Optimal Placement Of Wind Turbines On Non-Flat Terrain Using Cluster Identification And Multi-Objective Genetic Algorithm

Carlos Alejandro Garcia Rosales
University of Texas at El Paso, cagarciorosales@miners.utep.edu

Follow this and additional works at: https://digitalcommons.utep.edu/open_etd

Part of the Engineering Commons, and the Oil, Gas, and Energy Commons

Recommended Citation
https://digitalcommons.utep.edu/open_etd/2090

This is brought to you for free and open access by DigitalCommons@UTEP. It has been accepted for inclusion in Open Access Theses & Dissertations by an authorized administrator of DigitalCommons@UTEP. For more information, please contact lweber@utep.edu.
OPTIMAL PLACEMENT OF WIND TURBINES ON NON-FLAT TERRAIN
USING CLUSTER IDENTIFICATION AND MULTI-OBJECTIVE
GENETIC ALGORITHM

CARLOS ALEJANDRO GARCIA ROSALES
Department of Industrial, Manufacturing and Systems Engineering

APPROVED:

Tzu-Liang (Bill) Tseng, Ph.D., Chair

Jose F. Espiritu, Ph.D.

Paras Mandal, Ph.D.

Benjamin C. Flores, Ph.D.
Dean of the Graduate School
OPTIMAL PLACEMENT OF WIND TURBINES ON NON-FLAT TERRAIN

USING CLUSTER IDENTIFICATION AND MULTI-OBJECTIVE

GENETIC ALGORITHM

By

CARLOS ALEJANDRO GARCIA ROSALES, B. Tech.

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Industrial, Manufacturing and Systems Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

December 2012
ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Tseng for believing in me and choosing me for this research. I would like to thank Dr. Jose F. Espiritu and Dr. Paras Mandal for being my committee members and for their valuable suggestions and comments for this research.
ABSTRACT

To date, wind power has become very popular to produce electricity due to climate change, greenhouse gases and the fossil fuels crisis. Although using wind turbine technology to produce electricity is very mature, industries are looking to achieve the best utilization of the wind energy in order to fulfill the electrical needs for cities at a very affordable cost. In this thesis, a method entitled Cluster Identification Algorithm (CIA) and an optimization approach called a Multi-Objective Genetic Algorithm (MOGA) are integrated and implemented to maximize wind power efficiency and wind power in wind farms and minimize cost caused by the size and quantity of wind turbines installed in wind farms located on non-flat terrain (i.e., terrain with different heights). An analysis evaluating the fitness function for different populations and generations in order to select the best option was performed. Furthermore, assumption of one wind direction and different factors like different turbine capacities and different quantity of turbines available are considered in this thesis. Also, it considered how the downstream decay model from wind energy theory caused for a wind turbine positioning ahead on the wind farm layout affected the remaining. Finally, a model related to layouts of the wind farm with optimal combination of efficiency, power and cost is developed. A case study that solved three dimensional terrain optimization problems using the combination of CIA and MOGA is also discussed. This thesis forms the basis for solving many other similar problems that occur in renewable energy industries.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS ................................................................................................................................. iv

ABSTRACT .................................................................................................................................................... v

TABLE OF CONTENTS ............................................................................................................................. vi

LIST OF TABLES .......................................................................................................................................... viii

LIST OF FIGURES ......................................................................................................................................... ix

Chapter 1  INTRODUCTION ....................................................................................................................... 1

  1.1 Background ......................................................................................................................................... 1

  1.2. Statement Problem and Rationale of the Study .................................................................................. 2

  1.3. Objectives of the Study ...................................................................................................................... 2

  1.4. Scope and Limitations ....................................................................................................................... 3

  1.5. Plan of thesis ..................................................................................................................................... 3

  1.6 The function of the Wind Turbine and Wind Farm ............................................................................ 4

Chapter 2  LITERATURE REVIEW ............................................................................................................. 5

  2.1 The function of the Wind Turbine and Wind Farm ............................................................................ 5

  2.2 Wind turbine classification type ........................................................................................................ 6

  2.3 Power in wind that flows through a rotor ............................................................................................ 9

  2.4 The power generation process through a wind turbine ..................................................................... 10

  2.5 Layout of the wind farm ..................................................................................................................... 11

  2.6 Common assumptions in wind farm research .................................................................................... 12

  2.7 Problem identification ....................................................................................................................... 13

  2.8 Genetic algorithm ............................................................................................................................... 16

Chapter 3 METHODOLOGY ....................................................................................................................... 18

  3.1 The proposed methodology ............................................................................................................... 18

  3.2 Methodology and strategy ................................................................................................................ 20
3.2.1 Wind power, efficiency and wind farm cost ................................................................. 20
  3.2.1.1 Wind power generation ......................................................................................... 22
  3.2.1.2 Wind power efficiency ....................................................................................... 25
  3.2.1.3 Wind farm cost ................................................................................................. 26

3.2.2 Objective functions .................................................................................................... 26

3.2.3 Algorithm for wind farm terrain selection ................................................................. 28
  3.2.3.1 New Heights Matrix concept and contributions ................................................. 28
  3.2.3.2 Description of the proposed algorithm ............................................................. 30

3.2.4 Description of MOGA .............................................................................................. 40

3.2.5 Application of GA to wind farms ............................................................................. 40
  3.2.5.1 Proposed MOGA for wind farm ................................................................. 43

Chapter 4 CASE STUDY AND COMPUTATIONAL RESULTS ............................................. 45
  4.1 Case study description ................................................................................................. 45
  4.2 Data for case Study .................................................................................................. 45
  4.3 Methodology to solve the case study ........................................................................ 48

Chapter 5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK .......... 74
  5.1 Conclusions ............................................................................................................... 74
  5.2 Future work ............................................................................................................... 75

REFERENCES ................................................................................................................... 76
APPENDIX I VERTICAL AXIS WIND TURBINE COMPONENTS ..................................... 77
APPENDIX II WIND FARM TYPES .................................................................................. 80
APPENDIX III WAKE DECAY MODEL ........................................................................... 82
APPENDIX IV MATLAB CODE FOR MOGA ................................................................. 85
CURRICULUM VITA ......................................................................................................... 99
LIST OF TABLES

Table 2.1 WT Comparisons ..................................................................................................................... 7
Table 2.2 Assumptions in wind farm research ....................................................................................... 12
Table 2.3 Research issues and technical methodologies for power prediction, power optimization and best wind turbine placement .................................................................................................................. 13
Table 3.1 Input variables ........................................................................................................................ 21
Table 3.2 Values of α .............................................................................................................................. 27
Table 3.3 Example of the matrix of a turbine type K with the variables of interest .............................. 27
Table 3.4 Crossover and mutation .......................................................................................................... 44
Table 4.1 Data of turbines available ...................................................................................................... 46
Table 4.2 Wind speed data over a year .................................................................................................. 46
Table 4.3 Simplified table of wind speed base on histogram bins ......................................................... 47
Table 4.4 Alternative plan to test the methodology ............................................................................... 54
LIST OF FIGURES

Figure 1.1 VAWT (Vertical Axis Wind Turbine) components ............................................................... 5
Figure 2.1 Wind turbine representations with wind passing through the rotor ................................. 9
Figure 2.2 Power generation of a wind turbine .................................................................................. 10
Figure 2.3 Typical wind farms ............................................................................................................ 11
Figure 3.1 Flow chart of general methodology ................................................................................ 18
Figure 3.2 Flow chart of detailed methodology ................................................................................ 19
Figure 3.3 Efficiency of the power in the wind that the wind farm is exposed ................................... 25
Figure 3.4 Franklin mountains top view ............................................................................................ 29
Figure 3.5 Matrix of a large set of heights ......................................................................................... 29
Figure 3.6 MOGA steps ..................................................................................................................... 41
Figure 3.7 Random populations of n chromosomes (layouts) ............................................................ 43
Figure 4.1 Histogram representation of wind speed over a year ..................................................... 47
Figure 4.2 Matrix A representation .................................................................................................. 48
Figure 4.3 Matrix A with set of bins, highlighted in yellow the heights are into the bins .................. 49
Figure 4.4 Matrix B with entries of ones and zeros, Ones are highlighted in red and yellow .......... 49
Figure 4.5 Matrix A representation, highlighted in yellow are the heights into the bin ranges, in this case in a two column range ............................................................................................. 50
Figure 4.6 New Final Matrix B representation 1’s are highlighted in red and yellow ..................... 50
Figure 4.7 Incidence matrix B .......................................................................................................... 51
Figure 4.8 Cluster identification result ............................................................................................. 51
Figure 4.9 Cluster identification selected, matrix C ........................................................................... 52
Figure 4.10 Matrix a ......................................................................................................................... 52
Figure 4.11 3D scatter plot view of efficiency vs. power vs. cost ....................................................... 55
Figure 4.12 2D view of power along generations ............................................................................ 55
Figure 4.13 2D view of efficiency along generations ........................................................................ 56
Figure 4.14 2D view of efficiency along generations ........................................................................ 56
Figure 4.15 3D view of Pareto front at 30 generations ....................................................................... 57
Figure 4.16 Pareto front 2D view, cost (millions USD) vs. efficiency, 30 generations ...................... 58
Figure 4.17 Figure 4.17 Pareto front 2D view, cost (MM USD) vs. power (Kw) at 30 generations .... 58
Figure 4.18 Pareto front 2D view, efficiency vs. power (Kw) at 30 generations ............................... 59
Figure 4.19 Pareto front 3D view at 50 generations ........................................................................... 59
Figure 4.20 Pareto front 2D view, cost (millions USD) vs. power at 50 generations ....................... 60
Chapter 1

INTRODUCTION

1.1 Background

Some facts such as diminishing fossil fuel and the effect of the use of fossil sources on the environment are the two main reasons for interest in applying wind energy as a way to reduce these issues. Currently, wind energy is receiving considerable attention as an emission-free, low cost alternative to traditional energy sources. It is a widely available since is derivative of solar energy that has been captured by earth’s atmosphere. It has a wide range of applications such as battery charging, or auxiliary power on boats. For large grid-connected arrays of turbines, they are becoming an increasingly important source of wind power-produced commercial electricity.

In this thesis, a method entitled Cluster Identification Algorithm (CIA) and an optimization approach called a Multi-Objective Genetic Algorithm (MOGA) are integrated and developed to solve the problem of determining the optimal wind farm layout on non-flat terrain and at the same time maximize wind power, maximize the efficiency of wind power affected by the aerodynamic losses and minimize cost due to the size and quantity of wind turbines installed in wind farms. Before selecting the optimal wind farm, there exist some important variables that the methodology has to deal with, such as different heights of the terrain and initially undetermined optimal wind turbine positions. The terrain is defined with the use of Cluster identification Algorithm (CIA), because with CIA is possible obtain a cluster of positions into a specific range of heights, after that only a subset of positions are selected from the total land area. Another important variable is that the wind turbine capacities and characteristics are not the same; characteristics like rotor area and turbine height that play a big role in calculating the wind power that the turbine is exposed to.
1.2. Statement Problem and Rationale of the Study

The motivation to develop this work is based on the research issues found in the literature review, mostly in journal papers of optimization methodologies for wind turbine position placement in wind farms. Then grew the idea of developing a methodology to solve the problem of determining the optimal wind farm layout on a non-flat terrain; based on that the most of the papers reviewed make reference to 2-dimensional terrain (flat terrain) although terrain roughness (with different heights) is common in real world cases. Other of the issues during literature review is that turbine placement papers do not mention a pre-selection terrain method from a large scale terrain, making the wind farms not so big or the wind farms installation are far from cities; for that reason in this study is presented Cluster Identification Algorithm (CIA) as an option to fulfill this need.

