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Optimization of the auxiliary access in a wind farm design using a minimum spanning tree algorithm

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Abstract

An effective approach based on a graph-heuristic is proposed in this paper to solve the optimization problem of auxiliary access in a wind farm design. A greedy algorithm for the study of the logic of Minimum Spanning Tree (MST) was used to achieve this approach. When testing, a square site is divided into 25 square cells which may be the location of possible wind turbines and, therefore, wind turbines are scattered over the site to share the best wind between many machines. This database will create a graph that shows the topography of the network, this topography is fully specified by the connection information node–branch, or by the matrix incidence network graph, then based on a greedy algorithm for calculating the MST, the program will calculate the length and configuration of the network of auxiliary roads.

Keywords: wind farms, Minimum spanning tree (MST), optimization, wake effect.

1. Introduction

Today, the part of production from renewable energy sources has increased dramatically compared to fossil fuels. This is generally due to some factors such as the high and rising price of traditional fossil fuels, during this, great social and environmental concerns and institutional support undertake to reduce foreign fossil fuels. Many countries have already invested in green energy and they will invest even more because of dwindling resources of fossil fuels, the commitment of the Kyoto Protocol and the obligations for all countries with regard to the protection of the environment. By focusing on the types of renewable energy, it is a well-known fact that wind energy has increased the most.

That is why the development of an efficient tool for the design and construction of wind farms has a special importance. Already, wind turbines are mature in terms of technology, but for the multi-megawatt production in the wind farms must conduct a production optimization financially competitive for traditional forms of energy, it seems absolutely necessary for us to invest in new ways of optimal energy production from wind. As is evident, this optimization can make it with new wind turbine models that operate more efficiently or with better planning of wind farms, in terms of wind turbine set or the choice of location. In addition, other costs must be kept in mind when calculating the initial investment, the cost of ancillary access in the design of parks as shown in Table.1 represents a sizable portion of the total cost the initial investment.

During the development of a wind project, always take into account the costs related to the construction of a road to allow heavy trucks to earn the site to ensure the delivery of the various components of a machine and allow the crane to move the site to perform the installation. Each wind park will be provided access to the turbine foundation, and that in order to enable the delivery, montage and assembly of the machine.

Table 1: The initial structure cost of a wind farm

Item	%
turbines	65-75
Substation and electrical infrastructure	10-15
Civil work	5-10
Component installation	0-5
Other	5

In this study, the optimization is done by the average of a greedy algorithm for finding the logic of minimum tree

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coverage. The purpose of this document is to provide an approach for the optimization of auxiliary access in the design of a wind farm.

The remainder of this paper is organized as follows: The remainder of this paper is organized as follows: Formulation of the problem, then the optimization algorithm is proposed. A solution procedure based on a greedy algorithm is developed for the model shown. Finally, a numerical example is provided to demonstrate the feasibility and effectiveness of the method presented.

2. Formulation of the problem

The main objective is the minimization of costs related to the construction of auxiliary access to a wind farm for designers' parks. Thus, the minimization problem is a constrained optimization problem that can be formulated as follows:

The constrained optimization problem is to find an optimal solution among all feasible solutions (which do not violate any constraint). The problem is twofold [1], on the one hand we have a search for feasible solutions and also a search for an optimal solution. The problem is modeled intuitively by a triplet (X, D, C) where

- $X = \{x_1, \dots, x_n\}$ is a finite set of n variables of the problem,
- $D = \{D_{x_1}, \dots, D_{x_n}\}$ is the set of n finite domains for variables. D_{x_i} is the set of possible values for the variable x_i,
- $C = \{c_1, \dots, c_m\}$ is the set of m constraints.
- $f =$ function.

The objective to our constrained optimization model is to find the best route (shortest), passing through the turbines. The function f is modeled intuitively by

$$f = \min\left(\sum_{i=1}^{n-1} \delta_{x_i, x_{i+1}}\right) \tag{1}$$

Where n is the number of turbines and $\delta_{x_i, x_{i+1}}$ represents the distance between turbines. Minimum spanning trees of weight is a concept graph that can be used for our constrained optimization model and is explained as follows [2].

