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Optimizing the unrestricted wind turbine placements with different turbine hub heights

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ABSTRACT
Wind farm layout optimization is an effective means to mitigate the wind power losses caused by the wake interventions between wind turbines. Most of the researches in the field are conducted on the basis of fixed wind turbine hub height, while it has been proved that different hub height turbines may contribute to the reduction of wake power losses and increase the wind farm energy production. To demonstrate this effect, the results of simple two-wind-turbine model are reported by fixing the first wind turbine hub height while varying the second one. Then the optimization results for a wind farm are reported under three different wind conditions, consisting of constant wind speed and wind direction, constant wind speed and variable wind directions, and variable wind speeds and variable wind directions. Unlike the previous researches using the grid based method to conduct the optimization studies, the wind farm layout optimization with differing hub heights is carried out using the unrestricted coordinate method in this paper for the first time. Different optimization methods are applied for the wind farm optimization study to investigate their effectiveness by comparison. It shows that the selection of the identical wind turbine hub height yields the least power production with the most intensive wake effect. The value of optimum wind turbine hub height is dependent on several factors including the surface roughness length, spacing between the two wind turbines and the blowing wind direction. The simultaneous optimization method is more effective for the complex wind conditions than for the simple constant wind condition.

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KEYWORDS: Wind farm study; Layout optimization; Hub height optimization; Simultaneous optimization;

1 INTRODUCTION
Wind energy plays a very important role as an alternative energy supply nowadays, due to its properties of renewability and generality on earth. In the year of 2011, the worldwide installed wind power capacity was reported to reach 237 Gigawatt (GW). It is expected that the total installed wind power capacity will be 1000 GW by 2030, as reported by the World Energy Association [1]. For most of them, the utilization of wind energy is achieved in the form of transformation to the electricity using wind turbines. In order to make full use of local wind energy resources, multiple wind turbines are placed in cluster which is called the wind farm or wind park. However, the non-isolated wind turbines bring about the wake interactions, namely, wake interference or wake effect, which greatly reduce the total power production of a wind farm. By optimizing the wind farm layout, the power losses can be regained to a large extent.

Among all the previous wind farm layout optimization studies reported, most of them have considered the scenario with constant wind turbine hub height [2, 3]. However, for a wind farm mostly using the identical type of wind turbine, the hub height of turbines can be selectable. Meanwhile, it is reported that the use of different wind turbine hub heights have the potential to reduce the power losses caused by the wake interaction and hence contribute to the wind farm layout optimization. For the existing literature that report the optimization with different hub heights [4, 5], none of them have claimed to apply the unrestricted coordinate method (use wind turbine coordinate to determine the position in wind farm) to study the layout optimization, which is believed to be supreme than the counterpart method. Therefore, this paper attempts to discuss the wind farm layout optimization using the unrestricted coordinated while considering different wind turbine hub heights. The effect of applying different wind turbine hub heights on the power production for both single wind turbine and wind farm is discussed in detail through simple two turbine model and wind farm model. In the meantime, different optimization methods including the single layout optimization, hub height optimization and simultaneous optimization are applied to evaluate their effectiveness under different wind conditions.

The rest of the paper is organized as follows. Section 2 discusses the methods applied for the wind farm layout optimization studies. It includes the optimization algorithm applied for the studies, the calculation of the objective function, the representation of the solution for the objective function using different optimization methods and finally process of the wind farm layout optimization studies using different methods. Section 3 discusses the results and Section 4 draws the conclusion.

2 METHODS

The methods for the three different types of optimizations are introduced in this section. They are presented in the aspects of optimization solution for the methods, optimization algorithm, objective function calculation and finally the optimization process for the methods

2.1 Optimization algorithm

For all the three different optimization methods as described above, one feature that they have in common for the solution X is that they all applied the simple real coding method with different number of variables. Therefore, simple Single Objective Genetic Algorithm (SOGA) is employed in this paper to study the optimization of wind farm with different hub heights. GA is a search heuristic that mimics the process of natural selection [6]. It begins with encoded solutions to the optimization problem. The main principle of GA is the maintenance of these encoded solutions which are evolved with the generations to be guided towards the optimum solutions step by step. A simple GA works as follows [7]:

