



# **DESIGN OF WIND FARM LAYOUT USING A GENETIC ALGORITHM**

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# ABSTRACT

## DESIGN OF WIND FARM LAYOUT USING A GENETIC ALGORITHM

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M.Sc. Program in Industrial Engineering

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The usage of renewable energy gains importance in current energy management systems when sustainability issues are considered. This conversion trend leads to increasing implementation of wind farm projects throughout Europe. Therefore, while optimizing such systems, getting a threshold between different objective functions (like total produced power capacities; total investment costs; production efficiencies; etc.) plays a significant role for restricted application areas. In this study, it is aimed to minimize the total investment cost per unit power by optimizing the wind farm layout in a certain area. By comparing obtained solution sets with the other two benchmark studies in the literature, some important outcomes are shared to be used in decision support systems of stakeholders. The efficiency of obtaining a solution set by using a genetic algorithm and the advantages of using the coordinate method are investigated in detail. Based on the obtained results, the cost per unit power is reduced

up to 13,74% and the placement of 40 turbines is successfully satisfied with the flexible layout provided by using the coordinate method.

Keywords: wind farm layout optimization, genetic algorithm, coordinate method, grid method



# ÖZET

## GENETİK ALGORİTMA KULLANARAK RÜZGAR SANTRALİ YERLEŞİMİ DİZAYNI

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Endüstri Mühendisliği Yüksek Lisans Programı

Tez Danışmanı: Dr. Öğr. Üyesi Hamdi Giray Reşat

Ocak, 2022

Sürdürülebilirlik problemleri ele alındığında, mevcut enerji yönetim sistemlerinde yenilenebilir enerji kullanımı çok daha fazla önem kazanmaktadır. Bu eğilim, Avrupa genelinde rüzgar santrali projelerinin artan şekilde uygulanmasına yol açmaktadır. Bu nedenle, potansiyel rüzgar santralleri için çeşitli hedeflerin (toplam üretilen güç, toplam yatırım maliyetleri, üretim verimlilikleri gibi) optimize edilmesi büyük önem taşımaktadır. Bu çalışmada, belirli bir alanda rüzgar çiftliği yerleşimi optimize edilerek birim güç başına toplam yatırım maliyetinin minimize edilmesi amaçlanmıştır. Elde edilen çözüm setleri literatürdeki diğer iki çalışma ile karşılaştırılarak paydaşların karar destek sistemlerinde kullanılmak üzere bazı önemli sonuçlar paylaşılmıştır. Genetik algoritma kullanılarak bir çözüm seti elde etmenin verimliliği ve koordinat yöntemini kullanmanın avantajları detaylı olarak

arařtırılmıřtır. Elde edilen sonulara gre birim g bařına maliyet % 13,74'e kadar dřrlmřtr ve koordinat yntemi kullanılarak saėlanan esnek yerleřim ile 40 trbinin yerleřimi bařarıyla saėlanmıřtır.

Anahtar Kelimeler: rzgar santrali yerleřim optimizasyonu, genetik algortima, koordinat metodu, grid metodu



*Dedicated to my mother and father*



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# TABLE OF CONTENTS

ABSTRACT.....	iii
ÖZET.....	v
ACKNOWLEDGEMENTS .....	viii
LIST OF TABLES .....	xi
LIST OF FIGURES .....	xii
NOMENCLATURE.....	xiii
CHAPTER 1: INTRODUCTION .....	1
CHAPTER 2: LITERATURE RESEARCH.....	3
CHAPTER 3: THEORETICAL BACKGROUND.....	6
3.1. <i>Wind Resource</i> .....	6
3.2. <i>Wind Condition Modelling</i> .....	8
3.3. <i>Power Extraction</i> .....	10
3.4. <i>Jensen's Wake Model</i> .....	13
CHAPTER 4: WIND FARM PROJECTS OVERVIEW.....	16
4.1. <i>Finding the Right Site and Site Characteristics</i> .....	16
4.2. <i>Wind Farm Design</i> .....	18
4.3. <i>Permissions and Licenses</i> .....	19
4.4. <i>Financing</i> .....	20
CHAPTER 5: WIND FARM LAYOUT OPTIMIZATION .....	22
5.1. <i>Problem Description</i> .....	22
5.2. <i>Factors in Wind Farm Design and Assumptions</i> .....	22
5.2.1 <i>Site</i> .....	22
5.2.2. <i>Available Infrastructure and Budget Constraints</i> .....	23
5.2.3. <i>Environmental Impact</i> .....	23
5.2.4. <i>Wind Turbine Properties</i> .....	23
5.2.5. <i>Auxiliary Constraint</i> .....	24

5.2.6. <i>Wind Distribution</i> .....	24
5.2.7. <i>Wake Model</i> .....	25
5.2.8. <i>Power and Cost Calculation</i> .....	25
5.3. <i>Layout Design Methods</i> .....	27
5.4. <i>Genetic Algorithm</i> .....	28
CHAPTER 6: RESULTS AND DISCUSSION.....	33
6.1. <i>Layout Optimization with Fixed Number of Turbines</i> .....	34
6.2. <i>Layout Optimization with the Optimal Number of Turbines</i> .....	37
CHAPTER 7: CONCLUSION.....	40
REFERENCES.....	42
APPENDICES .....	49
<i>Appendix A</i> .....	49

## LIST OF TABLES

Table 1. Wind Turbine Properties .....	24
Table 2. Parameters of the Genetic Algorithm From the Previous Studies and Present Study .....	32
Table 3. Parameters Used in the Present Study.....	33
Table 4. Results From Previous Studies and Present Study with Fixed Number of Turbines.....	35
Table 5. Results From Previous Studies and Present Study with Optimized Number of Turbines.....	39



## LIST OF FIGURES

Figure 1. Typical Vertical Profiles of Surface Layer Wind Speed for Different Static Stabilities ( $V_{bl}$ : Mixed Layer Wind Speed).....	7
Figure 2. A Sample of a Wind Rose .....	9
Figure 3. A Sample of a Weibull Distribution ( $k=2,1$ ; $c=8,5$ ).....	10
Figure 4. Typical Power Curve of a Wind Turbine .....	12
Figure 5. Demonstration of Jensen's Wake Model .....	14
Figure 6. The Wind Farm Project Timeline .....	16
Figure 7. Typical Cost Breakdown for an Onshore Wind Farm .....	21
Figure 8. Size of the Wind Farm in the Present Study and Angular Demonstration of Wind Direction.....	23
Figure 9. Wind Distribution of Case 2.....	25
Figure 10. Demonstration of Layout Design Methods. a) Coordinate Method b) Grid Method .....	27
Figure 11. Flowchart of a Genetic Algorithm.....	29
Figure 12. Crossover Operation in the Present Study .....	31
Figure 13. Mutation Operation in the Present Study.....	31
Figure 14. a) Optimal Layout for Case 2 from Mosetti, Poloni and Diviacco (1994) b) Optimal Layout for Case 2 from Grady, Hussaini and Abdullah (2005) .....	36
Figure 15. Optimal Layout Reported by Present Study .....	36
Figure 16. Cost Per Unit Power Values for Each Genetic Algorithm Operator Combination ( $\times 10^{-3}$ 1/kW).....	37
Figure 17. Objective Function Value for Different Number of Turbines .....	39
Figure 18. Final Layout for 40 Wind Turbines .....	39

# NOMENCLATURE

## Acronyms

WFLO	Wind Farm Layout Optimization
WT	Wind Turbine
QIP	Quadratic Integer Programming
CP	Constraint Programming
MILP	Mixed Integer Programming
WWEA	World Wind Energy Association
PDF	Probability Density Function
CDF	Cumulative Distribution Function
EAA	National Environmental Affairs Agencies
EIA	Environmental Impact Assessment
NIA	Noise Impact Assessment
PPA	Power Purchase Agreement

## Symbols

$P$	Power Output
$p_d$	Probability of Wind State $d$
$v_{id}$	Velocity of Wind Turbine $i$ at Wind State $d$
$\rho$	Air Density
$C_p$	Betz Coefficient
$A$	Swept Area
$r$	Rotor Radius
$r_1$	Wake Radius

$r_d$	Downstream Rotor Radius
$N_t$	Number of Wind Turbines
$v$	Incoming Wind Velocity
$v_0$	Free Stream Wind Velocity
$vd$	Velocity Deficit
$vd_i$	Velocity Deficit for Wind Turbine $i$ Affected by Multiple Wakes
$v_i$	Final Incoming Wind Speed for Wind Turbine $i$ Affected by Multiple Wakes
$z_0$	Surface Roughness
$\alpha$	Entrainment Constant
$a$	Axial Induction Factor
$C_t$	Thrust Coefficient
$z$	Hub Height of Wind Turbine
$x$	Distance Between Two Wind Turbines
$v_z$	Horizontal Wind Velocity at Height $z$
$v^*$	Friction Velocity
$K$	Von Karman Constant
$d$	Zero-Plane Displacement
$L$	Monin Obukhov Length
$\varphi$	Stability
$k$	Shape Parameter
$c$	Scale Parameter
$\bar{v}$	Mean Value of Wind Speed
$\sigma$	Standard Deviation of Wind Speed
$m$	Mass

$m_{air}$	Air Mass
$E_{kinetic}$	Kinetic Energy
$V_c$	Cut in Speed of Wind Turbines
$V_r$	Rated Wind Speed
$V_f$	Cut Out Wind Speed
$P_{rated}$	Rated Power Output
$P_{asc}$	Turbine Power Output as The Percentage of $P_{rated}$
$P_{tot}$	Projected Total Power Output of Wind Farm



## CHAPTER 1: INTRODUCTION

Energy consumption in households and industrial areas has significantly accelerated due to industrialization and higher penetration rates of developing technologies (automation, robotics, etc.) in recent years. These higher energy consumption trends lead to enormous affects over the environment, health, and socioeconomic status of societies. Therefore, many governments and industries investigate and convert their conventional energy production resources into more sustainable and emission-free systems. In this conversion phase, wind energy is one of the popular renewable energy solutions for governments. Jacobson (2009) conducts a comparative analysis of wind energy and other renewable energy sources and reported that wind energy performs best in terms of air pollution, energy security, and global warming-related emissions (Jacobson, 2009).

World Wind Energy Association (WWEA) statistics in 2019 shows that the total capacity of all wind turbines installed worldwide by the end of 2019 was 650,8 gigawatt, which can supply more than 6% of global energy consumption (WWEA, 2020). Therefore, any partial improvement in the usage and design of the wind farms is expected to save significant gains over environmental and financial aspects.

Wind turbine is a device that converts the energy in the wind flow into electricity. This is accomplished by using blades attached to a hub that spins in reaction to the wind's aerodynamic force. This rotation drives a generator, which generates electricity that is fed into the electrical power grid. A wind farm is formed when numerous wind turbines are clustered together in a limited region. The fixed expenses (management costs, electrical network related costs, and project development costs) of a wind farm project are spread over a larger investment, making wind energy more attractive and competitive (Burton et al., 2001).

Before constructing a new wind farm, decision-makers gather many different parameters and conduct assessments (such as wind resource assessments, alternative technical spectrums of wind turbines, meteorologic datasets, geographic information, noise assessment of a site, etc.) in order to create pre-implementation scenarios for expected cases in terms of potential costs, energy production, and efficiencies. All these researches and analyzes shape the wind farm design process. While designing a wind farm, the main goal is to optimize power production while lowering total costs,

and the process of optimizing the design of a wind farm is called micro-siting. This process is facilitated using many commercially accessible wind farm design tools (Mittal, 2010).

Energy production can be considered as an only source of revenue for wind farms, so maximizing the extracted energy from the wind farm is crucial for the overall profitability of the project. One of the ways to achieve this improvement is to reduce the wake effects formed between the turbines to be placed in the wind farm. A wind turbine in front facing the incoming free stream wind speed obtains a certain amount of energy from the wind it encounters and hence reduces the wind speed that will be reaching the turbines behind it. Therefore, there will be a decrease in the energy produced by the downwind turbine. This influence is called wake effect and wind farm layout design should be done by considering this effect.

The main contribution of this study is

- to investigate the advantages of genetic algorithm in positioning of the wind turbines in specified area with the use of coordinate method and the impact of different layout method applications on the wind farm layout optimization (WFLO) problem
- to assess the advantages of using the coordinate method as a layout design method over the grid method, which is mostly used in the literature
- to optimize a wind farm layout in order to reduce the wake effects between turbines with the minimum investment cost for a given wind distribution by using an analytical wake model.

The rest of this work is organized as follows: In Chapter 2, studies tackle the WFLO problem with different methods in the literature and their results are reviewed. Chapter 3 introduces the wind energy and its theoretical background. In Chapter 4, the process, requirements, and constraints of a typical wind farm project are explained. Chapter 5 describes the problem addressed, and the assumptions made for the problem. Chapter 6 includes the results of the computations, comparisons with two other benchmark studies, and the discussion. Lastly, in Chapter 7 we present the conclusion and share suggestions for future works.