3. Minimum spanning tree (MST)

Useful mathematical theories that are used for the simulation of network problems is graph theory. Given a graph $G = (X; A)$, Or X is a group whose elements are called vertices, and a symmetrical part A, whose elements are called edges ($(x, y) \in A \Leftrightarrow (y, x) \in A$).

In the presence of an edge $a = (x, y)$ can be denoted simply xy, we say that x and y are the extremities of a, and a is incident in x and y, and y is a successor, or neighbor of x [3].

We say that a graph is without buckle if A does not contain any edge of the form(x, x), that is to say, joining a summit itself (a tree is a connected graph without cycles).

We also note that $T = (X, T)$ is a tree if there is a single chain between any two vertices.

If the sum of the weights of all branches is minimum, such tree is called minimum spanning trees weight (MST). The problem to be solved therefore arises as follows:

Given a G is an undirected graph, connected, weighted by a positive function l attached to the edge. Given a spanning tree$T = (X; B)$, defined as the partial graph G with a set of edges B, its total weight (or total cost) is

$$l(T) = \sum_{a \in B} l(a) \tag{2}$$

We say that T is a minimum weight spanning tree of G if $l(T)$ is the minimum weight among all possible spanning trees of G. We can show that if all the edges are of different weights, the spanning tree of minimum weight is unique. Several algorithms have been proposed to solve this problem [4-5]. Most used Prim and Kruskal algorithms.

In this section, the greedy algorithm used is illustrated as follows.

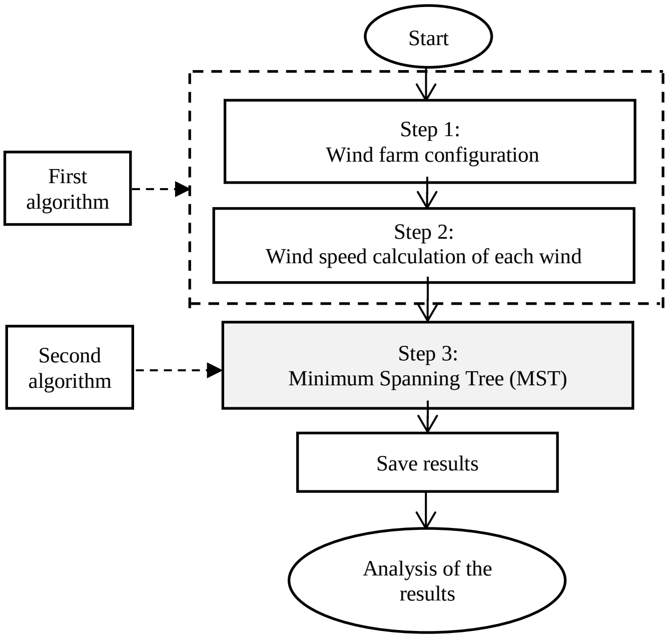

Figure 1: Evaluation methodology

The proposed method, as shown in Fig.1, is based on two mixed algorithms, the first will be considered an entry, take account of the situation, type, tower height and the topographic configuration of the generators.

To avoid turbulence generated behind each turbine does not affect too much wind energy production further downstream; the distance between the wind turbines is often even greater in the direction of prevailing winds. Wind turbines are scattered over the site to share the best wind between many machines.

The second algorithm is to calculate the length and configuration of the network of auxiliary roads by a greedy algorithm to compute the MST.

3.1 Problem of the optimal distribution of the turbines location

To represent the frequency distributions of the wind, the Weibull distribution is used, there is a probability density function of

$$f(v) = \frac{K}{C}\left(\frac{v}{C}\right)\exp\left(-\left(\frac{v}{C}\right)^{K}\right) \tag{3}$$

Where f (v) is the probability density of the velocity v, K isthe shape factorof the curve (dimensionless), C is the scale factor of the curve in m/ s. The parameters K and C are determined approximately by

$$K = 1 + 0{,}483\ (v - 2)0{,}51 \tag{4}$$

$$C = 1{,}125\ \frac{v}{(1 - B)} \quad \text{for } 1{,}5 < K < 3 \tag{5}$$

$$B = 1 - 0{,}81(v - 2)0{,}89 \tag{6}$$

Turbines interact with the wind captures part of the kinetic energy and are converted to usable energy. According to the first law of thermodynamics, this energy extraction creates a gap between the outgoing wind turbine and the oncoming wind turbine. Thus, the wind speeds at the rear of the turbine is lower than the wind speed upstream and consequently a reduction in output power is generated by the turbines. The wake effect also causes high levels for turbulence in the wind turbines, giving rise to an additional mechanical strain, which may reduce their lifetime.