1) A random initial population (a set of encoded solutions) is created.
2) The fitness of each individual (the single encoded solution) is evaluated based on the optimization objective function.
3) The raw fitness values are transformed into the range of values that are suitable for the selection process through the fitness scaling procedure.
4) The individuals with the best fitness values are guaranteed to survive to the next generation, while other individuals are used to select parents to produce new population individuals for the next generation.
5) Other new population individuals are generated through the crossover and mutation operators.
6) The current population is replaced with the new generation
7) Steps 2 to 6 are repeated until the stopping criteria is met

2.2 Calculation of objective function

Before calculating the wind farm power, the single wind turbine power P_{WT} and the wind speed approaching the rotor of every single wind turbine should be determined first. In this paper, the wind turbine model applied in [8] is employed, and means of determining the wind speed for the turbines affected by the multiple wakes can be referred in [9].

For the discrete wind condition applied in this paper, based on the individual wind turbine power model and the approaching wind velocity for each wind turbine, *i*-th wind turbine power Pi can be obtained. The total power output P_{tot} with NWT number of wind turbines and finite number of wind directions N_d can be calculated as:

$$P_{tot} = \sum_{j=1}^{N_d} p_j \left[\sum_{i=1}^{N_{WT}} P_i \right]_{\text{j-th direction}} \quad (1)$$

where p_j is the probability of occurrence of *j*-th wind direction. The wind farm power output is calculated as the accumulation of all wind turbine power output:

$$P_{tot} = \sum_{i=1}^{N_{WT}} P_i \quad (2)$$

Based on the calculation of wind farm power output and the wind farm cost models, the Cost of Energy (CoE), which is the objective function for the wind farm optimization study in this paper, can be represented by:

$$\text{CoE} = cost / P_{tot} \quad (3)$$

where *cost* is the wind farm cost given in reference [10] and P_{tot} is the wind farm power output calculated above.

2.3 Optimization solution

The optimization solution *X* indicates the individual of encoded solution, and each encoded element among them indicates the variable needs to be optimized through the algorithm.

a) Layout optimization

For the simple wind farm layout optimization with identical wind turbine hub height, the optimization solution *X* can be represented as follows:

$$X = \underbrace{\boxed{x_1}\cdots\boxed{x_i}\cdots\boxed{x_N}\boxed{y_1}\cdots\boxed{y_i}\cdots\boxed{y_N}}_{2\times \text{N decimal digits}} \quad (4)$$

Where x and y stores the X and Y coordinates for different wind turbines. N is the number of wind turbines to be optimized which is predetermined by the user. So X applies the real variable value codification with altogether 2*N number of variables.

b) Hub height optimization

For the simple wind turbine hub height optimization, it is conducted based on the result of the optimized wind farm layout through the simple wind farm layout optimization method. The optimization solution X for the optimization method can be represented as follows:

$$X = \underbrace{\boxed{H_1}\cdots\boxed{H_i}\cdots\boxed{H_N}}_{\text{N decimal digits}} \quad (5)$$

Where H stores the wind turbine hub height value for different wind turbines and X has N number of variables in total.

c) Simultaneous optimization

For the simultaneous wind farm layout and wind turbine hub height optimization, the optimization solution X can be represented as follows:

$$X = \underbrace{\boxed{x_1}\cdots\boxed{x_i}\cdots\boxed{x_N}\boxed{y_1}\cdots\boxed{y_i}\cdots\boxed{y_N}\boxed{H_1}\cdots\boxed{H_i}\cdots\boxed{H_N}}_{3\times\text{N decimal digits}} \quad (6)$$

Where it is obvious that the solution X for the method can be regarded as the integration of the two solutions for the last two optimization methods.

2.4 Optimization process

Fig. 1 depicts the general process of the three methods applied in this paper for the wind farm layout optimization studies. Initially, the wind farm design parameters are randomly generated for the different optimization approaches. For the simple wind farm layout optimization method, the random layout parameter (wind turbine position) of the initial population is generated with fixed wind turbine hub height. For the simple hub height optimization method, the random wind turbine hub height values of the initial population is generated while the wind turbine positions are fixed which are imported from the layout optimization results. Unlike these two optimization methods, both wind turbine positions and wind turbine hub height are variable and optimized during the process for the simultaneous optimization. Hence both parameters are initialized randomly as the initial population for this method. After the initialization, all the related wind turbine parameters used for the calculation of wind farm power output are ready using different optimization approaches. Then individuals of the initial population are evaluated according to the objective function (see Appendix 1) followed by GA optimization procedures. The process excluding the initialization part is repeated until the GA stopping criteria is met.

