Optimizing the layout of wind turbines by upgrading a wind farm

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Abstract. The optimization of the size of wind farms is little studied in the literature. The objective of this study is to renew the existing wind farms by inserting new wind turbines with different characteristics. To evaluate our approach, a genetic algorithm was chosen to optimize our objective function, which aims to maximize the power of the wind farm studied at a reasonable cost, the Jensen wake model was chosen for the power calculation of the park. The results obtained from the simulation on the Horns-rev wind farm showed a significant increase in energy and a relatively reasonable cost of energy.

1 Introduction

The strong demand for renewable energies has pushed the designers of wind farms to redouble their efforts on the optimization of the energy produced by a wind farm, in fact wind power has become more competitive compared to other sources of energy. energy such as (solar photovoltaic and fossil fuels) [1], it is also thanks to the advantages of wind energy, such as the low emission of greenhouse gases and the cleanliness of this energy [2]. Power production by country is shown in Figure 1, it shows that China is the largest producer of wind power. However, a lot of effort is being made by the International Energy Agency [3] to meet global needs of 18% by 2050.
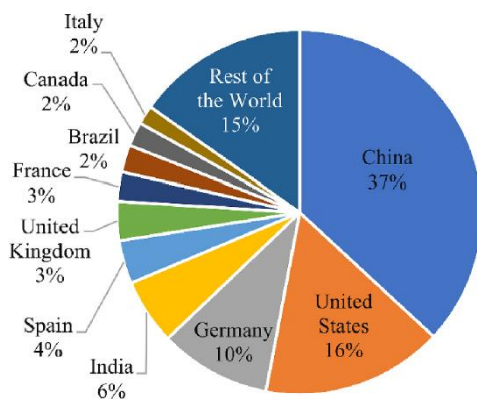

Fig. 1. Below the Wind energy produced by country [4].

Designing a wind farm generally refers to choosing an appropriate location of one wind turbine relative to the other within a limited area [5]. This choice constitutes a major challenge for designers, mainly due to the interference of wakes generated by upstream wind turbines [6-7]. The random nature of these interferences and its strong dependence on installation site variables and design parameters not only affects the performance

of wind farms but of course the entire viability of the wind project [8]. Therefore, it is interesting when designing a wind farm to understand how these different variables act on the interactions between wind turbines and therefore on the quality of production performance. In addition, for a wind farm of a few wind turbines, designers warn of simple methods of listing possible configurations or attempting to find them by hand. However, these methods are no longer obvious and effective with the current trend of large wind farms and with a large number of wind turbines [9]. Faced with this problem, it is crucial to resort to other more rational methods such as heuristic optimization methods [10-11] which are particularly effective in solving this kind of problem.

Choosing one configuration among others remains a major difficulty for designers. Indeed, in real wind projects the selection of a wind farm configuration is carried out according to the requirements defined by the decision maker [12-13]. That is, the design is carried out according to the preferences of the decision-maker and the importance given to the various design objectives. At this level an important question arises on how to formalize and integrate the preferences of the decision-maker in the process of optimizing the design of existing wind farms. A rigorous answer to this question constitutes our main contribution which consists in updating an existing wind farm by maximizing the energy and minimizing the cost of a wind farm.

Indeed, many wind farms founded in previous years have not updated in terms of optimization [14], previous studies have shown that after 20 to 25 years it is generally recommended to "repowered" or "decommissioned" them. old wind farms [15-16], the redevelopment of an existing wind farm consists of changing a few parts or even a turbine [17], in the event that the "repowered" method is delicate, the wind farm

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is decommissioned and consequently the shutdown of electricity production.

2 Wind farm modeling

2.1 Wake modeling

The wake downstream of the wind turbines is characterized by a high-speed deficit and level of turbulence which affects the performance of the wind turbines, the powers supplied are reduced and the loads on the rotors are greater [18-19], which results in the reduction of their life. life. However, there are several models which predict the energy produced from a wind farm and which takes into account the wake effect, among the most used wake models in the literature is the Jensen model [20], figure 2 shows the influence of the downstream turbine by the propagation of the wake from the upstream turbine.
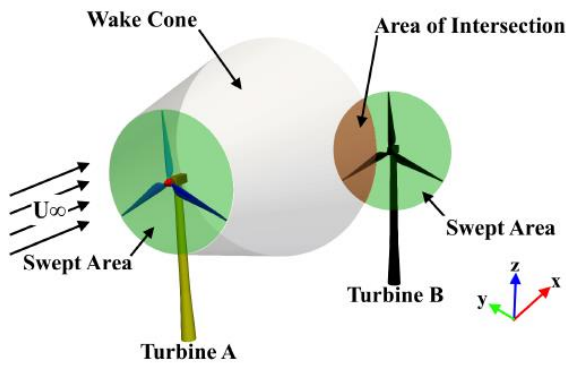
Fig. 2. influence of the downstream turbine by the propagation of the wake from the upstream turbine [21].