Many studies on the wake effect were conducted, and several models have been developed by researchers, as mosaic tile model [8], the Frandsen model [7], Ainslie [6] model, the model Jensen [9] and CFD (Computational Fluid Dynamics) model [10]. The choice of model depends on the desired accuracy of the prediction and the calculation time.

A wake models most widely used, developed by Jensen [9], was chosen for this study because it provides sufficient accuracy and a reduction in computation time.

3.1.1 Wake model

The turbine interact with the wind, capture a portion of its kinetic energy and converts it into useable energy, this extraction of energy creates a gap between the outgoing wind turbine and the oncoming wind turbine. Thus, the wind speeds at the rear of the turbine is lower than the downstream speed of the wind, as a result it decreases the production of output energy [15]. The wake effect also causes high levels of turbulence in the outgoing wind turbines, giving rise to an additional mechanical stress, which may affect them; this behavior caused by the turbulent is neglected in this study because it does not affect directly output power.

In both works of Mosetti and Grady's [11-12] the model used is similar to the model developed by Jensen [9]. Here we assume that the movement is kept inside the wake.

For a single turbine, the downstream wake zone will be considered as a trapezoid such that the average speed of the wind can be expressed by the following equation

$$u = u_0\left[1 - \frac{2a}{\left(1+\alpha\left(\frac{x}{r}\right)^2\right)^2}\right] \tag{7}$$

Where α is the entrainment Constant, a is the axial induction factor, x is the distance from the turbine, and r is the radius of the turbine downstream, as shown in Fig. 2.

The relationships between r, r_r the radius of turbine and C_T the thrust coefficient are represented in the equations

$$r = r_r\sqrt{\frac{1-a}{1-2a}} \tag{8}$$

$$C_T = 4a(1 - a) \tag{9}$$

The entrainment Constant is empirically given by

$$\alpha = \frac{0.5}{\ln\left(\frac{z}{z_0}\right)} \tag{10}$$

Where z is the hub height of the wind turbine, and z_0 is the surface roughness of the site.

When the turbine downstream is not completely immersed in a wake, if A_w is the part of the rotor area that is inside the upstream turbine wake, as shown in Fig. 2, the effect of the corresponding deficit must be reduced according to

$$(U_p - U_0)^2 = \frac{4A_w}{\pi D_0^2}(U - U_0)^2 \tag{11}$$

Assuming that R and r are respectively the radii of the bigger and lower circumferences (general but not necessarily the wake and rotor ones respectively) and X is the distance between their centers, the overlapped area A_w yields

$$A_w = R^2\cos^{-1}\left(\frac{R^2+X^2-r^2}{2RX}\right) - R^2 0.5\sin\left(2\cos^{-1}\left(\frac{R^2+X^2-r^2}{2RX}\right)\right) + r^2\cos^{-1}\left(\frac{R^2-X^2-r^2}{2RX}\right) - r^2 0.5\sin\left(2\cos^{-1}\left(\frac{R^2-X^2-r^2}{2RX}\right)\right) \tag{12}$$

For multiple wakes we supposed that the loss of kinetic energy is equal to the sum of the energy losses. So, for N turbines, the downstream speed can be expressed by the following expression

$$u_i = u_0\left[1 - \sqrt{\sum_{i=1}^{N}\left(1 - \frac{u}{u_0}\right)^2}\right] \tag{13}$$