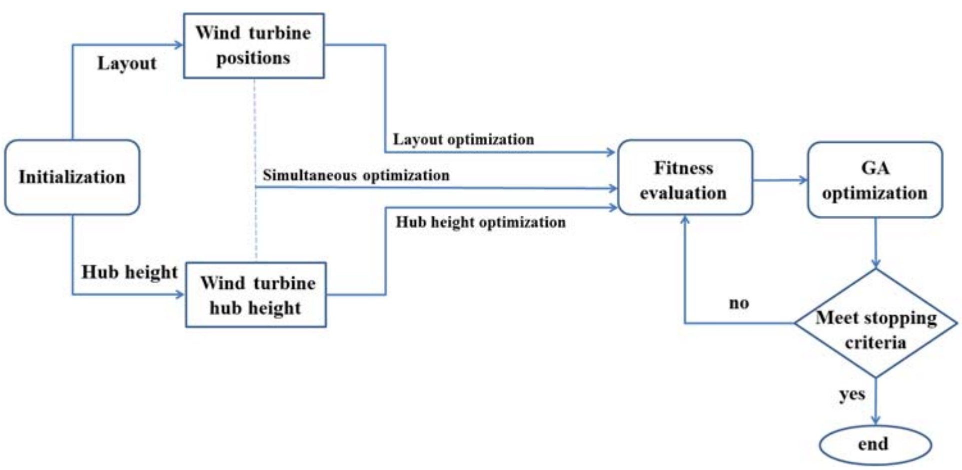

Fig. 1 Process of the wind farm layout optimization study using different optimization methods

3 RESULTS AND DISCUSSION

Before applying different wind turbine hub heights while designing the wind farm, the simple two wind turbine model is employed to study the influence of the factors including surface roughness, wind turbine spacing and wind direction on the wake-affected wind turbine power production with different hub heights. After this, the wind farm layout optimization study using different optimization methods are carried out and the effectiveness of the methods are compared.

3.1 Two wind turbine model results

For the two wind turbine model, we fix the first wind turbine hub height and study the variation of the second wind turbine power affected by the wake effect (normalized to the free stream wind turbine power) with different hub heights. First, the influence of the surface roughness length (Z_0) on the results is studied with wind direction aligned with the wind turbines and fixed spacing of 15D (D is rotor diameter). Fig. 2 (a) depicts the study model while four different surface roughness values are employed from the smooth surface of open sea (Z_0 = 0.0002) to the tough surface of high crop obstacle ground (Z_0 = 0.3). As can be seen from Fig. 2 (b), the tougher surface is, the more power wake-affected wind turbine produces in general. When the surface roughness length value is big (0.3), there is no need to apply different wind turbine hub heights for the back turbine in this case since it is in full wake of the front turbine anyway. When the surface roughness length value is small (Z_0 is less than 0.001), the variation of Z_0 won't have much impact on the power production, and increase of power production by applying different hub height is more prominent. The bigger difference back turbine hub height has from front turbine hub height, the larger power production increase it yields compared with constant hub height.

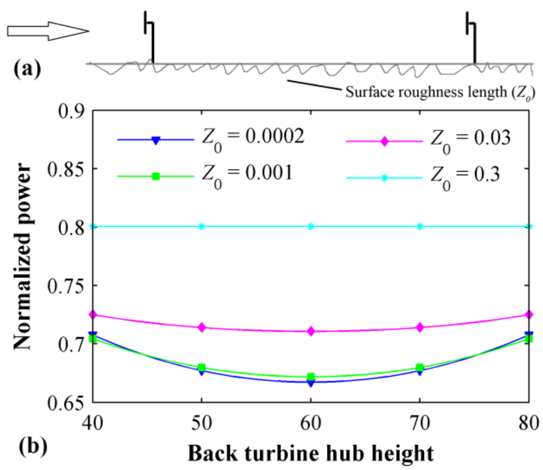

Fig. 2 Variation of normalized wake-affected *wind* turbine power production with different wind turbine hub height for four characteristic surface roughness lengths

Fig. 3 indicates the results of back turbine power production with different hub heights for different spacing (*S*) between the two turbines from 5D to 20D (D is the rotor diameter). Obviously, the more distance between turbines, the less wake power losses it has. Also it is found that the percentage of power increase due to the enlarged distance becomes less as it continues. Still when applying different wind turbine hub heights, there is basically the same power increase regardless of the spacing it applied. For the wake-affected back turbine, its power productions with different hub heights are symmetrical with that of the front turbine hub height value (60 m), at which point the back turbine has the most wake power losses.

