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To cite this article: Yuhong Sun *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **237** 062018

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Continuous Optimization and Economic Evaluation of Wind Farm Layout Based on Genetic Algorithm with Elitist Strategy

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Abstract. To improve the overall output power and efficiency of the wind farm, considering the cost model of a wind turbine and the multi-turbine wake interference model, using genetic algorithm with elitist strategy, the real-coded method is used to optimize the wind farm layout. The optimal calculation results of three typical flow conditions show that: Compared with the results of the discrete optimization method, the continuous optimization can increase the output power and efficiency of a wind farm by about 1.05% ~ 4.27% in the same amount of wind turbines, increase the economy of a wind farm by about 1.04% ~ 4.10%, and avoid the influence of grid step size on the optimization results, so that it is possible to perform a finer micro-siting.

1. Introduction

The layout optimization of wind turbines in farm is one of the classic applications of modern operations researches. The wind turbine operating in an actual wind farm captures wind energy from the flow, and the rotating rotor will cause the velocity of wake to decrease, which in turn affects the downstream wind turbines [1]. After the macro-siting of the wind farm, considering the annual mean wind speed characteristics of the site, the output of the overall energy of a wind farm is closely related to the number and layout of the wind turbines in the farm [2]. Therefore, the layout optimization of a wind farm is to calculate the specific position of each turbine in the farm through an optimization algorithm, so that the overall energy output of the entire wind farm is maximized.

In the previous research, most scholars used discrete optimization methods to solve the optimization problem of wind farms [3-7]. Mosetti et al. [3] used the genetic algorithm (GA) to calculate a square area of 2000m×2000m. In the simulation, the whole region was divided into 10×10 grids, and wind turbines could be arranged in the center of each grid unit. Based on the researches of Mosetti, Grady et al. [4] improved the algorithm flow and obtained a better layout of wind farm. In the discrete optimization, the position of the wind turbine can only be located in the center of the grid unit. When the grid steps become different, the result of optimization isn't unique [7]. Unlike discrete optimization, in the continuous optimization, the variable is a continuous variable, and the position of the wind turbine is not limited by the grid step size, which is more suitable for the calculation of layout optimization of a large wind farm. Therefore, based on GA, this paper develops a continuous optimization algorithm for the layout optimization of wind farm by using a real number coding



method, and compares it with the results of Mosetti [3] and Grady [4] to verify the accuracy of this simulation.

2. Calculation Model

2.1. Turbine Model

For the convenience of comparison, this paper takes the same turbine model as the turbine in the research of Mosetti and Grady for layout optimization. The characteristic parameters of the turbine are shown in table 1.

Table 1. Characteristic parameters of the wind turbine

Rotor diameter /m	Hub height /m	Thrust coefficient	Surface roughness /m
40	60	0.88	0.3

When the incoming wind speed is between the cut-in wind speed and the rated wind speed, the total wind power is calculated as:

$$P = \sum_i^N 0.3u_i^3 \quad (1)$$

where P is the output power of the entire wind farm; u_i is the wind speed in front of each wind turbine; N is the number of wind turbines arranged in the farm.

2.2. Cost Model

The cost model is also the same as the model in the study of Mosetti and Grady. The cost model mainly considers the influence of the number of turbines, and assumes that the annual dimensionless cost of a single wind turbine is 1. Considering the law of diminishing marginal cost, it is assumed that as the number of wind turbine layouts increases, the apportioned cost is reduced by a maximum of 1/3. Therefore, the wind farm cost model is:

$$Cost = N \left(2/3 + 1/3 \cdot e^{-0.00174N^2} \right) \quad (2)$$

2.3. Wake Model

Assuming that the velocity distribution of a section in the wake is constant, the velocity distribution in the Jensen model is

$$u = u_0 \left[1 - \frac{2a}{1 + (\alpha x / (\alpha x + r_l))^2} \right] \quad (3)$$

where u_0 is the mean wind speed in the flow, a is the axial induced factor, x is the distance after the turbine, α is the wake diffusion coefficient, and r_l is the radius of the velocity deficit zone at the x distance after the rotor in the wake region.

$$\begin{cases} r_l = \alpha x + r_r \\ \alpha = \frac{0.5}{\ln(z_{hub} / z_0)} \end{cases} \quad (4)$$

where r_r is the rotor radius, z_{hub} is the hub height, z_0 is the surface roughness.