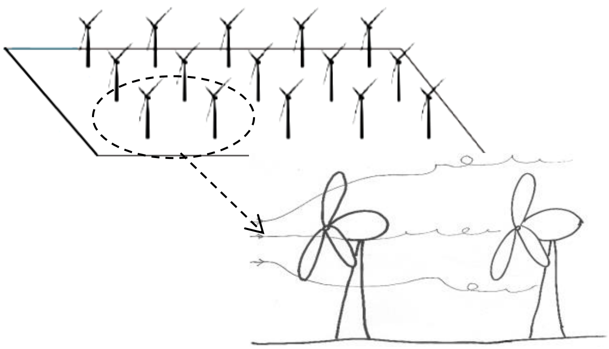

Figure 2: Partial wake

3.1.2 Cost model

The electricity generated by an aero generator, is a function of the local wind speed. Furthermore, the hub height, the thrust coefficient and the rotor diameter also affects the extracted power.

The total power P extracted from the wind is a function of the local section and wind speed, as shown in the following expression

$$P = \sum_{i=0}^{N} 0.3u_i{}^3 \tag{14}$$

To calculate the total cost, we modeled the investment cost such a way that only the number of wind turbines must be taken into consideration.

The total cost per year for the entire wind farm can be expressed as follows

$$\mathrm{cost} = N\left(\frac{2}{3} + \frac{1}{3}e^{-0.00174N^2}\right) \tag{15}$$

Where N is the total number of wind turbines.

The objective function that will lead to optimization (minimum cost per unit of energy produced) is expressed as follows (9)

$$\text{objective function} = \frac{\mathrm{cost}}{P_{\mathrm{total}}} \tag{16}$$

Where P_{total} is the total production, while the cost is calculated as mentioned in equation (14). Minimize the objective function leads to a solution with the lowest cost of producing wind energy [18]. Wind turbines must be spread over the site to share the best wind between many machines. This database will create a graph that shows the topography of the network, this topography is fully specified by the connection information node–branch, or by the matrix incidence network graph [16]. Consider the problem of connecting for n turbines by a road network by the most economical manner possible [17]. We assume the known $l_{ij} = l(a_{ij})$ the length of access necessary to connect the turbines i with j. The network must obviously be connected and it must not admit of cycles for to be the minimum cost, so among all the trees of the network, the minimum spanning trees of weight is that the total length of the branches is minimum.

3.2 The implementation of the greedy algorithm for the minimum spanning tree

The implementation of this algorithm is easily achieved using a marking procedure as follows. We associate to each vertex i, a real number π(i) called the summit mark of i.

At any stage, the mark π(i) of a vertex $i \in X \setminus S$ is the weight of the minimum weight edge in the set of edges joining i with S [5-13]. Furthermore, in a table α we kept α (i) index which permit the edge to assign to vertex i, the mark π(i).