## CHAPTER 2: LITERATURE RESEARCH

The wind farm layout optimization problem is a complex problem that has been tackled for years mainly by using heuristic methods such as genetic algorithm, greedy algorithm, particle swarm algorithm. The nonlinearity of the wake model is the main reason behind the choice of heuristic methods by most studies in the literature for the problem (Samorani, 2010). Although not as many as heuristic methods, deterministic methods such as mixed integer linear programming (MILP), quadratic integer programming (QIP) or constraint programming (CP) have also been used by the motivation of obtaining the global optimum.

One of the most known studies in the field is presented by Mosetti, Poloni, and Diviacco (1994). In the study, genetic algorithm is used, and they consider a single type of turbine on a square grid of 2.000 x 2.000 meter that is divided into 100 equal square cells, each with a possible turbine location. Different direction and intensity scenarios are considered, and they aim to optimize the extracted power production with the minimum investment cost and number of turbines by obtaining optimal positioning for turbines. They use the wake model proposed by Jensen, Hojstrup, and Katic (1986). Non-optimized results are compared to the optimized ones. In the wind scenario where a single wind speed and wind direction are considered, the efficiency is found to be better than the random configuration with fewer turbines. In the case of multiple wind direction and intensity, efficiency of wind farm goes from 0,34 to 0,84, while random layout design has 42 turbines whereas optimized design has 15 turbines installed. For this scenario, the energy produced is decreased yet the installation cost is reduced by 50%. Grady, Hussaini, and Abdullah (2005) also used genetic algorithm to find an optimal positioning for wind turbines. They consider three different cases as in the study of Mosetti, Poloni, and Diviacco (1994) which are uniform direction and intensity, uniform wind and variable direction and non-uniform wind and variable direction. They compare their results with the study of Mosetti, Poloni, and Diviacco (1994). They state that the reason behind that the results are different from each other is that Mosetti, Poloni, and Diviacco (1994) did not run their algorithm with enough individuals and generations, along with the differences in coding.

The method of dividing a defined area into equal-sized square cells and placing the turbines in the centers of these cells is called the grid method while placing the turbines by assigning coordinates to them anywhere in the defined area is called the coordinate

method. Despite the fact that the coordinate method can theoretically achieve better results by providing a more flexible approach to positioning wind turbines than the grid method (Wang, 2019), most studies in the literature have employed the grid method, including such Mosetti, Poloni, and Diviacco (1994) and Grady, Hussaini, and Abdullah (2005). Mittal, and Taylor (2012) use a genetic algorithm for the WFLO problem as their objective is the cost per unit power and they compare their results with Mosetti, Poloni, and Diviacco (1994) and Grady, Hussaini, and Abdullah (2005) since the three cases they used are the same. In the study, they use densified grid spacing by reducing the grid spacing to 1/40 wind turbine rotor diameter to make room for more turbines, while referred studies set the grid spacing as 5 rotor diameters. By using the refined spacing method, they manage to improve the objective function for all three cases they used compared to the other two studies. Kusiak, and Song (2010) use a continuous-location model to tackle the problem, allowing turbines to be located anywhere inside the wind farm. The only limitations are the minimum turbine proximity and a defined wind farm boundary, which are then translated into a second objective function. The transformed bi-criteria optimization problem is solved using a multi-objective evolutionary strategy algorithm that optimizes expected energy output while minimizing constraint violations. Beyer et al. (1996) tackle the WFLO problem for three different types of wind farms using the coordinate method as representation of the wind turbine positions. They find significant improvements on the power output and economic return. Feng, and Shen (2015b) also apply the coordinate method using the random search algorithm for the WFLO problem. They aim to reach a better point than the results that can be reached through the genetic algorithm by first applying the improved random search algorithm on three test cases that Mosetti, Poloni, and Diviacco (1994) used in his study. Then it is applied to a real case scenario, and they deduced that the optimized layouts obtain better results in power production than its original layout, both for the real and test cases. Wang, Tan, and Gu (2015) conduct a comparative analysis of the grid and the coordinate methods, finding that the coordinate method can achieve better results by allowing more flexibility as in the placement of wind turbines.

Deterministic methods are less applied in the literature. Perez, Minguéz, and Guanche (2013) use mathematical programming technique in their study while employing the coordinate method on an offshore wind farm. Zhang et al. (2014)

present a novel mixed integer programming-based decomposed model and a CP model to handle the nonlinearity of the wake model. They aim to maximize the expected power production and results show that the CP model shows worse results than the novel mixed integer programming-based model. Turner et al. (2014) prefer to use mathematical programming to guarantee the optimum results. Since they consider all wake interaction between the turbines, the initial objective function, maximizing power generation while minimizing kinetic energy deficit, is nonlinear. In some other studies, the wake models are basically based on single turbine wakes or linear superposition technique is used for the cases with multiple wake effects. They develop two different approaches to handle the nonlinearity of the model: Mixed integer and quadratic integer programming. With these approximations, they get better results handling the same cases used in the Mosetti, Poloni, and Diviacco (1994) and Grady, Hussaini, and Abdullah (2005) studies. Apart from the heuristic and deterministic methods, there are only few studies on this specific problem where data-driven and robust methods are preferred. Fischetti, and Fraccaro (2019) solve this optimization problem on nearly 3.000 farm layout instances by using a mixed integer programming method and used the obtained optimized or near-optimum results as input to machine learning methods they used. Thus, it would not be necessary to re-run the computational expensive optimization method for hours for possible new farm cases determined at the wind farm selection phase, and they would instantly obtain an optimized result proper for the new case. They compare several machine learning methods in terms of accuracy and time, and the support vector machine method is found to be the most promising.

## CHAPTER 3: THEORETICAL BACKGROUND

To address the wind farm layout problem with the right scope, we first need to understand the energy source wind, and how energy is extracted from this source.

### *3.1. Wind Resource*

Wind speed varies with height, and this variation of wind speed is defined as wind shear. There are several reasons to explain this variation. One of them is topography. Different landforms will result in different wind flows and these landforms can be characterized by surface roughness. This concept is called topography. Surface roughness describes the impact of surface vegetation on vertical velocity gradients in the lower part of the atmosphere. Air slows down as it enters the surface of the objects such as trees, buildings, rocks, etc. Since the impact of these impediments lowers as one rises in altitude, the wind speed naturally increases.

Another reason for the wind speed varying with height, is due to air density. Since there is less space between air molecules at the surface, the density of the air is highest at the surface. Thus, it decreases as you go higher. That is, a force applied to the air at a higher point will move the air more easily than a force of the same amount applied to the air at a lower point. As the air density decreases as we go up, it is easier to move the less dense air at a high speed (Danish Wind Industry Association, 2003).

The third reason is that the wind speed has a parallel relationship with the pressure gradient force. Warm air is less dense than dry air and different warmings and different amounts of water vapor in the atmosphere create regions of high and low pressure. This pressure difference causes air to move from areas of high pressure to areas of low pressure across the ground. These air currents are actually winds. The force that drives these currents is due to the pressure difference between the two regions. This is called the pressure gradient force.

Warmer air has a higher troposphere height since it is less dense and hence fills a larger volume, and the pressure difference between warm and cold air grows as altitude increases. The speed with which the wind goes from higher to lower pressure is determined by the strength of the pressure gradient. A stronger pressure gradient will cause stronger winds (Staroscik, 2018).

Wind energy engineers model the variation in wind with the logarithmic law, as shown in Equation (1) (Thuillier, and Lappe, 1964; Oke, 1987).

$$v_z = \frac{v_*}{K} \left[ \ln \left( \frac{z-d}{z_0} \right) + \varphi(z, z_0, L) \right] \quad (1)$$

where  $v_z$  is the horizontal wind velocity at height  $z$  (m) above the ground,  $v_*$  is the friction velocity (m/s),  $K$  is the Von Karman constant ( $\sim 0.4$ ),  $d$  is the zero-plane displacement (m) which explains the elevation in meters above the ground at which zero wind speed is achieved,  $z_0$  is the surface roughness (m),  $\varphi$  is a stability term where  $L$  is the Monin-Obukhov length. Under neutral stability conditions,  $z/L$  is equal to zero and  $\varphi$  drops out. Thus, Equation (1) can be simplified to,

$$v_z = \frac{v_*}{K} \left[ \ln \left( \frac{z-d}{z_0} \right) \right] \quad (2)$$

Atmospheric conditions that are stable, neutral, or unstable can be found in any location and have an impact on the wind profile at that location. Figure 1 depicts the relationship of these three atmospheric profiles to the height and wind speed (Wallace, and Hobbs, 2006).

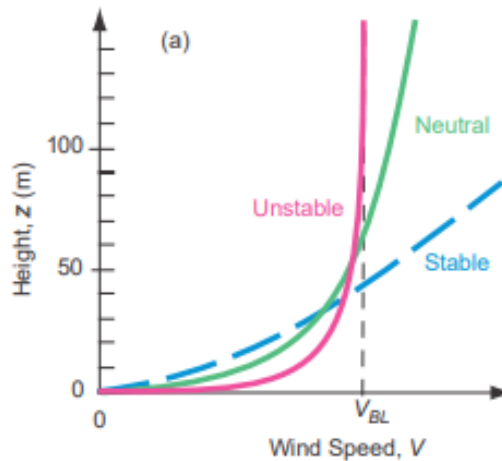


Figure 1. Typical Vertical Profiles of Surface Layer Wind Speed for Different Static Stabilities ( $V_{BL}$ : Mixed Layer Wind Speed) (Source: Wallace, and Hobbs, 2006, p. 394)

### 3.2. Wind Condition Modelling

Wind scenario generally means a model that includes changes in wind speed and wind direction. For the WFLO problem, the simplistic wind scenario has been widely used in the literature. It is primarily utilized for evaluating the efficiency of newly proposed approaches and techniques, and it often includes discrete wind speed/direction descriptions.

Weibull distribution has been used in many studies since it is considered a good representation for real case wind conditions which are continuous and random wind speed/direction variations (Manwell, McGowan, and Rogers, 2002). The Weibull distribution reflecting the probabilities of different wind speeds in a given direction can be built using a few steps. First, wind directions are divided into sectors, then the frequency of occurrence of the wind speed, the two Weibull parameters, scale and shape parameters are assigned for each direction sector.

Wind velocities recorded at a site are first disaggregated into directional sectors and then into wind speed bins (Donovan, 2008). Wind speed frequency distributions for each direction are produced by this process of dividing data by sector and after that, by wind speed. Equations (3) and (4), shows the calculations for the Weibull Probability Density Function (PDF) and its associated cumulative distribution function (CDF) respectively.

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (3)$$

$$F(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (4)$$

where  $f(v)$  is the probability density function of wind speed  $v$  and, the scale parameter is  $c$  and  $k$  is the shape parameter. The Weibull shape parameter is generally around the value of 2 in Northern Europe, however a wind atlas is needed to set this more accurately since conditions vary. The shape and scale factors can be found with the mean  $\bar{v}$  and standard deviation  $\sigma$  values of wind speed (Manwell, McGowan, and Rogers, 2009; Feng, and Shen, 2015a):

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1,086} \quad (5)$$

$$c = \frac{\bar{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (6)$$

$$\Gamma(x) = \int_0^{\infty} e^{-t} t^{x-1} dt \quad (7)$$

where  $\Gamma(x)$  is the gamma function.

A wind rose is a demonstration of distribution of wind direction and wind speed over a period of time at a given location. By creating 8 direction sectors in 45-degree angles (generally at least 12 sectors), we can obtain a wind rose similar to Figure 2 for any wind data for a certain period length. For each of the 8 direction sectors, the calculations can be used to obtain 8 segmented Weibull distribution with the frequency of occurrence, shape, and scale factors. It should be noted that Figure 2 and Figure 3 have different wind speed data and both demonstrations are presented as an example.