In the rest of this paper, we will use Jensen's model for our wind speed calculation. Therefore, the speed deficit is expressed as follows:

$$V_{df} = V_f \left[\left(1 - \sqrt{1 - C_T}\right) \left(\frac{D}{D_{wake}}\right)^2 \right] \quad (1)$$

Where,
D: Rotor Diameter (m)
D_{wake}: Wake diameter (m)
C_T: Trust coefficient
V_f: Free incoming wind speed (m/s)
V_{df}: Wind velocity deficit (m/s)

The variation of the wake diameter depends on the size of the rotor and on a wake minimization coefficient [22].

2.2 Modeling of energy production

To calculate the energy produced in a wind farm and under the wake effect, we will use the expressions established in [23], so the approximate expressions of the power of a wind turbine is as follows:

$$P_{WT} = \frac{1}{2}\rho\pi\frac{D^2}{4}C_{EF}(V_f - V_{df})^3 \quad (2)$$

Where,

C_{EF} is the efficiency factor that we calculate it as follows:

$$C_{EF} = C_p\eta_m\eta_g \quad (3)$$

The power of the wind farm P_{WF} is easily deduced by adding up each wind turbine in the farm.

$$P_{WF} = \sum_{i=1}^{N_t} P_{WT} \quad (4)$$

Equation 5 expresses the efficiency of the wind farm:

$$\eta_{WF} = \frac{P_{WF}}{\left(\frac{1}{2}\rho\pi\frac{D^2}{4}C_{EF}V_f^3\right)} \quad (5)$$

The coordinates of the wind turbines are denoted by (x, y), the spacing between the wind turbines and the deficit are expressed in [24] [25], So the speed deficit calculation is expressed by equation 6:

$$V_{dft} = \sqrt{\sum_{i=1}^{N_{up}} \left(\frac{A_{OV}}{A}\right)(V_{df})^2} \quad (6)$$

Where, A_{OV} is the overlap area (m^2), A represents the swept area of the wind turbines (m^2), and N_{up} is the number of upstream wind turbines.

2.2 Case study: Horns Rev 1 Wind Farm

The Horns-rev1 [26-27] wind farm is located in the North Sea 14 km from the west coast of Denmark and covers an area of approximately 20 km2. It is composed of 80 Vestas type wind turbines with a rotor diameter equal to 80, a height of 70 m and a nominal power of 2 MW. The wind turbines are placed in a regular arrangement of 8 rows and 10 columns with the inter-distance between the wind turbines equal to 7 times the diameter of the rotor for a wind direction equal to 0 ° as shown in Figure 3.
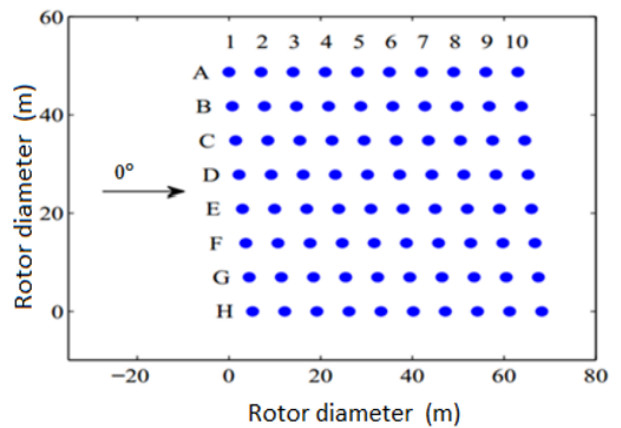
Fig. 3. Presentation of the Horns-rev 1 marine wind farm [28].

3 Methodology

3.1 Objective function

The aim of the studied objective function is to maximize the power and minimize the cost of a wind farm.

Indeed, to achieve the expectations of the objective function, we will try to update the wind farm studied by installing new wind turbines outside or inside a wind farm while respecting the constraints related to the wind farm. area of the wind farm and the cost of installation.