This information is easily possible to obtain the edge of minimum weight in the co cycle $\omega(S)$, it is indeed enough to determine the summit $i \in X \setminus S$ having a minimal mark, so that the edge searched is $\alpha(i)$. Moreover, as shown by the MST algorithm, when the subset S is increased by the vertex i, the marks are updated by examining all edges from i were the other extremity j is not yet part of the tree $j \in X \setminus S$and then performing the substitution $\pi(j) \leftarrow \min(\pi(j), l_{ij})$ [14].

```
Algorithm: Finding a minimum spanning tree of weight
(a) - initializations
$\pi(1) = 0$
 $\pi(i) = \infty, \forall i \in \{2,3 \ldots, n\}$
 $\alpha(i) = \infty, \forall i \in \{2,3 \ldots, n\}$
$S = \emptyset$
(b) - Select i such that $\pi(i) = \min_{j \in X \setminus S} (\pi(i))$
If $\pi(i) = \infty$  whose S = X then end
$S \leftarrow S \cup \{i\}$
(c) - For all edges $a = (i, j)$ as $j \in X \setminus S$ do
        If $l_{ij} < \alpha(i)$ when $\pi(i) = l_{ij}, \alpha(i) = a$
Back in (b)
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4. Numerical example

To assess the relevance of the proposed method, a numerical example is analyzed. The first input depends on the position of the wind turbines and is calculated according to the characteristics as shown in Table 2. When the number of turbine is generated, the problem becomes the optimization problem. The greedy algorithm is applied to solve our model because they are effective for constrained optimization problems.

As can be seen in Fig. 3, a flat surface of a square kilometer along each side, discretized by 5 × 5 square cells is the possible location of wind turbines. Each cell in the center of which a wind turbine can be placed, has a width which is equal to five times the diameter of the rotor (or 5D 200m). The rule of thumb spacing requirements in all directions is satisfied by the size of the 5D square grid.

