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# Application of Differential Evolution for Wind Turbine Micrositing

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RECEIVED ON 04.11.2015 ACCEPTED ON 22.11.2016

## ABSTRACT

WTM (Wind Turbine Micrositing) has been an important topic of discussion in recent times. A number of Evolutionary Algorithms have been applied to the WTM problem. The DEA (Differential Evolution Algorithm) is used for a bi-constrained optimization for getting maximum power production at the least cost from a 2x2 km space. It is shown that the DEA performs comparably to the GA (Genetic Algorithms) for wind farm optimization. The optimal configuration obtained enlists the number of turbines, the cost of power generated as well as the power produced. Moreover, this study is augmented by comparison with past approaches by using the GA for the same purpose.

**Key Words:** Wind Turbine Micro-Siting, N.O. Jensen Model, Heuristics, Wind Turbine Optimization, Differential Evolution Algorithm, Genetic Algorithm.

## 1. INTRODUCTION

A sustainable and secure supply of energy can be produced from wind turbines. Recent advances have been pushing for increase in rotor swept area so that the turbines are able to work in lesser wind conditions as well. The wind farms can produce a varying number of power output based on the turbines spatial position in the wind farm. Traditional wind farm design relies on the straight up linear arrangement of the turbines. But it has been shown [1]

that a number of times that the turbine position if modifies optimizes the power produced from the wind farms.

WET (Wind Energy Technology) of today has come a long distance from its early days a decade ago. It is cost effective and more efficient due to the wide spread use of composite materials and cutting edge technology. The present study is an endeavour to improve the efficiency by systematically or recursively reducing the cost and increasing the power production [2].

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A number of algorithms have been applied for the solution of the WTO (Wind Turbine Optimization) problem and the application of the DEA is another step in that direction. This work fills the gap in which the research carried out in this field has not yet explored the potential of the DEA.

Our work builds upon the work of a decade of research in this area as referenced in [3-12]. It is true that previous research on optimization of WTM was based on GAs but researchers have also tried other algorithms for the same problem and compared the results with GAs; for example: [13-14,1]. Literature shows that the results from other algorithms are in good comparison to those by GAs and in some instances are better [1]. Hence, in this work we have used DEA – which has encouraging stability properties as compared to GA for WTM.

The WTO problem was first tackled by Mosetti [15]. He based his calculation on the Jensen model due to the ease of calculation of multiple wake interaction. He evaluated the wake interaction on a wind farm for three scenarios, as outlined below:

- (1) Constant speed Wind from one direction
- (2) Constant speed Wind from multiple directions
- (3) Variable speed Wind from multiple directions

All the studies in this domain followed the 2x2 km area plan of Mosetti [15]. It was clearly shown that the Jensen model was of much practical usage with the least computational effort. The prediction of the Jensen model held true for a good number of wind turbine installations and a reduction of cost by a factor of 1/3 was seen for every new wind turbine included in the simulation.

This work was followed up by Grady [3] by the use of GAs for the solution of the WTO problem [3]. He reported better results as compared to Mosetti.

Improvements from Marmidis [16] followed and he used the Probabilistic Monte Carlo Simulation. Some significant results were also obtained by using modified objective function by Emami [17].

Then Mittal [16] used GA for the solution of the WTO problem and he evaluated the highest number of turbines that can be installed in a 2x2 km area with the highest power at the least cost of installing such turbines [4].

Other wind turbine models are, the Fradsen model, the Fuga Model, the Larsen Model, The N.O. Jensen Model, the Ainslie Model and the UPMWAKE Model [18-20].

The remainder of this paper has been organized as follows. The wind farm optimization problem is reviewed next in section 2. This is followed by the DEA that is elucidated in section 3. The DEA is followed by a discussion of the parameters used in section 4. The data evaluation is carried out in section 5 and the conclusions are drawn in section 6.

## 2. THE WIND FARM OPTIMIZATION PROBLEM

The Jensen model is used for evaluation of the multiple wake interaction behind turbines. The basic principle of conservation of momentum is utilized within multiple wakes. For the sake of simplification, it neglects the effects of turbulence in the near and far wakes [19].

In this model we consider the widely used basic assumptions in which Rotor radius is equal to 40 m, the Hub height is equal to 60 m, and the Thrust coefficient is equal to 0.88 [19].

The wake expands onwards by beginning at the rotor radius  $r_r$  in a cone shaped trajectory in the wind direction and is denoted by  $r_1$ , at a distance of  $X$  from the rotor [19].

The wind speed is given by the equation (1); behind the rotor [19]:

$$U = u_0 + \left( 1 - \frac{2a}{1 + \alpha \left( \frac{X}{r_1} \right)} \right) \quad (1)$$

Where  $U$  is the wind speed behind the rotor (located at some finite distance,  $X$ ),  $u_0$  is the initial wind speed,  $a$  is the axial induction factor,  $\alpha$  is the constant of entertainment,  $X$  is the distance and  $r_1$  is the wake radius [19].

Fig. 1 Illustrates the wake effect as a cone shaped phenomenon starting at the rotor with radius  $r_r$  and expanding to  $r_1$ , at a distance of  $X$  [19].