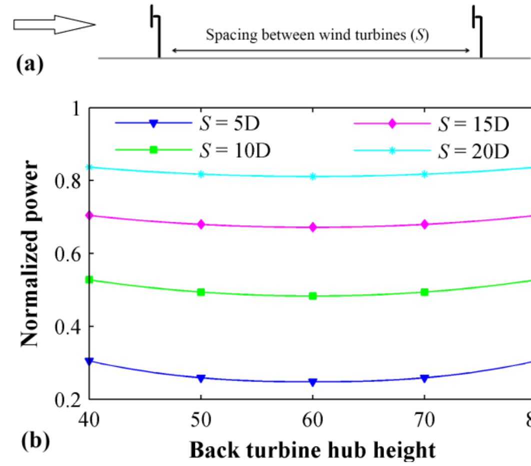

Fig. 3 Variation of normalized wake-affected wind turbine power production with different wind turbine hub height for different spacing between wind turbines

Next we study the effect of wind scenarios on the power production of wake-affected wind turbine by applying different hub heights. When varying the wind speed with fixed wind direction still aligned with the two wind turbines, it is found that the wake effects are the same for the back turbine with constant normalized power production, and the results are not quantitatively shown here. Fig. 4 reports the variation of normalized power production of wind turbine with different hub heights when the wind blowing angle varies from 0 degree to 10 degree. The model is illustrated in Fig. 4 (a) and the results are shown in Fig. 4 (b). As can be seen when the wind direction is very much aligned with the two wind turbines (up to 4 degree), the power production of the back turbine is the same regardless of the hub heights applied. The power production increases as the wind direction continues to increase, and the power increase due to the use of different wind turbine hub heights is also increasingly pronounced along with the wind direction (up to 9 degree). When the wind direction exceeds 10 degree, the back turbine is not located in the wake of the front turbine anymore, which reaches its maximum power production with free stream wind.

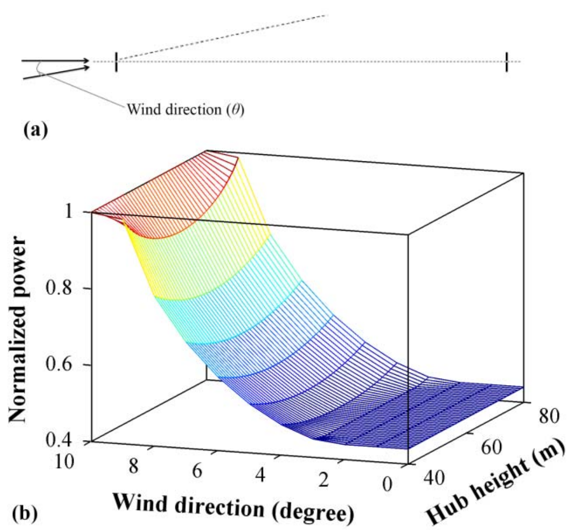

Fig. 4 Variation of normalized wake-affected wind turbine power production with different wind turbine hub height under different wind blowing angles

3.2 Wind farm results

Three characteristic wind farm conditions, which have been popularly employed for the wind farm layout optimization study, are applied in this paper to compare the effectiveness of different optimization methods for the wind farm with different hub heights.