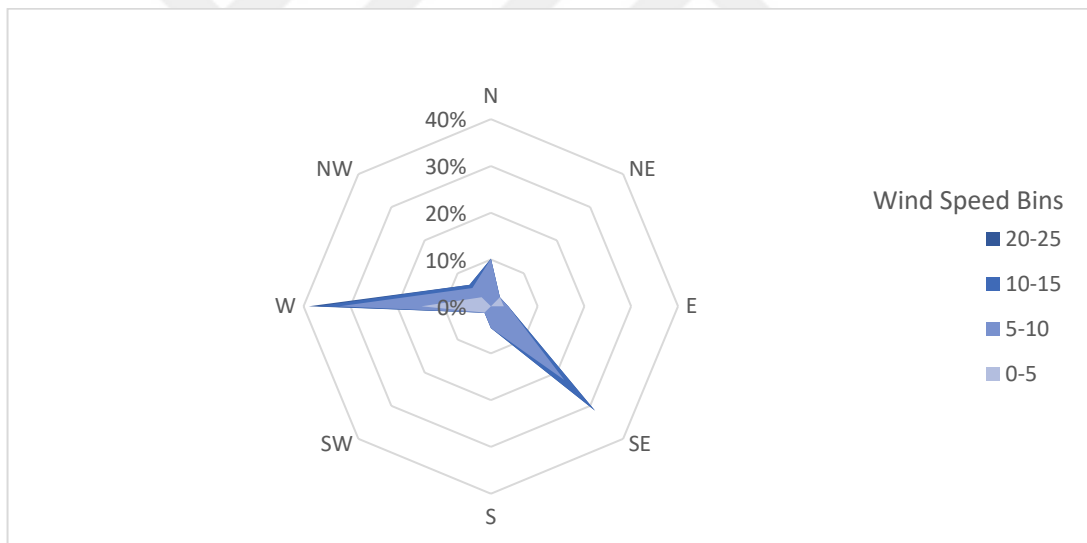


Figure 2. A Sample of a Wind Rose

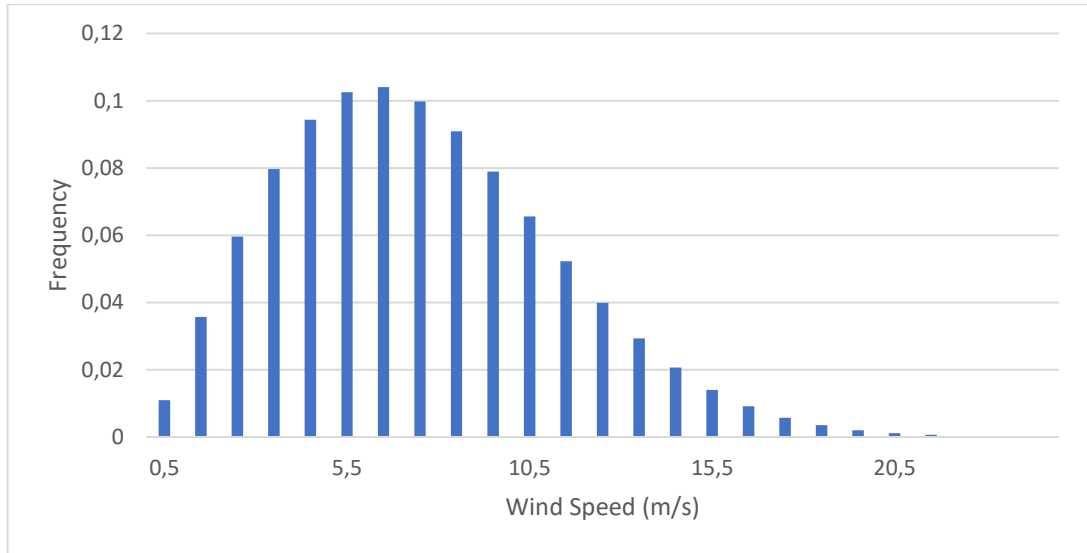


Figure 3. A Sample of a Weibull Distribution ( $k=2,1$ ;  $c=8,5$ )

The Weibull distribution may not be always suitable for short-time wind data measurements or for representative scenarios (Kusiak, and Song, 2010). In our proposed algorithm, a simplified wind scenario is used where a single wind speed value of 12 m/s is considered for all 36 wind direction sectors to calculate the wind energy output of the wind farm. The motivation behind choosing a simplified wind scenario is that we are aiming to investigate the efficiency of our method using the same wind condition test cases used by Mosetti, Poloni, and Diviacco (1994) and Grady, Hussaini, and Abdullah (2005) in their work.

### 3.3. Power Extraction

The wind flow is the movement of the wind, and this movement actually means the kinetic energy of the wind. In the following, how the power calculation is derived from the kinetic energy formula is explained.

$$E_{kinetic} = \frac{1}{2}mv^2 \quad (8)$$

An object's kinetic energy is proportional to its mass  $m$  and the square of its velocity  $v$ . In the case of wind, the mass of air that is passing through the wind turbine with rotor area  $A$ . The mass of air is calculated in Equation (9) where the wind velocity is  $v$ , the time is  $t$ , and the air density is  $\rho$  (Kalmikov, 2017).

$$m_{air} = Avt\rho \quad (9)$$

Adapting Equation (9) to Equation (8) and taking the derivative with respect to time, it will give us the total wind power equation (Kalmikov, 2017):

$$P = \frac{dE}{dt} = \frac{1}{2} \rho A v^3 \quad (10)$$

The efficiency of the power to be obtained from wind energy depends on the turbine characteristics as well as the wind conditions. This argument brings us to Betz Law. In 1919, German physicist Albert Betz investigated the relationship between a wind turbine's input and output wind velocity. He discovered that 59,3 percent of the kinetic energy in the wind inflow is the theoretical limit for wind energy extraction for any particular wind turbine (Gatscha, 2016). This suggests that a turbine's maximum efficiency is 59,3 %. Modern wind turbines can only attain 75 to 80 percent of the Betz limit. When we add the Betz coefficient to the power formula above, we get the following equation:

$$P = \frac{1}{2} C_p \rho A v^3 \quad (10.1)$$

Power generation from the wind source will vary with turbine characteristics; but the basic structure for the power to be produced via the wind turbine is the same. As shown in Figure 4, typical turbine has a cut-in speed, a rated speed, and a cut-out speed. The cut-in speed represents the wind speed value for a turbine to start generating power. The power to be obtained between the cut-in speed and the rated wind speed is approximately calculated by Equation (10.1). The rated wind speed, which is normally around 12 m/s, is the point at which the electrical generator reaches full capacity and produces the most electricity. When the wind speed exceeds the cut-out speed, which is typically 25 m/s for a wind turbine, the power generation is shut down to avoid damage to the turbines (Fjellanger, 2016).

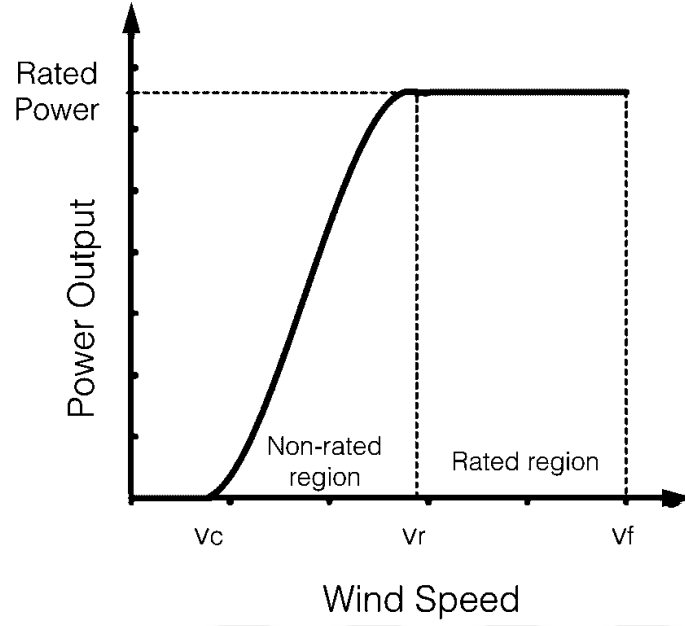


Figure 4. Typical Power Curve of a Wind Turbine (Source: Dupont, Koppelaar, and Jeanmart, 2018)

The power curve of a wind turbine indicates the wind conditions required to maintain a satisfactory power output. It also demonstrates that variations between the cut-in ( $V_c$ ) and rated wind speed affect turbine performance, however when the wind speed starts to exceed the nominal/rated speed of the turbine ( $V_r$ ), as the wind speed increases, the power output remains constant in response to the power control mechanisms until the cut-out speed is reached ( $V_f$ ) (Albadi, and El-Saadany, 2010). Therefore, Equation (10.1) can be written as follows:

$$P = P_{rated} \times \begin{cases} 0 & v < V_c \text{ or } v > V_f \\ P_{asc} & V_c \leq v \leq V_r \\ 1 & V_r \leq v \leq V_f \end{cases} \quad (11)$$

$P_{rated}$  is the rated output power of the wind turbine,  $P_{asc}$  is the turbine output as the percentage of  $P_{rated}$ . Under the Weibull distribution wind condition, the projected total produced power  $P_{tot}$  can be expressed by,

$$P_{tot} = \sum_{d=1}^M \left[ p_d \int_0^{\infty} P_{farm_d}(v_d) f_d(v) dv \right] \quad (12)$$

$$= \sum_{d=1}^M \left[ p_d \int_0^{\infty} \left( \sum_{i=1}^{N_t} P(v_{id}) \right) f_d(v) dv \right] \quad (12.1)$$

In above equations,  $M$  is the number of wind direction bins,  $p_d$  is the probability of each wind direction, and  $P_{farm_d}(v_d)$  is the extracted power of the wind farm for the speed value  $v_d$  in the  $d^{th}$  wind direction. Number of turbines is indicated by  $N_T$ , the incoming speed of turbine " $i$ " in the wind direction " $d$ " is  $v_{id}$ , and  $P(v_{id})$  is the power output for  $v_{id}$  through the power curve.  $f_d(v)$  is the probability density function (PDF) of the wind speed in the direction  $d$ , which can be calculated by Equation (3).

### **3.4. Jensen's Wake Model**

Wind turbines cause turbulence in the wind and reduce downstream wind speeds. The turbine wake is the term for this area of reduced wind speed downstream. Wind turbine wake behavior is a significant input into layout design because of its impact on downstream wind speeds (and thus energy).

Analytical wake models and computational wake models are the two main types of wake models. Analytical wake models, such as those developed by Jensen (1983), Larsen (1988), and Frandsen et al. (2006), use momentum mixing rate simplifications to quickly assess wake losses while discarding complex flow phenomena found in wind farms, whereas in computational wake models capturing detailed wake interactions, the wake velocity field is obtained by solving fluid flow equations such as Reynolds-averaged Navier-Stokes models, large eddy simulations, and vortex-wake models (Sanderson, Pijl, and Koren, 2011; Mehta et al., 2014; Antonini et al., 2015; Antonini, Romero, and Amon, 2018a; Antonini, Romero, and Amon, 2018b).

One of the most widely used analytical wake model is developed by Jensen, Katic, and Hojstrup (1986). The model's fundamental idea is based on the following two assumptions. First, the wake has a conical shape with an initial diameter equal to the rotor's diameter. With increasing downstream distance from the rotor, the diameter and hence the width of the wake grows linearly. Second, the wind speed is constant over the wake's cross-section. Due to conservation of mass, the wind speed increases with downstream distance.

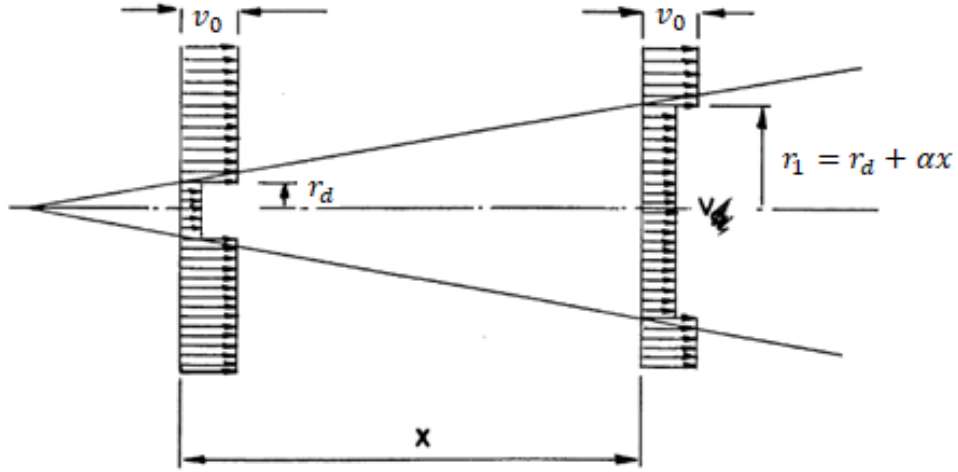


Figure 5. Demonstration of Jensen's Wake Model (Source: Jensen, 1983)

The radius of the wake  $r_1$  at a certain distance  $x$  is calculated with the following equation, where  $r_d$  is the downstream rotor radius,  $\alpha$  is the entrainment constant (Jensen, 1983) which indicates how fast or slow wake expands.

$$r_1 = r_d + \alpha x \quad (13)$$

The velocity deficit  $vd$  in the wake of a wind turbine can be given as the fractional reduction of free-stream wind velocity and the incoming wind speed  $v$  of the objective wind turbine is calculated by:

$$v = v_0(1 - vd) \quad (14)$$

Velocity deficit due to the wake effect of a single wind turbine at a distance  $x$  is calculated by,

$$vd = 2a \left( \frac{r_d}{r_d + \alpha x} \right)^2 \quad (15)$$

where  $a$  is the axial induction factor which defines the induction percent of wind speed reduction, and it can be calculated from the thrust coefficient,  $C_T$ , of the wind turbine.

$$C_T = 4a(1 - a) \quad (16)$$

$\alpha$  is the entrainment constant and can be calculated using following expression,

$$\alpha = \frac{0,5}{\log(z/z_0)} \quad (17)$$

Here,  $z_0$  is the surface roughness of the site, and  $z$  is the hub height of the wind turbine. As mentioned in Section 3.1, surface roughness describes the impact of surface vegetation on wind speed and changes according to the terrain features.