Where,  $U_0$  is the free stream wind speed. The following equation (2) gives the value of the axial induction factors as follows [19]:

$$C_r = 4 a(1-a) \quad (2)$$

Where, the wake radius is given by Equation (3), where  $X$  is the downstream distance from the turbine with radius  $r_1$  [19]:

$$r_1 = r_r^2 \sqrt{\frac{1-a}{1-2a}} \quad (3)$$

Hence,  $a$ , the entertainment constant, where  $z$  is the hub height (meters) and  $z_0$  is the factor of terrain roughness (meters) which is about 0.3 m for flat lands [19], is given by equation (4):

$$\alpha = \frac{0.5}{\ln \left( \frac{z}{z_0} \right)} \quad (4)$$

The following equation gives the estimation of the wind speed and can be used to simulate multiple wakes located in tandem behind each other [19]:

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

In Equation (5),  $N_t$  gives the total number of wind turbines in the particular wake vortex,  $u_0$  is the initial wind speed,

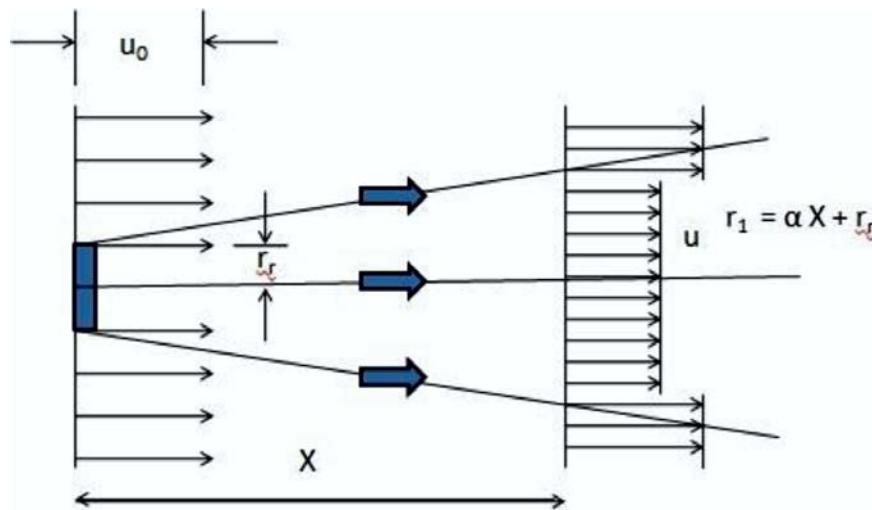


FIG. 1. WAKE EFFECT AS A CONE SHAPED PHENOMENON STARTING AT THE ROTOR

$u_i$  is the  $i^{\text{th}}$  turbine wind speed, and finally the factor  $u$  gives the resultant wind speed after multiple wake interactions [19].

The Jensen model is useful for depicting the wake orders due to the placement of multiple turbines [19].

### 2.1 Power Calculation Equations

The Available Power is defined as equation (6) with reference to [19]:

$$\text{Available Power} = \frac{1}{2} \rho A u^3 \quad (6)$$

By incorporating the efficiency parameter,  $\eta$  [19], equation (6) reduces to equation (7):

$$\text{Available Power} = \eta \frac{1}{2} \rho A u^3 \quad (7)$$

Hence, we may solve to get equation (8):

$$\text{Power Produced} = 0.3 u^3 \text{ Kilowatts} \quad (8)$$

The optimization objective function for getting the maximum power is given in equation (9):

$$\arg \max \sum \eta \frac{1}{2} \rho A u_i^3 \quad (9)$$

### 2.2 Efficiency Calculations

The Betz's limit gives the aerodynamic efficiency of the wind turbines as equation (10) [19]:

$$\text{Efficiency, } \eta = \frac{\sum_{i=1}^{N_t} 0.3 \times u_i^3}{N_t (0.3 \times u_o^3)} \quad (10)$$

Which may be written as equation (11):

$$\text{Efficiency} = \frac{\text{Power}_{\text{Total}}}{N_t (0.3 \times u_o^3)} \quad (11)$$

## 23 Cost Model

A non-dimensional classical cost model equation (12), is used for the purposes of this study. It decrements the cost by one third with the addition of every new turbine [19]:

$$\arg \min N_t = \left( \frac{2}{3} + \frac{1e^{-0.00174N_t}}{3} \right) \quad (12)$$

Which is subject to:

$$N_t \in \{0, 100\} \quad (13)$$

The cost model used in this study assumes that operating costs are negligible [19].

## 3. THE DIFFERENTIAL EVOLUTION ALGORITHM (DEA)

This algorithm is a Stochastic Direct Search Algorithm from the family of Evolutionary Algorithms. It is useful for determining the global maxima or minima in bounded domain. It is somewhat similar to GA, PSO (Particle Swarm Optimization), Evolutionary Strategy Algorithm and Evolutionary Programming Algorithms [20].

The general behaviour of the DEA can be deduced from [21], as the DEA has significant advantages over GA when compared in terms of:

- (1) The speed of convergence of the algorithm
- (2) The complexity of the code structure etc.
- (3) The overall accuracy as compared from both algorithms by nearness to the optimal solution
- (4) The stability of the solution set

In various studies, it has been demonstrated that the greatest advantage of using the DEA is that the sample space is continuously improved with each run of the algorithm so that the average solution at any instant is

very close to the best solution. For a large sample size, convergence time of both the techniques is somewhat similar. However, the greatest advantage that the DEA technique offers is the stability of the solution. Moreover, the GA is known to falter for a less than optimal solution or a local optima due to premature convergence [21].

The DEA is much improved as compared to GA and other algorithms of the same class and is quoted in [22-24]. The DEA is robust and stable in problems having multiple dimensions, that are often multi-modal and have inherent noise that are otherwise tedious to resolve using other methods. The main reason for the use of the DEA is the Crossover. Another impressive trait of differential evolution is that its parameters NP, CR and F are able to self-tune themselves in according to the requirements of the problem; a trait which is not available in other Metaheuristic Algorithms [25].

