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An Efficient 3D Simulator for Optimal Wind Farm Modelling and Simulation using Particle Swarm Optimization (PSO) Algorithm

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ABSTRACT

Wind Farm Layout Optimization (WFLO) is essential to meet power demand and expenditures. In recent years, Wind Farm Optimization (WFO) has received much more attention. Wind turbines extract the energy from wind, the rotation of wind turbine rotor reduces the wind speed behind it and swirls the air flow that is called wake effect. Therefore, optimal modelling of wind farm layout to decline wake effect is a key challenge. The current study presents a 3D simulator for the simulation of optimal wind farm layout with different hub heights of turbines as well as same hub heights of turbines in a continuous space of $3\text{km} \times 3\text{km}$ by implementing Particle Swarm Optimization (PSO) algorithm based on Frandsen's wake model. The PSO algorithm is used to find the best position of turbines while Frandsen's wake model is used to measure velocity deviation. It is examined that power generation of 42 wind turbines having 80 meters hub height at a wind speed of 8 m/s is 46.65903 MW, while the same number of turbines having different hub height generates 55.48799 MW. Furthermore, it is also observed that power generation of 42 turbines having 60 meters hub height is 26.57688 MW. The proposed simulator offers accessibility to the user by providing efficient 3D simulations according to their design parameters. The effect of wake meandering also reduces the power output and increases the cost of farm.

Keywords: **Frandsen's Wake Model, Particle Swarm Optimization, Wind Farm Layout Optimization, Wind Farm 3D Simulator.**

1. INTRODUCTION

At present, electrical energy has turned out to be the greatest considerable measure of social life [12]. Reduction of the fossil fuels has led to thoughtful shortage of energy production from the traditional sources stimulating an increase in utilization of the non-conventional energy sources like wind, solar and biogas *etc*. [13]. One of the productive ecological and renewable source of energy is the wind energy [8]. The wind power production modelling has become a popular research topic because capabilities of installed generation are growing rapidly in many countries in recent years [4]. The maximum power potential with reliable optimum wind farm design strongly depends on the particular area measurements of the farm position [14]. During the development of wind farm placement of turbines is usually improved to take full advantage of the energy yield by reducing the wake effect [16].

To get more power generation while using wind energy factors such as local wind condition, the type of wind energy conversion systems and the location of the farm should be considered. When these factors are determined, the individual location of turbines in the

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wind farm becomes important because positions of turbines will alter the wind condition. Therefore, wind turbine positioning becomes an important task in wind farm design [1].

Mosetti *et al.* [11] were the first who scientifically adjusted turbine locations in a wind farm by means of Genetic Algorithm (GA). Based on Mosetti *et al.* [11], Grady *el al.* [7] tied up 600 individuals and 3000 generations in a genetic algorithm to catch out the better layout of a wind farm. To meet the wind farm layout optimization in the occurrence of invariable wind speed and wind direction, Marmidis *et al.* [10] employed Monte Carlo Simulation (MCS). Later on Wan *et al* [17] used binary-encoded genetic algorithm and innovative wind farm and turbine models to express an optimum control structure of the wind farm with respect to decreased rate per unit energy. In the above studies wind farm was segregated into square cells. The width of cells was 5D of the turbine rotor for protection purpose. The turbines could only be engaged in the center of each cell while, this kind of "discrete" placement was convenient for the recognition of optimum methods. Also, the Definite Point Selection (DPS) was used to locate the turbines in safe region to take maximum efficiency as well as power generation [15, 20]. Wang *et al*. [20] designed a wind farm in complex terrain having the asymmetrical boundary constraints and also calculated the wind speed over non-flat terrain at different heights. In order to maximize power production of a wind farm Wan *et al*. [18] suggested a system in which each turbine could be freely allocated inside its cell. Ominously, as the limitations on minimum turbine distance was not deliberated, the turbines could be positioned fairly close particularly when the wind direction was governing. Duan *et al.* [2] used an integer encoding method and modified Genetic Algorithm techniques regarding Net Present Value (NPV) and the hub height optimization.

In the existing literature, positions of turbines in a wind farm were optimized by different techniques. Nevertheless, the PSO technique is more appropriate and operational for wind farm layout optimization. In contrary to traditional evolutionary algorithms, PSO is more convenient, fast and efficient.

In this research an advanced and efficient 3D simulator is developed to optimize the hub height and X and Y positions of turbines in wind farm by using heuristic technique based on Frandsen's wake model. The rest of research is organized as follows. Section 2 describes methodology, optimization technique, wake model, power calculation and the algorithm. Section 3 presents 3D simulator architecture, wind farm builder and computing hub. Section 4 presents the results and discussion. Section 5 provides the conclusion.

2. METHODOLOGY

The development engine named as "UNITY" is used to develop the 3D Simulator. It provides a platform to design 3D environment simulations with better performance for different operating systems. The minimization of wake effect is necessary to achieve better performance of wind farm. There are different wake models available for the calculation of the wake effect. A well-known wake model named as "Frandsen's Wake Model" along with PSO is used in this research. The PSO algorithm is used for optimal wind farm layout to obtain maximum power generation.

2.1. Optimization technique

The PSO is population centered stochastic optimization technique that was developed by Kennedy and Eberhard in 1995 [3]. The PSO technique was developed by inspiration of social behavior of bird flocking. In Participle Swarm Optimization (PSO) different particles or potential solutions are used to find the best placement of each turbine with minimum velocity deficit. The PSO places each particle location by calculating the velocity deficit on each coordinate. It stores the objective function value in arrays during run time and only returns the best objective function value. In Particle Swarm Optimization (PSO) technique, every particle recalls its own previous best value [19]. Therefore, it has a more operative memory ability than the Genetic Algorithm (GA).