In an actual wind farm, the downstream wind turbines are often affected by the wake of several upstream wind turbines. Equation (5) is a formula for calculating the inflow velocity u_i in front of the turbines arranged in the wake of the upstream wind turbines, which assumes that the total kinetic energy reduction caused by multiple wakes is equal to the sum of the kinetic energy reductions caused by each wake [8]. The flow velocity u_i in front of a wind turbine in the wake is:

$$u_i = u_0 \left[1 - \sqrt{\sum_{i=1}^N \left(1 - \frac{u}{u_0} \right)^2} \right] \quad (5)$$

3. Continuous optimization

For the optimization problem of continuous variables, the way of binary coding causes redundant coding and decoding processes. When the solution accuracy is high, the binary coding method requires a longer coding length and a larger population size, which leads to a slower convergence speed and a 'Hamming cliff' problem, so the real code is directly used in this paper. The optimization objective function (i.e. the fitness function) is shown in equation (6), which reflects the economic evaluation of different layouts.

$$\min \frac{\text{Cost}}{P} = \frac{N \left(2/3 + 1/3 \cdot e^{-0.00174N^2} \right)}{\sum_i^N 0.3u_i^3} \quad (6)$$

The layout results should meet the constraints of the minimum spacing and the size of wind farm. When the discrete optimization method is adopted, the wind turbine is arranged at the center of each grid, so the actual effective arrangement range is 100m~1900m in the x and y directions. When continuous optimization is adopted, the grid limitation is avoided. Therefore, the actual effective arrangement range is 0~2000m. In order to facilitate comparison with the results of the discrete optimization method, this paper still limits the layout of the turbine within 100~1900m. The specific constraints are:

$$\begin{cases} (x_i - x_j)^2 + (y_i - y_j)^2 \geq (8R)^2, & i, j = 1 \dots N, i \neq j \\ x_i, y_i \in [100, 1900], & i, j = 1 \dots N \end{cases} \quad (7)$$

where x_i and y_i are the position coordinates of the wind turbine in the farm.

The standard GA using only crossover, mutation and selection will cause the loss of the optimal individual to some extent, and it is difficult to obtain the global optimal. The strategy of using elite retention can effectively avoid this phenomenon. Therefore, we calculate the above models based on the real-coded GA with elite retention strategy.

4. Results and Discussions

4.1. Case A: one wind direction

Case A is a continuous northerly wind of 12 m/s. The layout calculation is performed using 26 turbines (Mosetti's results) and 30 turbines (Grady's results). The results are shown in figure 1. Because the wind direction in the case A is a single steady wind speed and geometrical area symmetry, Grady simplifies the geometric area along the incoming wind direction into a single-column calculation domain of 200m×2000m in the simulation, and then copies the optimization result to other columns. Mosetti directly calculated the entire area without symmetry simplification. Figure 1(a) is a comparison of the results of this paper with the results of Mosetti. The calculation results of the continuous optimization algorithm used in this paper are more uniform in the overall distribution of the wind farm, which is consistent with the characteristics of the incoming wind. Table 2 shows the comparison of the total power, fitness value and the efficiency of the wind farm. It can be seen from the table that under the same number of turbines, the total power and wind farm efficiency of our results increased by 4.27%, and the fitness value decreased by 4.10%. Figure 1(b) is a comparison of the results of this paper with Grady's calculation results. When a symmetrical simplification is used, the total power and efficiency of the entire wind farm are related to the position of the intermediate wind turbine in a single row. Due to the discrete optimization, in Grady's calculation, the position of

the wind turbine can only be located in the center of the grid, and the algorithm of this paper captures the optimal arrangement position of the middle wind turbine. Compared with discrete optimization, the results of continuous optimization are about 3.37% higher in total power and wind farm efficiency, and about 3.26% smaller in fitness value.