To keep the necessary distance between two adjacent turbines, the cell size is suitably selected and all turbines are only installed on the center of a cell so that, the wake effect of a column of turbines would not interfere with the turbines in the other columns.

The thrust coefficient C_T be considered constant throughout the process.

Table 2: characteristics of turbines

Description	Parameter	value
Hub height	z	60 m
Radius of the rotor	r_r	40 m
Thrust coefficient	C_t	0.88

In order to estimate the optimal number of wind turbines and for comparative purposes we will take the following basic conditions: uniform wind direction and speed steady wind of 12 m / s. This case has been discussed in detail in [1-11-12] where different approaches were used.

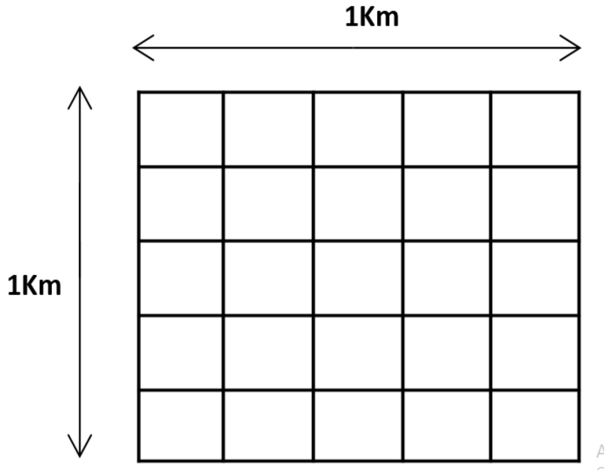
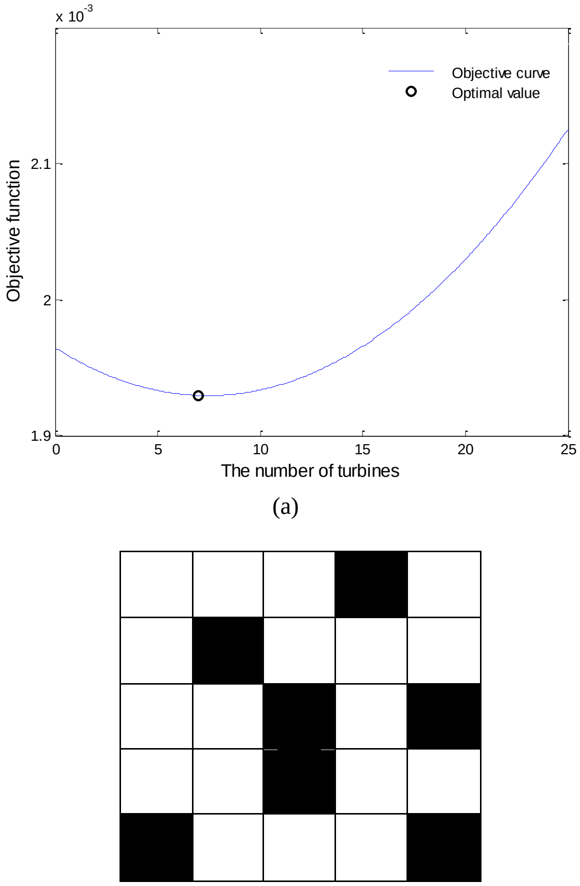


Figure 3: Subdivision of the wind farm area

The two parameters of the call function are:
L: the matrix of length (if there is no arc between the vertex i and vertex j, then $l_{ij} = \infty$ is conventionally the $l_{ii} = 0$).
dep: number of vertex starting for construction of the tree searched.
Output, we get:
α: table of series indicating the borders constituting the tree.
Graphically, the vertices can be represented by points and the edge a = (x, y) by a line connecting x y. Note that the arrangement of the points and the length or the shape (curved or straight) lines is irrelevant. Only the incidence of the various edges and vertices account.
To demonstrate the ability of the proposed method for solving the optimization problem, a network of seven turbines (nodes) from 1 to 8 was chosen with the standard characters, as shown in Fig. 4. For this case, the possible access for nodes on the network is illustrated in Fig. 5 (1).The distance between each two node is indicated as the shortest route. The actual values of the distances between each two nodes are measured either using the geographic information system (GIS), on-site inspection or simply with the numeric calculate based on the location of turbines in the network set implemented in the proposed simulation.