The PSO algorithm starts with a residents of particles whose positions $\mathbb{P}$ and speeds U are randomly initialized in the exploration area. In current research $\mathbb{P} = [\mathbb{P}_1^T, \mathbb{P}_2^T, \mathbb{P}_3^T \ \ldots \ \mathbb{P}_{SS}^T]^T$ indicates the position of turbines for all the possible solutions in the swarm, and $U = [U_1^T, U_2^T, U_3^T \ \ldots \ U_{SS}^T]^T$ is the amendment to the position $\mathbb{P}$, where "SS" represents the sample size. The exploration for optimal position is supported out by bring up to date the speeds and positions of the particles iteratively. The exploration of particles is motivated towards favorable regions by fascinating the particles' velocities vector toward both their own historical best positions $\mathbb{P}^{\mathfrak{p}}$ and the swarm's historical best position $\mathbb{P}^{\mathfrak{g}}$. The velocities and the position of particles are usually updated by the equation.

$$U(x+1) = wU(x) + c_1R_1.\times\left(\mathbb{P}^{\mathfrak{p}}(\mathbf{x}) - \mathbb{P}(x)\right) + c_2R_2.\times\left(\mathbb{P}^{\mathfrak{g}}(\mathbf{x}) - \mathbb{P}(x)\right) \quad (1)$$

Here, the best position of a particle or the swarm corresponds to the smallest fitness value defined in equation (2).

2.1.1. Objective function

Objective function of the present research is to minimize the wake losses due to velocity deficit and to maximize power generation of the farm.

$$U_0 = \frac{1-\sqrt{1-C_r}}{1+2\left(\frac{KS}{R}\right)} \quad (2)$$

where the wind velocity of downstream turbine is U_o, C_T is thrust coefficient, K is wake decay constant, R is the rotor radius of turbine and S is the distance between up and down stream turbines.

2.2. Wake model

Frandsen *et al.* [5] introduced surface drag induced internal boundary layer methodology, which modifies the wind speed side view within Planetary Boundary Layer (PBL) according to the increasing space downstream in front of wind turbine. This model works on three different regions. In First region multiple wake is applied on the turbines. The Wake effect of neighboring turbines is combined and wake will expand only vertically in second region. In third region the turbines are located at the boundary of wind farm. As some turbines wake effect can be viewed analytically and wake effect of some turbines will be calculated as realistic planned. Therefore, this model is known as semi-analytical model [6].

When an identical wind comes across a wind turbine, a linearly growing wake behind the turbine occurs. A part of the free stream wind speed will be declined from its original speed U_{up} to U_{down}. Fig. 1 demonstrates the idea of wake behind a wind turbine [9].

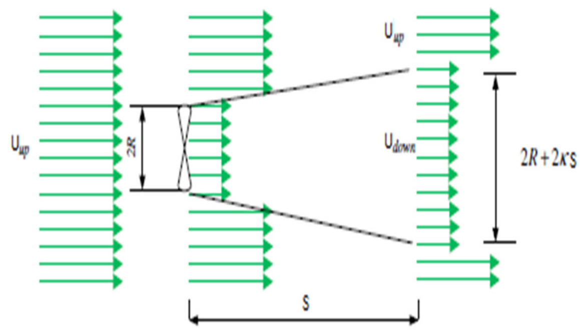

Fig. 1: Wind turbine wake model [9]

2.3 Power Calculation

The power generated from single turbine in wind farm is calculated by using equation (3) [14]:

$$P_p = \eta \frac{1}{2} \rho A u_0^3 C_p \quad (3)$$

where the power production of a turbine is P_p, η is efficiency of turbine, ρ is air density, A is turbine area, u_0 is wind speed and C_p is power coefficient.

2.4 Algorithm

The algorithm developed in this research includes following steps:

1: Initialize all the particle locations with default start positions of wind form
2: Initialize the two dimensional dynamic arrays to store the particle objective function values and their coordinates
3: Repeat
4. for all i ∈ T (T-Number of possible turbines) do
   I. Find objective value for each turbine T[i]

II. Increment in X coordinate position by 0.1 until XD Max Limit reached
III. Increment in Y coordinate position by 0.1 until YD Max Limit reached
IV: If calculated objective function value is better than last found objective function value
    i. Swap current coordinate to last calculated coordinate Array [i, 0] = Objective function value
    ii Array [i, 1] = Coordinate value
V: end if
5: end for
iii: Update the dynamic coordinate array with previously calculated coordinates
iv: Find minimum value of objective function from dynamic array.
v: for all individual turbines, T[i] until all turbines completed T do
    i: Set objective function value (velocity deficit value) to each turbine
    ii: Set position of turbine T[i] with array [i, 1]
VI: end for
6: until all possible turbines objective find or Turbine coordinates become out of wind farm angle.

3. 3D SIMULATOR ARCHITECTURE

The 3D wind farm designer and simulator architecture is composed of two different modules as illustrated in Fig. 2 that are interlinked with a component known as scene manager. Scene manger will work as a bridge or linker between these two modules and save object states during transition of one scene to another scene. The proposed modules are namely:

1. Wind farm builder
2. Computing hub.

3.1. Wind Farm Builder

The wind farm builder is the first scene that appears at the starting time of software. Wind farm builder is the interactive scene for the user, where the user can input values of different factors. The wind farm builder has Front End for user interaction and Back End for further computing of turbine placement according to coordinates in 3D environment. Wind farm builder is composed of different components that perform their prescribed functionality.

Fig. 3: Wind farm builder

3.1.1. Input

The Front End interactive component (Fig. 3) that gets by default input values of different factors and user can replace the default value with his/her desired value is named as input. User can replace the desired input values of these factors in labeled textboxes. After this the values of these factors will be passed to the next component for their further processing. The input deals with nine factors namely:

1. Area in square meters
2. Minimum turbine height
3. Thrust coefficient
4. Value of K
5. Power coefficient
6. YD max limit
7. XD max limit
8. Boolean value (Same height or not)
9. Boolean value (Grid based or not)

3.1.2. Area designer

The area designer is used to design the 3D environment according to input value of area in square meters. It designs the terrain width and length according to input value. It also places the texture on terran. The green texure image provides some basics of reality in 3D environment of the simulator.