The DEA formulates its solutions on the basis of careful selection and then evaluation and finally by the process of recombination of the results. It is a self-adapting algorithm which is a crucial property that enables it to escape local minima or maxima very easily [26]. It takes three members of the species, takes a weighted difference of two of them and adds them to the third member to obtain a unique new member. The evaluation of the fitness of the new member introduced is done recursively with respect to the given objective function. The best member is selected on the basis of survival of the fittest and is hence a basic property of all evolutionary algorithms [20].

The DEA requires that the user properly configures the algorithm by appropriate representation, refining the selection process used and then setting the parameters of use [26]. Of these three processes the most important is the parameter setting which is of foremost concern before deploying the DEA [26].

It is also known as a directed parallel method of search. Therefore, the total population is denoted by NP each having D-Dimensions in each generation, [13]:

$$x_{i,G} \quad i=1,2,3,..NP \quad (13)$$

The DEA assumes that the NP remains the same during the iterative optimization process. It utilizes the Uniform Distribution to make the random guess about the next member of the population [13].

Hence, Uniform Distribution selects three members of the population and these are subjected to selective mutation and crossover to produce offspring. The process of selection yields the vector described by equation (13):

$$x_{i,G} \quad i=1,2,3,..NP \quad (13)$$

which is mutated by the process stated in equation (14):

$$v_{i,G+1} = x_{r1,G} + F \cdot (x_{r2,G} - x_{r3,G}) \quad (14)$$

The following indexes  $r_1, r_2, r_3 \in \{1,2,3,.. NP\}$  of the mutation vector are two dimensional integers in our case. And it is given for a finite weighted value of  $F > 0$  [13].

The DEA is further augmented by the use of crossover by having a trial vector:

$$U_{i,G+1} = (u_{1i,G+1}, u_{2i,G+1}, \dots, u_{Di,G+1}) \quad (15)$$

Therefore,

$$U_{ji,G+1} = \begin{cases} v_{ji,G+1} & \text{if } (\text{randb}(j) \leq CR \text{ or } j = \text{rnbr}(i)) \\ v_{ji,G} & \text{if } (\text{randb}(j) > CR \text{ or } j \neq \text{rnbr}(i)) \end{cases} \quad (16)$$

$$j=1,2,..,D \quad (17)$$

Hence, the DEA uses the function of r and b(j) to evaluate the value of the function in its jth value for a range of values between 1 and 0. In addition the crossover constant, CR is evaluated between the value of 1 and 0. Thus generating an index rnbr(i) that decides whether crossover takes place for a minimum of one species during the algorithm implementation [13].

The cost function is compared with the resultant vector  $u_{i,G+1}$  and with the initial vector  $x_{i,G}$ . If there is an improvement in the value then the value of  $u_{i,G+1}$  is carried over to the value of  $x_{i,G+1}$  otherwise the historical value of  $x_{i,G}$  is kept [13].

This algorithm is often written as (DE/x/y/z), where z denotes the binary or exponential operator, y shows the difference vector between two random members of the population and x shows the type of solution to be arrived at such as the random solution or the best solution. The most widely used configurations of DEA are (DE/rand/1/\*) and the (DE/Best/2/\*) [20].

#### 4. PARAMETERS USED

In our present study the results of the DEA have been compared with the results of GAs and have been categorized on the basis of [14]:

- (1) Total Power dissipated
- (2) Cost per unit power and the Cost per turbine

At the end of the simulation the results were obtained and matched with those of Rajper's work [14].

The values of the parameters for which the DEA code is run is as follows [14]:

$$a = 0.326795$$

$$\alpha = 0.09437$$

$$r_r = 40\text{m}$$

$$C_r = 0.88$$

$$X = 200\text{m}$$

$$U_0 = 12\text{m/s}$$

$$Z = 60\text{m}$$

$$Z_0 = 0.3$$

We have also followed the conventional cost analysis as also in Mittal [4] and Rajper [8] which is primarily done

for the case of  $U_0 = 12$  m/s. The configuration of the DEA is done as follows:

$$\text{Population size (nP)} = 100$$

$$\text{Feed slave process (feedSlaveProc)} = 5$$

$$\text{Maximum iterations (maxiter)} = 900$$

$$\text{Maximum time (maxtime)} = 900$$

#### 5. DATA EVALUATION

When the first turbine experiences a steady wind of 12 m/s it derives a power of 518.4 kW at a standard cost at 0.0019279 and at a full efficiency equal to 1. In our simulation the value of the efficiency decreases below the ideal value of 1 when the 14<sup>th</sup> turbine is installed. This is a nominal dip in the value and the efficiency again reaches a value of 1 by the addition of the 15<sup>th</sup> turbine to the simulation. This value then decrements by the installation of the 16<sup>th</sup> turbine. From our simulation, it can be concluded that the power radiated from the turbines increases till the time the 81<sup>st</sup> turbine is installed which is deemed to be the optimal number.

A comparison of the DEA and the GA reveals that the power generated reaches a higher value with the usage of the DEA (Fig. 2). This difference is evident by the time the 19<sup>th</sup> turbine is installed. Hence, from the 20<sup>th</sup> turbine and onwards the power difference is evident and the DEA performs better than GA.

A thorough comparison of the cost of using the both techniques reveals that the cost remains the same till the addition of the 15<sup>th</sup> turbine to the simulation (Fig. 3). But, there is a marked difference from the 16<sup>th</sup> to the 100<sup>th</sup> turbine onwards. For the sake of simplification of the cost model the values are taken as non-dimensional or not in monetary terms like all the previous studies. It is also assumed that the operation and maintenance costs do not affect this calculation greatly.

The maximum power that can be harnessed by using GA's [4] is till the time 54 turbines are introduced to the simulation but a maximum of 81 turbines can be inserted by using DEA. After the installation of these maximum turbines the power produced reduces from the maximum value.