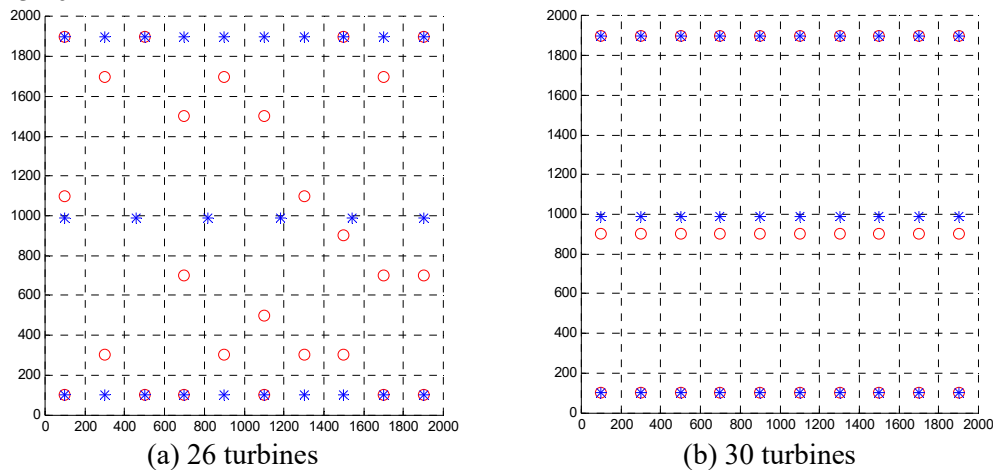


Figure 1. The layout of wind farm in the case A. Among them, * is present study, and \circ is other scholars' studies.

Table 2. Comparison of the results in the case A

Case A	Mosetti (26 turbines)	Present study (26 turbines)	Grady (30 turbines)	Present study (30 turbines)
Total power (kW)	12352	12880	14310	14792
Fitness value (10^{-3})	1.6197	1.5533	1.5436	1.4933
Efficiency (%)	91.645	95.560	92.015	95.113

4.2. Case B: multiple wind direction

In the case B, the calculation is performed when the wind direction is changed by 10° in the range of $0^\circ \sim 360^\circ$ at a constant wind speed of 12 m/s. The layout optimization was carried out using 19 turbines (Mosetti's results) and 39 turbines (Grady's results). The results are shown in figure 2. Since the direction of the incoming wind speed varies uniformly from 0° to 360° , the results of our algorithm show that the position of the wind turbine is concentrated in the peripheral area of the farm, and the regularity and uniformity of the layout are better, and the output of power is more. As shown in table 3, compared with the calculation results of Mosetti and Grady, our algorithm can increase the total power and wind field efficiency by about 1.05% and 1.84%, respectively, and reduce the fitness values by about 1.04% and 1.80%, respectively.

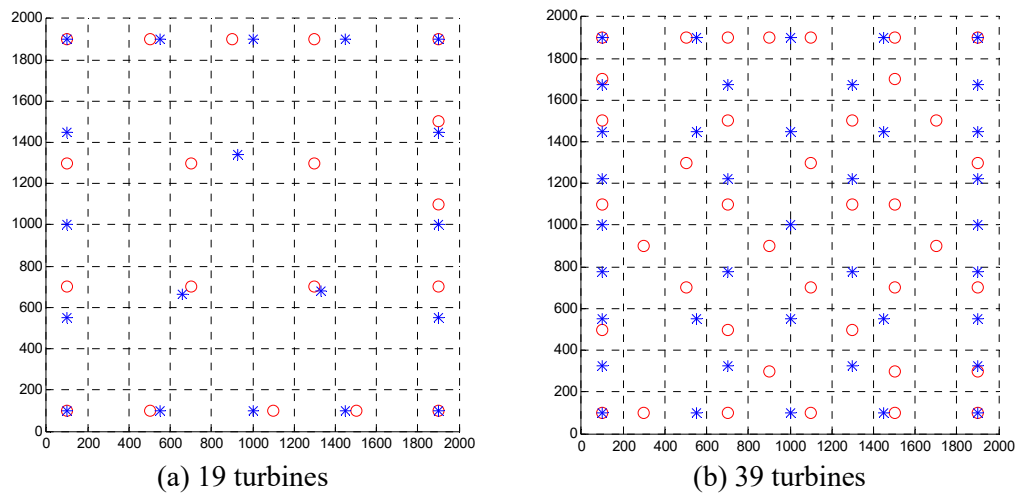


Figure 2. The layout of wind farm in the case B

Table 3. Comparison of the results in the case B

Case B	Mosetti (19 turbines)	Present study (19 turbines)	Grady (39 turbines)	Present study (39 turbines)
Total power (kW)	9244.7	9341.7	17220	17536
Fitness value (10^{-3})	1.7371	1.7191	1.5666	1.5384
Efficiency (%)	93.859	94.843	85.174	86.736

4.3. Case C: multiple wind direction with variable

The velocity in an actual wind farm may follow the characteristics of a certain fluctuation wind speed spectrum [9]. The variation of the magnitude and direction of the wind speed will be very severe. In this study, it is converted into the case C. The inflow condition of the case C contains 36 different wind directions and 3 different wind speed magnitudes, and the probability distribution is shown in figure 3. The wind speed is highly probable in the range of 270° ~ 350° , so the position of the wind turbine should be mainly within this range. The results are shown in figure 4. Layout optimization was carried out using 15 turbines (Mosetti's results) and 39 turbines (Grady's results). Table 4 shows the comparison of total power, fitness value and wind farm efficiency. Compared with the results of Mosetti and Grady, the total power and wind farm efficiency are increased by 1.20% and 1.30%, respectively, and the fitness value is reduced by 1.18% and 1.28%, respectively.