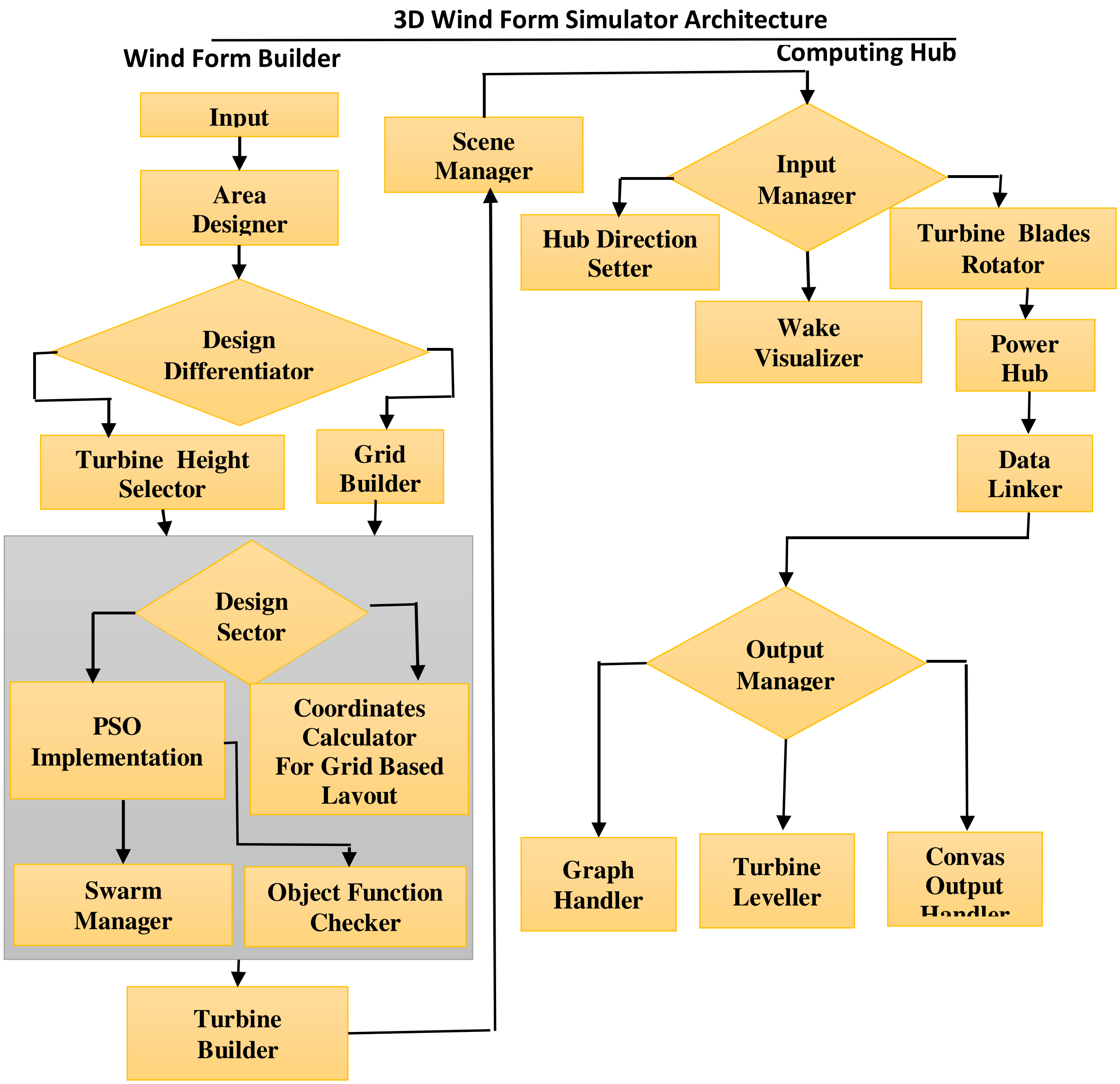

Fig. 2. Flow chart of proposed 3D wind farm simulator

3.1.3. Design differentiator

The design differentiator is used to design wind farm layout according to the Boolean inputs. "Is Grid" and "Same Height". If user checks the Boolean input "Is Grid" the design of wind farm layout will be set as grid based according to the XD max limit value. The design differentiator will pass the input values to the grid builder in case of the "IS Grid" box is checked. Although, the "Is Grid" box is unchecked the design differentiator will pass the input values to turbine height selector where height of turbines of the farm has selected either turbines with same height or different height. If the "Same Height" box is checked the design of wind farm will have the turbines of same height otherwise wind farm will have turbines with different hub heights. Grid builder and turbine height selector are described.

I. Grid Builder

The grid builder is used to build the grid layout on surface of terrain according to the terrain size. It calculates the number of rows and columns in the grid layout according the XD max limit value. As XD max limit value increases the number of columns and decreases the rows, which means it shows the inverse effect between XD max limit, number of rows and columns on surface of terrain.

II. Turbine height selector

The turbine height selector is used for selecting the height according to Boolean parameters of “Same Height”. If user checks the Boolean parameter “Same Height” turbine height selector will pass the value of 80 meters hub height to the coordinate’s builder and if user unchecks the Boolean parameter “Same Height”, it will pass the minimum turbine height value by taking the value from parameters “Min Turbine Height”. The default value of “Min Turbine Height” is 30 meters but users can change the value of this parameter according to their own requirement.