The interest of utilized a well probed multi-objective algorithm such as MOGA is based on that in the literature review is considered just 1 or 2 objective variables while in real world problems could be consider as much objective variables are required. Also was necessary increased the input variables by adding a wind wake decay model to simulate the disturbance that causes the turbines interacting with each other; and used different turbine types because this increased the opportunities to find a better wind farm lay out solution.

1.3. Objectives of the Study

As a main objective in the present study is proposed a methodology integrated by a method entitled Cluster Identification Algorithm (CIA) and an optimization approach called a Multi-Objective Genetic Algorithm (MOGA) that allow determine a wind farm layout on a non-flat terrain, and at the same time maximize wind power that the wind farm is exposed to, maximized efficiency of the wind power, and minimize cost due to the quantity of turbines in the wind farm.
Secondly is presented a methodology steps about how to deal with variables such as different quantity of turbines and different types, (different hub height, rotor area, etc.), situation that is not easy to find in literature review and appear in the real world cases.

Thirdly, since the methodology is a long computational time consuming was developed a MATLAB code, see Appendix iv, which include and consider all variables mentioned above and can be useful for future works.

1.4. Scope and Limitations

The proposed methodology can develop a wind farm layout maximizing the wind power that wind farm is exposed to. To maximize the electrical power output, is necessary considering the efficiency of the entire system, situation is not consider in this study. A limitation is that is considering just 1 wind direction that is not the case in real world situations. At least this methodology can be useful as an initial approach to get a wind farm layout solution which can be compared with the solution of other approaches. There is the intention of the author complicating the methodology to make it stronger and more reliable for the real world applications.

1.5 Plan of thesis

Along the next chapters is presented the technical part regarding wind energy and wind turbines. Next, sections described the used methodology that start with the basic equations from wind farm theory to define wind power, efficiency of wind power, and total cost concept used in optimizations equations; basically, the methodology describes step-by-step how conduct the variables mentioned above, specifically the variable that the terrain has different heights. Further, is presented step-by-step the proposed methodology that involved the steps to apply the Cluster Identification Algorithm (CIA), whose output is a selected terrain to be the input of the Multi-
Objective Genetic Algorithm (MOGA) that is also part of the algorithm to develop the wind farm layout. At the end is presented a case study, again explained step by step with an analysis of the results generated.
Chapter 2

LITERATURE REVIEW

The next sections described some of the material founded in literature review that were consider important to make mention in this study because are necessary and useful concepts to understand the methodology chapter.

2.1 The function of the Wind Turbine and Wind Farm

The contemporary wind turbines are made up of several components. Each one of them contains a specific function correlated to each other in order to conduct better extraction of energy (see Figure 1.1); further, the decomposition of components help the owner of a wind turbine to pay for less expensive parts when they need to be replaced [2].

By analyzing each component it is possible to get a better understanding of the product; Figure 1.1 shows the components of vertical axis wind turbines, and Appendix I illustrates different wind turbines.

Figure 1.1 VAWT (Vertical Axis Wind Turbine) components [2]
Wind turbines are machines that produce electrical power from wind kinetic energy. Wind turbines are designed and created by different companies making them accessible to us in different sizes and therefore with a range of power ratings. With a wind turbine size of a rotor among 8 ft. to 25 ft. in diameter and 30 ft. tall, this wind turbine is able to supply energy to a home or a small business. On the other hand they can be as big as a building 20 stories high and its rotor bigger than a football field energizing an average of 1,400 homes.

Until now has been presented how a wind turbine works, the energy produced, classifications, general advantages and disadvantage, the next concept to discuss is the wind farm.

A wind farm is a group of interconnected wind turbines which provide more overall power, and the electricity from a wind farm can be fed into a grid to allocate it to its customers, like your local power plant. Wind farms can be separated into four different types described in Appendix II.

### 2.2 Wind turbine classification type

In today’s world market, mainly it is found that wind turbines are classified in two types regardless their size: horizontal axis (HAWT) and vertical axis (VAWT). Refer to Table 2.1 (page 7 to 9) that showed the classification of wind turbine by type and presented some advantages and disadvantages of HAWT and VAWT; also exist modified versions and some other types. See also Appendix I for HAWT and VAWT figures.
<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAWT</td>
<td>1. Efficient</td>
<td>1. Does not cope well with frequently changing wind and direction</td>
</tr>
<tr>
<td></td>
<td>2. Proven product</td>
<td>2. Does not cope well with buffering</td>
</tr>
<tr>
<td></td>
<td>3. Widely used</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Most economic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Many products available</td>
<td></td>
</tr>
<tr>
<td>VAWT</td>
<td>1. Quite efficient</td>
<td>1. Not efficient</td>
</tr>
<tr>
<td></td>
<td>2. Different Wind directions</td>
<td>2. Comparatively uneconomic</td>
</tr>
<tr>
<td></td>
<td>3. Less sensitive to turbulence than a HAWT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Create fewer vibrations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Can benefit from turbulent flows</td>
<td></td>
</tr>
<tr>
<td>DAWT (Diffuser-Augmented Wind Turbines or Ducted Rotor)</td>
<td>1. The ducted rotor can operates in a wide range of winds and generate a higher power per unit of rotor area</td>
<td>1. The duct is usually quite heavy, which puts an added load on the tower</td>
</tr>
<tr>
<td></td>
<td>2. The generator operates at a high rotation rate, so it doesn't require a bulky gearbox, so the mechanical portion can be smaller and lighter</td>
<td></td>
</tr>
<tr>
<td>Maglev wind turbine</td>
<td>1. Magnetic levitation turbines are an experiment in adapting maglev bearings for wind turbines. If successful they are likely to reduce substantially wind speeds necessary for power generating and increase operating efficiency</td>
<td>1. The opposing experts believe that this vertical axis wind turbine has some serious design flaws</td>
</tr>
<tr>
<td></td>
<td>2. This large wind turbine from maglev industries will also increase generation capacity by 20% at the same time decreasing operational costs by 50% over the traditional wind turbine</td>
<td>2. The opposing experts believe that it has too many blades leaving the turbine to look “solid” to the wind as it speeds up in strong winds</td>
</tr>
<tr>
<td></td>
<td>3. Is capable of generating power from wind speeds as low as 1.5 m/s and reported to operate in winds reaching 40 m/s</td>
<td>3. Stators are also lacking in the design to direct the flow more effectively onto the blades</td>
</tr>
<tr>
<td>Co-axial, multi-rotor horizontal-axis turbines</td>
<td>1. Power multiplied several times using co-axial</td>
<td></td>
</tr>
<tr>
<td>Counter-rotating horizontal-axis turbines</td>
<td>1. Counter rotating turbines increases the rotation speed of the electrical generator</td>
<td>1. Overall, this is a more complicated design than the single-turbine wind generator, but it taps more of the wind's energy at a wider range of wind speeds</td>
</tr>
<tr>
<td>Type</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Modified HAWT</td>
<td><strong>Telescopic blades</strong> 1. Telescopic blades make a turbine more productive by increasing the turbines rotor diameter during low wind conditions 2. In high wind conditions when the turbine is in need of reducing loads the blades can be retracted to make the rotor smaller</td>
<td>1. The extendable blades cost more to make</td>
</tr>
<tr>
<td>Aerial</td>
<td>1. It has been suggested that wind turbines could be flown in high speed winds at high altitude taking advantage of the steadier winds at high altitudes</td>
<td>1. No such systems currently exist in the marketplace</td>
</tr>
<tr>
<td>Vaneless ion wind generator</td>
<td>1. A vaneless ion wind generator or power fence is a proposed wind power device that produces electrical energy directly by using the wind to pump electric charge from one electrode to another, with no moving parts 2. The bird deaths, vibration noise, and moving shadows associated with wind turbines would not occur with ion based power generation</td>
<td>1. The main advantage of this system is that it has no moving parts except the water droplets. The disadvantages are that it needs a constant supply of water, its wind profile cannot be reduced, it requires many small parts, and it has to be well-crafted to reduce corona discharge losses</td>
</tr>
<tr>
<td>Piezoelectric wind turbines</td>
<td>1. Piezoelectric wind turbines could be very useful for generating energy by having a building covered with a small leaf-shaped piezoelectric material similar to an ivy-clad house, which then take and store wind energy as it blows around the building</td>
<td>1. The power densities coming out of recent studies of this kind suggest that they are 'orders of magnitude' away from the desired output, typically around 0.15-0.2μW</td>
</tr>
<tr>
<td>Solar updraft towers</td>
<td>1. It combines three old and proven technologies: the chimney effect, the greenhouse effect, and the wind turbine 2. The air current from the greenhouse up the chimney drives turbines, which produce electricity 3. The main advantages of the solar updraft tower model is the simplicity of its design and the low maintenance costs after the system is operating</td>
<td>1. A disadvantage of a solar updraft tower is the much lower conversion efficiency than concentrating solar power stations have, thus requiring a larger collector area and leading to higher cost of construction and maintenance 2. The intensive amount of land needed to build the collector to an appropriate scale. Not only are large, flat pieces of land required, but this land cannot be in an area prone to natural disasters or frequent bad weather</td>
</tr>
</tbody>
</table>
2.3 Power in wind that flows through a rotor

![Wind turbine representations with wind passing through the rotor](image)

The theoretical power in the wind which flows through a rotor of a wind turbine is directly proportional to the air density, the rotor radius, and the wind speed before passing through the rotor (refer to Figure 2.1 and equation 2.1).

$$P_w = 0.5\rho\pi R^2 V_b^3 \quad \text{.......................... (2.1)}$$

Where $P_w$ is the power in the wind which flows through the rotor, $\rho$ is the air density, $R$ is the rotor radius, and $V_b$ is the wind speed before passing the rotor. Maximization of the power from the wind required the optimal control settings of the wind turbine parameters and the power in wind available that flows through the rotor. [4]
2.4 The power generation process through a wind turbine

![Diagram of wind turbine power generation](image)

**Figure 2.2 Power generation of a wind turbine**

To understand the basic concept of wind turbine power optimization considers the following.

The rotor blades convert some of the kinetic energy of the wind to mechanical energy on the rotor shaft, Figure 2.2. The efficiency of this conversion depends on several factors such as blade profiles, pitch angle, tip speed ratio and air density. The pitch angle, $\beta$, is the angle of the blades towards the rotational plane. If the pitch angle is low, the blades are almost perpendicular to the wind and if it is high (near 90 degrees) the blades are almost in parallel with the hub direction.

There are several density functions which can be used to describe how the wind speed is distributed. The two most common are the Weibull and the Rayleigh functions [5].

Comparisons with measured wind speeds over the world show that the wind speed can be reasonably well described by the Weibull density function if the time period is not too short. Periods of several weeks to a year or more is usually reasonably well described by the Weibull distribution but for shorter time periods the agreement is not so good [5].


2.5 Layout of the wind farm

A typical wind farm can be represented by the sketch presented in Figure 2.3. As seen in Figure 2.3, a general layout of a wind farm consists of a number of elements, wind turbines, local wind turbine grid, collecting point, transmission system, and wind farm interface to the point of common connection (PCC). The local wind turbine grid connects the wind turbine units to the collecting point. The wind turbine units are connected in parallel to radials, unless otherwise is specified. In the collecting point, the voltage is increased to a level suitable for transmission. The energy is then transmitted to the wind farm grid interface over the transmission system. The wind farm grid interface adapts the voltage, frequency and the reactive power of the transmission system to the voltage level, frequency and reactive power demand of the grid in the PCC. [5]

Figure 2.3 Typical wind farms [5]
2. 6 Common assumptions in wind farm research

Modeling the wind farm layout design problem calls for assumptions. However, the assumptions made could be acceptable in industrial applications and they could be modified or even removed, if necessary. Next table 2.2 showed some assumptions [6].