As the wind reaches the wind turbine blades, the width of the turbine blades makes the wake radius expands. Therefore, the wake radius just behind the turbine is called the downstream rotor radius of the wind turbine,  $r_d$ , and is computed using following formula, where  $r$  is the rotor radius of the wind turbine.

$$r_d = r \sqrt{\frac{1-a}{1-2a}} \quad (18)$$

Jensen's (1983) model is extended for cases with a wind turbine exposed to multiple wake effects from several upstream wind turbines (Jensen, Katic, and Hojstrup, 1986). The resultant kinetic energy deficit for a wind turbine in multiple wakes is equal to the sum of the square of the kinetic energy deficits which are caused by all other upstream wind turbines. Equation (19) expresses the velocity deficit for a wind turbine  $i$  that is affected by multiple wakes of up to  $N_T$  wind turbines.

$$vd_i = \sqrt{\sum_j^{N_T} \left( 2a \left( \frac{r_d}{r_d + \alpha x_{ij}} \right)^2 \right)^2} \quad (19)$$

The eventual incoming wind speed of the wind turbine affected by multiple wakes is computed by:

$$v_i = v_0(1 - vd_i) \quad (20)$$

## CHAPTER 4: WIND FARM PROJECTS OVERVIEW

The wind farm project timeline in Figure 6, shows that there are several factors to be considered before the construction of a wind farm. These factors form the development phase of the timeline.

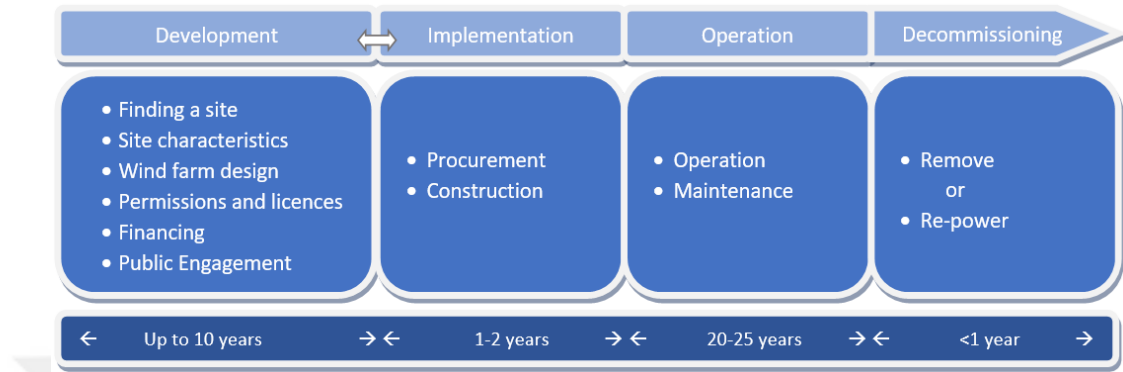


Figure 6. The Wind Farm Project Timeline (Source: Free Online Coursera Courses, Technical University of Denmark, 2016)

### 4.1. Finding the Right Site and Site Characteristics

One needs to take a close look at the characteristics of the site to make sure that it is suitable for the project. Although it varies by offshore and onshore areas, these characteristics include finding an accessible area with a consistent and good average wind speed. In detail, the decision of selecting the right site is commonly based on the following general factors: (1) the existing infrastructure (2) the environmental impact (e.g., considering the natural habitats of plant species or animals); and (3) the wind potential assessment (Herbert-Acero et al., 2014)

The first consideration is that there should be sufficient infrastructure in terms of electrical, telecommunication and civil engineering, so that the project does not end up having high additional costs by constructing auxiliary infrastructure (Morthorst, and Jacobsen, 2004; Morthorst et al., 2009; Gelman, 2012).

The wind farm's size and location are another decision-making point of the site selection phase. These characteristics of the site should be convenient for accessing suitable electrical connecting points, which must be able to manage the electricity delivered by the wind farm.

Another key part of accessibility is the installation of low-grade roadways to transport wind farm components and large construction trucks. The available civil

engineering infrastructure should enable route access to the wind farm location (i.e., via roads, bridges, tunnels, railways, and so on). Airports and/or seaports are also advantageous for improving logistical operations during the construction phase. Civil engineering and telecommunication infrastructures are rarely found in the potential areas where wind farm can be established, so the wind farm designer has to deal with additional costs by building auxiliary infrastructures that are dependent on the local terrain structures, wind farm layout, and restricted areas (Morthorst, and Jacobsen, 2004; Morthorst et al., 2009; Gelman, 2012). Restrictions regarding minimum distance from, for example, residential areas, existing roads should be considered.

Considering the second factor, environmental impact, the World Health Organization acknowledges wind energy as the power conversion technology with the least impact on individuals and the environment (WHO, 2004; Colby et al., 2009; Mann, and Teilmann, 2013). Nevertheless, taking precautions during the design phase will create positive progress. Environmental effects can be explained as all of the possible effects that the wind farm will have on the surrounding environment during construction and operation. Current guidelines of the National Environmental Affairs Agencies (EAA) should be followed when conducting Environmental Impact Assessments (EIA), and these assessments often include analysis of effects on water, air, and soil. Furthermore, EIAs must investigate the implications of potential pollutant emissions and their spatial and temporal distributions, noise outputs, visual impact, and the effects on animals and biodiversity. Additionally, wind farms can cause short- and long-term loss and degradation of bird and marine life (for offshore wind farm cases) habitats on local wildlife (Longridge, 1986; Hunt, 1999; Burton et al., 2001; Petersen et al., 2006; Herbert-Acero et al., 2014).

Wind farms have a low visual impact when compared to other electricity-generating technologies. Visual effects can be determined by the observer's proximity to the turbines, the extent and view orientation of the turbines, the local topography, the surrounding structures, and the local vegetation. Therefore, these effects are site specific effects. Global public surveys show high support for locating wind turbines near metropolitan areas (Vestas, 2012). However, depending on the wind farm site and the proximity of wind turbines to residential areas, arguments against wind farms may occur.

The entire noise created by a wind turbine (WT) can be explained as in two categories: (1) mechanical noise and (2) aerodynamic noise. The whirling mechanism of the WT causes the mechanical noise (e.g., generator, gear box) (Pinder, 1992; Burton et al., 2001). The aerodynamic noise is caused by WT rotors' inefficiency in transferring kinetic energy from the wind to mechanical energy (ETSU-R-97, 1996; Burton et al., 2001). As a result, some of the kinetic energy is converted into noise and heat, with the former dominating. To reduce noise nuisance, sufficient distances between WTs and sensitive receptors should be maintained and Noise Impact Assessment (NIA) studies should be conducted throughout wind farm layout design process (OSHA, 1991; Van den Berg et al., 2008; Colby et al., 2009).

The third factor, wind resource assessment can be conducted according to atmospheric variables that show temporal and spatial variability (Bailey et al., 1997; Probst, and Cardenas, 2010; Brower, 2012; Belu, and Koracin, 2013). Examples include wind speeds (m/s) and wind directions ( $^{\circ}$ ) at various heights, solar radiation ( $W/m^2$ ), temperatures ( $^{\circ}C$ ) at various heights, relative humidity (percent), and pressure (Pa). Due to the random character of atmospheric variables, extra analyses are performed to predict the potential of the wind farm site such as computing their probability density functions.

Meteorologists assess the quality of available wind data and optimize the location of existing and future met towers based on topography, initial wind characteristics, and anticipated turbine designs. The modeling of the wind data will help modify the placement and operation of the wind turbines for optimal output given the climatic circumstances of the site over the following one to two years. Because the specific location of the wind turbines is established by wind resource modeling, the precise location of the wind turbines won't be known until the final months of development, when decisions about the best turbine will be made (Martin, 2009).

#### ***4.2. Wind Farm Design***

Several aspects of the wind farm project can be included in the designing such as positioning and configuration of wind turbines (specified by positions in spatial coordinates (x, y, z), with resolutions down to 1 m), electrical interconnections of turbines and the supplementary infrastructures within the constrained land area.

The ideal design for a wind farm is achieved as a result of optimization by including all economic, structural, environmental, social, and technological constraints. Assuming that the standards for all factors such as energy and environment are met, in order to calculate the estimated economic profit of the project, economic simulations are carried out during the design phase of the wind farm layout with all available incentives considered. After determining the economic feasibility of the preliminary project, the landowners are contacted to get involved in the project and they can earn money by renting their land, as well as a certain percentage of the project's gross profit. Redesign of a wind farm may be required, depending on the landowner's cooperation (Martin, 2009). The legal, licensing, and planning application processes are not simple and might take a long time to complete. Furthermore, best practices for community participation and public consultation in the wind energy industry encourage wind farm builders to create community outreach initiatives. In this respect, a large sum of money is spent on wind farm design even though there is no certainty that the project will be realized.

#### ***4.3. Permissions and Licenses***

Various approvals are necessary for project development in the wind energy industry. The procedure of acquiring licenses frequently takes a large amount of time because it requires contacting several (and numerous) competent authorities.

Permits are necessary, among other things, based on the capacity of the windmill and can be obtained from a variety of sources, including local, federal, and national governments. Furthermore, energy restrictions differ depending on which country the project would be conducted in. The wind farm designer should understand the laws controlling the generation, transmission, transformation, and sale of power, as this will determine the project's potential profitability. As a result, the wind farm designer must adhere to local, and national development plans, as well as the electricity market.

In general, permits might be (Energypedia, 2015):

- permit for site visits and measurements
- planning permit
- permit for land use
- permit for installation

- environmental impact assessment (EIA)
- interconnection agreements

#### ***4.4. Financing***

Wind turbines characteristics, grid-connection, construction of the roads, legal and tax advice, planning and monitoring of the construction process, cost of planning, environmental studies and project approval are all factors that must be considered while evaluating the proposed layout (Energypedia, 2014).

The wind farm developer must be able to receive funds from banks or other financial institutions once the design and organization are complete. The funding will be accepted or rejected based on the findings of the wind resource assessment, feasibility studies, construction agreements, electrical interconnection, and Power Purchase Agreements (PPAs) for the energy to be converted and supplied (Burton et al., 2001). Thus, the project revenue uncertainty, is one of the most crucial aspects in selecting a successful financing.

The cost of building a wind farm varies based on the quantity of labor and materials required for foundations, roads, and cables linking the wind turbines, transformer station, and the external electricity grid. In contrast to the aforementioned components of maximizing production, the problem also comprises cost minimization. Roads and cables are relatively inexpensive in comparison to wind turbines, and it is common for these costs to be overlooked until after the wind turbine locations have been selected. Typical cost breakdown for an onshore wind farm is shown in Figure 7.

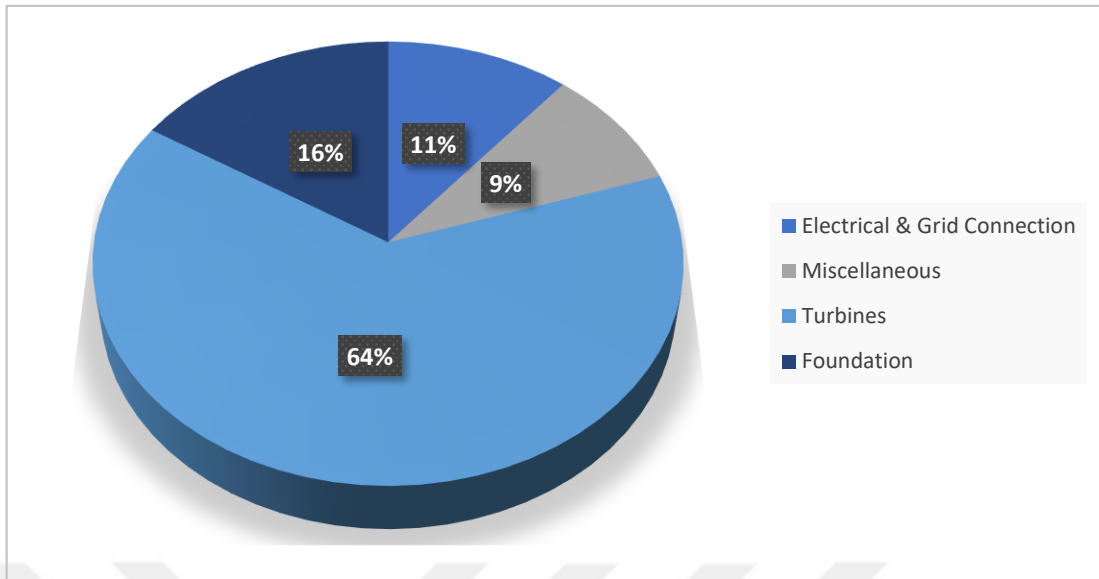


Figure 7. Typical Cost Breakdown for An Onshore Wind Farm  
(Source: Yang et al., 2015)

The development and implementation phases are an iterative process that continues until the final design is achieved. It entails stages of layout design for optimum energy efficiency, tests for environmental compliance, and readjustment of the plan based on infrastructure issues, which could result in poor solutions (Romero et al., 2014). Any assumptions and/or limits placed on the decision variables will aid the optimization process, but also narrow the design space for the best solution, potentially resulting in significant opportunity costs. However, most of the studies in the literature make certain assumptions due to the random nature of the factors described earlier.