3.1.3. Coordinates builder

The coordinate’s builder is very important component of whole architecture. The coordinate’s builder finds the optimal coordinates for each turbine positioning. The coordinate’s builder can design the wind farm in grid based and continuous spaced wind farm layout. Coordinates builder is composed of three sub components named as.

I Design selector
II PSO implementer
III Grid based coordinates calculator

I. Design Selector

The design selector is used to identify mods of wind farm layout. It takes input from design differentiator. If grid based design is selected then it will pass values to the grid based coordinates calculator.

II. PSO Implementer

The PSO implementer is important component that implements the Frandsen’s wake model and Particle Swarm Optimization (PSO) technique. The PSO implementer places each turbine on the terrain according to the optimum value of objective function. The computation time is 0.76 second.

The PSO implementer is composed of two different components named as-

i Objective function checker
  As discussed in objective function.
ii Swarm manager

The swarm manager implements the PSO algorithm to find the best position for each turbine. It uses different factors to get optimal position of turbine like turbine height, rotor diameters, value of K, thrust coefficient and distance between previous turbines, XD max limit and YD max limit. To get best position of wind turbine the PSO manager calls the objective function calculator multiple times for each turbine until the optimum objective function value is achieved. It stores the optimum objective value and particle coordinates into dynamically declared two dimensional array. After this the PSO performs computation for all turbines. It returns the array value to the turbine builder to build the turbines according to their hub height.

III. Coordinates calculator for grid based layout

The grid based coordinates calculator simply verifies the position of rows and columns on terrain and calculates the distance between turbines in same rows. If any grid whose area is not fitted inside the terrain area then this grid will be discarded. Grid based coordinates calculator will return the array of coordinates of each turbine that can be placed on surface of terrain.

3.1.4. Turbine Builder

The turbine builder is used to build and place the turbine on surface of wind form. It sets the turbine size according to the rotor diameters and place the turbine according to the received coordinates from design selector. It is to show the wake effect for further computation by setting the position of particle system at hub height.

3.2. Computing Hub

Computing hub is a brain like component in this structural design. It works on the Back End of the architecture. Computing hub calculates the run time values *e.g*. individual power of each wind turbine. It receives wind input from turbine builder and rotates the blades of turbine according to the wind speed. It also combines the power of individual turbines, shows the total power generated on the canvas of scene and the velocity deficit by particle system. In simple words, the computing hub is responsible for run time computation and output of the wind farm.

The computing hub is composed of several components which are discussed below.

3.2.1. Input Manager

The input manger (Fig. 4) is responsible for collecting the input from text boxes presented on canvas and sent them to different components according to the call. Input manger receives multiple values and distributes them to different components on requirement. It keeps track of each input value and their relation with the other components. Therefore, related values will be passed for their proper functionality.

3.2.2. Hub Direction Setter

The hub direction setter is used to set the direction of turbine hub according to the provided values of wind direction. It rotates the turbine hub as the values of wind direction are changed. Wind direction can be set among these directions: North, North-East, East, South-East, South, South-West, West, North-West and again North. The users can set the wind direction from the tool given in Fig. 5.

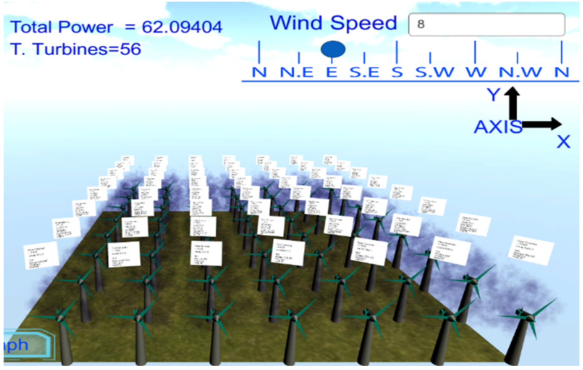

Fig. 4. Input Manager

Fig. 5: Wind direction Front End user interactive control

3.2.3. Wake Visualizer

Wake visualizer calculates and visualizes the wake effect at run time, as shown in Fig 6. Wake effect changes according the speed of wind. If user changes the wind speed then the wake effect will change and resultant value will pass to output manager to show on the canvas.

The wake visualizer calculates the wake for each turbine by using Frendsen's wake equation. So, the turbine will simulate properly in running environment. To calculate the wake equation (1) is used.

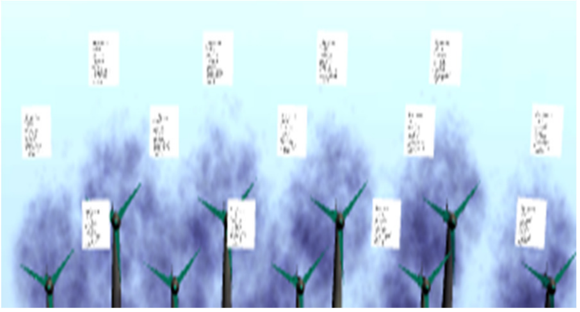

Fig. 6: Wake Visualizer

3.2.4. Turbine blades rotator

The turbine blades rotator is used to rotate the rotor of turbine for generating the output. It receives the wind input from input manger and passes to the function "Calculate Wind Speed". This function takes two values turbine hub height and reference Wind Speed, after processing it will give the actual wind speed according to hub height. This wind speed will be used for rotation of wind turbine rotor.

3.2.5: Power hub

The power hub is used to collect output power from each turbine. Power hub has the reference of each turbine placed on surface of terrain. The power hub makes loop through each reference of turbine object and combines the power of turbines. After collecting the power, it sends the total number of turbines and total power generated by these turbines to data linker.

3.2.6. Data Linker

The data linker is responsible for communication of data between power hub and output manager. As output manger is distinct component that only handles the Front End to show the output. So, the data linker works as a bridge between the power hub and output manger. Data linker stores the data into dynamic arrays and sends it to the output manager when there will be call for data.