Constant wind speed and wind direction

Fig. 5 reports the wind farm layout optimization results under constant wind speed of 12 m/s and constant wind direction that is aligned with the wind farm length direction (defined as 0 degree). Fig. 5 (a) shows the optimized fitness of the objective function, which is the normalized value for cost of energy production (CoE) using the three methods. The standard deviation of the fitness results with repeated calculation are incorporated in the figure as well. It can be seen that the simultaneous optimization method achieves the best optimization results (the smallest fitness value) through repeated calculation, while it has large deviation and hence relies on the repetition to obtain the best optimization result. When using simple layout optimization method, it also has large deviation. Based on its best optimization result through repeated calculation, the hub height optimization attempts to further optimize the wind turbine hub height but has little improvement. It is also found that the hub height optimization method has no deviation through repeated calculation which means that the results are unchanged and the performance is stable. Fig. 5 (b) shows the optimal wind farm layout using different wind turbine hub height after the optimization comparison. It should be noted that the selectable range of wind turbine hub height is from 60 m to 70 m in this paper for the wind farm optimization study with all three different wind conditions. The distribution of the wind turbine is obvious for the simple constant wind condition. Nearly half number of turbines is located near to the one side of the wind farm boundary perpendicular to the wind direction in windward direction, and they all have the lower bound of the hub height value which is 60 m. Most of the rest of wind turbines are distributed near to the other normal side of the wind farm boundary in leeward direction. As can be seen, most of them have higher hub height than that of the wind ward turbines to escape from the wake of upstream wind turbines.

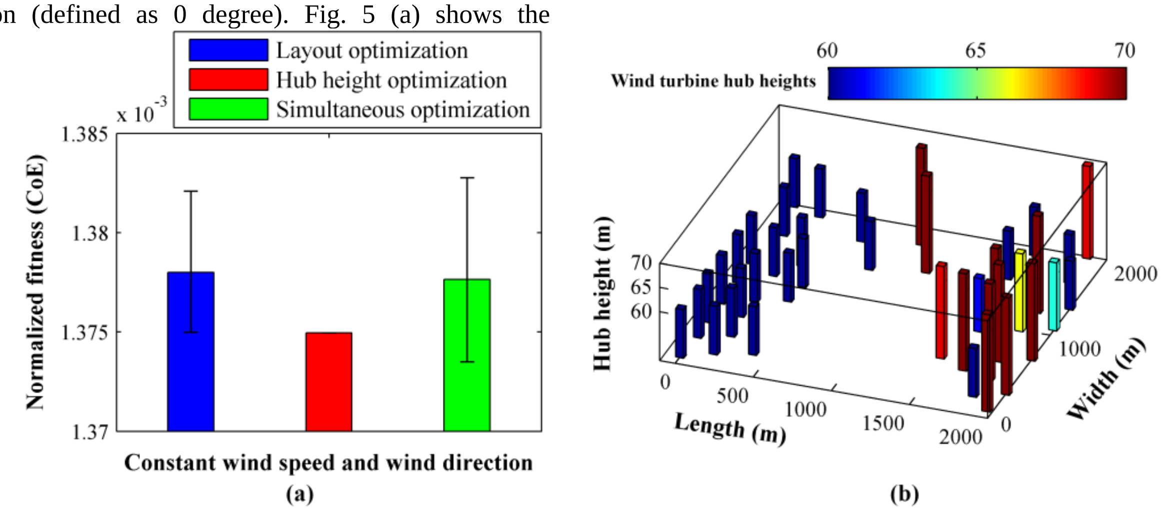

Fig. 5 Results of constant wind speed and constant wind direction aligned with wind farm length: (a) normalized fitness of the objective function using different optimization methods (standard deviation depicted) and (b) optimal wind farm layout with different wind turbine hub heights (turbines are represented by the cuboid with different heights indicated by colors)

performance of the method is more stable. In comparison, the simple layout optimization method has large deviation and obtains worst optimization results, while the results of hub height optimization is also inferior to the simultaneous optimization method and the deviation of the hub height optimization with repeated calculation is still zero. By observing the optimal wind farm layout shown in Fig. 6 (b), it is obvious that most of wind turbines are distributed along the four sides of wind farm boundaries. Seven of them have the upper bound of hub height value (70 m), and the rest of wind turbine has hub height of 60 m.