## **CHAPTER 5: WIND FARM LAYOUT OPTIMIZATION**

The wind farm layout optimization problem mainly focuses on maximizing power output by optimally placing wind turbines in the specific area where the farm is decided to be established. Some of the variables and parameter values in the problem change due to the requirements of the project or the research outline.

### ***5.1. Problem Description***

Mosetti, Poloni, and Diviacco (1994) and Grady, Hussaini, and Abdullah (2005) are the first ones to address the problem of wind farm layout optimization. In their work, they aim to minimize the cost per unit power by optimally placing a certain number of turbines in a defined area using a genetic algorithm. The power calculation is a simplified power model that is often used in the literature. They use the grid method for the placement of wind turbines. We aim to investigate the efficiency of our method by making the same assumptions made in these studies by using genetic algorithm and coordinate method. The assumptions and parameters used in this study are explained in the following section and shown in Table 3.

### ***5.2. Factors in Wind Farm Design and Assumptions***

#### ***5.2.1 Site***

The process of designing a wind farm is a complicated process with numerous constraints which are mentioned in Chapter 4. The initial consideration in the development of a wind farm is land availability, which defines the amount of area available for the wind farm. Figure 8 depicts a 2.000 m by 2.000 m square area that is considered in our research. The terrain is assumed to be flat with a surface roughness height of 0,3 m which is a typical measurement of a land or onshore site.

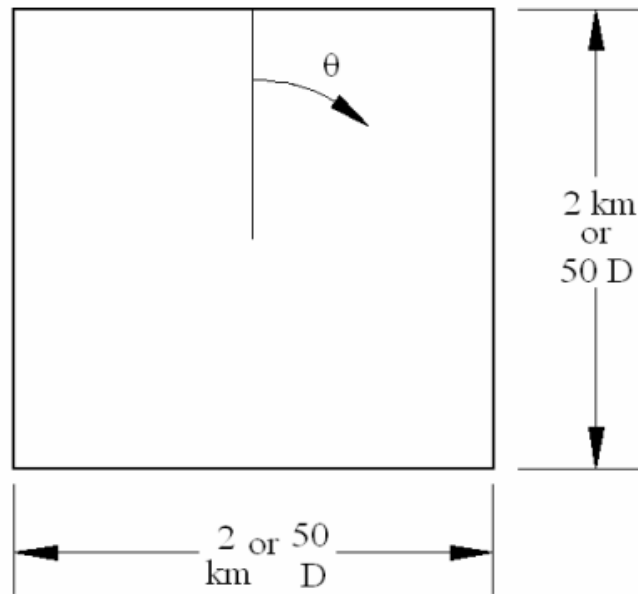


Figure 8. Size of the Wind Farm in The Present Study and Angular Demonstration of Wind Direction

### **5.2.2. Available Infrastructure and Budget Constraints**

The maximum installed capacity and the overall cost of the wind farm are two other key constraints. The maximum installed capacity of a wind farm is the maximum quantity of power it can generate, which is normally determined by available grid connections and the terms of the power purchase agreement. The quantity of funding available for wind farm development determines the final cost of the wind farm. These two parameters are not considered in this research. This means that the amount of power produced, and the overall cost of the wind farm are both unlimited.

### **5.2.3. Environmental Impact**

Other factors, such as the impact of noise from the wind farm on nearby residential areas and the visual impact of the wind farm, are not considered in this study as they are site specific.

### **5.2.4. Wind Turbine Properties**

The rotor diameter of the wind turbines is assumed to be 40 meters and the hub height to be 60 meters. The thrust coefficient of a wind turbine is assumed to be constant at 0,88. The perspective of modeling the impacts of numerous types of wind turbines or the same wind turbine with different hub heights (or the same turbines on different terrain) is out of our scope.

Table 1. Wind Turbine Properties

Parameter	Value
Rotor Diameter	40 m
Hub Height	60 m
Thrust Coefficient	0,88

#### ***5.2.5. Auxiliary Constraint***

Another constraint should be taken into account is the distance between turbines. The greater the velocity deficit associated with the upwind turbine, the closer the turbines are spaced. Thus, the downwind turbine's power output is reduced, and the overall electricity generated by the wind farm drops. Even though no turbine is affected by the other's velocity deficit when the wind blows from a dominant direction or where the wind distribution is unidirectional, the turbine spacing perpendicular to that direction must still be accounted for. Therefore, it is determined that the minimum distance between any two turbines to be 200 m (corresponding to five wind turbine rotor diameters) which is the industry standard for wind farm design (Kusiak, and Song, 2010). If the distance of any turbine to any other turbine is less than this distance, the algorithm identifies that turbine as not operational and does not include it in the current solution.

#### ***5.2.6. Wind Distribution***

The wind distribution of the second case in the study of Mosetti, Poloni, and Diviacco (1994) has a constant wind speed throughout the wind farm area with a value of 12 m/s. Wind direction is variable and has an equal probability of occurrence for each wind direction with 10° angles discretized in 36 segments. The angular correspondence of the direction North is 0 and 360 degrees. In real-life cases, generally, there would be a few dominant wind directions where the wind blows with the probability of occurrence for each direction segment. In Figure 9, the wind distribution for the case is shown.

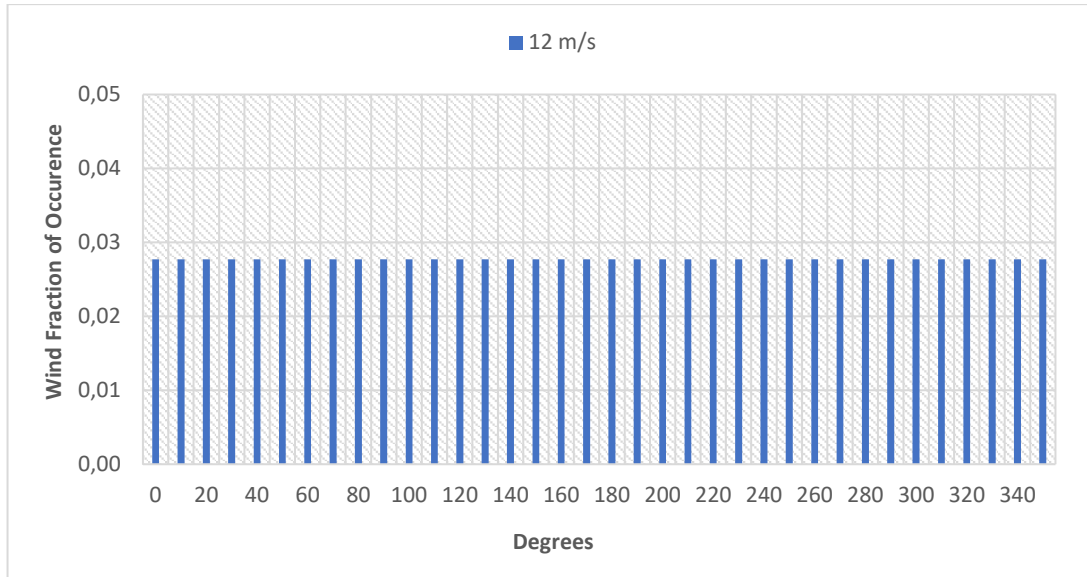


Figure 9. Wind Distribution of Case 2

### 5.2.7. Wake Model

Wake model proposed by Jensen, Katic, and Hojstrup (1986) is adapted in this study. The model gives an expression for determining the velocity in multiple wakes as a function of downstream distance. Formulations of the wake model are discussed in Section 3.4.

### 5.2.8. Power and Cost Calculation

To optimize the cost per unit power for a wind farm, the total power produced, and the total cost of the wind farm need to be calculated.

$$\text{Cost per Unit of Power} = \frac{\text{Total Cost}}{\text{Total Power}} \quad (21)$$

Our algorithm attains the coordinates (x and y) of each wind turbine and calculates the power output for each of them, then adds it up to get the total power extraction of the wind farm. For a wind turbine, extracted power is calculated by,

$$P = \frac{1}{2} C_p \rho A v^3$$

Assuming wind turbine efficiency as 40 %, air density as 1,2 and the rotor radius of a turbine as 20 meters, we get the following formula,

$$\text{Power Produced} = \frac{1}{2} \times \frac{40}{100} \times 1,2 \times \pi \times (20)^2 \times v^3 \quad (22)$$

$$= 301 \times v^3 W \quad (22.1)$$

$$= 0,3 \times v^3 kW \quad (22.2)$$

For the real case scenarios, the  $C_p$  value of the wind turbines is not a constant number. The generally accepted value for this parameter is between 0,4 and 0,5 for various wind turbines (Fjellanger, 2016).

In the literature, the value of  $1,225 \text{ kg/m}^3$  is taken as a default value for air density, representing the air density at sea level (Manwell, McGowan, and Rogers, 2010). However, Farkas (2011) investigates the effect of variable air density on power output calculations in this study. Using a simple neural network, the power curve obtained as a result of a 3-year wind data taken from the Enercon E-40 wind turbine is first fitted with an average air density value of  $1,229 \text{ kg/m}^3$  and then with variable air density in a range of  $1,124 - 1,395 \text{ kg/m}^3$ . Farkas (2011) proposes that the use of variable air density gives more accurate results in power calculations. In the study, the (RMSE) error rate obtained as a result of the fitting made with the mean value is  $12,06 \text{ kW}$ , while the RMSE error value he obtained with the variable air density which is  $10,15 \text{ kW}$ .

Based on Equation (22.2), wind farm's power generation can be calculated with the following model:

$$P_{tot} = \sum_{i=1}^{N_T} \sum_{d \in M} \frac{1}{3} v_{id}^3 p_d \quad (23)$$

where  $N_T$  denotes total number of turbines,  $v_{id}$  is the incoming wind speed for the turbine  $i$  at the wind state  $d$ , and  $p_d$  is the probability that wind state  $d$  would occur.

Earlier studies (Mosetti, Poloni, and Diviacco, 1994; Grady, Hussaini, and Abdullah, 2005; Marmidis, Lazarou, and Pyrgioti, 2008) use a cost model to calculate the investment cost of a wind farm. In this model, the total cost of the wind farm is simply defined by the number of wind turbines installed and it is also based on the fact that when a large number of wind turbines are acquired, a discount is given. Thus, when a large number of wind turbines are purchased, a cost reduction of  $1/3$  is possible. The total cost of the wind farm is calculated by the following equation where  $N_T$  is the number of turbines (Mosetti, Poloni, and Diviacco, 1994).

$$Total\ Cost = N_T \left[ \frac{2}{3} + \frac{1}{3} e^{-0.00174N_T^2} \right] \quad (24)$$

### 5.3. Layout Design Methods

In the wind farm layout optimization problem, the distance between two nodes (grid points) where a wind turbine can be placed is called grid spacing.

In the coordinate method, the turbine locations are shown continuously with the Cartesian coordinates. In the grid method, the defined area is divided into equal-sized square cells by separating it as rows and columns, and the positions of the wind turbines are only allowed to be placed in the center of the cells. This placement of the turbines into the centers restricts the flexibility (Long et al., 2017). Therefore, the choice of grid density is of great importance in grid-based methods.

Figure 10 shows the uses of the two layout design methods in a square shaped wind farm.