3.2.7. Output Manager

The output manger is distinct component that handles the Front End on second scene to display the output. It receives data from data linker and is responsible for output of data through different sub components. It visualizes the computed data into different form like text and graphical forms as shown in Fig. 7 and 8 respectively. The output manager is composed of three sub components, which are as described below.

I. Graph Handler

The graph handler is responsible to visualize the data in graphical form as shown in Fig. 7. The graph shows value in integral based data but when a user checks by the mouse over any category it also shows the value into the decimal form at the top head of the graph, that is the limitation of graph and chart library.

II. Turbine Labeler

The turbine labeler is responsible to represent data of each turbine on canvas as shown in Fig. 8. It also manages the canvas rotation according to the user camera. Whenever, users move camera to change the visualization the turbine canvas also moves according to the user's camera.

It shows the parameters on each turbine that are as under:-

- Power generated
- Velocity deficit
- WI (Wind input)
- X axis position coordinates
- Y axis position coordinates
- Height of turbine

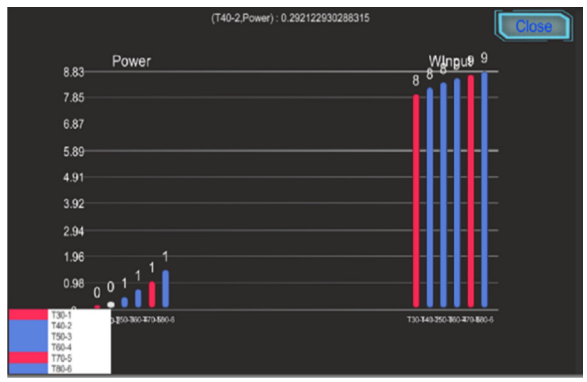

Fig. 7: Power and Wind Input graph

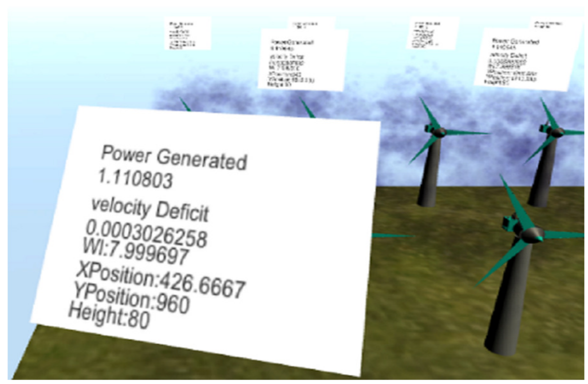

Fig. 8: Turbine canvas placed on each turbine

III. Canvas output handler

The canvas output handler is responsible to display the data on static canvas presented on second scene. It shows the total power and total number of turbines on canvas at run time. It also shows the position of turbines of wind farm in the grid. It receives the input from data linker and presents the information in textual and grid form as shown in Fig. 9.

4. RESULTS AND DISCUSSION

The three scenarios are implemented and simulated in the proposed 3D simulator. The brief description of results of these scenarios is discussed in the following sub sections.

Fig. 9: Canvas output handler to show total power and total turbines

4.1. Scenario 1: Grid based layout design

Input values for the simulation of the grid based wind farm layout are given in Table 1.

In the scenario 1, 56 turbines of 80 hub height have been installed that give 62.09404 MW power output. It is pointed out that all the turbines are placed at the center of each sub cell. Consequently, each turbine is placed immediately behind the previous turbine. The results of scenario 1 are as under:-

Table 1: Inputs of grid based layout design

Terrain area in square meters	Turbine height	Thrust coefficient	Value of K	Power coefficient (CP)	YD max limit	XD max limit
3000	80	0.8	2	0.4	4D	4D

In Table 2, positions of turbines along X-axis and Y-axis in grid based layout are given. X: 1280, Y: 0 represents the turbines of third column and first row respectively.

Table 2: Turbine coordinates of grid based layout

Coordinates of turbines (m)		Coordinates of turbines (m)		Coordinates of turbines (m)		Coordinates of turbines (m)	
X:426.6667	Y: 0	X:426.6667	Y:853.3333	X:426.6667	Y:1706.667	X:426.6667	Y:2560
X:853.3333	Y: 0	X:853.3333	Y:853.3333	X:853.3333	Y:1706.667	X:853.3333	Y:2560
X:1280	Y: 0	X:1280	Y:853.3333	X:1280	Y:1706.667	X:1280	Y:2560
X:1706.667	Y: 0	X:1706.667	Y:853.3333	X:1706.667	Y:1706.667	X:1706.667	Y:2560
X:2133.333	Y: 0	X:2133.333	Y:853.3333	X:2133.333	Y:1706.667	X:2133.333	Y:2560
X:2560	Y: 0	X:2560	Y:853.3333	X:2560	Y:1706.667	X:2560	Y:2560
X:2986.667	Y: 0	X:2986.667	Y:853.3333	X:2986.667	Y:1706.667	X:2986.667	Y:2560
X:426.6667	Y:426.6667	X:426.6667	Y:1280	X:426.6667	Y:2133.333	X:426.6667	Y:2986.667
X:853.3333	Y:426.6667	X:853.3333	Y:1280	X:853.3333	Y:2133.333	X:853.3333	Y:2986.667
X:1280	Y:426.6667	X:1280	Y:1280	X:1280	Y:2133.333	X:1280	Y:2986.667
X:1706.667	Y:426.6667	X:1706.667	Y:1280	X:1706.667	Y:2133.333	X:1706.667	Y:2986.667
X:2133.333	Y:426.6667	X:2133.333	Y:1280	X:2133.333	Y:2133.333	X:2133.333	Y:2986.667
X:2560	Y:426.6667	X:2560	Y:1280	X:2560	Y:2133.333	X:2560	Y:2986.667
X:2986.667	Y:426.6667	X:2986.667	Y:1280	X:2986.667	Y:2133.333	X:2986.667	Y:2986.667