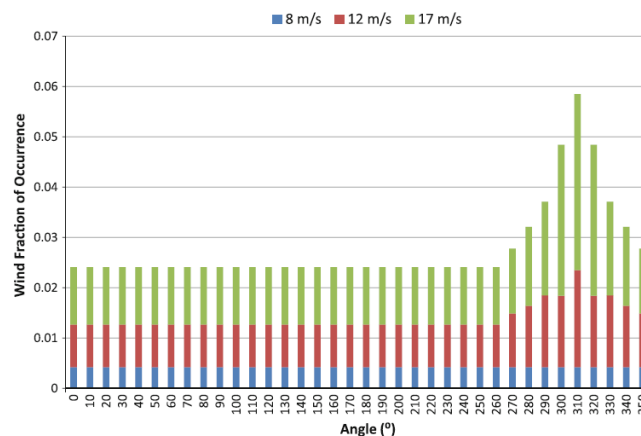


Figure 3. Inflow condition of case C

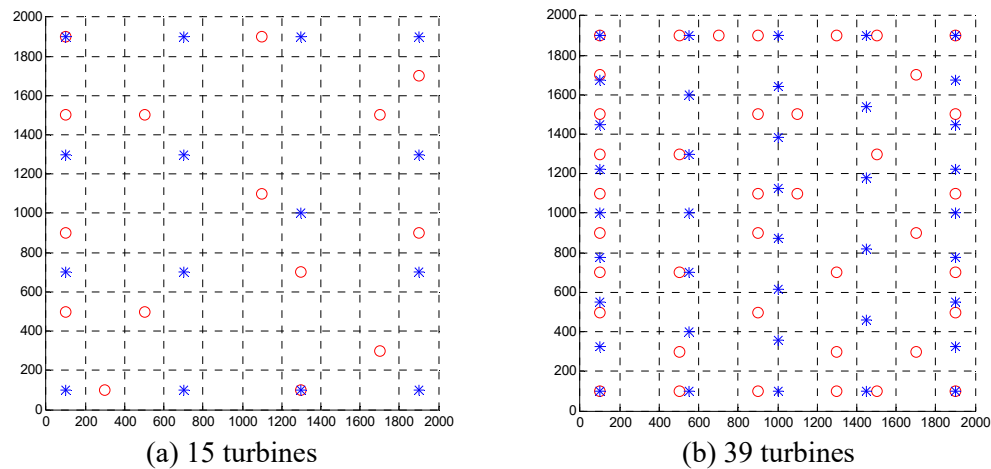


Figure 4. The layout of wind farm in the case C

Table 4. Comparison of the results in the case C

Case C	Mosetti (15 turbines)	Present study (15 turbines)	Grady (39 turbines)	Present study (39 turbines)
Total power (kW)	13460	13621	32038	32455
Fitness value (10^{-3})	0.99405	0.98230	0.80314	0.79282
Efficiency (%)	94.619	95.752	86.619	87.746

5. Conclusion

Based on the GA with elite retention strategy, this paper develops a continuous optimization algorithm for the layout optimization of wind farms by real number coding, and compares it with the results of Mosetti and Grady to verify the accuracy of the algorithm. The results show that the continuous optimization algorithm can capture the optimal arrangement position of the wind turbine because it is not limited by the grid step size, which makes the wind farm more efficient and economical. Under the same number of wind turbines, the continuous optimization can increase the output power and efficiency of a wind farm by about 1.05% ~ 4.27%, and increase the economy of a wind farm by about 1.04% ~ 4.10%, which is of great significance for the layout of the wind farm.

Acknowledgments

This work was funded jointly by the National Basic Research Program of China (973 Program) under Grant No. 2014CB046200, the Jiangsu Provincial Natural Science Foundation under Grant No. BK20140059, the Priority Academic Program Development of Jiangsu Higher Education Institutions, the National Natural Science Foundation of China under Grant No. 11172135. All simulations were carried out using the equipment provided by Gansu Provincial Computing Center.

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