Table 2.2 Assumptions in wind farm research

<table>
<thead>
<tr>
<th>Assumption Number</th>
<th>Assumption description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumption 1</td>
<td>For a wind farm project, the number of wind turbines N is fixed and known before the farm is constructed. A typical wind farm project has its total capacity goal dictated by various factors, such as finances and turbine availability. For example, to achieve 150MW (Mega Watt) capacity, a hundred 1.5MW turbines are needed.</td>
</tr>
<tr>
<td>Assumption 2</td>
<td>Wind turbine location is characterized by its two dimensional Cartesian coordinates (x, y), represented as a vector x of the length. This assumption implies that the terrain has relatively small variations of surface roughness.</td>
</tr>
<tr>
<td>Assumption 3</td>
<td>The wind turbines considered for a wind farm are homogenous, i.e., they all have the same power curve function P = f (v), where v is the wind speed at the wind turbine rotor with a fixed height, P is the turbine power output.</td>
</tr>
<tr>
<td>Assumption 4</td>
<td>Wind speed v (at a given location, height, and direction) follows a Weibull distribution.</td>
</tr>
<tr>
<td>Assumption 5</td>
<td>Wind speeds at different locations with the same direction share the same Weibull distribution across a wind farm.</td>
</tr>
<tr>
<td>Assumption 6</td>
<td>Any two turbines in a wind farm are separated from each other by at least 4 rotor diameters. Ensuring sufficient spacing between adjacent turbines reduces interactions, e.g., wind turbulence, thus diminishing the hazardous loads on the turbine.</td>
</tr>
</tbody>
</table>
2.7 Problem identification

To solve power optimization problems in wind turbines and wind farms, existed some different approaches and technical methodologies that could be applied depending the different scenarios and condition such as: data available, variables, terrain conditions, turbine type, wind farm capacity, wind farm characteristics, it also must consider what kind of assumptions could be apply, resources available, time and cost, etc.

Table 2.3 present us a summary of some research issues, technical methodologies for power prediction, power optimization and best wind turbine placement, for different scenarios.

<table>
<thead>
<tr>
<th>Research Issues</th>
<th>Technical methodology</th>
<th>Optimization scenario and approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased prediction accuracy of wind power to be produced at future time periods is often bounded by the prediction model complexity and computational time involved [7].</td>
<td>Clustering approach methodology [7].</td>
<td>For short-term prediction of power produced by a wind turbine. Low wind speeds scenarios when a model is produced with data mining algorithms</td>
</tr>
<tr>
<td>The wind power industry is rapidly expanding, and accurate power forecasting is essential. Wind power forecasts are used as input for various simulation tools, including market operations, unit commitment and economic dispatch [8].</td>
<td>Data Mining algorithms: SVM (the support vector machine regression), multi layer perception network (MLP), radial basis function (RBF) network, classification and regression (C&amp;R) tree and random forest [8]</td>
<td>The direct prediction of wind farm power.</td>
</tr>
<tr>
<td>Research Issues</td>
<td>Technical methodology</td>
<td>Optimization scenario and approaches</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>There is no industry standard for power ramp rate (PRR) prediction. PRR on 10 min intervals is to benefit the grid management and power scheduling in the wind industry [9].</td>
<td>Data Mining algorithm: MLP (multilayer perception network), SVM (support vector machine), Random Forest, C&amp;R tree (classification and regression tree), Pace regression [9]</td>
<td>Developing power and PRR (power ramp rates) and prediction models for wind farms.</td>
</tr>
<tr>
<td>Power production can be influenced by many factors and usually fluctuates rapidly, imposing considerable difficulties on the management of combined electric power systems. Several different techniques have been presented to estimate and predict the highly variable energy production [10].</td>
<td>Prediction by Regression Model and Neural Network [10].</td>
<td>To estimate and predict the highly variable energy (power) production of wind farms.</td>
</tr>
<tr>
<td>The rapid expansion of alternative energy creates challenges related to the power quality. The power quality issue can be addressed at the wind turbine or the wind farm level [4].</td>
<td>Data Mining algorithms and evolutionary computation algorithm [4].</td>
<td>Optimization for the Active Power and Power Factor for Low speed and High speed wind scenarios.</td>
</tr>
<tr>
<td>Due the low-speed operation, direct-drive PM wind turbine concepts may have disadvantages such as the large diameter, heavy weight, and high cost of generators. With the increase of rated power levels and the decrease of wind turbine rotor speeds, these direct-drive systems are becoming larger and even more expensive, and also have higher technical difficulties of transport and assembly. Therefore, an interesting alternative may be a mixed solution with a single-stage planetary gearbox and a medium-speed PM generator, which was first introduced by Multibrid of Germany [11].</td>
<td>Improved genetic algorithm (IGA) [11].</td>
<td>Optimization of the electromagnetic design of the investigated wind generator systems.</td>
</tr>
<tr>
<td>Research Issues</td>
<td>Technical methodology</td>
<td>Optimization scenario and approaches</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>The wind climate in complex terrain and offshore can be substantially different from that of normal flat terrain. This will affect turbine design assumptions and represents a potential for cost reduction by site-specific design. Such design can be achieved by optimization of the wind turbine for the specific site, by taking into account terrain and wind conditions [12].</td>
<td>Design tools based on numerical optimization and earolastic were combined with a cost model [12].</td>
<td>To allow optimization for minimum cost of energy, where site characteristics were incorporated into the design process of wind turbines.</td>
</tr>
<tr>
<td>The wind energy industry is looking for novel ways of reducing costs. Examples of areas where the cost could be reduced include: site selection for wind farms, layout design, and predictive maintenance. The site selected and layout design of a wind farm could extend the lifetime of turbines as well as increase wind energy production. Another meaningful way to reduce costs is to optimize the capture of energy from the wind with effective control strategies [13].</td>
<td>Evolutionary computation algorithm [13].</td>
<td>Maximization of the power produced by wind turbines.</td>
</tr>
<tr>
<td>Wind energy poses challenges such as the reduction of the wind speed due to other turbines. Normally, if a turbine is within the area of turbulence caused by another turbine, or the area behind another turbine, the wind speed suffers a reduction, and therefore there is a decrease in the production of electricity [14].</td>
<td>Viral based optimization algorithm [14]</td>
<td>To find the optimal solution to wind turbine placement problems.</td>
</tr>
<tr>
<td>Obtain the maximum energy production combined with the minimum cost. The basic factor that is examined is the optimal positioning of wind turbines in a wind farm [15].</td>
<td>Monte Carlo simulation [15]</td>
<td>Optimal placement of wind turbine In a wind park (wind farm).</td>
</tr>
</tbody>
</table>
### Research Issues

Some works for wind turbines positioning are based on the genetic algorithm. Genetic algorithms always take a lot of time to get a solution, and this will be an obstacle when the wind condition is complicated. Besides, there is no guarantee about the quality of the solution. That means there is no knowledge about how good the solution is. And in those works, only the flat terrain is considered. While in many real-world instances, wind farms are built in mountains or some other types of terrain, not always in a flat area [16].

Where large wind resources exist, wind energy converters are even becoming economically competitive compared to electrical power produced by other conventional means. However, for multi-megawatt production, a large number of wind turbines must be installed, and the efficiency of the wind farm is highly influenced by their positioning. The present work discusses a novel approach to the wind turbine positioning problem [17].

### Technical methodology

<table>
<thead>
<tr>
<th></th>
<th>Greedy Algorithm For Turbine Positioning [16].</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>To maximize the total extracted power of a wind farm by turbine positioning.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>The genetic algorithm applied to wind farms [17].</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>To find the best wind farm configuration on a given terrain.</td>
</tr>
</tbody>
</table>

### Optimization scenario and approaches

<table>
<thead>
<tr>
<th></th>
<th>Greedy Algorithm For Turbine Positioning [16].</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>To maximize the total extracted power of a wind farm by turbine positioning.</td>
</tr>
</tbody>
</table>

### 2.8 Genetic algorithm

Genetic algorithm was developed by Holland and his colleagues in the 1960s and 1970s. It is inspired in evolutionist theory explaining the origin of species. GA belongs to the larger class of evolutionary algorithms, which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover.

Along the time genetic algorithms has suffer a lot of modifications, it could be found and extensive literature review that showed it well performance against the different methods, so it is well proved methodology.

A common GA terminology is that for a solution vector $x \in X$ is called an individual or a chromosome. These chromosomes are made of discrete units called genes that control one or
more features of the chromosomes. These genes are assumed to be binary digits. A collection of chromosomes is known as a population. The population is normally initialized randomly. Furthermore, it is used two operators to generate new solutions from existing ones. The first operator is the crossover. This is the most important operator of GA. In here, generally two chromosomes, called parents, are combined to form new chromosomes, called offspring.

The parents are selected among existing chromosomes in the population based on fitness so that offspring is expected to get good genes which make the parents filter. By applying the crossover, genes of good chromosomes are expected to appear more frequently in the population. For the mutation operator, it introduces random changes into characteristics of chromosomes. It is generally applied at the gene level. Commonly, the mutation rate is very small and depends on the length of the chromosome. As a consequence, the new chromosome produced by mutation will not be very different from the original.
Chapter 3

METHODOLOGY

Based on the literature review and the aforementioned research issues, the solution approach that involved CIA and MOGA is proposed in Section 3.1

3.1 The proposed methodology

Figure 3.1 demonstrates a conceptual framework of the proposed methodology, and Figure 3.2 depicts more detailed steps in the methodology.

Figure 3.1 Flow chart of general methodology
Figure 3.2 Flow chart of detailed methodology
3.2 Methodology and strategy

As an initial concept of the next methodology, it is understood that the rows and columns of the matrices generated are used as an input and output data and are based on terrain reference coordinates of integers and represent only the coordinates of the terrain; the function of the coordinates are tracked the wind turbine position from the beginning of the methodology until the end of it. The coordinates will be a normal row and column sequence (i.e., starting from left to right and from high to low). Also as a constraint in this methodology it is consider that wind direction goes from west to east.