Table 3: Turbine power and wind input of grid based layout

Power generation (MW)	Wind input without wake losses (m/s)
Power of turbine height 80- Row 1 : 1.111029	Wind input of turbine height 80- Row 1 : 8
Power of turbine height 80- Row 2 : 1.110327	Wind input of turbine height 80- Row 2 : 7.998554
Power of turbine height 80- Row 3 : 1.109725	Wind input of turbine height 80- Row 3 : 7.997108
Power of turbine height 80- Row 4 : 1.109123	Wind input of turbine height 80- Row 4 : 7.995661
Power of turbine height 80- Row 5 : 1.108521	Wind input of turbine height 80- Row 5 : 7.994215
Power of turbine height 80- Row 6 : 1.10792	Wind input of turbine height 80- Row 6 : 7.992769
Power of turbine height 80- Row 7 : 1.107318	Wind input of turbine height 80- Row 7 : 7.991323
Power of turbine height 80- Row 8 : 1.106717	Wind input of turbine height 80- Row 8 : 7.989876

The generated power by individual turbine each row without losses due to velocity deficit of grid based layout is illustrated in Table 3. In grid based layout all the turbines are of 80 meter hub height.

Results of scenario 1 are as follows:
Total turbines = 56
Generated power = 62.09404
Power generation of each turbine of first row = 1.111029
Actual Power = 56x1.111029 = 62.217624
Efficiency = (Generated power ×100) / Actual power
= (62.09404×100) / 62.217624 = 99.80%

4.2. Scenario 2: continuous spaced wind farm layout, turbines with same hub height

Table 4 presents the input values for the simulation of the continuous spaced wind farm layout having turbines of same hub height.

In the scenario 2, 53 turbines are installed that generate total output power of 58.76847 MW. In this scenario there is the least chance for the placement of turbine immediate behind the previous one.

The power generated by individual turbine each row without losses due to velocity deficit of continuous spaced layout having turbines with same hub height of 80 meters is illustrated in Table 5. In continuous spaced layout having turbines with same hub height all the turbines are of 80 meter hub height.

Results of scenario 2 are as follows:
Total turbines = 53
Generated power = 58.76847
Power generation of each turbine of first row = 1.110929
Actual power = 53x1.110929 = 58.879237
Efficiency = (Generated power x 100) / Actual power
= (58.879237×100) / 58.76847= 99.812%

4.3. Scenario 3: continuous spaced wind farm layout, turbines with different hub height

Table 6 presents input values for the simulation of continuous spaced wind farm layout having turbines with different hub height. The layout having turbines with different hub heights starts from turbines of 60 m

Table 4: Inputs of continuous spaced layout, turbines with same hub height

Terrain area in square meters	Turbine height	Thrust coefficient	Value of K	Power coefficient (C_P)	YD max limit	XD max limit
3000	80	0.8	2	0.4	4D	4D

Table 5: Turbine power and wind input of grid based layout

Power generation (MW)	Wind input without wake losses (m/s)
Power of turbine height 80- Row 1 : 1.110929	Wind input of turbine height 80- Row 1 : 8
Power of turbine height 80- Row 2 : 1.11033	Wind input of turbine height 80- Row 2 : 7.998557
Power of turbine height 80- Row 3 : 1.109725	Wind input of turbine height 80- Row 3 : 7.997108
Power of turbine height 80- Row 4 : 1.109123	Wind input of turbine height 80- Row 4 : 7.995661
Power of turbine height 80- Row 5 : 1.108521	Wind input of turbine height 80- Row 5 : 7.994215
Power of turbine height 80- Row 6 : 1.107934	Wind input of turbine height 80- Row 6 : 7.992769
Power of turbine height 80- Row 7 : 1.107318	Wind input of turbine height 80- Row 7 : 7.991324
Power of turbine height 80- Row 8 : 1.106717	Wind input of turbine height 80- Row 8 : 7.989876

Table 6: Inputs of continuous spaced layout, turbines with different hub height

Terrain area in square meters	Turbine height of 1st row	Thrust coefficient	Value of K	Power coefficient (C_P)	YD max limit	XD max limit
3000	60	0.8	2	0.4	4D	4D

hub height with increment of 10 meters in each row and ends at 100 meters hub height. In this study all the turbines after the row of turbines of 100 meters hub height will have hub height equal to 100 meters.

In the scenario 3, 42 turbines have been installed that give 55.4614 MW power output. It is pointed out that all the turbines are placed in way that there is no one turbine placed immediate behind the previous one. The results of scenario 3 are as under:

In Table 7, turbines positioning along X-axis and Y-axis of continuous spaced PSO based layout, turbines with different hub height is presented. X: 320 and X: 640 represent the turbine positioning of first and second column respectively. Y: 0 and Y: 320 represent the turbine positioning of first and second row respectively.

The power generated by each row of turbines and wind speed input without wake losses given to each row of turbines for the continuous spaced wind farm layout having turbines with different hub height is presented In Table 8. As this scenario have varying hub height of turbines so, wind input increases as hub height increases in this scenario.

The power generated by single turbines of each row and wind speed without losses due to velocity deficit given to each row of turbines of continuous spaced wind farm layout having turbines with different hub height are presented in table 8. Table 8 states power of row 1 is 0.6327829 and wind input for row 1 is 8m/s but power of row 4 is 1.600703 and wind input of row 4 is 8.318554, power of row 7 is 1.993183 and wind input of row 7 is 8.398432.

Fig. 10 displays the turbine height, number of turbines in each row and original wind speed input for continuous spaced wind farm layout having turbines with different hub height. Hub height of turbines of first row is 60 meters, there are 9 turbines in the first row and wind speed for those turbines is 8 m/s.