Table 1 illustrates that it is possible to install more turbines by using the DEA in comparison to using the GA [14]. It

is evident that more power can be reaped from the same area used by introducing 81 turbines.

TABLE 1. THE MAXIMUM COST TO POWER BY GA AND BY DEA

	Genetic Algorithm	Differential Evolution Algorithm
Number-of-Turbines	54	81
Peak-Power-produced	27,169.52	40,700.84
Cost-per-unit-power	0.0013292	0.0013268

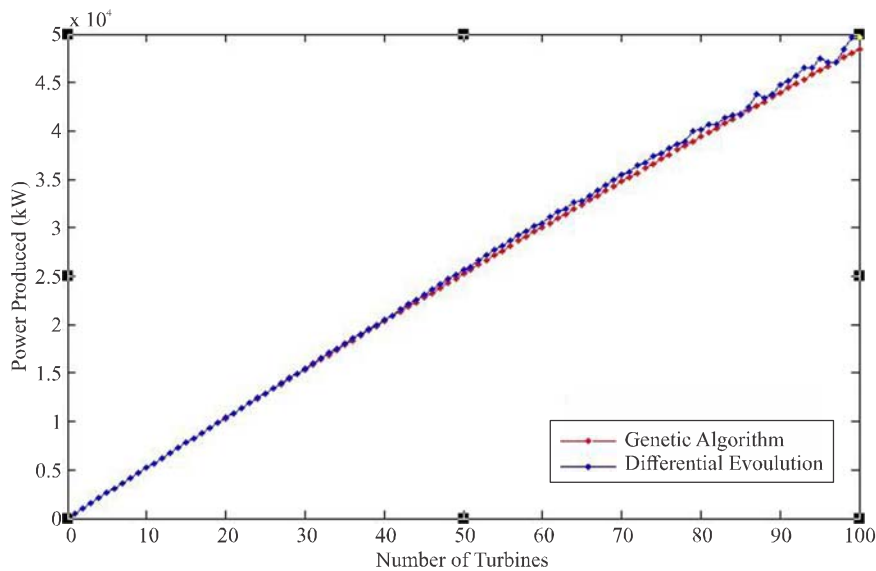


FIG. 2. THE POWER PRODUCED BY GA AND DEA

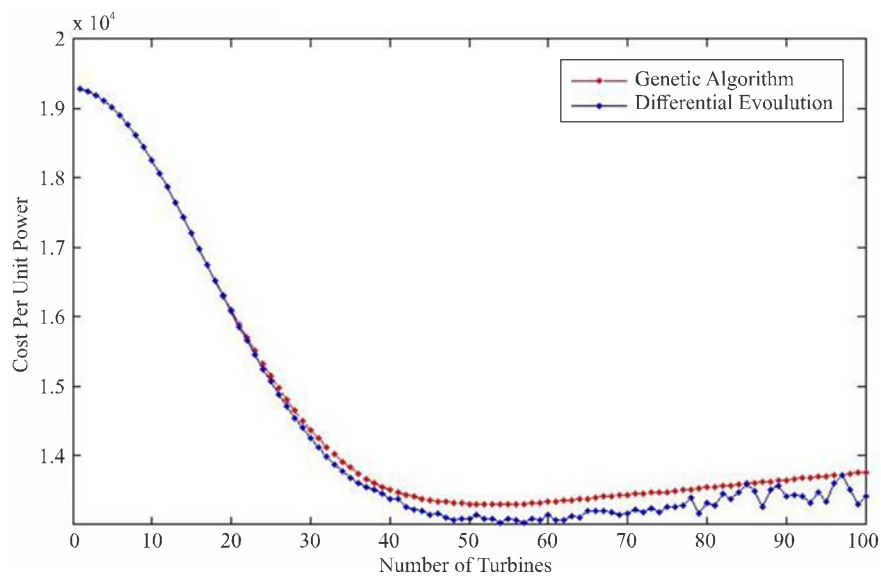


FIG. 3. THE COST ATTAINED BY USING GA AND BY THE DEA

In Table 2 a comparison is drawn with the results obtained by Mosetti [15] and by the use of GA's [14] with our present study. This comparison is drawn at the installation of the 26<sup>th</sup> turbine in the simulation. It is clearly evident that the DEA performs better than both the GA's and Mosetti's work [14-15]. For the peak power produced, the DEA returns a value of 13,448kW as compared to 13,364 by the GA and 12,352 by Mosetti. However, in the case of the cost/objective function the value of DEA is 0.0014970 which is slightly higher than GA's at 0.001423 but in comparison it fares better than that of Mosetti at 0.0016197. In the above comparison the efficiency of the DEA is the best at 99.7795%, which is followed by GA's at 99.152% and by Mosetti at 91.645%.

As per Table 3, a comparison of the work of Grady [3], GA's [14] and by using DEA is drawn. Again the power produced by the DEA is the highest at 15,502.19 kW

followed by GA [14] at 15,372.49 and then by Grady [3] at 14,310.00 at the instance when 30 turbines are functioning on the wind farm. However, the cost or the objective function value of GA's [14] is the lowest at 0.001423 followed by DEA at 0.0014249 and then by Grady [3] at 0.0015436. But again the highest efficiency is achieved by the use of the DEA at 99.6797% followed by GA [14] at 98.846% and Grady [3] at 92.015%. Hence, it would be safe to conclude that the DEA outperforms both comparative approaches.