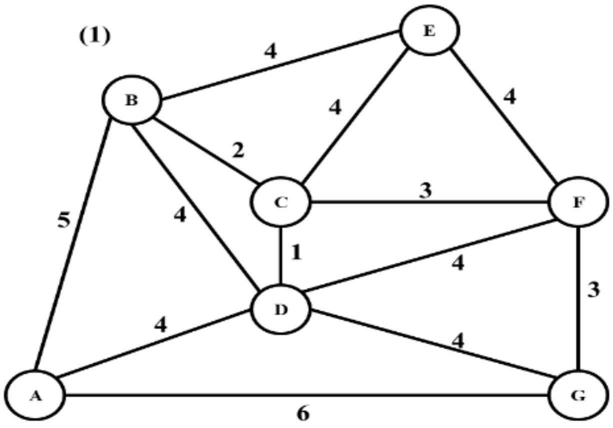


(a)

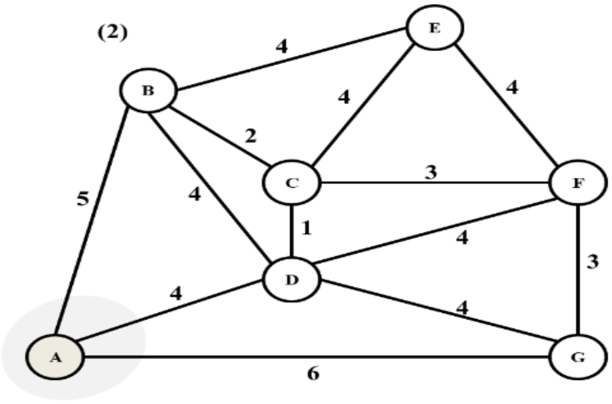
(b)

Figure 4: (a) The objective curve and (b) the wind farm configuration

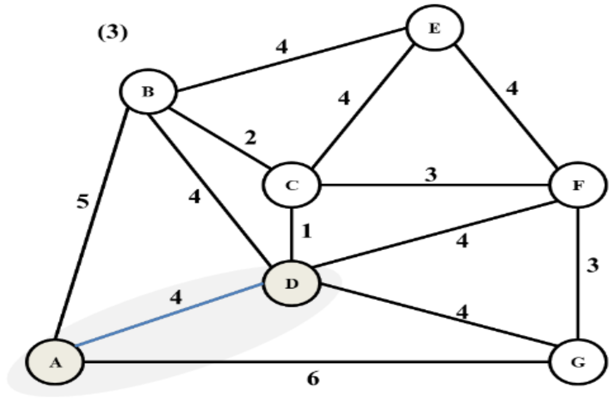
In practice, access is selected based on the urban environment and geographical constraints, but in our case, all possible routes is candidates, the data base will build a graph that represents the network topography. The steps are illustrated in detail in Fig. 5 and 6.



Complete Graph



	A	B	C	D	E	F	G
D[]	0	5	∞	4	∞	∞	6
A	0	5	∞	4	∞	∞	6
B	5	0	2	4	4	∞	∞
C	∞	2	0	1	4	3	∞
D	4	4	1	0	∞	4	4
E	∞	4	4	∞	0	4	∞
F	∞	∞	3	4	4	0	3
G	6	∞	∞	4	∞	3	0



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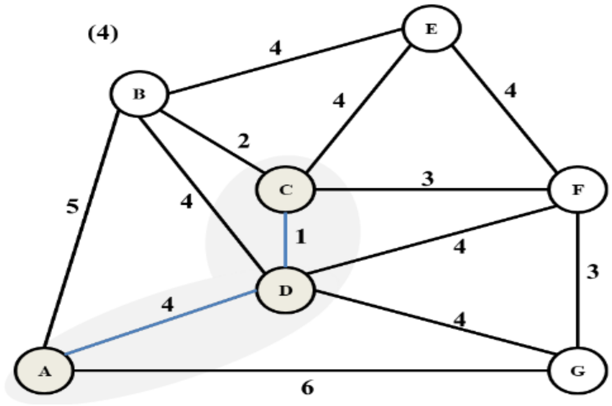
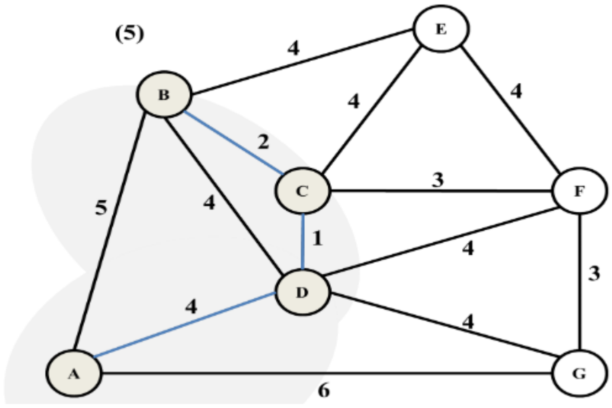
A	0	5	∞	4	∞	∞	6
B	5	0	2	4	4	∞	∞
C	∞	2	0	1	4	3	∞
D	4	4	1	0	∞	4	4
E	∞	4	4	∞	0	4	∞
F	∞	∞	3	4	4	0	3
G	6	∞	∞	4	∞	3	0



	A	B	C	D	E	F	G
D[]	0	2	1	4	4	3	4
A	0	5	∞	4	∞	∞	6
B	5	0	2	4	4	∞	∞
C	∞	2	0	1	4	3	∞
D	4	4	1	0	∞	4	4
E	∞	4	4	∞	0	4	∞
F	∞	∞	3	4	4	0	3
G	6	∞	∞	4	∞	3	0



	A	B	C	D	E	F	G
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A	0	5	∞	4	∞	∞	6
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D	4	4	1	0	∞	4	4
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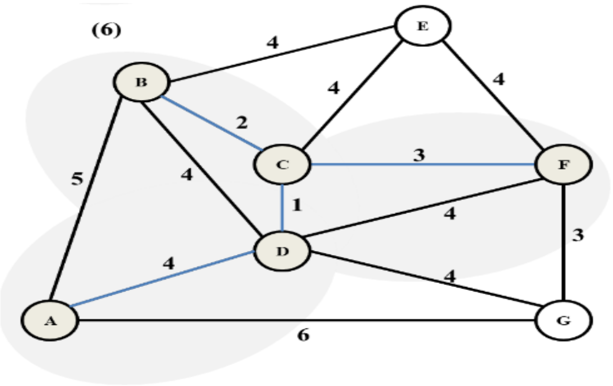
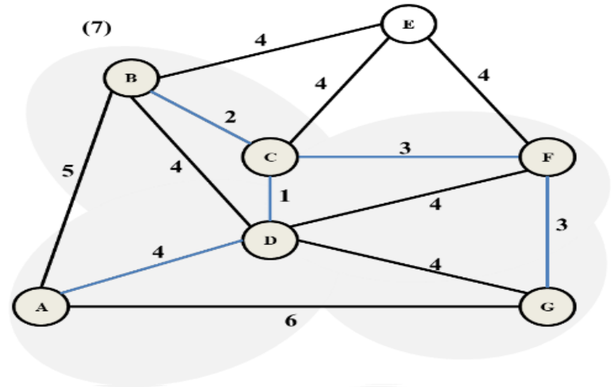
F	∞	∞	3	4	4	0	3
G	6	∞	∞	4	∞	3	0



	A	B	C	D	E	F	G
D[]	0	2	1	4	4	3	3
A	0	5	∞	4	∞	∞	6
B	5	0	2	4	4	∞	∞
C	∞	2	0	1	4	3	∞
D	4	4	1	0	∞	4	4
E	∞	4	4	∞	0	4	∞
F	∞	∞	3	4	4	0	3
G	6	∞	∞	4	∞	3	0



	A	B	C	D	E	F	G
D[]	0	2	1	4	4	3	3
A	0	5	∞	4	∞	∞	6
B	5	0	2	4	4	∞	∞
C	∞	2	0	1	4	3	∞
D	4	4	1	0	∞	4	4
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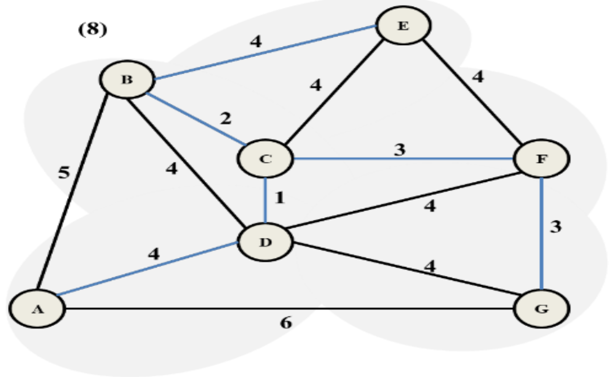
F	∞	∞	3	4	4	0	3
G	6	∞	∞	4	∞	3	0



	A	B	C	D	E	F	G