Table 7**:** Turbine coordinates of continuous spaced layout, turbines with different hub height

Coordinates of Turbines (m)		Coordinates of Turbines (m)		Coordinates of Turbines (m)	
X:320	Y: 0	X:2240	Y:320	X:2880	Y:1120
X:640	Y: 0	X:2613.333	Y:320	X:1066.667	Y:1600
X:960	Y: 0	X:2986.667	Y:320	X:1600	Y:1600
X:1280	Y: 0	X:853.3333	Y:693.3333	X:2133.333	Y:1600
X:1600	Y: 0	X:1280	Y:693.3333	X:2666.667	Y:1600
X:1920	Y: 0	X:1706.667	Y:693.3333	X:533.3333	Y:2133.333
X:2240	Y: 0	X:2133.333	Y:693.3333	X:1066.667	Y:2133.333
X:2560	Y: 0	X:2560	Y:693.3333	X:1600	Y:2133.333
X:2880	Y: 0	X:2986.667	Y:693.3333	X:2133.333	Y:2133.333
X:373.3333	Y:320	X:480	Y:1120	X:2666.667	Y:2133.333
X:746.6667	Y:320	X:960	Y:1120	X:1066.667	Y:2666.667
X:1120	Y:320	X:1440	Y:1120	X:1600	Y:2666.667
X:1493.333	Y:320	X:1920	Y:1120	X:2133.333	Y:2666.667
X:1866.667	Y:320	X:2400	Y:1120	X:2666.667	Y:2666.667

Table 8: Power and wind input of continuous spaced layout, turbines with different hub height

Power generation (MW)	Wind input without wake losses (m/s)
Power of turbine height 60- Row 1 : 0.6327829	Wind input of turbine height 60- Row 1 : 8
Power of turbine height 70- Row 2 : 0.8746518	Wind input of turbine height 70- Row 2 : 8.11867
Power of turbine height 80- Row 3 : 1.208898	Wind input of turbine height 80- Row 3 : 8.22857
Power of turbine height 90- Row 4 : 1.600703	Wind input of turbine height 90- Row 4 : 8.318554
Power of turbine height 100- Row 5 : 1.993222	Wind input of turbine height 100- Row 5 : 8.398486
Power of turbine height 100- Row 6 : 1.993183	Wind input of turbine height 100- Row 6 : 8.398432
	Power of turbine height 100- Row 7 : 1.993183

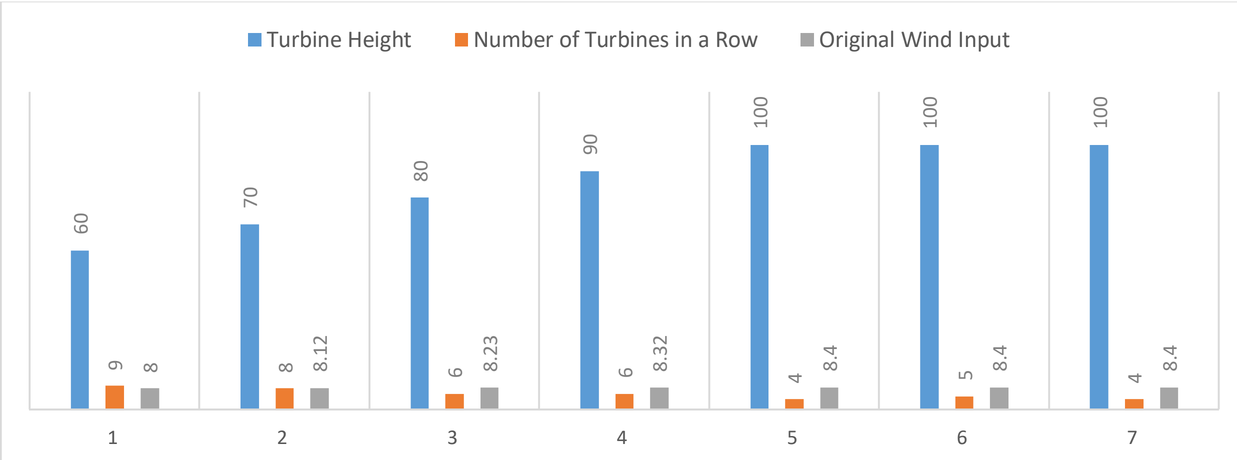

Fig. 10. Turbine quantity and original wind input of continuous spaced layout, turbines with different hub height

Table 9: Wind input, power output of single wind turbine, total turbines in each row and actual power generation at different wind speed due to different hub height

Wind input without losses	Output power of individual turbine	Number of turbines	Generated output
8	0.632782848	9	5.695046
8.11867	0.874651581	8	6.997213
8.22857	1.208897831	6	7.253387
8.318554	1.600703065	6	9.604218
8.398486	1.993221826	4	7.972887
8.398432	1.993183378	5	9.965917
8.398432	1.993183378	4	7.972734
		Sum	55.4614