Similarly in Table 4, we may view the comparison of the three studies at the installation of 32 turbines. It is evident that the peak power produced is at its best value by using the DEA approach at 16,538.89 kW followed by Marmidis [16] at 16,395.00 and then by GA [14] at 16,376.65. Moreover, the cost or the objective function value by using the DEA is lowest at 0.0013985 followed

TABLE 2. COMPARISON OF GA [14], MOSETTI [15] AND THIS STUDY

	Mosetti	Genetic Algorithm	Differential Evolution Algorithm
Number-of-Turbines	26	26	26
Peak-Power-produced-(kW)	12,352	13,364.16	13,448.68
Objective-function-value-(by-use-of-Excel-Sheet)	-	0.001497	-
Objective-function-value	0.0016197	0.001423	0.0014970
Efficiency-(%)	91.645	99.152	99.7795

TABLE 3. COMPARISON OF GA [14], GRADY [3], AND THIS STUDY

	Grady	Genetic Algorithm	Differential Evolution Algorithm
Number-of-Turbines	30.0	30.0	30.0
Peak-Power-produced-(kW)	14,310.00	15,372.49	15,502.19
Objective-function-value-(by-use-of-Excel-Sheet)	-	0.0014369	-
Objective-function-value	0.0015436	0.001423	0.0014249
Efficiency-(%)	92.015	98.846	99.6797



by Marmidis [16] at 0.0014107 and by the use of GA's [14] at 0.001423. Last but not the least, the value of the efficiency of the DEA approach is the best at 99.6991% as compared to Mittal [4] which was not reported and GA's at 98.721%.

Again in Table 5, it is evident that the DEA outperforms the comparative approaches at the introduction of the 44th turbine. The DEA reports a peak power of 22,600.06 kW at an objective function value of 0.0013203 and an efficiency of 99.0814%, these values are the best in their respective categories. The GA [14] returns the second best value of 22,306 kW for the peak power produced and the third best value of the cost or the objective function at 0.001423 and the second best efficiency of 97.790%. The results of Mittal [4] follow with the third best value of peak power produced at 21,936 kW, with second best value of objective function at 0.0013602 and the third best value of efficiency at 96.100%.

Fig. 4 depicts the final result of installation of 81 turbines in a 4 km<sup>2</sup> area. The peak power produced is equal to 40,700.84. This value is above the value of peak power of 40,670.61 kW, after installing the next or 82nd turbine.

The cost function behaves in a sporadic manner due to the inherent nature of the DEA but it is evident that its value remains lower as compared to GA, till the installation of the 100th turbine.

Thus the, Power, Cost and Efficiency of the same wind turbine may be compared at speeds of 6, 8 and 10 m/s to yield the following graphs.

Fig. 5, which depicts the Power produced illustrates the effect of wind speed on the power production of the wind turbines. Since the power produced is a function of the cube of the wind speed therefore, the higher the wind speed the more the power produced.

TABLE 4. COMPARISON OF GA [6], MARMIDIS [16], AND THIS STUDY

	Marmidis	Genetic Algorithm	Differential Evolution Algorithm
Number-of-Turbines	32.0	32.0	32.0
Peak-Power-produced-(kW)	16,395.00	16,376.65	16,538.89
Objective-function-value-(by-use-of-Excel-Sheet)	-	0.0014123	-
Objective-function-value	0.0014107	0.001423	0.0013985
Efficiency-(%)	Not reported	98.721	99.6991

TABLE 5. GA [6], MITTAL [4] AND THIS STUDY

	Mittal	Genetic Algorithm	Differential Evolution Algorithm
Number-of-Turbines	44	44	44
Peak-Power-produced-(kW)	21,936.00	22,306.78	22,600.06
Objective-function-value-(by-use-of-Excel-Sheet)	-	0.0013376	-
Objective-function-value	0.0013602	0.001423	0.0013203
Efficiency-(%)	96.100	97.790	99.0814

Fig. 6 of cost produced illustrates the effect of wind speed on the cost of running such a facility. Since there are two types of cost involved in any wind power project, the first is the installation cost and the other is the operating

cost. It can be seen that the effects of installation cost are lower after the installation of the 40<sup>th</sup> turbine. After the installation of the 40<sup>th</sup> turbine it becomes economical to add more turbines and the cost function levels off.