3.2.1 Wind power, efficiency and wind farm cost

This section is focused on describing the concepts of power in the wind, efficiency of the power in the wind that a wind farm is exposed and cost for wind farms. As input data we have controllable, non-controllable, and performance parameters representing the land characteristics, wind speed and wind turbines characteristics. Next is a table 3.1 that classified the input data and showed its definition and its symbol.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V^3)_{avg}</td>
<td>Average wind velocity</td>
<td>m^3</td>
</tr>
<tr>
<td>ρ</td>
<td>Air density</td>
<td>1.225 kg/m³</td>
</tr>
<tr>
<td>U</td>
<td>The wind speed downstream of the turbine</td>
<td>m/s</td>
</tr>
<tr>
<td>U₀</td>
<td>The wind speed before reach the turbine</td>
<td>m/s</td>
</tr>
<tr>
<td>A_{ij}</td>
<td>Sweep rotor Area</td>
<td>m²</td>
</tr>
<tr>
<td>r₀</td>
<td>Pivot wind turbine rotor radius</td>
<td>m</td>
</tr>
<tr>
<td>P_{ij}</td>
<td>Ideal power in the wind that a wind turbine is exposed</td>
<td>Kw</td>
</tr>
<tr>
<td>P'_{ij}</td>
<td>Real power in the wind that a wind turbine is exposed</td>
<td>Kw</td>
</tr>
<tr>
<td>R_P</td>
<td>Total real power in the wind that wind farm is exposed</td>
<td>Kw</td>
</tr>
<tr>
<td>P_{avg}</td>
<td>The specific power average in the wind at a height H₀</td>
<td>W/m²</td>
</tr>
<tr>
<td>Y_{ij}</td>
<td>Is the height of the terrain at an specific (i, j) position in meters, where (i=1, 2….m) (j=1, 2….n)</td>
<td>m</td>
</tr>
<tr>
<td>L_K</td>
<td>Hub height</td>
<td>m</td>
</tr>
<tr>
<td>H₀</td>
<td>wind data normally 10 m</td>
<td>m</td>
</tr>
<tr>
<td>α</td>
<td>Is the friction coefficient, the table 3.3 showed common values for specific terrain characteristics</td>
<td>No units</td>
</tr>
<tr>
<td>X_{ijk}=1, 0</td>
<td>I mean exist a turbine and 0 not exist in the i row and j column position, with a k value that correspond to a turbine type.</td>
<td>No units</td>
</tr>
<tr>
<td>Z_K</td>
<td>Wind turbine Power Rate in KW for a K turbine type</td>
<td>Kw</td>
</tr>
<tr>
<td>Y_{min}</td>
<td>Maximum and Minimum height in the large scale terrain</td>
<td>m</td>
</tr>
<tr>
<td>Y_{max}</td>
<td>Maximum and Minimum height in the large scale terrain</td>
<td>m</td>
</tr>
<tr>
<td>Increment</td>
<td>Range increment of the bins where the Algorithm for terrain selection</td>
<td>m</td>
</tr>
<tr>
<td>LL_j</td>
<td>Lower height limit</td>
<td>m</td>
</tr>
<tr>
<td>UL_i</td>
<td>Upper height limit</td>
<td>m</td>
</tr>
<tr>
<td>Matrix A</td>
<td>Matrix that represent a large terrain that is dived in cells that contained the height, the row and columns identification are the terrain reference coordinates, normally use in a XY graph. In integers numbers</td>
<td>Entries in m</td>
</tr>
<tr>
<td>Matrix B</td>
<td>Matrix that represent a large terrain that is dived in cells that contained 1 or 0, after the classification based on LL_j and UL_i, the row and columns identification remain the same as in Matrix A, and the terrain reference coordinates are as normally use in a XY graph in integers numbers</td>
<td>Entries: 1 or 0</td>
</tr>
<tr>
<td>Matrix C</td>
<td>Matrix C that represent a subset of Matrix B, the row and columns identification remain the same after matrix B decomposition</td>
<td>Entries: 1 or 0</td>
</tr>
<tr>
<td>Matrix a</td>
<td>Sub set of Matrix A, that contains the heights based on the rows and columns from Matrix C, since is a subset of Matrix A,</td>
<td>Entries: m</td>
</tr>
</tbody>
</table>
### 3.2.1.1 Wind power generation

In this section, some assumptions are made, such as: all the wind turbines have different capacities and characteristics, the wind speed is based on a Weibull distribution, and only one wind direction is considered.

First, to calculate the average wind velocity based on the data, is necessary applied the next equation 3.1:

\[
(V^3)_{avg} = \sum_{i=0}^{n} [V_i^3 \text{(probability}(V = V_i)] \\
\]

\[\text{..................} \text{........................................ (3.1)}\]

Then, the specific power average in the wind has to be calculated with the following equation 3.2:

\[
P_{avg} = 1/2\rho(V^3)_{avg} \text{................................................................. (3.2)}\]

At this point it is necessary to remember that the wind farm concept is an array of turbines, each positioned in an i j position and on an i j height (Yij). Then, once the Pavg value is obtained, it is necessary to use the value to calculate the power in the wind that flows through the rotor for all the turbines positioned on each i j position of the wind farm. First evaluating individual Pij and then adding up all Pij values, the result is the power in the wind that the wind farm is exposed to.

Next, equation 3.3 defined the ideal total power in the wind that the wind farm is exposed to.

\[
P_{total} = \sum_{j=1} \sum_{i=1} P_{ij} = \sum_{j=1} \sum_{i=1} P_{avg}(\frac{Y_{ij} + L_k}{H_0})^{(3+\alpha)} X_{ij} A_{ij} \text{.................................................. (3.3)}\]

One important factor that has to be taken into account is a downstream effect that is the quantity
of reduced power in the wind that the remaining turbines are exposed to by placing a turbine on a position ahead. Refer to Appendix III for theory and equations.

Most of the wake decay theory is considered in a flat terrain, and based on that it is necessarily helpful to know how proceed in the mountain terrain; as a rule or criteria for this work the wake decay model will be considered only if $r_1$ overpasses more than the 50% of rotor area of the affected turbine.

That is, a pivot position $ij$ is considered to calculate downstream effect only when the $r_1$ effect is covering at least 0.5 of the rotor area of the affected turbine, and is then considered significant.

This assumes that none of the turbines have to be behind a higher terrain height that is obviously going to block the wind, so it is then easy to apply the wake decay model to determine the losses caused by the turbine ahead.

Next are described the equations of the wake decay model applied to each turbine individually.

The wind speed downstream is represented in next equation 3.4:

$$U = U_0 \left[ 1 - \frac{2a}{\left(1 + a \left(\frac{r_1}{r_2}\right)\right)^2} \right]$$

Where $U_0$ is calculating, using equation 3.5:

$$\left(\frac{P}{P_0}\right) = \left(\frac{1/2 \rho A U_0^3}{1/2 \rho AV_0^3}\right) = \left(\frac{U_0^3}{V_0^3}\right) = \left(\frac{H}{H_0}\right)^{3a}$$

$U_{0ij}$ has to be calculated for all the turbines on all the positions in the wind farm. That will give the data is needed to calculate $U_{ij}$. 

Next equation 3.6 showed how to calculate $r_1$:

$$r_1 = \alpha x + r_r$$ \hspace{8cm} (3.6)

Once the $ij$ turbine pivot position is selected, it has to compute the $r_1$ which is a dependent function of the position of the remaining turbines due the distance $x$ among turbines; then, it has to be evaluated if $r_1$ affects more than the 50% of $r_r$ of the turbine affected. If it is, it is necessary to calculate the $U_{ij}$ values for all the positions that affect the pivot position by using the previous equation 3.4.

Then we use these downstream $U_{ij}$ values to calculate the power in the wind that the next turbines are exposed to.

Finally the power in the wind that the turbines affected are exposed to uses the next equation 3.7.

$$R_{ij} = 1/2 \rho U_{(ij)}^3 X_{ij} A_{ij}$$ \hspace{8cm} (3.7)

Therefore the real power (RP) in the wind that the wind farm is exposed to can be described by the next equation 3.8

$$RP = \sum_{i=1}^{\text{wind farm}} \sum_{i=1}^{\text{wind farm}} P_{ij} = \sum_{i=1}^{\text{wind farm}} \sum_{i=1}^{\text{wind farm}} 1/2 \rho U_{(ij)}^3 X_{ij} A_{ij}$$ \hspace{8cm} (3.8)

Therefore, the losses of power in the wind that the wind farm is exposed to, due to the wake decay model, is the difference among the ideal total power in the wind that a wind farm is exposed to, equation 3.3, and the real power (RP) in the wind that the wind farm is exposed to by
equation 3.8. This could be observed in next equation 3.9.

\[
\text{Total Losses} = \sum_{j=1}^{\cdot} \sum_{i=1}^{\cdot} P_{ij}' - \sum_{j=1}^{\cdot} \sum_{i=1}^{\cdot} P_{ij} \tag{3.9}
\]

Equation 3.9 is the basis to understand and define the efficiency of the power in the wind that the wind farm is exposed to and is affected by for the aerodynamic losses.

### 3.2.1.2 Wind power efficiency

At this point, and based on the concept that in a system the efficiency is defined as the output divided by the input. The input is considered the ideal power in the wind that the wind farm is exposed to without losses due to the way decay model, as in a perfect system, equation 3.3 and the output is the real power in the wind that the wind farm is exposed including losses, equation 3.9; Is an abstract efficiency since it has to be used the definition of ideal power in the wind that the wind farm is exposed. Next equation 3.10 defined wind farm efficiency.

\[
\text{Efficiency} = \frac{\sum_{j=1}^{\cdot} \sum_{i=1}^{\cdot} 1/2(\rho U_{(ij)}^3 X_{ij} A_{ij})}{\sum_{j=1}^{\cdot} \sum_{i=1}^{\cdot} P_{avg}(\frac{Y_{ij} + L_i K}{H_o})^{3 \cdot \alpha} X_{ij} A_{ij}} \ldots \tag{3.10}
\]

Figure 3.3 Efficiency of the power in the wind that the wind farm is exposed
3.2.1.3 Wind farm cost

To evaluate the cost of the wind farm, only the price of the wind turbines was considered. Installation, maintenance and others were not considered in order to formulate the problem simpler.

3.2.2 Objective functions

The main objective of this paper is to determine the optimal positioning of wind turbines that will maximize wind power generation, maximize wind power efficiency and minimize the cost by using the genetic algorithm in a non-flat terrain application. It can be summarized in the next optimization statement:

Efficiency of wind power that the wind farm is exposed to:

\[
\text{Max} \left\{ \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} 1/2 \rho U_{ij}^3 \left( X_{ij}A_{ij} \right) \right\} / \left[ \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \rho \left( \frac{Y_{ij} + L_K}{H_0} \right)^{3+\alpha} X_{ij}A_{ij} \right]. \tag{3.11}
\]

Wind power that the wind farm is exposed to:

\[
\text{Max} \left\{ \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} 1/2 \rho U_{ij}^3 \left( X_{ij}A_{ij} \right) \right\}. \tag{3.12}
\]

Cost

\[
\text{Min} \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} X_{ij} \text{(Unit cost)} \quad \forall \ i = 1, 2, 3 \ldots \ n, j = 1, 2, \ldots m \tag{3.13}
\]

Where:
\[
P_{avg} \text{= the average power in the wind at a height H0 in W/m2}
\]
\[
Y_{ij} \text{= is the height of the terrain at a specific (i, j) position in meters, where (i=1, 2,...m) (j=1, 2,...n)}
\]
\[
L_K \text{= Hub Height in meters}
\]
\[
H_0 \text{= 10 m}
\]
\[
\alpha \text{= is the friction coefficient, the following table 3.3 showed us common values of } \alpha \text{ for specific terrain characteristics.}
\]
Table 3.2 Values of $\alpha$

<table>
<thead>
<tr>
<th>Terrain Characteristics</th>
<th>Friction Coefficient $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth hard ground, calm water</td>
<td>0.1</td>
</tr>
<tr>
<td>Tall grass on level ground</td>
<td>0.15</td>
</tr>
<tr>
<td>High crops, hedges and shrubs</td>
<td>0.2</td>
</tr>
<tr>
<td>Wooded countryside, many trees</td>
<td>0.25</td>
</tr>
<tr>
<td>Small town with trees and shrubs</td>
<td>0.3</td>
</tr>
<tr>
<td>Large city with tall buildings</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$X_{ijk} = 1$, 0 mean exist a turbine and 0 not exist in the $i$ row and $j$ column position, with a $k$ value that corresponds to a turbine type.

$A_{ij} =$ Sweep rotor Area in m$^2$

$U =$ The wind speed downstream of the turbine in m/s

$Z_K =$ Wind turbine power rate in KW for a $K$ turbine type.

<table>
<thead>
<tr>
<th>Turbine Type $K$</th>
<th>$Z$ Power Rate (KW)</th>
<th>Sweep Area ($m^2$)</th>
<th>L Hub height (m)</th>
<th>C Cost USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kesim</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unit Cost= Turbine cost (Constant)

Constraints:

$a \leq \sum X_{ij} \leq b$, $\forall i,j$ where $i=\{1,2,3\ldots\}$, $j=\{1,2,3\ldots m\}$ and where $a$ and $b$ are the minimum and maximum number of turbines

$\sum X_{ij1} \leq b_1$, $\sum X_{ij1} \leq b_2$, $\sum X_{ij1} \leq b_3$, $\sum X_{ij1} \leq b_4$ where $b_1$, $b_2$, $b_3$ and $b_4$ are the maximum number of turbines by type.