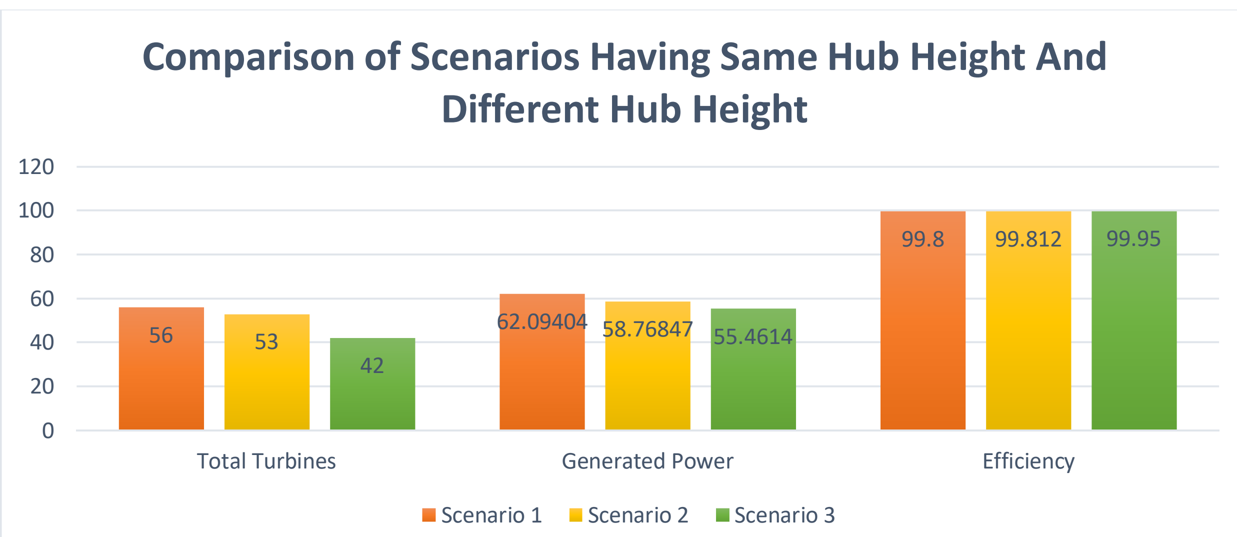

Fig. 11: Comparison of output and efficiency of three scenarios

Wind input without losses due to velocity deficit, power output of single wind turbine of each row, total turbines in each row and power output generated by each row in the continuous spaced wind farm layout having turbines with different hub height is presented in Table 10.

4.3.1. Wind input, power output of single wind turbine, total turbines in each row and power output of scenario 3

Table 9 shows input wind, power output of single wind turbine, total turbines and power output of each row for scenario 3.

Results of scenario 3 are as follows:

Total turbines = 42
Generated power = 55.4614
Actual generated power = 55.488
Efficiency = (Actual generated power x 100) / Total power generated
= (55.4614×100) / 55.488 = 99.95%

Fig. 11 shows the comparison of total turbines, power generated and efficiency by three described scenarios of wind farm layout. Fig. 12 illustrates the comparison of generated power from continuous spaced Particle Swarm Optimization (PSO) based wind farm layouts that have same number of turbines i.e. 42. The layouts have turbines of 60 meters hub height, 80 meters hub height and different hub height. The layout having turbines with different hub height starts from turbines of 60 meters hub height and there is increment of 10 meters in hub height for next row and ends at 100 meters. Moreover, all the turbines will be of 100 meters hub height after the turbines row of 100 meters hub height. It is concluded that power generation of wind farm layout having turbines with different hub height is more than the wind farm layout having turbines with same hub height.

5. CONCLUSION

The proposed research presents a 3D simulator for optimal wind farm layout design. An innovative framework is implemented in the developed 3D simulator in which multiple components and their modules are used to place a turbine in a wind farm where the wake losses are minimum.

The present research determines the generated power from different layouts of a wind farm having 42 turbines in 3km × 3km square shaped continuous space. It is examined that the power generation of 42 wind turbines having 80 meters hub height at a wind speed of 8 m/s is 46.65903 MW while, 55.48799 MW is generated by the same number of turbines having different hub height. Furthermore, it is also observed that the power generation of layout having 42 turbines of 60 meter hub height is 26.57688 MW. It is concluded that the wind farm layout having turbines with different hub heights provides much more power generated than other layouts. It also concluded that this research proposes an advance, compact, user friendly and efficient 3D simulator for the optimal modelling and simulation of a wind farm using heuristic technique.

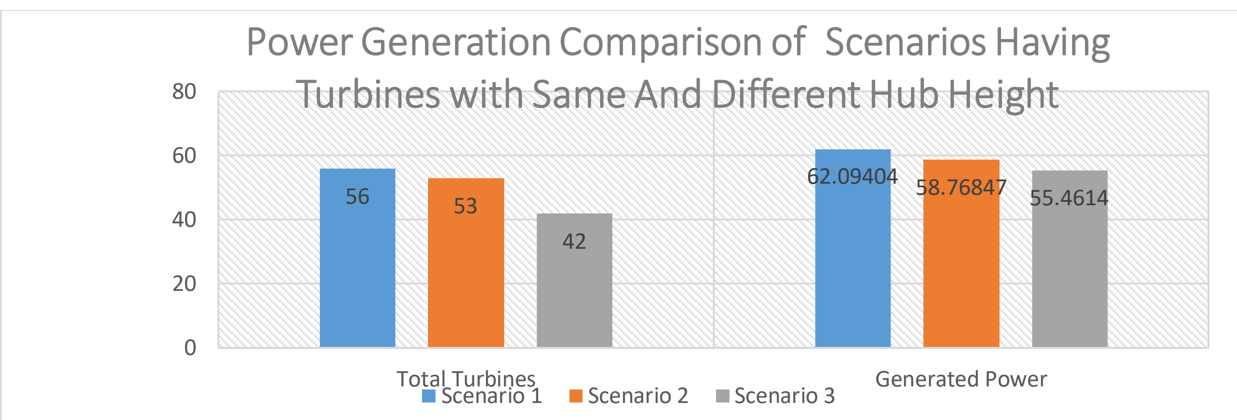

Fig. 12: Comparison of power generation

6. FUTURE WORK

This research work leads to merging more comprehensive modeling of the terrain to contemplate the result of very irregular terrains. Furthermore, the influence of atmospheric instability and instability produced due to the wind turbine can be amalgamate as these instabilities disturb the wake reclamation. Cost is not considered, that can be incorporated while designing the wind farm. Additionally, it can be real time based by storing real time wind and simulation data into an online databases.

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