Constant wind speed and variable wind directions

Fig. 6 reports the optimization results for the constant wind speed of 12 m/s and variable wind directions. The wind is coming from 36 wind directions evenly distributed with 10 degree interval, that is 0 degree, 10 degree, …, and 350 degree. It can be from Fig. 6 (a) that for this wind condition the simultaneous optimization achieves way much better results than the counterpart method. Meanwhile, the deviation of repeated calculation for the method is relatively small compared with the results of above constant wind condition, which implies the

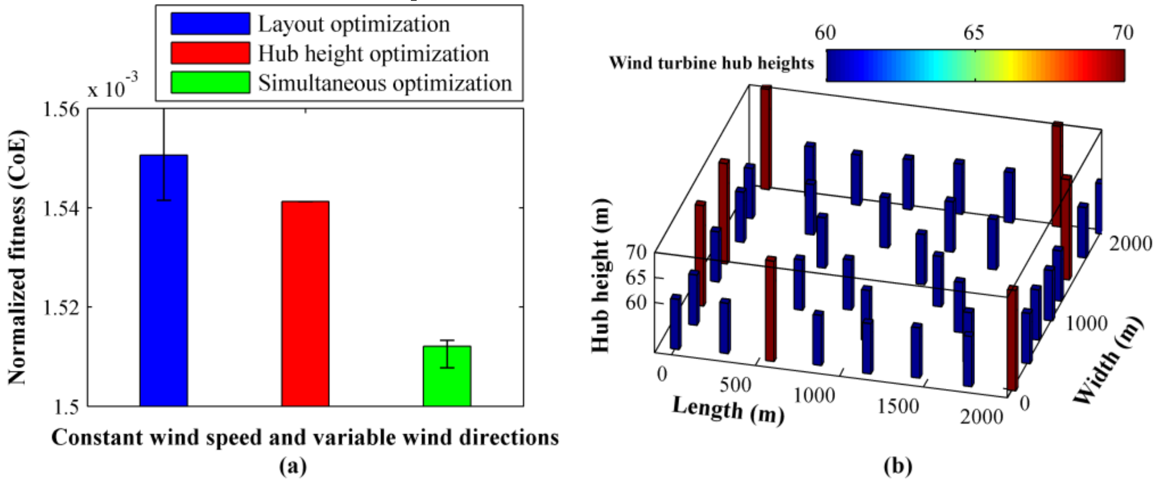

Fig. 6 Results of constant wind speed and variable wind directions: (a) normalized fitness of the objective function using different optimization methods and (b) optimal wind farm layout with different wind turbine hub heights

Variable wind speeds and variable wind directions

Before discussing the results under the variable wind speeds and variable wind directions, the wind condition is introduced here as shown in Fig. 7. The wind condition also consists of 36 wind directions with 10 degree interval. Every component of the wind directions comprises three different wind speeds and each wind speed in each wind direction is assigned with a value to represent the probability of occurrence. The same wind condition is also applied in [8, 10, 11].

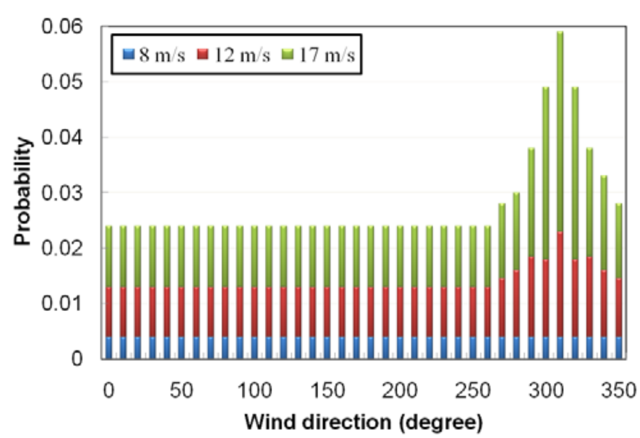

Fig. 7 Histogram of the wind condition for variable wind speeds and variable wind directions

Results of the wind farm layout optimization study with different hub heights for this wind condition are shown in Fig. 8. Like the above condition of constant wind speed and variable wind directions, the simultaneous optimization achieves the best fitness results with the small deviation of repeated calculations. The results using the layout optimization method are the worst with large deviation, based on which there is a small improvement for the results of hub height optimization without deviation of repeated calculation for it. According to the optimal wind farm layout for this wind condition shown in Fig. 8 (b), most of the wind turbines are spread along the four sides of wind farm boundaries to enlarge the distance between wind turbines with blowing wind from all 360 degrees. Five of them employ the largest wind turbine hub height with 70 m, and for the rest of wind turbines the hub heights of them are near to 60 m.