$X_{ij} = 0, 1 \forall i,j$
3.2.3 Algorithm for wind farm terrain selection

To find an optimal wind farm layout and solve wind turbine placement problems the next sections described how applied the methodology.

In the turbine positioning problem, the available terrain can be subdivided into cells. To keep the necessary distance between two adjacent turbines, the size of a cell is suitably chosen and every turbine is installed only on the center of a cell. So, the available positions are finite, and has to be found from a large set of terrain cells to provide the genetic algorithm a terrain with proper characteristics.

3.2.3.1 New Heights Matrix concept and contributions

To apply the previous optimization equations is necessary introduce one variable that is called potential position with height $Y_{ij}$ that is a potential area that could be used to positioning a wind turbine in a large terrain. To understand the concept of variable $Y_{ij}$, refer to next Figure 3.4 that is a top view of the Franklin mountains at west of El Paso TX area. Let’s take a square portion area of this figure and sub-divided in a square matrix, see figure 3.5, with all possible WT positions with height of each position.
Figure 3.4 Franklin mountains top view

Figure 3.5 Matrix of a large set of heights
It is consider that the wind direction goes from west to east, now it has to defined that not all positions are suitable to be considered since could occurred the case that a high hill ahead blocks the wind to the next position and therefore the wind turbine will not receive and optimal wind speed and make the case costly unnecessarily. Therefore to use the MOGA properly is necessary to apply the next Algorithm where the input is large set of heights of a terrain matrix and the output is a small subset of the original height matrix with the objective to have a suitable terrain with no high hills that block the next wind turbine position. At the end by common sense it is obtained a matrix subset where all the heights of columns are into a specific range with limits incrementing from column to column as a cluster bins making the position heights incrementing for less to more.

### 3.2.3.2 Description of the proposed algorithm

#### Assumptions

1. - Single wind direction (west to east)

2. - Matrix coordinates identification are the terrain reference coordinates, normally use in a XY graph.

3. - Turbine can have different characteristics such as rotor area, hub height etc, and quantity is variable not fixed, just a maximum value is give

4. – Large scale terrain characteristics are a terrain with mountains and from the beginning is selected an area with a certain tendency from lower to higher hill in the direction of the wind.

5. – Downstream wake decay model 50 % rule, explained in detailed in methodology part

6 – No cut in and cut off wind speed will be considered for calculations.
**Algorithm**

**Step 0.** Divide the terrain (Area) in sections of 5D X 5D, where D is the average of the diameters of the rotors of the wind turbines available and plug in the average terrain height. This will generate the rows and columns of matrix A where each entry is the height information for every cell.

Following is the representation of Matrix A.

<table>
<thead>
<tr>
<th>Position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>...</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y11</td>
<td>Y12</td>
<td>Y13</td>
<td>Y14</td>
<td>Y15</td>
<td>Y16</td>
<td>Y17</td>
<td>...</td>
<td>Y1m</td>
</tr>
<tr>
<td>2</td>
<td>Y21</td>
<td>Y22</td>
<td>Y23</td>
<td>Y24</td>
<td>Y25</td>
<td>Y26</td>
<td>Y27</td>
<td>...</td>
<td>Y2m</td>
</tr>
<tr>
<td>3</td>
<td>Y31</td>
<td>Y32</td>
<td>Y33</td>
<td>Y34</td>
<td>Y35</td>
<td>Y36</td>
<td>Y37</td>
<td>...</td>
<td>Y3m</td>
</tr>
<tr>
<td>4</td>
<td>Y41</td>
<td>Y42</td>
<td>Y43</td>
<td>Y44</td>
<td>Y45</td>
<td>Y46</td>
<td>Y47</td>
<td>...</td>
<td>Y4m</td>
</tr>
<tr>
<td>5</td>
<td>Y51</td>
<td>Y52</td>
<td>Y53</td>
<td>Y54</td>
<td>Y55</td>
<td>Y56</td>
<td>Y57</td>
<td>...</td>
<td>Y5m</td>
</tr>
<tr>
<td>6</td>
<td>Y61</td>
<td>Y62</td>
<td>Y63</td>
<td>Y64</td>
<td>Y65</td>
<td>Y66</td>
<td>Y67</td>
<td>...</td>
<td>Y6m</td>
</tr>
<tr>
<td>7</td>
<td>Y71</td>
<td>Y72</td>
<td>Y73</td>
<td>Y74</td>
<td>Y75</td>
<td>Y76</td>
<td>Y77</td>
<td>...</td>
<td>Y7m</td>
</tr>
<tr>
<td>8</td>
<td>Y81</td>
<td>Y82</td>
<td>Y83</td>
<td>Y84</td>
<td>Y85</td>
<td>Y86</td>
<td>Y87</td>
<td>...</td>
<td>Y8m</td>
</tr>
<tr>
<td>9</td>
<td>Y91</td>
<td>Y92</td>
<td>Y93</td>
<td>Y94</td>
<td>Y95</td>
<td>Y96</td>
<td>Y97</td>
<td>...</td>
<td>Y9m</td>
</tr>
<tr>
<td>10</td>
<td>Y101</td>
<td>Y102</td>
<td>Y103</td>
<td>Y104</td>
<td>Y105</td>
<td>Y106</td>
<td>Y107</td>
<td>...</td>
<td>Y10m</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>n</td>
<td>Yi1</td>
<td>Yi2</td>
<td>Yi3</td>
<td>Yi4</td>
<td>Yi5</td>
<td>Yi6</td>
<td>Yi7</td>
<td>...</td>
<td>Yij</td>
</tr>
</tbody>
</table>

**Step 1.** Determine the minimum and maximum height value $Y_{\min}$, $Y_{\max}$ of Matrix A.

**Step 2.** Obtain the increment of the limits by the next formula:

\[
\text{Increment} = \frac{(Y_{\max} - Y_{\min})}{m}
\]

**Step 3.** To establish the limits of each column position of Matrix A, create a set of limits using the next equation for all positions:

**Lower and Upper Limits of Column 1:** $LL_1 = Y_{\min} \times 1$, $UL_1 = Y_{\min} + \text{Increment}$

**Limits of remaining columns:** $LL_j = Y_{\min} + \text{Increment} \times \text{Column position} j$, 

$UL_j = LL_j + \text{Increment}$
Step 4. Once the limits are created for each column is necessary classified each \( Y_{ij} \) value as 1 or 0 in a new created Matrix B of size nxm. As follows:

If \( LL_j < Y_{ij} < UL_j \) then place a 1 in the matrix B in the \( ij \) position if not enter a 0.

Note: in case it is consider by the designer the ones founded in the Matrix B are not enough for implement a feasible wind farm. It is require wide up the limits combining 2 consecutive columns and using the limits as \( LL_j \) and \( UL_{j+1} \) as new bins in pairs, if the total column is not pair include the last column with the last pair of columns and use as limits \( LL_j \) and \( UL_{j+2} \).

Step 5. Once created the matrix B of 1 and 0’s is necessary apply the Cluster Identification Algorithm (CIA).

Cluster Identification Algorithm

Step 5.0. Set iteration number \( k = 1 \).
Step 5.1. Select row \( i \) of incidence matrix \([aij](k)\) and draw a horizontal line \( h_i \) through it (\([aij](k)\) is read: matrix \([aij]\) at iteration \( k \)).
Step 5.2. For each entry of 1 crossed by the horizontal line \( h_i \) draw a Vertical line \( v_j \).
Step 5.3. For each entry of 1 crossed-once by the vertical line \( v_j \) draw a horizontal line \( h_k \).
Step 5.4. Repeat steps 2 and 3 until there are no more crossed-once entries of 1 in \([aij](k)\). All crossed-twice entries 1 in \([aij](k)\) form row cluster RC-\( k \) and column cluster CC-\( k \).
Step 5.5. Transform the incidence matrix \([aij](k)\) into \([aij](k+1)\) by removing rows and columns corresponding to the horizontal and vertical lines drawn in steps 1 through 4.
Step 5.6. If matrix \([aij](k+1)\) = 0 (where 0 denotes a matrix with all empty elements ), stop; otherwise set \( k = k + 1 \) and go to step 1.

Step 6. From the final decomposition result is necessary to pick the cluster matrix from all created that is fulfill with ones if that is the case or go to the next selection criteria.

Cluster matrix selection criteria:

- Search for the well form arrangements, not the non shaped arrangements.
- Look the matrix that fitter the wind farm size or turbines available.
• If pretty similar cluster matrices, pick the one where the optimal wind turbine positions are in the highest side
• Select the terrain with higher population of optimal positions.
• To test the hypothesis that the best cluster was selected it is recommended to finish the algorithm with different matrix arrangements.

_Step 7._ The matrix pick from step 6 will be the Height Matrix input (subset of matrix A) used in the Genetic algorithm methodology that will be called Matrix a.

_Step 8._ Use Matrix a and applied MOGA to get a set of non-dominated solutions with the local optimal solutions.

**Algorithm Example #1 from step 0 to 7**

_Step 0._ Matrix A: Average terrain heights.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67</td>
<td>77</td>
<td>204</td>
<td>135</td>
<td>162</td>
<td>136</td>
<td>202</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>91</td>
<td>139</td>
<td>237</td>
<td>192</td>
<td>65</td>
<td>200</td>
<td>69</td>
<td>231</td>
</tr>
<tr>
<td>3</td>
<td>71</td>
<td>249</td>
<td>106</td>
<td>69</td>
<td>37</td>
<td>96</td>
<td>72</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>101</td>
<td>51</td>
<td>179</td>
<td>120</td>
<td>100</td>
<td>74</td>
<td>120</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>238</td>
<td>78</td>
<td>144</td>
<td>89</td>
<td>83</td>
<td>245</td>
<td>155</td>
<td>171</td>
</tr>
<tr>
<td>6</td>
<td>244</td>
<td>239</td>
<td>146</td>
<td>232</td>
<td>56</td>
<td>246</td>
<td>244</td>
<td>195</td>
</tr>
<tr>
<td>7</td>
<td>44</td>
<td>85</td>
<td>174</td>
<td>216</td>
<td>123</td>
<td>89</td>
<td>91</td>
<td>135</td>
</tr>
</tbody>
</table>

_Step 1._ Ymin=37, Ymax=249

_Step 2._

Increment=(249-37)/8
Increment=26.5
Step 3. Create a set of limits using the next equation for all positions:

**Lower and upper Limits of Column 1:**

\[
\begin{align*}
LL_1 &= Y_{\text{min}} \times 1 \\
UL_1 &= Y_{\text{min}} \times \text{Increment}
\end{align*}
\]

\[LL_1 = 37 \times 1 = 37\]
\[UL_1 = 37 + 26.5 = 63.5\]

**Limits of remaining columns:**

\[
\begin{align*}
LL_j &= Y_{\text{min}} + \text{Increment} \times \text{Column position } j \\
UL_j &= LL_j + \text{Increment}
\end{align*}
\]

\[LL_2 = 37 + 26.5 \times 2 = 63.5\]
\[UL_2 = 90 + 26.5 = 90\]

\[LL_3 = 37 + 26.5 \times 2 = 90\]
\[UL_3 = 90 + 26.5 = 116.5\]

\[LL_4 = 37 + 26.5 \times 3 = 116.5\]
\[UL_4 = 116.5 + 26.5 = 143\]

\[LL_5 = 37 + 26.5 \times 4 = 143\]
\[UL_5 = 143 + 26.5 = 169.5\]

\[LL_6 = 37 + 26.5 \times 5 = 169.5\]
\[UL_6 = 169.5 + 26.5 = 196\]

\[LL_7 = 37 + 26.5 \times 6 = 196\]
\[UL_7 = 196 + 26.5 = 222.5\]

\[LL_8 = 37 + 26.5 \times 7 = 222.5\]
\[UL_8 = 116.5 + 26.5 = 249\]
Step 4. Matrix A: With columns limits. The highlighted values in red are the values felt into the Bin that will be converted in ones.