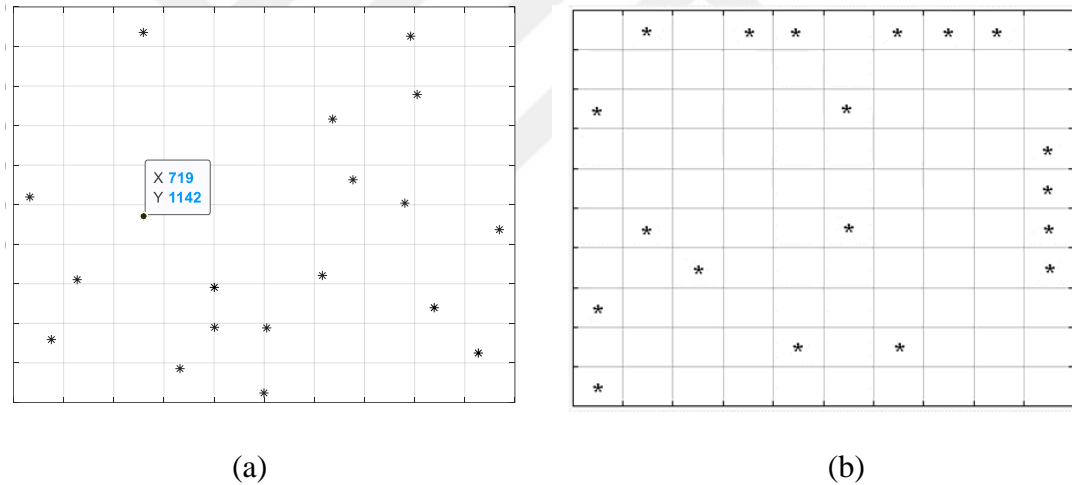


Figure 10. Demonstration of Layout Design Methods. a) Coordinate Method b) Grid Method

Wang, Tan, and Gu (2015) conduct the wind farm layout optimization problem using these two different design methods. They aimed to compare the best result obtained by applying the grid method with three different densities (10x10, 20x20, 50x50) with the results obtained by using the coordinate method. The results showed that the coordinate method achieves better results than the grid method based on the computed total cost and the number of turbines installed. Long et al. (2017) also investigated the efficiency of the two layout methods on different wind scenarios by using multi-swarm

optimization method in their study. They conclude that the coordinate method gives better results than the grid method in the comparison of power maximization and computational time. Mittal, and Taylor (2012) conduct a study to emphasize the importance of grid density. They applied the grid method by reducing the grid density to 1/40 rotor diameter and made a comparison using the cases of Mosetti, Poloni, and Diviacco (1994) and Grady, Hussaini, and Abdullah (2005). They find that more turbines could be placed for each case by increasing the density of the grid cells.

In our study, we aimed to increase the flexibility in the placement of the wind turbines by using the coordinate method. By doing so, we investigated how many more turbines can be placed than the number of turbines installed in the studies of Mosetti, Poloni, and Diviacco (1994), Grady, Hussaini, and Abdullah (2005) while keeping the cost per unit power at minimum.

#### **5.4. Genetic Algorithm**

Genetic Algorithm is a stochastic search algorithm based on natural competition between individuals for limited natural resources (Saeed, 2013). It's commonly utilized when there are large search spaces to evaluate in order to find the best possible solutions for a problem.

A possible solution of a problem is encoded as chromosomes. Each chromosome, that is, the individual, has a certain number of genes that contain information related to the problem. The whole of a certain number of chromosomes is defined as a population, and a population with a certain number of iterations is defined as a generation. A fitness function is computed for each individual, and evaluation is done based on their fitness value. To avoid the algorithm get stuck in local optima, a subset of all the individuals is chosen, with "good" or "fit" parents and an acceptable number of "bad" parents available. Parents produce new offspring using a crossover procedure that divides their genetic code into numerous bits and then reassembles it so that the offspring have genetic information from both parents. A low mutation rate translates genetic information in a random manner to allow for potential random alterations. Figure 11 shows the general steps of genetic algorithm.

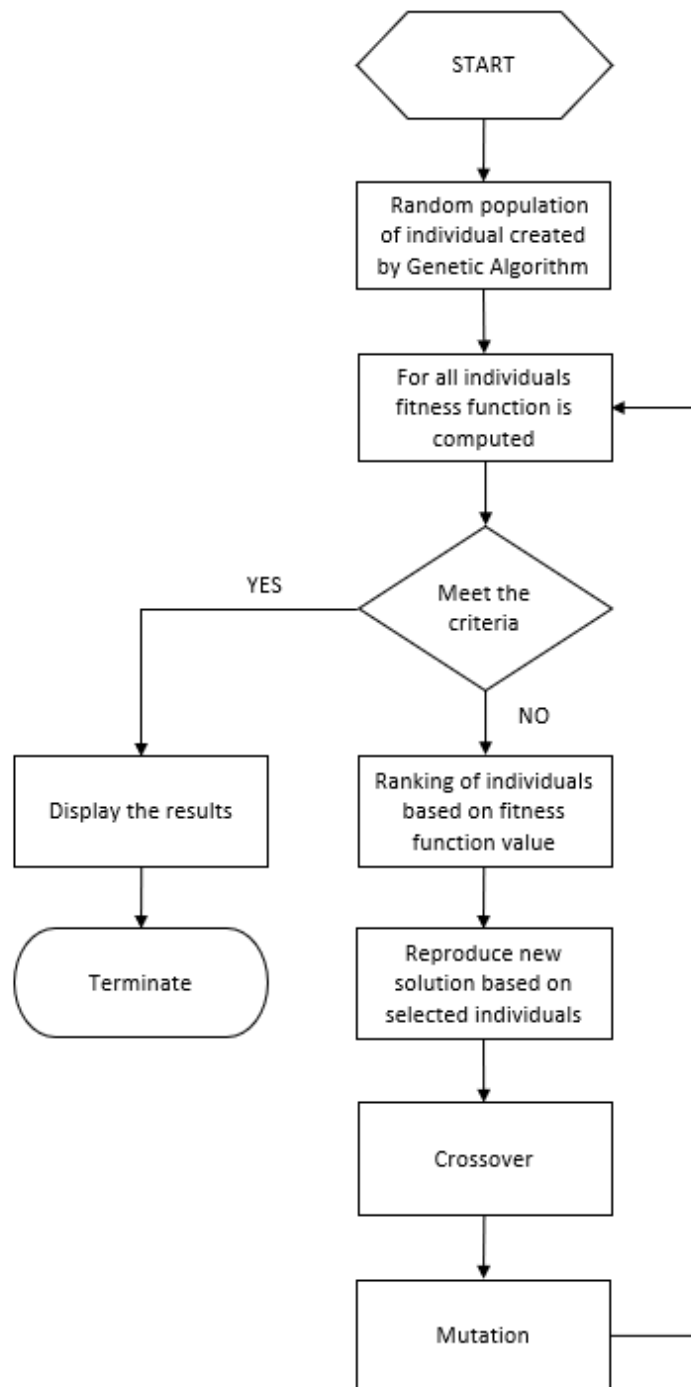


Figure 11. Flowchart of a Genetic Algorithm

The correct selection and definition of the necessary parameters is critical to the quality of a genetic algorithm. A well-constructed genetic algorithm for a certain problem could be an effective way to approach the solution with minimal resources.

In our study, we developed a code using a genetic algorithm for the wind farm layout optimization problem. This code is developed on the R2021a version of MATLAB, which is a high-performance language for technical computing.

### **Initialization:**

Initialization is the first step of genetic algorithm. A population is formed by the random creation of a particular number of individuals.

In the WFLO problem, each individual corresponds to a randomly created wind farm layout. The chromosome string constitutes the coordinates of a fixed number of wind turbines. With the input of the data in Table 1, the number of chromosomes up to the population size, which is set to 600 individuals, is generated until the optimization criteria are met.

### **Selection:**

Fitness function of each individual is calculated using Equation (21). After the initial solution is created, each individual whose fitness functions are calculated is evaluated and ranked according to this function. The best individuals will be placed at the top of the ranking and will be included in the reproduction process according to the preferred selection method. In this study, the elitism selection method is implemented, which ensures that the best individuals participate in reproduction as long as the optimization criteria have not yet been met.

### **Crossover:**

To recombine the genetic codes and create new individuals, single point crossover method is used, where the genetic code is cut in two pieces randomly.

The chromosome string, which is in the length of the turbine number to be installed, consists of genes, each of which corresponds to the X and Y coordinates. The crossover operation splits the chromosome string from a random point into two pieces and then combines these two chromosome parts as shown in the Figure 12.

	1	2	3	...																$N_T$
X	424	1942	687	1292	1022	1179	957	390	1522	2192	362	1183	922	1690	1916	402	779	787	680	
Y	1360	1581	886	336	676	1813	1237	2020	1718	1616	287	1094	1963	1034	389	977	347	1605	1920	

X	1977	159	346	921	1718	1461	1711	465	1436	393	993	1909	1529	647	1289	773	1575	2140	426
Y	298	1466	624	1054	433	2113	1253	1723	996	1998	1266	881	1656	1312	1238	1959	1814	1249	1502

Figure 12. Crossover Operation in the Present Study

In order to find the most fitted crossover and mutation rates for this specific problem, we run our algorithm repeatedly with many different combinations of operation rates. The value 0,7 is found to be best fitted rate for crossover operator with a mutation rate of 0,04. In Chapter 6, Figure 16 shows the analysis of the various crossover and mutation operator rates for the objective function.

**Mutation:**

Mutation is the final stage before a new set of solutions (a new population) is ready. This stage involves making some random modifications to a few solutions. This step is critical since it aids in the preservation of diversity in the solution set. In the mutation operation of our algorithm, minor changes are made on a randomly selected gene within the specified range with the mutation rate of 0,04. The algorithm analyzes this new set of solutions, and the iterative process continues until one of the optimization requirements is met.

All of the genetic algorithm parameters are presented in Table 2.

	1	2	3	...																$N_T$
X	424	1942	687	1292	1019	1179	957	390	1522	2192	362	1183	922	1690	1916	402	779	787	680	
Y	1360	1581	886	336	675	1813	1237	2020	1718	1616	287	1094	1963	1034	389	977	347	1605	1920	

↓

X	424	1942	687	1292	1019	1179	957	390	1522	2192	362	1183	922	1690	1916	402	779	787	680
Y	1360	1581	886	336	675	1813	1237	2020	1718	1616	287	1094	1963	1034	389	977	347	1605	1920

Figure 13. Mutation Operation in the Present Study

Table 2. Parameters of the Genetic Algorithm from the Previous Studies and the Present Study

	<b>Present Study</b>	<b>Mosetti, Poloni and Diviacco (1994)</b>	<b>Grady, Hussaini and Abdullah (2005)</b>
<b>Number of Generations</b>	3.000	400	3.000
<b>Population Size</b>	600	200	600
<b>Crossover Rate</b>	0,7	$0,6 < P_c < 0,9$	x
<b>Mutation Rate</b>	0,04	$0,01 < P_m < 0,10$	x



## CHAPTER 6: RESULTS AND DISCUSSION

Using the Equations (13-20) the incoming wind speeds are calculated for each turbine. Then, the objective function values which is the investment cost per unit of power for the wind farm is obtained through the Equations (21) and (24) and compared to the results from two benchmarked studies. There are three different cases discussed in these studies,

Case 1: Constant Wind Speed and Wind Direction

Case 2: Constant Wind Speed and Variable Wind Direction

Case 3: Variable Wind Speed and Variable Wind Direction

In the present study, results are obtained only for the case where the wind speed is constant and wind direction is variable, due to time-related issues. All parameter values used in our study can be found listed in Table 3.

Table 3. Parameters Used in the Present Study

Parameter Set	Value
Size of the Site	2.000 x 2.000 (m)
Rotor Radius ( $r$ )	20 m
Hub Height ( $z$ )	60 m
Surface Roughness ( $z_0$ )	0,3 m
Thrust Coefficient ( $C_t$ )	0,88
Turbine Efficiency ( $C_p$ )	40%
Rotor Swept Area ( $A$ )	$\pi r^2$
Wind Speed ( $v_0$ )	12 m/s
Wind Direction	36 Segment ( $^\circ$ )
Air Density ( $\rho$ )	1,2 kg/m <sup>3</sup>

In the first phase of our work, we aim to find the optimal placement for a particular number of turbines since the number of turbines to be placed is fixed in the previous studies (Mosetti, Poloni, and Diviacco, 1994). The objective function is the cost per unit power (Equation 21). In the second stage of our work, our goal is to find the optimum number of turbines we can place through the extra spaces we will obtain by applying the coordinate method.

The results are compared with two benchmark studies. The comparison is based on the power output of the wind farm, investment cost per unit power and efficiency. Efficiency refers to the ratio of the power output when the wake effect is considered, to the power output calculated with the free stream velocity when there is no wake effect between wind turbines.

