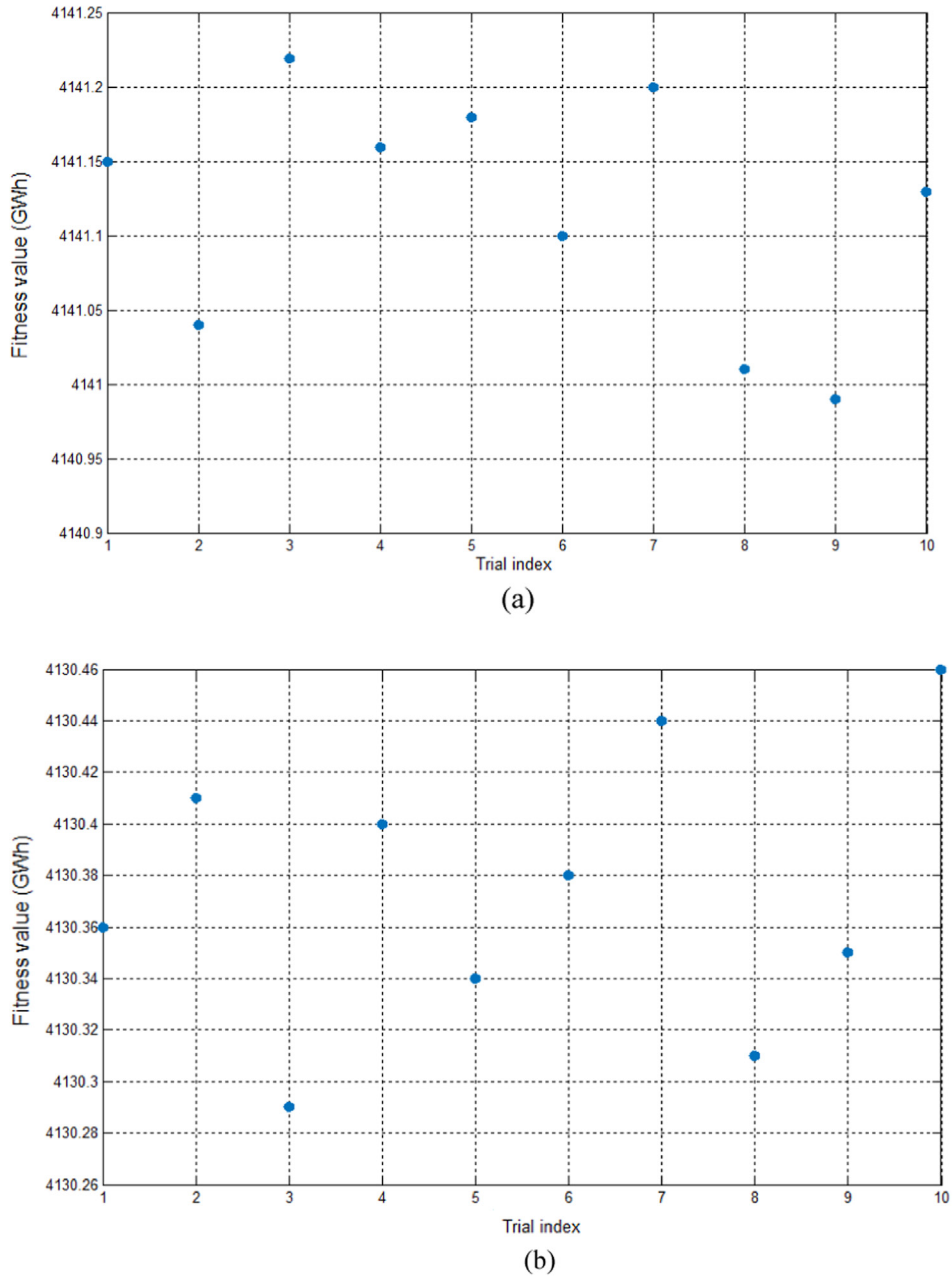


Fig. 13. Fitness values for 10 trials (a) IA-PSO. (b) Traditional PSO.

Table 5
Average efficiency of algorithms for Case B.

Types	Average Fitness value (GWh)	Average Calculation Time (s)
Traditional PSO	4130.37	178,354
IA-PSO	4141.12	62,196

In addition, the wind farm layout optimization is implemented without considering the wind farm noise problems. The relevant optimized results for the annual power generation for the wind farm and noise evaluation are provided in Table 2. As displayed in Fig. 7 and Table 2, whether before or after the layout optimization, if the noise problem is not considered, the noise values of the observation area exceed the specified value of 45 dB(A). Remarkably, the overall power production is improved by 4.9% after optimization, which was also achieved in numerous previous studies. Thus, whether for residential areas, industrial areas, or even bird sanctuaries near any WT, noise considerations are quite necessary.