<table>
<thead>
<tr>
<th>limits---</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>37-63.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>63.5-90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90-116.5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>116.5-143</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>143-169.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>169.5-196</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>196-222.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>222.5-249</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>64</td>
<td>77</td>
<td>104</td>
<td>145</td>
<td>162</td>
<td>136</td>
<td>230</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>139</td>
<td>237</td>
<td>192</td>
<td>65</td>
<td>190</td>
<td>69</td>
<td>131</td>
</tr>
<tr>
<td>3</td>
<td>71</td>
<td>249</td>
<td>118</td>
<td>119</td>
<td>37</td>
<td>96</td>
<td>212</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>62</td>
<td>51</td>
<td>179</td>
<td>150</td>
<td>100</td>
<td>174</td>
<td>120</td>
<td>99</td>
</tr>
<tr>
<td>5</td>
<td>238</td>
<td>98</td>
<td>115</td>
<td>89</td>
<td>153</td>
<td>245</td>
<td>155</td>
<td>171</td>
</tr>
<tr>
<td>6</td>
<td>244</td>
<td>239</td>
<td>146</td>
<td>132</td>
<td>56</td>
<td>246</td>
<td>244</td>
<td>195</td>
</tr>
<tr>
<td>7</td>
<td>68</td>
<td>85</td>
<td>94</td>
<td>216</td>
<td>163</td>
<td>89</td>
<td>91</td>
<td>235</td>
</tr>
</tbody>
</table>

Matrix B: with ones and zeros. Note that the ones correspond to the previous highlighted values on Matrix A.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
**Step 5. Cluster identification Algorithm.**

**Step 5.0.**

Incidence Matrix B

<table>
<thead>
<tr>
<th></th>
<th>Layout columns</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**Step 5.1 & 5.2.**

Matrix after Steps 5.1 & 5.2

<table>
<thead>
<tr>
<th></th>
<th>Layout columns</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Step 5.3.

Matrix after Steps 3

Step 5.4.
Step 5.5.

Resultant Matrix

Iteration 2.

Iteration 3.

Final decomposition
**Step 6** Selected the Cluster matrix.

![Cluster matrix](image)

**Step 7** Subset of Matrix A to be used in the Genetic Algorithm that is called Matrix a

![Subset of Matrix A](image)

**Advantages of using CIA**

Advantages of using the Cluster identification Algorithm:

- Obtain a sub matrix terrain set making and arrangement from the original terrain.
- Identified different position set that will be used in the GA method
- Give us different wind farm arrays for wind turbines, square or rectangle.
- In general reduce the losses due high peak or valleys
- Work with terrain heights (columns) with increments from low to high, for a wind speed the highest the greater.
- The Matrix a that is the result of CIA is the input for The multi-objective Genetic algorithm that will improved the optimal positions selection and will play with different quantities
3.2.4 Description of MOGA

Being a population-based approach, GA is well suited to solve multi-objective optimization problems. A generic single-objective GA can be modified to find a set of multiple non-dominated solutions in a single run. The ability of GA to simultaneously search different regions of a solution space makes it possible to find a diverse set of solutions for difficult problems with non-convex, discontinuous, and multi-modal solutions spaces. The crossover operator of GA may exploit structures of good solutions with respect to different objectives to create new non-dominated solutions in unexplored parts of the Pareto front. In addition, most multi-objective GA does not require the user to prioritize, scale, or weigh objectives [19]. Although exist many different modified Multi-objective GA, the more common difference is the way they differ based on their fitness assignment procedure, elitism, or diversification approaches. In the present work is used a Pareto Ranking approach, the first Fitness metric is called Distance-based f1 (i): It is intended for maintaining population diversity. Se second Fitness metric is called Dominance Count-based f2 (i): Select those individuals which are more dominating. The MOGA steps and sequence procedure is presented in Figure 3.6 [18].

3.2.5 Application of GA to wind farms

The target of the evolution is to find the best wind farm configuration on a given terrain. For simplicity we can consider as design variable only the position of a number of turbines of a given type. Let us subdivide the available terrain into cells where a turbine could be installed. In this manner a string representation of a wind farm can be easily found: 1 if in the relative cell a turbine exists, 0 if it does not.

A wind farm configuration in a terrain divided into 10 cells will then be represented by a binary
number between $A=0000000000$ and $B=1111111111$.

A mutation will switch one bit, while a crossover between two parents will perform the following transformation:

Parent 1 = 0010110011
Parent 2 = 1110001010
Child 1 = 0010001010
Child 2 = 1110110011

In the example, the crossover locations that are exchanged between the two parents to create the children are from the fourth to the eighth bit. The "goodness" of each individual is defined by the fitness function that will be maximized.

Starting from a given population the fitness of each individual of the population must be evaluated through the wind farm model objective function and on the basis of the fitness value the next generation must be constructed. The new population is obtained through crossover and mutation among the fittest individuals and at random locations. Both operations will occur with a certain probability $0.6<P<0.9$ for a crossover and $0.01<Pro<0.1$ for a mutation.

A crossover has a higher probability because it is mainly responsible for the "local evolution" of the population while a mutation rarely occurs as it is responsible for the random introduction of new characters into the population. If only crossovers are applied, the population will soon get "sterilized" and probably converge to a local optimal, while if only mutations are applied, the algorithm becomes a sort of random search [17].

3.2.5.1 Proposed MOGA for wind farm

Step 1: Start- Generate a random population of $n$ chromosomes. Each chromosome represents a layout (see Figure 3.7), e.g. Consider a Matrix $a$ of $7\times8$, 7 rows and 8 columns.
Step 2: Objective function values evaluation. Evaluate efficiency, power, and cost.

Step 3: Pareto dominance evaluation. The initially created solutions are checked based on Pareto dominance criterion.

Pareto dominance criterion. In minimization problem for all objectives, a solution $X_1$ dominates a solution $X_2$, if only if the two following conditions are true:

- $X_1$ is not worse than $X_2$ in all objectives,

$$fi(X_1) \leq fi(X_2) \lor i,$$

- $X_1$ is strictly better than $X_2$ in at least one objective,

$$fi(X_1) < fi(X_2)$$

Then, a solution is said to be Pareto-optimal if it is not dominated by any other possible solution.

Step 4: Fitness evaluation- Evaluate the fitness functions of each chromosome $x$ in the population.
Fitness metric 1- Distance-based f1 (i): It is intended for maintaining population diversity.

Fitness metric 2- Dominance Count-based f2 (i): Select those individuals which are more dominating.

Aggregated Fitness metric –Fitness metric 1 + fitness metric 2,

\[ f_a (i) = f_1 (i) + f_2 (i) \]

**Step 5:** Selection. Every non-dominated individual is ranked in descending order based on the aggregated fitness values.

**Step 6:** Elitism. Select most elite members with a given % of elitism to prevent lost of best solutions. For this paper has been picked the 30% meaning 0.3 of the non-dominated solutions.

**Step 7:** Crossover. With a pre-defined crossover probability, crossover the parents to form new offspring, see Table 3.4. For the present work is given the 70% of probability crossover.

**Step 8:** Mutation- With a pre-defined mutation probability, mutate new offspring at a random position in the chromosome, see Table 3.4. For the present work is given the 10% of probability mutation.

**Step 9:** Replace. Use the new generated population for a further generation of the algorithm.

**Table 3.4 Crossover and mutation**

<table>
<thead>
<tr>
<th>Crossover:</th>
<th>Parents</th>
<th>Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>0010110011</td>
<td>0010001011</td>
<td></td>
</tr>
<tr>
<td>Crossover Points</td>
<td>1110001010</td>
<td>1110110010</td>
</tr>
<tr>
<td>Mutation:</td>
<td>1000111110</td>
<td>1010111100</td>
</tr>
</tbody>
</table>
Chapter 4

CASE STUDY AND COMPUTATIONAL RESULTS

The case study is presented in next section which is developed with using the proposed methodology in chapter 3. The computational process is based on the flow chart of Figure 3.2 that is the proposed algorithm and used the equations and theory explained in the methodology section.

4.1 Case study description

The purpose of the case study is to develop a set of wind farm layouts for a specific large scale terrain with mountains that maximized the power in the wind that the wind farm is exposed to, maximizing the efficiency of power in the wind that the wind farm is exposed to and minimizing the total cost of the turbines installed; objective functions were described in equations 3.11 to 3.13. For this purpose, specific data is available as quantity of turbines by type and their associated characteristics as sweep area, hub height and WT cost; this information is integrated in a table similar to Table 3.3. Also, terrain height information and wind speed data is available, which will be managed using equations 3.1 and 3.2.

4.2 Data for the case study

The size of the large scale mountainous terrain is 10 km by 12.5 km which is a hypothetical case. The data of the turbines that are used for the wind farm is defined in Table 4.1. Additionally, a sample from a large set of wind data at the terrain at 10 m height with measurements every hour over a year is concentrated in Table 4.2. To integrate wind speed data to apply equation 3.1, the
The histogram of Figure 4.1 is created, with Table 4.3 representing the data in the histogram.

Table 4.1 Data of turbines available

<table>
<thead>
<tr>
<th>Type</th>
<th>rotor area m²</th>
<th>Hub height m</th>
<th>Rotor Radius (Rr) m</th>
<th>cost (millions of dollars)</th>
<th>entertainment constant</th>
<th>axial induction factor</th>
<th>rate power KW</th>
<th>Quantity Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5300</td>
<td>80</td>
<td>41.2</td>
<td>6</td>
<td>1</td>
<td>0.4</td>
<td>2300</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>6800</td>
<td>80</td>
<td>46.5</td>
<td>8</td>
<td>1</td>
<td>0.5</td>
<td>2300</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>8000</td>
<td>80</td>
<td>50.5</td>
<td>9</td>
<td>1</td>
<td>0.3</td>
<td>2300</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>11300</td>
<td>90</td>
<td>60</td>
<td>11</td>
<td>1</td>
<td>0.4</td>
<td>3600</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 4.2 Wind speed data over a year

<table>
<thead>
<tr>
<th>Wind speed over a year m/s (Measurement every hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1000hrs</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>5.524092096</td>
</tr>
<tr>
<td>.</td>
</tr>
<tr>
<td>.</td>
</tr>
<tr>
<td>.</td>
</tr>
<tr>
<td>.</td>
</tr>
<tr>
<td>.</td>
</tr>
</tbody>
</table>

46
Table 4.3 Simplified table of wind speed base on histogram bins

<table>
<thead>
<tr>
<th>V m/s</th>
<th>Hrs/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td>1</td>
<td>251</td>
</tr>
<tr>
<td>2</td>
<td>543</td>
</tr>
<tr>
<td>3</td>
<td>742</td>
</tr>
<tr>
<td>4</td>
<td>814</td>
</tr>
<tr>
<td>5</td>
<td>945</td>
</tr>
<tr>
<td>6</td>
<td>951</td>
</tr>
<tr>
<td>7</td>
<td>906</td>
</tr>
<tr>
<td>8</td>
<td>804</td>
</tr>
<tr>
<td>9</td>
<td>656</td>
</tr>
<tr>
<td>10</td>
<td>567</td>
</tr>
<tr>
<td>11</td>
<td>429</td>
</tr>
<tr>
<td>12</td>
<td>337</td>
</tr>
<tr>
<td>13</td>
<td>266</td>
</tr>
<tr>
<td>14</td>
<td>177</td>
</tr>
<tr>
<td>15</td>
<td>118</td>
</tr>
<tr>
<td>16</td>
<td>82</td>
</tr>
<tr>
<td>17</td>
<td>45</td>
</tr>
<tr>
<td>18</td>
<td>39</td>
</tr>
<tr>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>21</td>
<td>6</td>
</tr>
<tr>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>total hours</td>
<td>8760</td>
</tr>
</tbody>
</table>

Figure 4.1 Histogram representation of wind speed over a year
Wind speed data concentrated in table 4.3 is suitable to apply equation 3.1, omitting calculation for simplicity $V^3 = 682 \text{ m}^3/\text{s}$.