### ***6.1. Layout Optimization with Fixed Number of Turbines***

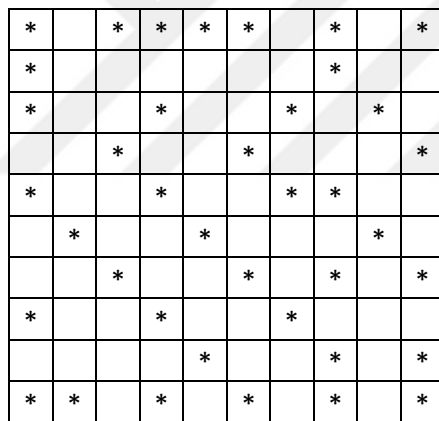
It is assumed that the wind speed comes with an equal probability of occurrence from all directions at 12 m/s and the wind direction is divided into 36 directional segments with 10-degree angles.

For Case 2, the optimum layout obtained for 19 wind turbines by Mosetti, Poloni, and Diviacco (1994) can be seen in Figure 14 (a). Since the wind blows at the same speed from all directions, the distance between the wind turbines is the most important element impacting the wind farm's efficiency and wake losses. Grady, Hussaini, and Abdullah (2005), on the other hand, increase the number of turbines installed, aiming to find an optimized configuration for minimum cost per unit power. Although they improved the generated power to 17.220 kW at the objective function of  $1,567 \times 10^{-3}$  by increasing the number of turbines installed from 19 to 39, they find the efficiency to be lower than Mosetti, Poloni, and Diviacco (1994) since the turbines are more compactly arranged.

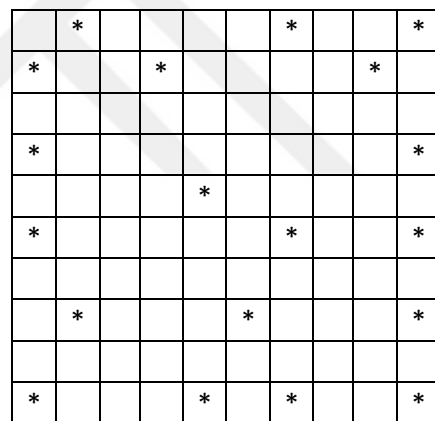
The results obtained by our algorithm are presented alongside the three other studies. While Mosetti, Poloni, and Diviacco (1994) find the cost per power unit for 19 turbines to be  $1,737 \times 10^{-3}$ , this value we obtained for same number of turbines is  $1,714 \times 10^{-3}$ . This difference shows that both our algorithm and the use of the coordinate method achieve better results. It should also be noted that as the number of turbines to be placed in the defined area decreases, the wake effect that the turbines will create between each other will also decrease. This explains why the difference between the results of Grady, Hussaini, and Abdullah (2005) and our results is larger in ratio. The objective function value we obtained for 39 turbines is found to be 3,5% better than the results of Grady, Hussaini, and Abdullah (2005), while this ratio is 1,3 % when compared to the results of Mosetti, Poloni, and Diviacco (1994).

Table 4. Results from Previous Studies and Present Study with Fixed Number of Turbines

	<b>Mosetti, Poloni and Diviacco (1994)</b>	<b>Present Study</b>	<b>Grady, Hussaini and Abdullah (2005)</b>	<b>Present Study</b>
<b>Number of Turbines</b>	19	19	39	39
<b>Total Power (kW)</b>	9.244,0	<b>9.332,9</b>	17.220,0	<b>17.819,2</b>
<b>Objective Function Value (1/kW)</b>	1,737x10 <sup>-3</sup>	<b>1,714x10<sup>-3</sup></b>	1,567x10 <sup>-3</sup>	<b>1,511x10<sup>-3</sup></b>
<b>Efficiency (%)</b>	93,85	<b>94,75</b>	85,14	<b>91,18</b>



(a)



(b)

Figure 14. a) Optimal Layout for Case 2 from Mosetti, Poloni, and Diviacco (1994)

b) Optimal Layout for Case 2 from Grady, Hussaini, and Abdullah (2005)

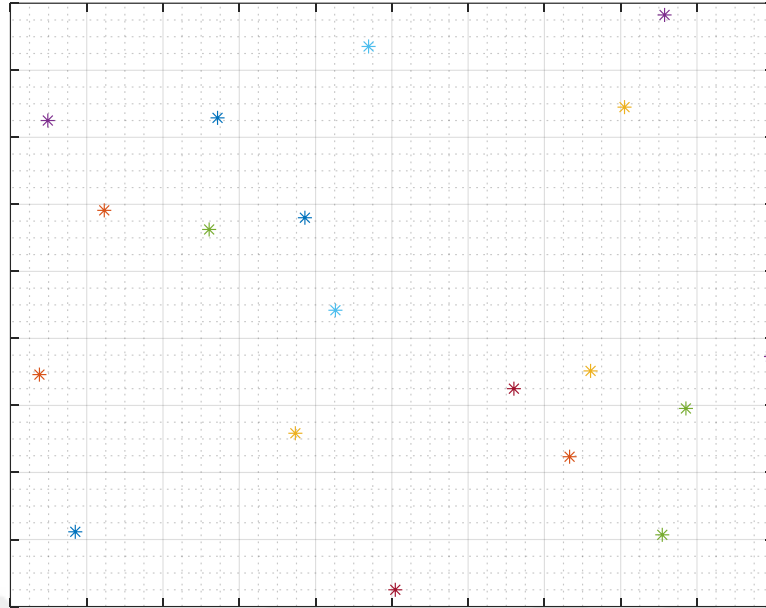


Figure 15. Optimal Layout Reported by Present Study

As mentioned in Section 5.4, Figure 16 shows the objective function results obtained by repeatedly running our algorithm with various combinations of crossover and mutation rates. The combination that gives the best result of cost per unit power according to the graph is the one with the value of 0,7 for crossover and 0,04 for mutation rate.

Studies using genetic algorithm for the WFLO problem do not include any detail on the choices of genetic algorithm operators. However, when the graph below is examined within the scope of this specific problem, it is seen that the cost per unit power value change by the selection of operator rates. Such differences are of great importance in the decisions to be made before the installation of the wind farm.

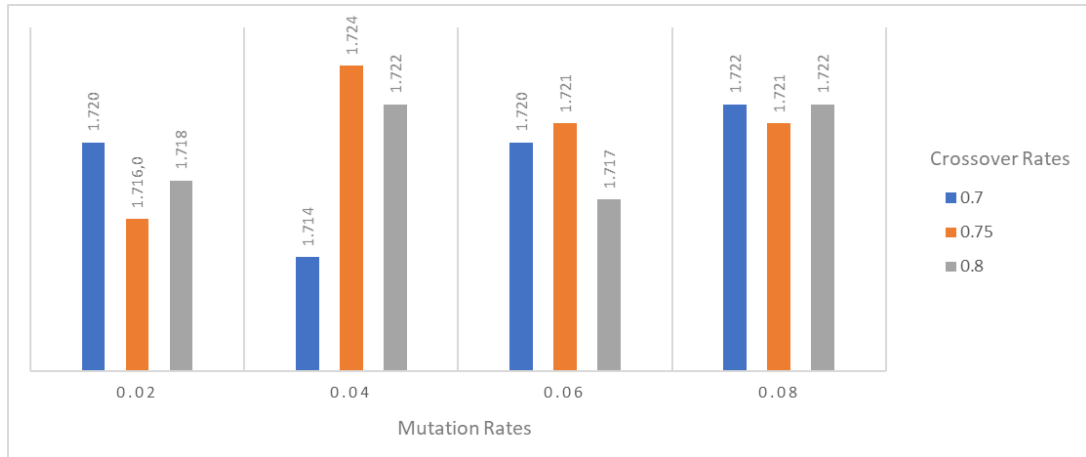


Figure 16. Cost per Unit Power Values for Each Genetic Algorithm Operator Combination ( $\times 10^{-3}$  1/kW)

## 6.2. Layout Optimization with the Optimal Number of Turbines

In order to use the extra spaces acquired by applying the coordinate method, we run our algorithm iteratively to find the optimal number of turbines that can be placed.

The Equation (24) is a function of the number of turbines, as seen in Figure 17. The cost value decreases to some point as the number of turbines increases. With the addition of more wind turbines to a wind farm, wake losses increase to the point where adding more wind turbines is no longer cost-effective.

Differently from the study of Mosetti, Poloni, and Diviacco (1994), Grady, Hussaini, and Abdullah (2005) aim to minimize the cost of per unit while finding the optimal number of turbines. They use the grid method with density of  $10 \times 10$  as a layout design method and find the cost per unit power as  $1,567 \times 10^{-3}$  kW with an efficiency of 85,17 % while the optimal number of turbines to be installed is 39.

Table 5. Results from Previous Studies and Present Study with Optimized Number of Turbines

	<b>Present Study (Coordinate Method)</b>	<b>Grady, Hussaini, and Abdullah (2005) (Grid Method)</b>	<b>Mosetti, Poloni, and Diviacco (1994) (Grid Method)</b>
<b>Number of Turbines</b>	<b>40</b>	39	19
<b>Total Power (kW)</b>	<b>18.276,7</b>	17.220,0	9.244,0
<b>Cost Per Unit Power (1/kW)</b>	<b><math>1,503 \times 10^{-3}</math></b>	$1,567 \times 10^{-3}$	$1,737 \times 10^{-3}$
<b>Efficiency (%)</b>	<b>88,14</b>	85,17	<b>93,85</b>

By running our algorithm iteratively with the use of the coordinate method, we found that 40 wind turbines can be placed within the wind farm borders which is 21 more turbines than Mosetti, Poloni, and Diviacco (1994) and 1 more than Grady, Hussaini, and Abdullah (2005) installed in their work while our objective function value is still lower than these two studies. The reason for the lower efficiency is the denser layout that we have by placing more turbines. This means that the interaction between the turbines is increased in comparison with the wind farm operating at full efficiency. However, when we look at Grady, Hussaini, and Abdullah's (2005) efficiency value, our efficiency value still seems a bit higher. We attribute this result to the advantage of flexible layout obtained by using the coordinate method. The final layout for 40 wind turbines is demonstrated in Figure . The results of the present study for the optimal number of turbines and the previous studies are shown in Table 5.

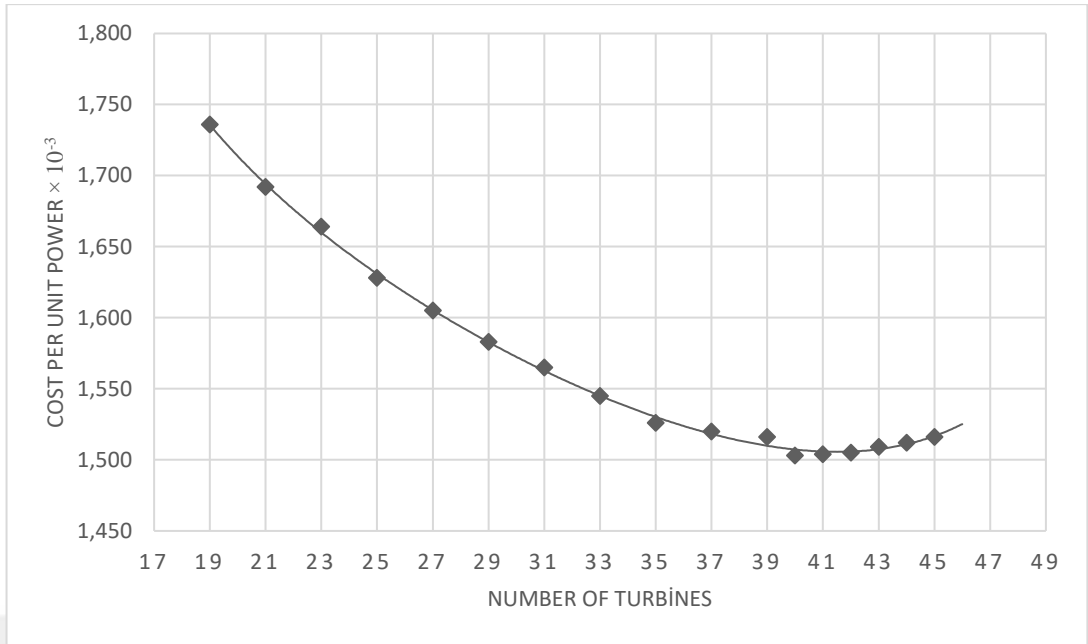


Figure 17. Objective Function Value for Different Number of Turbines

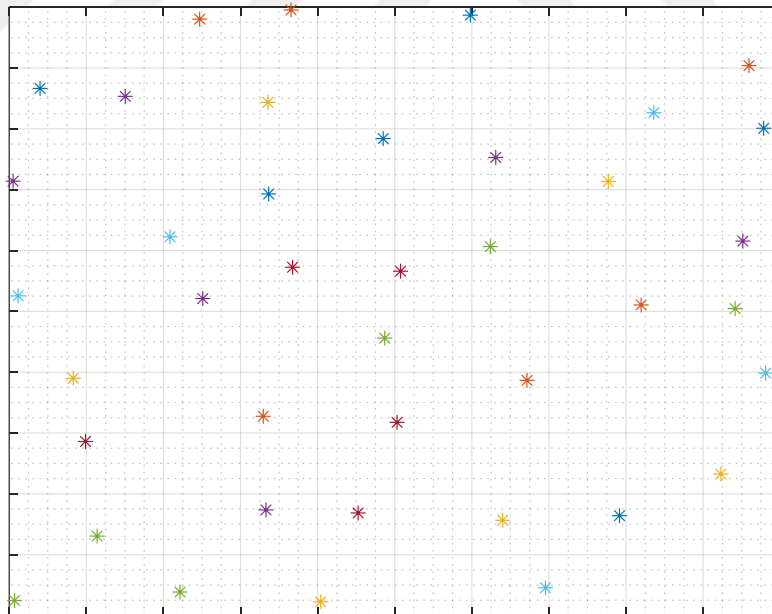


Figure 18. Final Layout for 40 Wind Turbines

## CHAPTER 7: CONCLUSION

We developed a code in which the genetic algorithm is adapted for the wind farm layout design problem. We compared the results we obtained by using the coordinate method as the layout design method with the results of three previous studies using the grid spacing method. By making this comparison, we aimed to investigate the advantages of the coordinate method. The objective function is the cost per unit of power and the farm area is assumed to be a square shaped and a flat area. In the wind condition scenario, the wind speed is a fixed value of 12 m/s, and the wind directions are divided into 36 segments.