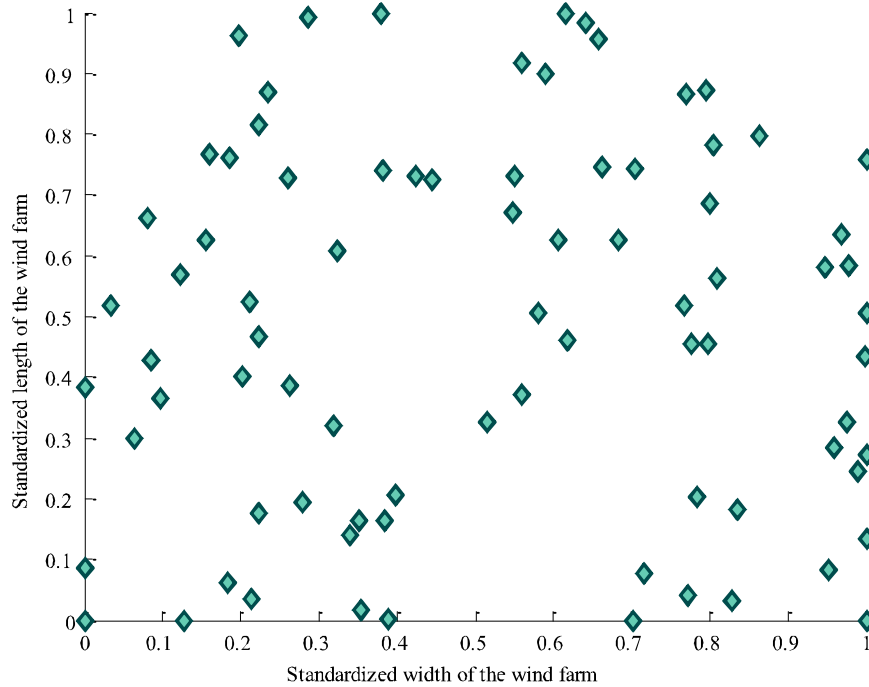


FIG. 4. OPTIMIZATION OF WIND TURBINES IN A STANDARDIZED AREA OF 2x2 km<sup>2</sup>

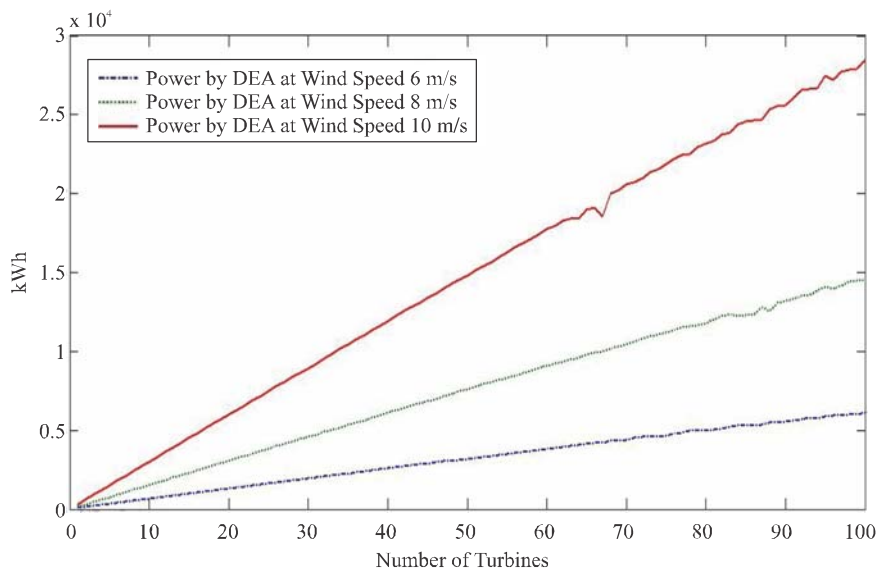


FIG. 5. COMPARISON OF POWER PRODUCED FOR 6, 8 AND 10 m/s WIND SPEED

Fig. 7 illustrates the effect of the stochastic nature of the DEA. It shows the variation in the results obtained as the simulation reports different values of efficiency depending upon the stochastic sequence generated by the computer.

Table 6 complete chart of the values of the peak power, the objective function and efficiency of the DEA and the GA's [14] is given for reference.