5.1. *Case A: Strict noise control zone*

The simulation of Case A is run in 10 trials to obtain a better optimal solution, and the results obtained from two algorithms, IA-PSO and the traditional PSO, are compared in Fig. 8. For the equations and the theories for IA-PSO refer to [45]. This method is only used here to obtain the calculation time. Moreover, there is no change in this algorithm; therefore, it is not explained in detail. Furthermore, the average computation times of the two are listed in Table 3 to present the applicability and efficiency of the proposed method. Subsequently, the best value of these trials is selected for the following analysis.

The strict noise control scenario is analyzed following the models and methods proposed above. The relationship between the fitness values and iterations is shown in Fig. 9. The optimized layout for strict noise control is presented in Fig. 10. In addition, the noise distribution

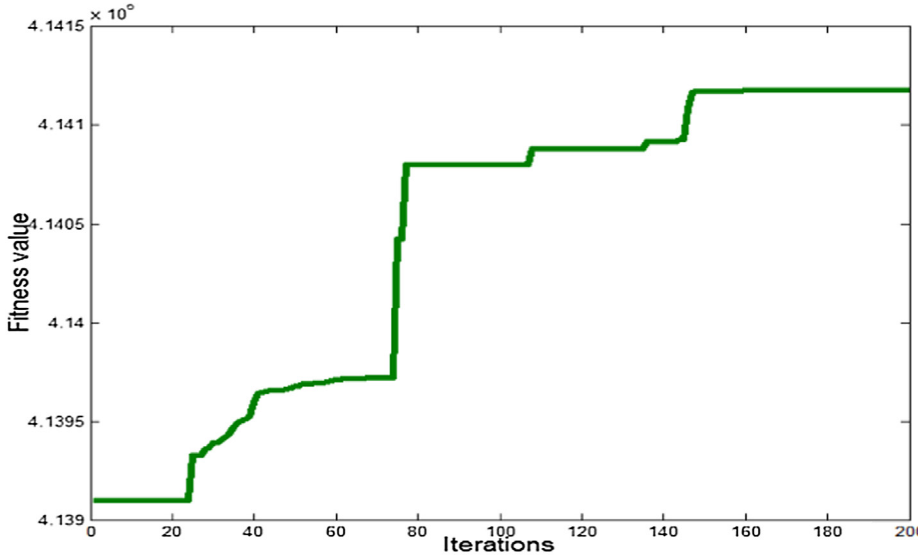


Fig. 14. Fitness values with iterations.

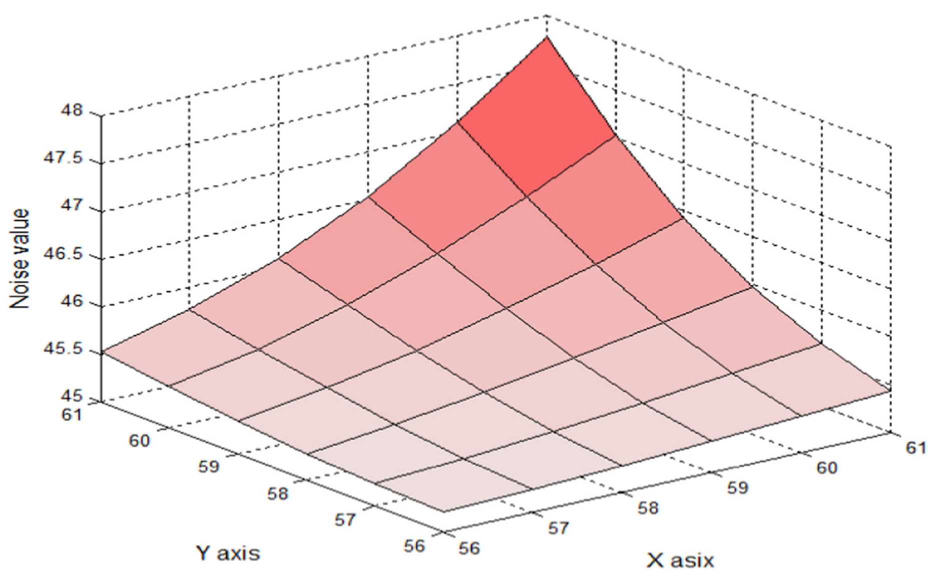


Fig. 15. Noise evaluation of the optimized layout for economic compensated noise control (Unit: dBA).

Table 6
Reference wind farm and two scenarios of optimized wind farms.

Names	Energy production (GWh)	Noise evaluation (dBA)	Noise exceed value (dBA)
Strict noise control	4140.72	44.95	0
Economic compensated noise control	4141.22	47.78	2.78

of this optimized layout for strict noise control in the observation area is described in Fig. 11. The results are provided in Table 4, where they are compared with the optimized results without considering noise.Fig. 12.