4.3 Methodology to solve the case study

Now with the basic data available is necessary start the algorithm that is performed step by step.

**Step 0.** Table 4.1 showed the rotor radius then is easy calculating de average diameter $D_{\text{avg}}$ of all the turbines.

$D_{\text{avg}} = 99.1 \text{ m}$, then is possible round it and leave it in 100 m in order simplified calculations.

To construct matrix $A$, it is necessary to divide terrain into a squared cell of 500 m due to the square is recommended with 5D of separation along with the average height in each cell. Later, based on a large scale terrain, a matrix $A$ of size 20 x 25 which represents the terrain coordinate of each cell with its associated height is acquired. Figure 4.2 showed Matrix $A$.

<table>
<thead>
<tr>
<th>Column</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>54</td>
<td>59</td>
<td>46</td>
<td>38</td>
<td>87</td>
<td>91</td>
<td>72</td>
<td>71</td>
<td>119</td>
<td>130</td>
<td>119</td>
<td>105</td>
<td>152</td>
<td>148</td>
<td>138</td>
<td>138</td>
<td>178</td>
<td>179</td>
<td>168</td>
<td>166</td>
<td>215</td>
<td>219</td>
<td>209</td>
<td>225</td>
<td>184</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>56</td>
<td>46</td>
<td>51</td>
<td>68</td>
<td>96</td>
<td>83</td>
<td>82</td>
<td>98</td>
<td>120</td>
<td>104</td>
<td>116</td>
<td>158</td>
<td>152</td>
<td>144</td>
<td>143</td>
<td>160</td>
<td>163</td>
<td>164</td>
<td>162</td>
<td>227</td>
<td>222</td>
<td>227</td>
<td>228</td>
<td>228</td>
</tr>
<tr>
<td>3</td>
<td>51</td>
<td>54</td>
<td>48</td>
<td>66</td>
<td>87</td>
<td>88</td>
<td>87</td>
<td>69</td>
<td>124</td>
<td>125</td>
<td>118</td>
<td>103</td>
<td>150</td>
<td>148</td>
<td>145</td>
<td>138</td>
<td>161</td>
<td>178</td>
<td>170</td>
<td>164</td>
<td>214</td>
<td>206</td>
<td>216</td>
<td>218</td>
<td>211</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
<td>57</td>
<td>69</td>
<td>68</td>
<td>79</td>
<td>94</td>
<td>87</td>
<td>89</td>
<td>120</td>
<td>116</td>
<td>111</td>
<td>99</td>
<td>129</td>
<td>152</td>
<td>132</td>
<td>132</td>
<td>173</td>
<td>169</td>
<td>174</td>
<td>179</td>
<td>206</td>
<td>207</td>
<td>192</td>
<td>223</td>
<td>199</td>
</tr>
<tr>
<td>5</td>
<td>58</td>
<td>58</td>
<td>49</td>
<td>39</td>
<td>73</td>
<td>93</td>
<td>94</td>
<td>73</td>
<td>107</td>
<td>121</td>
<td>106</td>
<td>112</td>
<td>153</td>
<td>131</td>
<td>146</td>
<td>152</td>
<td>189</td>
<td>178</td>
<td>188</td>
<td>182</td>
<td>230</td>
<td>208</td>
<td>193</td>
<td>221</td>
<td>185</td>
</tr>
<tr>
<td>6</td>
<td>57</td>
<td>67</td>
<td>71</td>
<td>65</td>
<td>43</td>
<td>71</td>
<td>72</td>
<td>75</td>
<td>78</td>
<td>76</td>
<td>121</td>
<td>116</td>
<td>100</td>
<td>103</td>
<td>143</td>
<td>130</td>
<td>145</td>
<td>140</td>
<td>166</td>
<td>172</td>
<td>162</td>
<td>161</td>
<td>223</td>
<td>188</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>71</td>
<td>49</td>
<td>66</td>
<td>46</td>
<td>83</td>
<td>98</td>
<td>78</td>
<td>73</td>
<td>113</td>
<td>117</td>
<td>126</td>
<td>102</td>
<td>134</td>
<td>145</td>
<td>146</td>
<td>134</td>
<td>185</td>
<td>178</td>
<td>174</td>
<td>172</td>
<td>228</td>
<td>207</td>
<td>219</td>
<td>211</td>
<td>193</td>
</tr>
<tr>
<td>8</td>
<td>68</td>
<td>65</td>
<td>43</td>
<td>71</td>
<td>72</td>
<td>75</td>
<td>78</td>
<td>76</td>
<td>121</td>
<td>116</td>
<td>100</td>
<td>103</td>
<td>143</td>
<td>130</td>
<td>145</td>
<td>140</td>
<td>166</td>
<td>172</td>
<td>162</td>
<td>161</td>
<td>223</td>
<td>208</td>
<td>197</td>
<td>204</td>
<td>202</td>
</tr>
<tr>
<td>9</td>
<td>68</td>
<td>67</td>
<td>76</td>
<td>74</td>
<td>80</td>
<td>91</td>
<td>84</td>
<td>87</td>
<td>103</td>
<td>105</td>
<td>99</td>
<td>117</td>
<td>157</td>
<td>152</td>
<td>137</td>
<td>150</td>
<td>188</td>
<td>186</td>
<td>188</td>
<td>180</td>
<td>228</td>
<td>203</td>
<td>195</td>
<td>225</td>
<td>195</td>
</tr>
<tr>
<td>10</td>
<td>56</td>
<td>70</td>
<td>40</td>
<td>53</td>
<td>93</td>
<td>96</td>
<td>72</td>
<td>73</td>
<td>98</td>
<td>105</td>
<td>130</td>
<td>103</td>
<td>159</td>
<td>148</td>
<td>155</td>
<td>142</td>
<td>163</td>
<td>176</td>
<td>169</td>
<td>169</td>
<td>230</td>
<td>192</td>
<td>224</td>
<td>193</td>
<td>197</td>
</tr>
<tr>
<td>11</td>
<td>57</td>
<td>53</td>
<td>45</td>
<td>59</td>
<td>92</td>
<td>95</td>
<td>96</td>
<td>76</td>
<td>112</td>
<td>118</td>
<td>100</td>
<td>128</td>
<td>132</td>
<td>153</td>
<td>150</td>
<td>143</td>
<td>189</td>
<td>172</td>
<td>169</td>
<td>175</td>
<td>209</td>
<td>203</td>
<td>174</td>
<td>224</td>
<td>223</td>
</tr>
<tr>
<td>12</td>
<td>59</td>
<td>63</td>
<td>48</td>
<td>58</td>
<td>94</td>
<td>95</td>
<td>98</td>
<td>71</td>
<td>121</td>
<td>116</td>
<td>119</td>
<td>118</td>
<td>149</td>
<td>144</td>
<td>134</td>
<td>141</td>
<td>180</td>
<td>169</td>
<td>164</td>
<td>186</td>
<td>192</td>
<td>223</td>
<td>199</td>
<td>229</td>
<td>197</td>
</tr>
<tr>
<td>13</td>
<td>57</td>
<td>62</td>
<td>45</td>
<td>54</td>
<td>84</td>
<td>93</td>
<td>93</td>
<td>72</td>
<td>110</td>
<td>122</td>
<td>100</td>
<td>126</td>
<td>157</td>
<td>148</td>
<td>144</td>
<td>139</td>
<td>179</td>
<td>156</td>
<td>165</td>
<td>177</td>
<td>220</td>
<td>204</td>
<td>203</td>
<td>175</td>
<td>130</td>
</tr>
<tr>
<td>14</td>
<td>64</td>
<td>65</td>
<td>68</td>
<td>69</td>
<td>83</td>
<td>68</td>
<td>68</td>
<td>79</td>
<td>81</td>
<td>122</td>
<td>107</td>
<td>105</td>
<td>114</td>
<td>136</td>
<td>157</td>
<td>136</td>
<td>158</td>
<td>181</td>
<td>174</td>
<td>185</td>
<td>170</td>
<td>204</td>
<td>208</td>
<td>223</td>
<td>206</td>
</tr>
<tr>
<td>15</td>
<td>64</td>
<td>63</td>
<td>66</td>
<td>51</td>
<td>92</td>
<td>72</td>
<td>79</td>
<td>80</td>
<td>80</td>
<td>114</td>
<td>124</td>
<td>133</td>
<td>113</td>
<td>150</td>
<td>134</td>
<td>136</td>
<td>136</td>
<td>185</td>
<td>165</td>
<td>169</td>
<td>192</td>
<td>192</td>
<td>222</td>
<td>194</td>
<td>203</td>
</tr>
<tr>
<td>16</td>
<td>64</td>
<td>56</td>
<td>62</td>
<td>50</td>
<td>91</td>
<td>81</td>
<td>81</td>
<td>78</td>
<td>116</td>
<td>98</td>
<td>113</td>
<td>102</td>
<td>157</td>
<td>159</td>
<td>131</td>
<td>138</td>
<td>173</td>
<td>184</td>
<td>186</td>
<td>170</td>
<td>223</td>
<td>221</td>
<td>217</td>
<td>192</td>
<td>195</td>
</tr>
<tr>
<td>17</td>
<td>59</td>
<td>58</td>
<td>60</td>
<td>51</td>
<td>89</td>
<td>96</td>
<td>82</td>
<td>83</td>
<td>112</td>
<td>100</td>
<td>113</td>
<td>115</td>
<td>137</td>
<td>155</td>
<td>148</td>
<td>137</td>
<td>171</td>
<td>184</td>
<td>162</td>
<td>169</td>
<td>223</td>
<td>211</td>
<td>220</td>
<td>195</td>
<td>228</td>
</tr>
<tr>
<td>18</td>
<td>59</td>
<td>59</td>
<td>37</td>
<td>45</td>
<td>87</td>
<td>86</td>
<td>86</td>
<td>78</td>
<td>98</td>
<td>116</td>
<td>112</td>
<td>99</td>
<td>155</td>
<td>144</td>
<td>152</td>
<td>141</td>
<td>179</td>
<td>185</td>
<td>188</td>
<td>192</td>
<td>215</td>
<td>216</td>
<td>203</td>
<td>222</td>
<td>215</td>
</tr>
<tr>
<td>19</td>
<td>54</td>
<td>55</td>
<td>58</td>
<td>37</td>
<td>86</td>
<td>96</td>
<td>70</td>
<td>76</td>
<td>107</td>
<td>115</td>
<td>114</td>
<td>114</td>
<td>152</td>
<td>159</td>
<td>143</td>
<td>130</td>
<td>179</td>
<td>187</td>
<td>158</td>
<td>166</td>
<td>227</td>
<td>207</td>
<td>229</td>
<td>228</td>
<td>221</td>
</tr>
<tr>
<td>20</td>
<td>53</td>
<td>53</td>
<td>38</td>
<td>56</td>
<td>98</td>
<td>85</td>
<td>95</td>
<td>76</td>
<td>112</td>
<td>120</td>
<td>109</td>
<td>114</td>
<td>151</td>
<td>154</td>
<td>142</td>
<td>141</td>
<td>184</td>
<td>151</td>
<td>168</td>
<td>177</td>
<td>206</td>
<td>188</td>
<td>224</td>
<td>219</td>
<td>214</td>
</tr>
</tbody>
</table>

Figure 4.2 Matrix $A$ representation, where the entries are the heights of terrain
**Step 1.**  
Ymin=37 m, Ymax= 230 m

**Step 2.**  
Increment = (230-37)/25  
Increment = 7.72

**Step 3.** Next Figure 4.3 showed Matrix A, with a set of limits (Bins) lower limit and upper limit then in yellow the cell that falls into the limits (Bin).