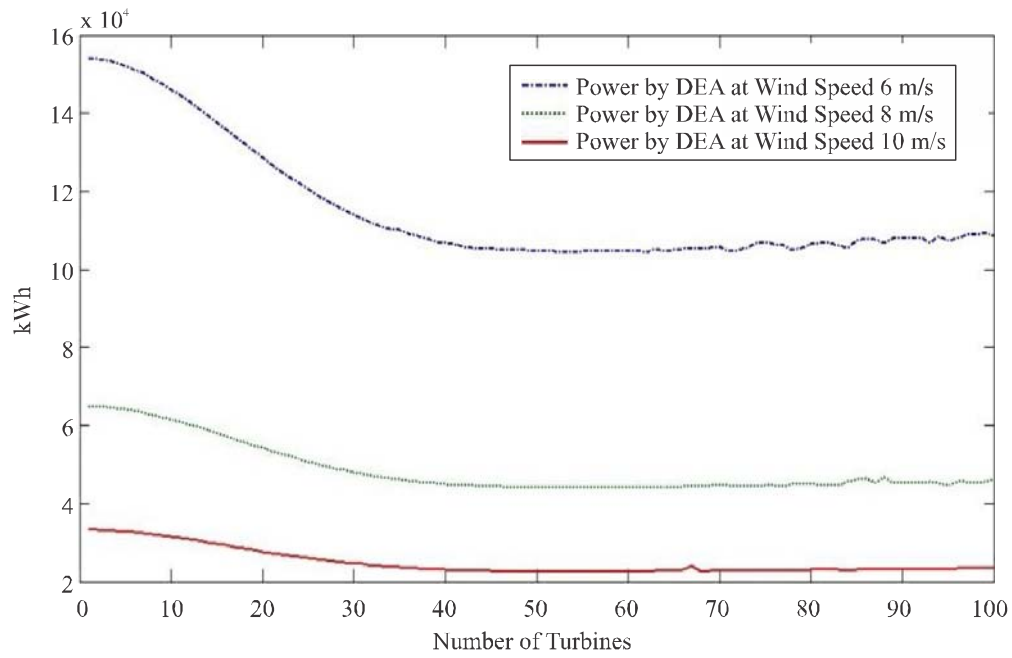


FIG. 6. COMPARISON OF COST FOR 6, 8 AND 10 m/s WIND SPEED

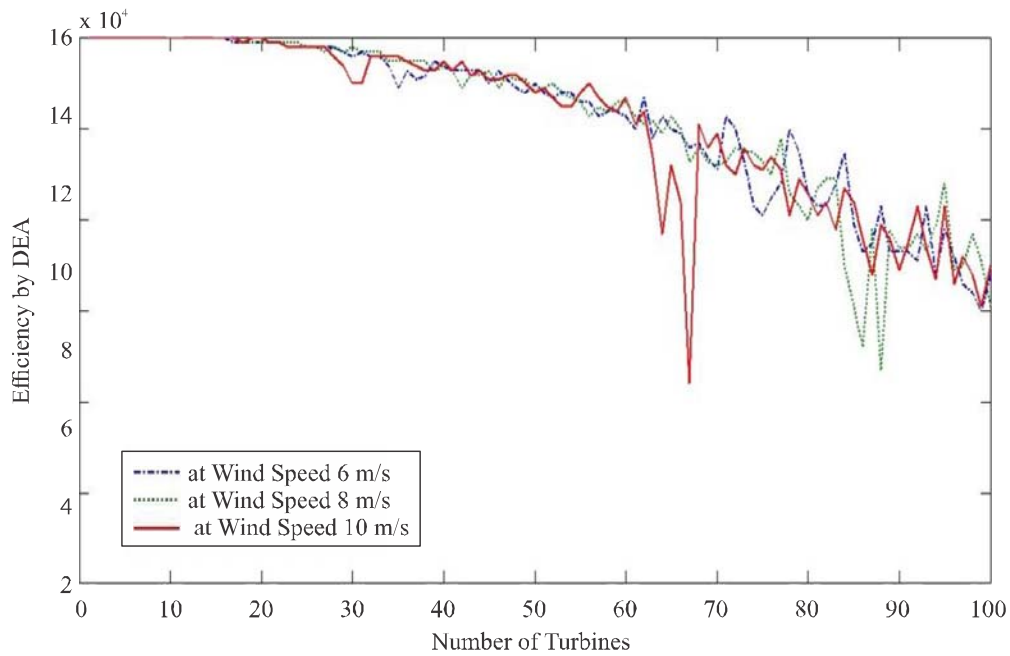


FIG. 7. COMPARISON OF EFFICIENCY FOR 6, 8 AND 10 M/S WIND SPEED

TABLE 6. TOTAL POWER GENERATED AS WELL AS ITS COST

No. of Turbine	Power by DE	Power by GA	Cost by DE	Cost by GA	Efficiency by DE	No. of Turbine	Power by DE	Power by GA	Cost by DE	Cost by GA	Efficiency by DE
1.	518.4	518.40	0.0019279	0.0019279	1	51.	26,016.96	25,710.70	0.0013139	0.0013296	0.984060
2.	1,036.8	1,036.80	0.0019246	0.0019246	1	52.	26,625.47	26,196.97	0.0013079	0.0013293	0.987709
3.	1,555.2	1,555.20	0.0019190	0.0019190	1	53.	27,116.55	26,683.25	0.0013079	0.0013292	0.986947
4.	2,073.6	2,073.60	0.0019114	0.0019114	1	54.	27,706.40	27,169.52	0.0013034	0.0013292	0.989741
5.	2592	2,592.00	0.0019016	0.0019016	1	55.	28,084.34	27,655.80	0.0013090	0.0013293	0.985001
6.	3,110.4	3,110.40	0.0018899	0.0018900	1	56.	28,635.46	28,142.07	0.0013065	0.0013294	0.986395
7.	3,628.8	3,628.80	0.0018764	0.0018765	1	57.	29,224.14	28,628.34	0.0013026	0.0013297	0.989013
8.	4,147.2	4,147.20	0.0018612	0.0018613	1	58.	29,605.24	29,099.31	0.0013079	0.0013307	0.984636
9.	4,665.59	4,665.60	0.0018444	0.0018445	1	59.	30,138.19	29,570.28	0.0013066	0.0013317	0.985372
10.	5,183.99	5,184.00	0.0018263	0.0018263	1	60.	30,467.18	30,041.24	0.0013141	0.0013328	0.979526
11.	5,702.39	5,702.40	0.0018069	0.0018069	1	61.	31,149.41	30,512.21	0.0013065	0.0013338	0.985043
12.	6,220.79	6,220.80	0.0017864	0.0017865	1	62.	31,633.49	30,983.17	0.0013074	0.0013349	0.984216
13.	6,739.19	6,739.20	0.0017651	0.0017652	1	63.	32,002.59	31,454.14	0.0013131	0.0013359	0.979895
14.	7,256.05	7,257.60	0.0017435	0.0017432	0.999787	64.	32,578.90	31,925.11	0.0013102	0.0013370	0.981955
15.	7,775.99	7,776.00	0.0017207	0.0017207	1	65.	32,823.12	32,396.07	0.0013206	0.0013380	0.974095
16.	8,292.98	8,294.40	0.0016982	0.0016979	0.999829	66.	33,359.45	32,867.04	0.0013193	0.0013391	0.975012
17.	8,809.73	8,812.80	0.0016755	0.0016749	0.999652	67.	33,851.47	33,338.00	0.0013198	0.0013401	0.974626
18.	9,326.39	9,331.20	0.0016528	0.0016519	0.999484	68.	34,395.80	33,808.97	0.0013182	0.0013411	0.975734
19.	9,841.61	9,849.60	0.0016304	0.0016291	0.999189	69.	34,990.95	34,279.94	0.0013148	0.0013421	0.978232
20.	10,362.59	10,351.68	0.0016074	0.0016091	0.999478	70.	35,449.87	34,750.90	0.0013165	0.0013430	0.976903
21.	10,881.62	10,853.76	0.0015852	0.0015893	0.999561	71.	35,822.02	35,221.87	0.0013215	0.0013440	0.973255
22.	11,387.00	11,355.84	0.0015654	0.0015697	0.001565	72.	36,393.53	35,692.83	0.0013190	0.0013449	0.975050
23.	11,902.21	11,857.92	0.0015449	0.0015506	0.998240	73.	36,781.25	36,163.80	0.0013232	0.0013458	0.971938
24.	12,417.42	12,360.00	0.0015250	0.0015321	0.998056	74.	37,433.83	36,634.76	0.0013179	0.0013467	0.975815
25.	12,931.86	12,862.08	0.0015060	0.0015142	0.997829	75.	37,704.10	37,105.73	0.0013262	0.0013475	0.969756
26.	13,448.68	13,364.16	0.0014876	0.0014970	0.997795	76.	38,204.72	37,576.70	0.0013262	0.0013484	0.969702
27.	13,969.24	13,866.24	0.0014698	0.0014807	0.998031	77.	38,677.94	38,032.84	0.0013272	0.0013497	0.968964
28.	14,474.64	14,368.32	0.0014544	0.0014652	0.997206	78.	38,849.36	38,488.98	0.0013385	0.0013511	0.960781
29.	14,984.48	14,870.41	0.0014395	0.0014506	0.996733	79.	40,007.73	38,945.12	0.0013164	0.0013523	0.976904
30.	15,502.19	15,372.49	0.0014249	0.0014369	0.996797	80.	40,061.22	39,401.26	0.0013313	0.0013536	0.965982
31.	16,021.05	15,874.57	0.0014111	0.0014241	0.996929	81.	40,700.84	39,857.40	0.0013268	0.0013548	0.969289
32.	16,538.89	16,376.65	0.0013985	0.0014123	0.996991	82.	40,670.61	40,313.54	0.0013441	0.0013560	0.956757