D[]	0	2	1	4	4	3	3
A	0	5	∞	4	∞	∞	6
B	5	0	2	4	4	∞	∞
C	∞	2	0	1	4	3	∞
D	4	4	1	0	∞	4	4
E	∞	4	4	∞	0	4	∞
F	∞	∞	3	4	4	0	3
G	6	∞	∞	4	∞	3	0

Minimum Spanning Tree

Figure 5: Implementation of the greedy algorithm for the MST problem (1-8) (step by step)

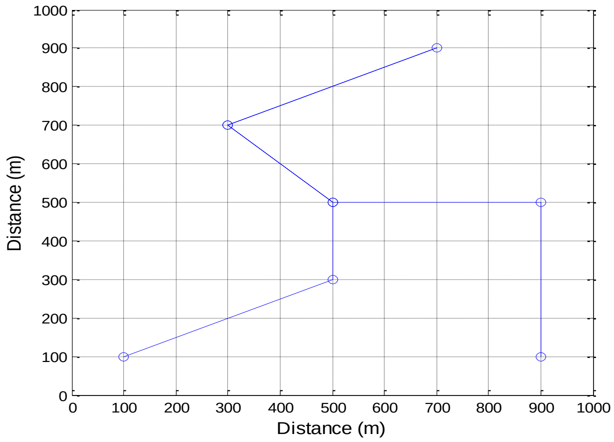


Figure 6: Routes planned for the case study

In this network, which consists of l access and n turbines, there are many different trees. Of every tree of the network, the minimum spanning tree is the one or the total branch lengths (departures) are minimum. In the first step of the algorithm MST all branches of the graph are marked as unvisited. In the next step, access to lower cost (length) is selected, the process continues and the algorithm then checks all other possible departures.

The optimization was carried out successfully. The results are promising and can be applied effectively to the optimization problem in wind farms. The greedy algorithm always leads to a good minimum covering.

5. Conclusion

An innovative and effective approach based on a greedy algorithm to solve the optimization problem of the auxiliary access in the design of a wind farm has been presented. In this work, the design problem is defined as an optimization problem, once the site of the appropriate wind farm has been identified; the arrangement of wind turbines is carried out in a heuristic trial base. Usually, a heuristic preliminary plan is performed, taking into account all the environmental, technical, and social. The proposed algorithm can define the auxiliary access network connecting the turbines scattered across the site, so as to share the best wind between many machines, the most economical way possible. The network associated must be connected, and it must not admit of cycles, for to be of minimum cost. The results are promising and can be applied effectively to the optimization problem.

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