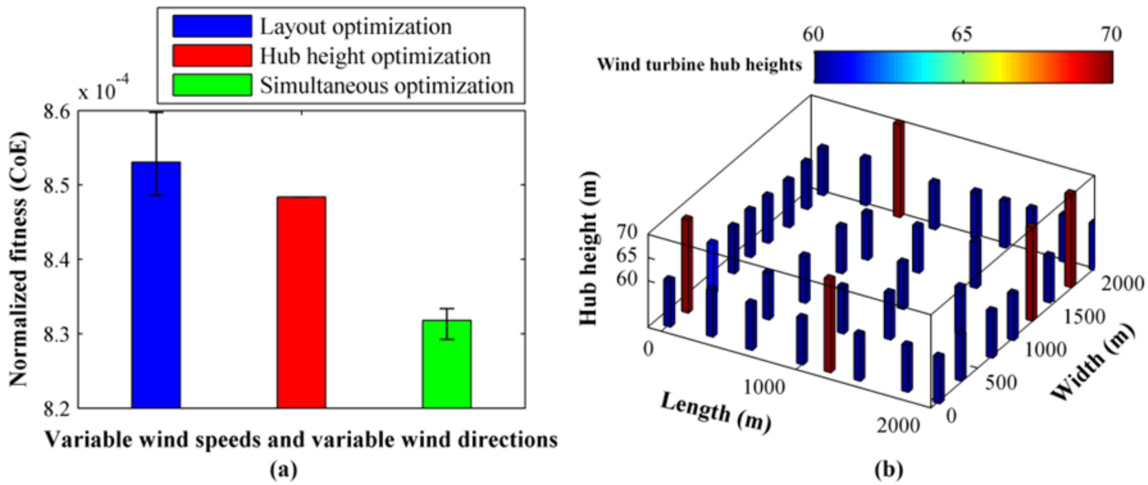

Fig. 8 Results of variable wind speeds and variable wind directions: (a) normalized fitness of the objective function using different optimization methods and (b) optimal wind farm layout with different wind turbine hub heights

6 CONCLUSIONS

The wind farm layout optimization, which applies the unrestricted coordinate method to determine the wind turbine position, is carried out in this paper for the first time by considering different wind turbine hub heights with same rotor diameter (same wind turbine type). Before introducing the wind farm design results, the simple two wind turbine model is studied in order to discuss the influence of related factors on the wake-affected turbine power output when applying different hub heights. It is found out by altering the back turbine hub height (either increasing or decreasing based on the front turbine hub height value), the power output of the back turbine can be regained. The bigger difference of hub height between the two turbines, the more power output increase it has. However, depending on the distance between the two turbines, the variation of the hub heights becomes ineffective when the surface roughness length exceeds certain value as the back turbine is always located in the full wake of front turbine. Based on the wake model applied in this paper, with all other fixed factors except for the blowing wind speed the normalized power output for the back turbine is unchanged regardless of the hub height employed. Nonetheless, it is closely related to the blowing wind direction. Under certain value of wind angle, the wake-affected turbine power is fixed as it is always in the full wake of upstream turbine regardless of the hub height employed. As wind direction increases, the effect of altering the turbine hub height on the increase of power output becomes pronounced since it enables the back turbine rotor to jump out of the wake zone or at least decrease the wake-affected area. When the wind direction exceeds certain value, the back turbine is not affected by the wake of front turbine even with constant hub height, and hence the use of different hub heights becomes needless.

Three characteristic wind conditions, which have been widely employed in the wind farm layout optimization studies, are applied in this paper to test the effectiveness of different methods for the different hub height optimization studies of wind farm. For the simplest wind condition of constant wind speed and constant wind direction, the layout optimization is effective enough to obtain the good results by repeated calculation. Based on the results, the improvement of applying hub height optimization is not evident. In comparison, the simultaneous optimization has large deviation with repeated calculation and the improvement of the best optimization results obtained by the simultaneous method is relatively small. For the other two wind conditions, the effectiveness of applying simultaneous optimization method is obvious compared with the counterpart method and the performance is more stable with relatively small deviation of repeated calculation. This is because for these two wind conditions incorporating all wind directions of 360 degrees the single layout optimization is inefficient with constant wind turbine hub height. Based on the inferior fixed wind turbine positions, the hub height optimization has little contribution to the increase of the final wind farm results. In contrast, the simultaneous optimization method facilitates the design to both optimize the wind turbine position and hub height at a time and hence much better results can be achieved.

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