33.	17,055.61	16,878.73	0.0013869	0.0014014	0.996985	83.	41,380.13	40,769.68	0.0013372	0.0013572	0.961720
34.	17,557.02	17,380.81	0.0013774	0.0013914	0.996109	84.	41,607.52	41,225.82	0.0013459	0.0013584	0.955493
35.	18,077.95	17,882.89	0.0013673	0.0013822	0.996360	85.	41,737.14	41,681.96	0.0013577	0.0013595	0.947194
36.	18,581.78	18,384.97	0.0013593	0.0013739	0.995680	86.	42,488.45	42,138.10	0.0013494	0.0013606	0.953032
37.	19,062.79	18,887.05	0.0013537	0.0013663	0.993848	87.	43,736.36	42,594.24	0.0013261	0.0013617	0.969747
38.	19,510.77	19,389.13	0.0013511	0.0013595	0.990434	88.	43,440.03	43,050.38	0.0013505	0.0013627	0.952231
39.	20,024.30	19,875.40	0.0013444	0.0013545	0.990439	89.	43,750.27	43,506.51	0.0013562	0.0013638	0.948256
40.	20,565.06	20,361.68	0.0013368	0.0013501	0.991756	90.	44,773.83	43,962.65	0.0013401	0.0013648	0.959659
41.	20,976.86	20,847.95	0.0013380	0.0013463	0.986942	91.	45,187.69	44,418.79	0.0013425	0.0013658	0.957886
42.	21,602.70	21,334.23	0.0013262	0.0013429	0.992187	92.	45,734.17	44,874.93	0.0013411	0.0013668	0.958932
43.	22,116.73	21,820.50	0.0013221	0.0013401	0.992173	93.	46,533.57	45,331.07	0.0013324	0.0013677	0.965202
44.	22,600.06	22,306.78	0.0013203	0.0013376	0.990814	94.	46,562.27	45,787.21	0.0013459	0.0013687	0.955523
45.	23,154.83	22,793.05	0.0013147	0.0013356	0.992577	95.	47,525.01	46,243.35	0.0013326	0.0013696	0.965014
46.	23,605.94	23,279.33	0.0013155	0.0013339	0.989916	96.	47,077.73	46,685.14	0.0013595	0.0013709	0.945974
47.	24,155.71	23,765.60	0.0013110	0.0013325	0.991418	97.	47,121.59	47,126.92	0.0013723	0.0013722	0.937094
48.	24,709.37	24,251.87	0.0013068	0.0013315	0.993014	98.	48,408.38	47,568.70	0.0013496	0.0013735	0.952861
49.	25,152.78	24,738.15	0.0013087	0.0013306	0.990205	99.	49,636.67	48,010.48	0.0013297	0.0013747	0.967169
50.	25,625.21	25,224.42	0.0013092	0.0013300	0.988627	100.	49,726.62	48,452.26	0.0013407	0.0013759	0.959233

The DEA approach is a stochastic one and has a faster convergence than the deterministic approach which describes the jumps in the algorithm results. The use of the DEA, rules out the manual approaches by application of the Finite Difference Method that would be tedious and almost impossible to compute given the vast number of calculations required.

It is concluded that the DEA approach used in this work and other recent approaches by firefly algorithm [1] and adjoint method [27] are better than the GAs and the finite difference methods [3]-[8] for Wind Farm Micrositing.

## 6. CONCLUSIONS

The performance of the DEA was evaluated as the number of turbines was increased. The DEA has proven itself to be robust and cost effective for the solution of this problem. The main feature of this algorithm is that it escapes local optima, multiple number of times during the running of this simulation. However, the small fluctuations in the values of the cost function can be eradicated by the use of extraneous computing power that results in an extensive search of the solution set.

It may be safely concluded that the DEA performs better as the number of turbines increases which is a quality of this algorithm reported in other applications. It may be concluded that the more the computing power the better and gradual results arise. Hence the DEA approach used in this work and other recent approaches are better than the GAs for Wind Farm Micrositing.

## ACKNOWLEDGEMENT

Authors would like to thank and acknowledge the efforts and feedback received from Prof. Naeem-ul-Hassan Janjua, Dr. Riazuddin Abro, and the reviewers for their valuable comments that have led to the enrichment of this work.

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