As can be seen from Tables 2 and 4, the noise values in the observation area are significantly reduced to approximately 11.32% compared to the reference layout or the optimized results without considering the noise problem, and the maximum noise does not exceed the specified value 45 dB(A). In addition, the power production has been optimized by 3.13% compared to the reference layout. Although the optimized result for the power production is slightly smaller (approximately 1.69%) than the result without considering noise, this outcome is of substantial significance to constructing a more environmentally friendly wind farm and avoiding possible large fines or even closures owing to the noise complaints. In a way, this outcome is more important than a small decrease in the electricity generation.

In addition, the minimum distance between WTs limits the WT positions to being evenly distributed within the preset construction range.

5.2. Case B: Economically compensated noise control

Here, the WT noise is allowed to exceed a specified value to trigger the economic compensated noise control and the subsequent subsidizing of the owners of the wind farm area based on the amount of excess noise. In this case, the subsidy expenditure and the wind farm production gains are evaluated in terms of trade-offs with the goal of generating as many benefits as possible. After the subsidies are subtracted, more wind energy is produced, which increases the benefits.

The simulation of case B is also run in 10 trials to get a better optimal solution, and the results of two algorithms are compared in Fig. 13. Furthermore, the average computation time of the two is given in Table 5. Subsequently, the best value of 10 trials are selected for the cases.

The optimized layout for this scenario is displayed in Fig. 12. The fitness values with the iterations are depicted in Fig. 14. The noise evaluation of the observation area is provided in Fig. 15. The total summary is given in Table 6. Different from case A, case B is not a strict noise control area, only a certain limited range. That is, the regional industry owners are willing to accept a small degree of noise pollution in return for a certain economic compensation, which should satisfy the expectations of the industry owner and the ordinary noise regulations.

As can be noted, the overall layout and several WTs are closer to the observation area than the optimized layout for strict noise control; this is done to apparently better utilize the construction area of the wind farm and to obtain better power production without too much noise consideration. It should be noted that all the coordinate data can be obtained using this method. As displayed in Table 4, although the noise value exceeds the standard, the power production is increased compared to case A. Although the electricity generation increase is not notable, the compensation for noise has, in fact, already been deducted, and it is compared with the optimized results of case A. In addition, the power production has been optimized by 3.14% compared to the original reference layout. If this proposal can be accepted, it is still more or less improved and obtains more benefits. Moreover, if the construction area of the wind farm or the subsidy amount is changed, it is possible to obtain better results. Additionally, the noise problem is even milder than in the two cases in Table 2. For the case where noise is not considered, the wind farm noise is still reduced by 5.74%. This outcome is a win–win situation for owners that are willing to accept the compensation for noise.

Remarkably, the choice of the amount of compensation for a unit of noise will affect the optimization results and notably requires negotiation in the actual process. This paper only describes a method. In addition, the overall balance of noise pollution and the power generation is better, and both the wind farm and the owner of the observation area can achieve mutual benefits.

The proposed method can further reduce the wind farm noise and increase the power production in the wind farm layout design process. The WTs have many potential noise sources including but not limited to the gear noise, and other noise such as mechanical, tip, inflow, and airfoil self-noise [17]. Therefore, these results also apply to all WT noise, which can be modelled using the Hubbard noise model, including the gearless WTs [33].

6. Conclusions

This paper proposes an approach to minimize the wind farm noise. Two strategies are presented to match different requirements of the wind farm designers: a strict noise control strategy and an economically compensated control strategy. The strict noise control can reduce noise to a minimum for the local residents. The compensated control strategy is more flexible and allows the wind farm owners and the surrounding properties to achieve an acceptable range of slight noise concurrently optimizing power output. Once the strategy is selected, only the basic characteristics of the target wind farm requires to be adjusted. The technique can be extended to any wind farm. The cases described here indicate that these methods have a significant effect on reducing the wind farm noise when maintaining or increasing the power output. Compared to the reference layout design, a strict control strategy can reduce noise by 11% and increase power production by 3.1%. The flexible strategy can reduce noise by 5.7% and increase power production by 3.1%. Thus, both techniques can effectively reduce the wind farm noise and increase the power production. As such, it is possible to choose a strategy based on the actual conditions and specific noise needs and obtain a benefit. Further work may take terrain impact into account for wind farm noise distribution in the wind farm layout optimization.

CRediT authorship contribution statement

Xiawei Wu: Methodology, Writing - original draft, Software. **Weihao Hu:** Conceptualization, Writing - review & editing. **Qi Huang:** Supervision. **Cong Chen:** Writing - review & editing. **Mark Z. Jacobson:** Supervision, Writing - review & editing. **Zhe Chen:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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