The objective function is defined by the equation 7.

$$FOBJ = \max\frac{P_{total}}{Cost} \tag{7}$$

The cost is expressed as a function of the number of wind turbines (N) installed in the equation 8.

$$Cost = N\left[\frac{2}{3} + \frac{1}{3}e^{-0.00174N^2}\right] \tag{8}$$

in this study we will adopt the simplified cost model [28] and we will use the equation 10 which expresses Total Cost Index, TCI.

$$TCI = 323\ UCI \tag{10}$$

Where UCI is Unit Cost Index [29]

3.1 Optimization algorithm

Many studies have shown that genetic algorithms (GA) are very effective in solving optimization problems [30] hence the use of (GA) in the optimization of wind farms even if they are expensive in his calculations.

The 5 steps of a genetic algorithm are noted below:

- Build an initial population of N solutions.
- Evaluate each of the individuals in the population.
- Generate new solutions by selecting parents in proportion to their assessment. Apply the crossing and mutation operators during breeding.
- When N new individuals have been generated, they then replace the old population. The individuals of the new population are evaluated in turn.
- If the allotted time has not been exceeded (or the maximum number of generations has not been reached), go back to step 3.

The flowchart in figure 4 shows the optimization procedure by the objective function defined previously
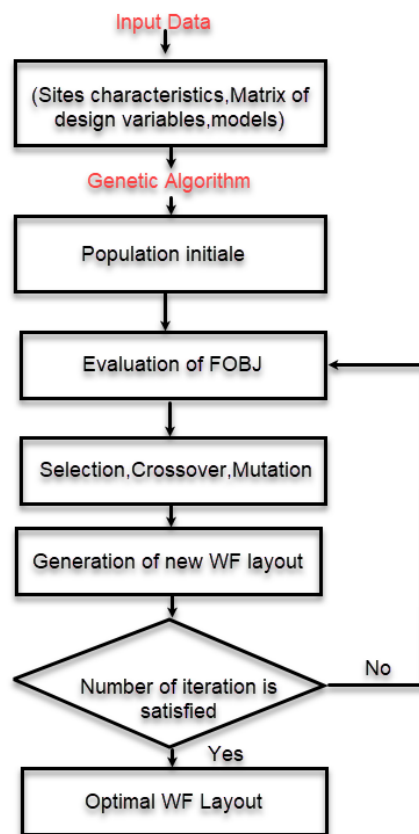

Fig. 4. Presentation Genetic algorithm steps [31].

The selection of turbines is limited to the same models of turbines existing in the studied wind farm (Vestas), the 19 turbines chosen have a power between 1.8 and 3.45 MW and a diameter between 80 and 136 m.

Table 1. Turbine data used in the optimization.

Turbine Code	1	2	3	4	5	6	7
Rated Power (Kw)	1815	1815	2000	2000	2000	2000	2600
Rotor Diameter(m)	90	100	80	90	100	110	100
Rated Speed (m/s)	13	11.5	14	13	12	11	15
Turbine Code	8	9	10	11	12	13	14
Rated Power (Kw)	3000	3000	3000	3075	3300	3300	3300
Rotor Diameter(m)	90	112	126	112	105	112	117
Rated Speed (m/s)	16	12	10.5	13	13.5	12.5	13
Turbine Code	15	16	17	18	19		
Rated Power (Kw)	3450	3450	3450	3450	3450		
Rotor Diameter(m)	105	112	117	126	136		
Rated Speed (m/s)	13.5	12.5	11.5	11.5	11		

The Table 1 gives the code, the diameter of the rotor, the nominal speed and the nominal power.

4 Results and discussion

To evaluate our approach, two wind farm upgrade proposals were tested, figure 5 and figure 6 respectively show these two proposals with the addition of a new turbine internally and externally, including the objective and to maximize the exploitation of the land and minimizing the cost of the infrastructure. the existing turbines are numbered from 1 to 80 while the others are numbered from 81.
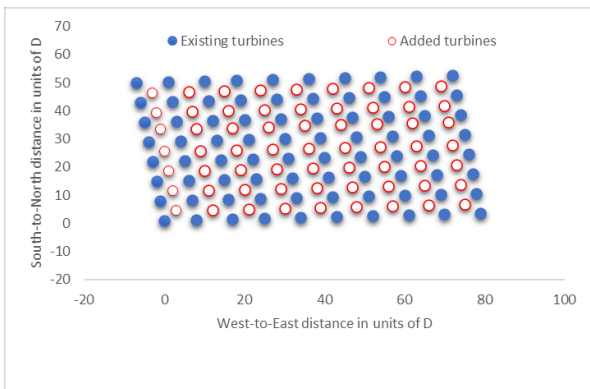

Fig. 5. Internal upgrade proposal.