In the first stage of our study, when the number of wind turbines is predetermined, the objective function for this particular number of turbines is minimized and the optimal layout configuration is found. With the use of our algorithm and the coordinate method, better results are obtained with a slight difference compared to the other two studies. Compared to Mosetti, Poloni, and Diviacco (1994) work, the objective function has been reduced by 1,04 % and the power produced has been increased by 0,94%.

In the second stage of our study, we have aimed to find out how many more turbines could be placed using the coordinate method. Accordingly, we conclude that 21 more turbines could be installed than the number of turbines Mosetti, Poloni, and Diviacco (1994) placed, one more than Grady, Hussaini, and Abdullah (2005) while the objective function value is reduced by 13,47 % and 4 % as compared to Mosetti, Poloni, and Diviacco (1994) and Grady, Hussaini, and Abdullah (2005) study, respectively.

The assumptions in our study, as in previous studies, includes simplified scenarios in order to measure the efficiency of the method used. Instead of using uniformly distributed wind speed as in our study, a more realistic study can achieve more realistic results by using the Weibull distribution with wind data over a period of time (wind speed, wind direction etc.).

A square shaped, flat wind farm is used in our study since it is considered as an ideal test case in the literature. More realistic study might be conducted by considering a site with irregular boundaries or a sloping land to accurately represent a real terrain.

Since the cost model used in our study only depends on the number of turbines to be installed, a more realistic study may include additional cost items such as electrical or infrastructural.



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## APPENDICES

### Appendix A

```
%% Variables
```

```
gridsize = 2400; % m^2 grid  
N=19; % number of turbines  
D = 40; %in meter  
SimVars = [gridsize N D];
```

```
V=12; %5.342  
%size = 50; % size of the windspeed array  
WindTurbine(N) = struct();
```

```
% Wind Turbine Properties
```

```
turb_specs = struct();  
turb_specs.diameter = 40; % in m  
turb_specs.rotorArea = 2*pi*20*20; % in m2  
turb_specs.hubHeight = 60; % in m  
turb_specs.cutInWindSpeed = 3; % in m/s  
turb_specs.cutOutWindSpeed = 20; % in m/s  
turb_specs.ratedWindSpeed = 7.5; % in m/s  
turb_specs.ratedPower = 126.5; % in kW
```

```
% GA Properties
```

```
GA_population = 600;  
GA_elites = 40;  
GA_mutations = 24;  
GA_crossovers = 420;  
GA_Param = [GA_population GA_elites, GA_mutations, GA_crossovers];
```

```
% direction segments in degrees
```

```
slices_drct = [360,linspace(10.0,350.0,35)];  
n_slices_drct = length(slices_drct);  
wind_inst_freq = 0.02777;  
directionBins = slices_drct;
```

```
Park = [];  
AEYmax = 0;  
k = 1; % Counter for number of iterations with no change  
iter = 1; % Number of total iterations
```

```
%% Iterate over the entire population
```

```
while k<1500 && iter < 3000 %Stop Conditions for the GA  
    tic  
    for p = 1:GA_population
```

```
%% Initialise Population
```

```
if isempty(Park)  
    [WindTurbine, Occupied] = InitialisePopulation(SimVars);  
    Park(:,3,p)=WindTurbine.x;  
    Park(:,4,p)=WindTurbine.y;
```

```

end

% Calculate Fitness Function
%Calculate total power of individual turbine
speedBins=12;
[AEP, ~] = powercalc([(WindTurbine.x); (WindTurbine.y)]',
,wind_inst_freq,directionBins,speedBins,turb_specs);

for i = 1:N
PassOn(i,1:4) = [AEP i WindTurbine(i).x WindTurbine(i).y];
end

AEYPark(p,1) = sum(AEP);
AEYPark(p,2) = p;
Park(i,:,p) = PassOn(i, :);

if AEYmax < AEYPark(p,1)
    AEYmax = AEYPark(p,1);
    k=-1;
    BestWindTurbine=[WindTurbine.x; WindTurbine.y];
end
end
k = k+1;
iter = iter + 1;

% Find elites; Do mutations; Do crossovers
[Park, WindTurbine] = NaturalSelection(Park, WindTurbine, AEYPark,
GA_Param, SimVars);

% Check while conditions
cost=N*(2/3+0.333*exp(-0.00174*(N^2)));
Objective=cost/AEYmax;
Efficiency= (AEYmax/(N*12^3*0.3))*100;

str = sprintf('While the number of turbines is %f \n\nThe result of
iteration %i are as follows:\n\nThe optimised value for the Total
Produced Energy is %f kW \n\nObjective Function is %f \n\nand the
efficiency is %f \n\nGeneration took %f seconds to process ', N, iter,
AEYmax, Objective, Efficiency, toc)

end

figure
for i = 1:N
grid on
grid minor
plot(BestWindTurbine(2,i),BestWindTurbine(1,i),"*");
hold on;
end

figure
for i = 1:N
grid on
grid minor
plot(BestWindTurbine(1,i),BestWindTurbine(2,i),"*");
hold on;
end

```

```

function [WindTurbine, OccupiedF] = InitialisePopulation(SimVars)

gridsize = SimVars(1); N = SimVars(2); D = SimVars(3);

    Occupied(gridsize,gridsize) = false;

    WindTurbine(1).x = randi([5*D+1 gridsize-5*D+1], 1, 1); x =
WindTurbine(1).x;
    WindTurbine(1).y = randi([5*D+1 gridsize-5*D+1], 1, 1); y =
WindTurbine(1).y;
    Occupied(x-5*D:x+5*D, y-5*D:y+5*D) = true;

for i = 2:N
    %Generate Random Coordinates
    WindTurbine(i).x = randi([5*D+1 gridsize-5*D+1], 1, 1); x =
WindTurbine(i).x;
    WindTurbine(i).y = randi([5*D+1 gridsize-5*D+1], 1, 1); y =
WindTurbine(i).y;

    %Check if the location is free and move to another random site
    while(Occupied(x, y) == true || ceil(x+D*5) > gridsize ||
ceil(y+D*5) > gridsize || floor(x-D*5) < 1 || floor(y-D*5) < 1)
        WindTurbine(i).x = randi([5*D+1 gridsize-5*D+1], 1, 1); x =
WindTurbine(i).x;
        WindTurbine(i).y = randi([5*D+1 gridsize-5*D+1], 1, 1); y =
WindTurbine(i).y;
    end

    %Set the coordinates as occupied
    Occupied(x-5*D:x+5*D, y-5*D:y+5*D) = true;

end
    OccupiedF = Occupied;
end

% Power calculation for each turbine

%%Adapted from: @Misc{,
    %author = {Fernando Nogueira},
    %title = {{Bayesian Optimization}: Open source constrained
global optimization tool for {Python}},
    %year = {2014--},
    %url = " https://github.com/fmfn/BayesianOptimization"
    %}

Function totpow =
velocitydef(WindTurbine,wind_drct,wind_sped,turb_specs)

n_turbs = length(WindTurbine);

turb_rad = 20;

```

```

Ct = 0.88;

% Wake decay constant
kw = 0.5/log(turb_specs.hubHeight/0.3); %surface roughness: 0.3

% converting wind direction from degrees to radians
wind_drct = wind_drct - 90.0;
wind_drct = deg2rad(wind_drct);

% Constants to be used in converting turbine euclidian coordinates
to downwind
% and crosswind coordinates
Vwind_North = cos(wind_drct);
Vwind_East = sin(wind_drct);

% initializing turbine power vector
power = zeros(n_turbs,1);

% Calculating wake effect of turbines on each other
impact_on_ibyj = zeros(n_turbs,n_turbs);

% i is the target turbine
for i=1:n_turbs

    for j=1:n_turbs

        x = (WindTurbine(i,1) - WindTurbine(j,1)) * Vwind_North - ...
            (WindTurbine(i,2) - WindTurbine(j,2)) * Vwind_East;

        y = (WindTurbine(i,1) - WindTurbine(j,1)) * Vwind_East + ...
            (WindTurbine(i,2) - WindTurbine(j,2)) * Vwind_North;

        % No wake effect of turbine on itself
        if i ~= j

            if (x <= 0) || (abs(y) > (turb_rad + kw*x))
                impact_on_ibyj(i,j) = 0.0;

            else
                impact_on_ibyj(i,j) = (1-sqrt(1-Ct)) * ...
                    ((23.52/(23.52 + kw*x))^2);
            end
        end
    end
end

    sped_deficit =
sqrt(sum(impact_on_ibyj(i,j).*impact_on_ibyj(i,j)));

% Effective wind speed at ith turbibe

```

```

    wind_sped_eff = wind_sped * (1.0 - sped_deficit);

    power(i)=(wind_sped_eff^3)*0.3;
    %0.5*0.4*1.2*3.14*400*0.001; %in kW

end

totpow=sum(power);

end

% Total Power calculation

% Calculates the wind farm power
function [AEP, farmpower] = powercalc(WindTurbine
,wind_inst_freq,directionBins,speedBins,turb_specs)

% Power produced by the wind farm from each wind instance
farmpower = zeros(length(directionBins),length(speedBins));

for i = 1:length(directionBins)

    % Wind speed and direction in the bin
    wind_drct = directionBins(i);
    wind_sped = speedBins;

    farmpower(i) = velocitydef(WindTurbine, PowerCurve, ...
                                wind_drct, wind_sped, ...
                                turb_specs);

end

farmpower = farmpower .* wind_inst_freq;

AEP = sum(farmpower);

end

function [Park, WindTurbine] = NaturalSelection(Park, WindTurbine,
AEYPark, GA_Param, SimVars)
GA_population = GA_Param(1);    GA_elites = GA_Param(2);
GA_mutations = GA_Param(3);    GA_crossovers = GA_Param(4);
N = SimVars(2);

sortrows(AEYPark);
Parknew(1:N,1:4,1:GA_population) = zeros(N,4,GA_population);

```

```

%% Elites
for i = 1:GA_elites

    Parknew(1:N,3:4,i) = Park(1:N,3:4,AEYPark(i,2));

end
%% Crossovers
for i = GA_elites+1:GA_elites+GA_crossovers
    p = 1:GA_elites; %because there is only elite number of
    tubines
        chosen = p(randi([1 GA_elites-1]));
        % Combine the coordinates of two wind turbines (mean scenario
        only)
        for j = 1:N
            m = randi([1,100]);
            n = 100 - m;
            Parknew(j,3,i) =
(m*Parknew(j,3,chosen)+n*Parknew(j,3,chosen+1))/100 ;
            Parknew(j,4,i) =
(m*Parknew(j,4,chosen)+n*Parknew(j,4,chosen+1))/100 ;

        end
    end
end

%% Mutations
for i =
GA_elites+GA_crossovers+1:GA_elites+GA_crossovers+GA_mutations
    %Mutate by a little bit in any direction
        p = 1:GA_elites;
        chosen = p(randi([1 GA_elites]));

        for j = 1:N
            Parknew(j,3,i) = Parknew(j,3,chosen)+randi([-3,3]) ;
            Parknew(j,4,i) = Parknew(j,4,chosen)+randi([-3,3]) ;
        end
    end
end

%% New Genes

for i = GA_elites+GA_mutations+GA_crossovers + 1 : GA_population
    for j = 1:N
        [WindTurbine ~] = InitialisePopulation(SimVars);

        Parknew(:,3,i) = WindTurbine.x;
        Parknew(:,4,i) = WindTurbine.y;
    end
end

Park = Parknew;
end

```