To respect a minimum distance of (3.5 D where D is the turbine diameter) between the turbines, the number of turbines added internally is 63 while externally equal to 40 and they all take on the red color.
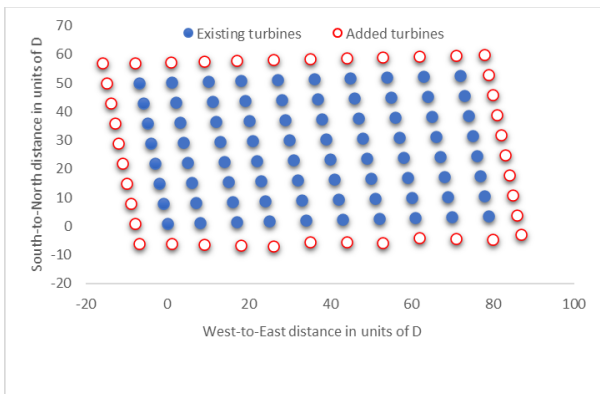

Fig. 6. External upgrade proposal.

The annual energy production (AEP) of each wind turbine is shown in figure7, the equation 11 gives the expression to calculate this annual energy.

$$AEP = 8766 \sum_{\theta=0}^{360} \sum_{\vartheta=4}^{25} f_{(\theta,\vartheta)} P_{WT_{(\theta,\vartheta)}} \qquad (11)$$

Where f is the frequency of occurrence of a particular freestream speed at particular direction.
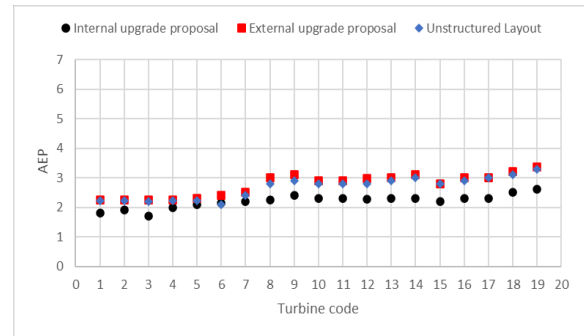

Fig. 7. Annual energy production for each turbine by the studied objective function.

The results of figure 7 and figure 8 show a compromise between the annual production of energy and the cost, however in the internal proposal of turbines the AEP varies between 1.95 and 2.70, moreover the cost varies according to the type of turbine between 1.40 to 2.85.
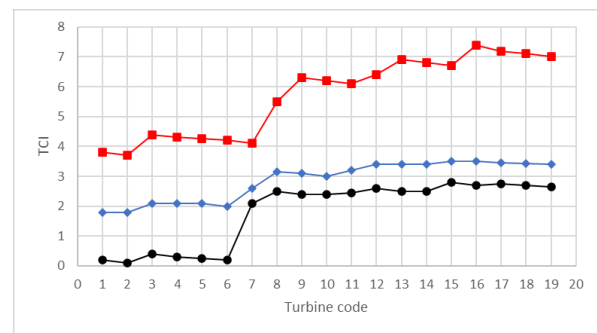

Fig. 8. Normalized total cost index

On the other hand, the external openings with only one type of turbine have an AEP value varying between 2.21 to 3.31 and with regard to the TCI the values vary between 3.85 and 7.4.

Small wind turbines are ideal for internal upgrades with a relatively reasonable cost and higher AEP, on the other hand large wind turbines increase the cost of energy production.

The increase of the AEP in the case of the external update is accompanied by the increase of the cost, this is explained by the added area which presents an important rate in the calculation of the cost.
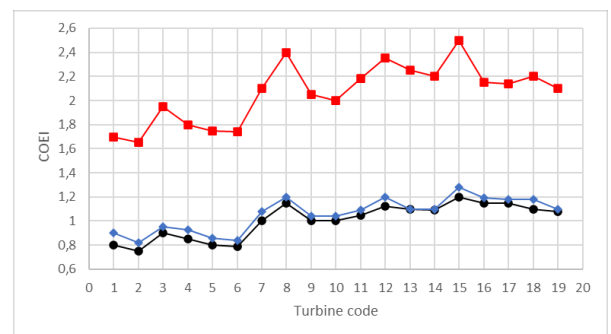

Fig. 9. Normalized cost of energy index.

From figure 9 we notice that the internal updates are close to unity, this is explained by an increase in AEP in accordance with the TCI.

5. Conclusions

In this article we tried to make a study of the leveling of wind farms and to evaluate the objective function which aims at maximizing energy and minimizing the cost.

Two approaches have been adopted, the first is the addition of the turbines internally and the second is the addition of the turbines externally.

The results showed that the two approaches are interesting in terms of annual energy production, on the other hand the cost is relatively high in updating externally than interna.

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