![Matrix A with set of bins, highlighted in yellow the heights are into the bins](image)

**Step 4** Matrix B: with entries ones and zeros (Figure 4.4)
To represent a case of note in step 4 of the proposed algorithm, see next Matrix A (Figure 4.5) where if the limits are specified by column and not enough quantity of ones where observed, then was carried out the note from step 4 about the combination of limits of two consecutive columns. Now, next is observed the matrix A, but classifying each entry based on limit of two columns.

**Figure 4.6 New Final Matrix B representation 1’s are highlighted in red and yellow.**
consecutive bins. It is observed the limits of two consecutive columns were combined (Figure 4.5). Finally is obtained the matrix B representation (Figure 4.6). This new matrix B contains 135 1’s against 63 of the old B (Figure 4.3).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.7 Incidence matrix B

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.8 Cluster identification result
**Step 5** The Cluster identification algorithm (CIA) was performed with a software developed by the department of Industrial, Manufacturing & Systems Engineering of the University of Texas at El Paso, note that in order to use the software the 1’s are substitute by X’s. It will not affect the result. Figure 4.7 represent the software input incidence matrix. And Figure 4.8 showed the cluster identification result.

![Figure 4.7: Software Input Incidence Matrix](image)

**Figure 4.7 Cluster identification input incidence matrix**

![Figure 4.8: Cluster Identification Result](image)

**Figure 4.8 Cluster Identification Result**

<table>
<thead>
<tr>
<th>Position</th>
<th>1</th>
<th>5</th>
<th>8</th>
<th>12</th>
<th>13</th>
<th>16</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>55</td>
<td>68</td>
<td>82</td>
<td>116</td>
<td>158</td>
<td>143</td>
<td>163</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
<td>79</td>
<td>89</td>
<td>99</td>
<td>129</td>
<td>132</td>
<td>169</td>
</tr>
<tr>
<td>5</td>
<td>58</td>
<td>73</td>
<td>73</td>
<td>111</td>
<td>153</td>
<td>152</td>
<td>178</td>
</tr>
<tr>
<td>8</td>
<td>68</td>
<td>72</td>
<td>76</td>
<td>103</td>
<td>143</td>
<td>140</td>
<td>172</td>
</tr>
<tr>
<td>9</td>
<td>68</td>
<td>80</td>
<td>87</td>
<td>117</td>
<td>157</td>
<td>150</td>
<td>186</td>
</tr>
<tr>
<td>11</td>
<td>57</td>
<td>92</td>
<td>76</td>
<td>128</td>
<td>132</td>
<td>143</td>
<td>172</td>
</tr>
<tr>
<td>13</td>
<td>57</td>
<td>84</td>
<td>72</td>
<td>126</td>
<td>157</td>
<td>139</td>
<td>156</td>
</tr>
<tr>
<td>14</td>
<td>64</td>
<td>83</td>
<td>81</td>
<td>114</td>
<td>136</td>
<td>158</td>
<td>174</td>
</tr>
<tr>
<td>15</td>
<td>64</td>
<td>92</td>
<td>80</td>
<td>113</td>
<td>130</td>
<td>136</td>
<td>165</td>
</tr>
</tbody>
</table>

**Figure 4.9 Cluster Identification Selected, Matrix C**

**Figure 4.10 Matrix a**
**Step 6.** Based on the list of rules, it is observed 3 well done form arrangements, and then is necessary figure out the matrix that fitter the wind farm size or turbines available, this case considers a wind farm of 1 to 60 turbines. It means the second cluster matrix could be a good option. For this case is not necessary go further in decision rules and was took cluster # 2, see next Figure 4.9. Finally as said in step 7 of the proposed algorithm, from matrix A will be extracted a sub matrix of heights with the same position (row, column) as the cluster matrix obtained in step 6.

**Step 7.** Figure 4.10 is the matrix $a$ obtained in step 7. Matrix $a$ is the input base for MOGA.

**Step 8**

Applied MOGA

Computational of MOGA has been developed using MATLAB coding.

Next table 4.4 is a Summary table changing conditions as elitism, populations size and quantity of generations, it just an example that could be consider an alternative plan to test the methodology and compare among ranges in order the Decision- Maker have the best set of solutions range and easy could find the local optimal. The present work will focus in the cases 13 to 16 that are the cases with a wider range of turbines and higher population size and not of all of them since computational time.
To determine a proper number of generations, first was tried with different generation quantity to analyze the graphs behavior and tendency of each objective along generations, graphing the solutions with the highest aggregated fitness function. Figure 4.11 to 4.14.

To make the graph labels short is understood by power: the power in the wind that the total of the turbines are exposed in the wind farm; by efficiency: the efficiency of the power in the wind that the wind farm is exposed and is affected for the aerodynamic losses and by cost: cost of turbines installed.

Table 4.4 Alternative plan to test the methodology

<table>
<thead>
<tr>
<th>Case #</th>
<th>Range of turbine quantity</th>
<th>Population Size</th>
<th>Elitism</th>
<th>Xover</th>
<th>Mutation</th>
<th>Generation Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 to 30</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>20 to 30</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>20 to 30</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>20 to 30</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>30 to 40</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>30 to 40</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>30 to 40</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>30 to 40</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>200</td>
</tr>
<tr>
<td>9</td>
<td>40-50</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>40-50</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>50</td>
</tr>
<tr>
<td>11</td>
<td>40-50</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>40-50</td>
<td>100</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>200</td>
</tr>
<tr>
<td>13</td>
<td>10 to 40</td>
<td>200</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>10 to 40</td>
<td>200</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>10 to 40</td>
<td>200</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>10 to 40</td>
<td>200</td>
<td>0.30</td>
<td>0.70</td>
<td>0.10</td>
<td>200</td>
</tr>
</tbody>
</table>
Figure 4.11 3D scatter plot view of efficiency vs. power vs. cost

Figure 4.12 2D view of power along generations
According to Figure 4.11 to Figure 4.14, one could observe that the objective values with the highest aggregated fitness are originally fluctuated before the 140 generation and become stabilized after the 140 generation. Consequently, it indicates that the Pareto set of each
generation is started to converge to the “true” Pareto set after the 140 generation.

Next are computational results of every case from case 13 to 16 showing the Pareto set and Pareto front which are the corresponding objective function values, in order the decision-maker can have a set of solutions. A reasonable solution to a multi-objective problem is to investigate a set of solutions, each of which satisfies the objectives at an acceptable level without being dominated by any other solution. A solution is said to be Pareto optimal if it is not dominated by any other solution in the solution space.

Figure 4.15 presented the Pareto front of case # 13 at 30 generations. It is observed diversity of the non-dominated solutions, spread along the solution space into the optimization variables ranges.

![Figure 4.15 3D view of Pareto front at 30 generations](image)

Figure 4.16, cost vs. efficiency at 30 generations, showed that while cost increased due a higher quantity of turbines the efficiency decreased due the aerodynamic losses caused by the turbines.
Figure 4.16 Pareto front 2D view, cost (millions USD) vs. efficiency, 30 generations

Figure 4.17 Pareto front 2D view, cost (millions USD) vs. power (Kw) at 30 generations

Figure 4.17, cost vs. power at 30 generations, showed that while power increased due a higher quantity of turbines the cost also increased.

Figure 4.18, efficiency vs. power at 30 generations, showed that while power increased due a higher quantity of turbines the efficiency decreased.
Figure 4.18 Pareto front 2D view, efficiency vs. power (Kw) at 30 generations

Figure 4.19 Pareto front 3D view at 50 generations

Figure 4.19 presented the Pareto front of case # 14 at 50 generations. It is observed diversity of the non-dominated solutions and even more compared with 30 generations that are spread along the solution space into the optimization variables ranges.
Figure 4.20 Pareto front 2D view, cost (millions USD) vs. power at 50 generations

Figure 4.21 Pareto front 2D view cost (millions USD) vs. efficiency at 50 generations

Figure 4.20, cost vs. power at 50 generations, showed that while cost increased due a higher quantity of turbines the power also increased. It is observed a point close 2.25 $10^6$ Kw and 195 MM, while with 30 generation the higher power was close 2.22 $10^6$ Kw for the same 195 MM. Figure 4.21 – Pareto front view of cost vs. efficiency in 50 generations shows that “cost” increases due to a higher quantity of turbines while “efficiency” decreases due to the
aerodynamic losses caused by the turbines. Basically, relationship between efficiency and cost is counter-proportional.

Figure 4.22 Pareto front 2D view efficiency vs. power (Kw) at 50 generations

Figure 4.23 Pareto front 3D view at 100 generations

Figure 4.22, efficiency vs. power at 50 generations, showed that while power increased due a higher quantity of turbines the efficiency decreased. It is observed points with power close of $2.25 \times 10^6$ Kw with an efficiency close 0.7, while at 30 generations $2.2\times10^6$ Kw for the same efficiency.
Figure 4.24 Pareto front 2D view, cost (millions USD) vs. efficiency at 100 generations

Figure 4.25 Pareto front 2D view, cost (millions USD) vs. power (Kw) at 100 generations

Figure 4.23 presented the Pareto front of case # 15 at 100 generations. It is observed diversity of the non-dominated solutions that are spread along the solution space into the optimization variables ranges.
Figure 4.24, cost vs. efficiency at 100 generations, showed that while efficiency increased the cost decreased. It is also observed points in the middle region concentrate some of the non-dominated solutions.

Figure 4.26 Pareto front 2D view, efficiency vs. power (Kw) at 100 generations

Figure 4.25, cost vs. power at 100 generations, showed that while power increased due a higher quantity of turbines the cost also increased. In this graph it is observed a point close $2.2 \times 10^6$ Kw with the cost close 170 MM when the previous generations that power was close 180 MM.

Figure 4.26, efficiency vs. power at 100 generations, showed that the non-nominated solutions concentrate between $2.05 \times 10^6$ and $2.1 \times 10^6$ Kw.

The Figure 4.27 is a Pareto set with objective values table at 150 generations.
Figure 4.27 Pareto set with objective values at 150 generations

Figure 4.28 Position matrix C1 and type matrix at 150 generations

The Figure 4.28 is the representations of the position matrix with 1’s (C1) and it associated type matrix that represent the position and the WT Type, from 100 to the 150 generation.

64
Figure 4.29 presented the Pareto front cost vs. efficiency of case # 16 at 200 generations. It is observed diversity of the non-dominated solutions that are spread along the solution space into the optimization variables ranges similar the previous generations. It is observed the same tendency that previous generations, while efficiency increased the cost decreased.

Figure 4.30, cost vs. power at 200 generations, showed that while power increased due a higher quantity of turbines the cost also increased. In this graph it is observed a point close 2.2 X10^6
Kw with the cost close 155 MM when the previous generations that power was close 170 to 180 MM.

Figure 4.31 Pareto front 2D view, efficiency vs. power (Kw) at 200 generations

Figure 4.32 Objective values at 200 generations

Figure 4.31, efficiency vs. power at 200 generations, showed that the non-nominated solutions improved relative the previous generations mainly in the regions close $2.2 \times 10^6$ Kw and 0.84 of
efficiency

Figure 4.32 is a Pareto set with objective values at 200 generations

<table>
<thead>
<tr>
<th>C1 -</th>
<th>C1 -</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 1 0 1</td>
<td>0 0 0 0 1 0 1</td>
</tr>
<tr>
<td>0 0 0 0 1 0 1</td>
<td>0 0 0 0 1 1 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1</td>
<td>0 0 0 0 0 0 1</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1</td>
<td>0 0 0 0 0 0 1</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1</td>
<td>0 0 0 0 0 1 1</td>
</tr>
<tr>
<td>0 0 0 1 0 0 1</td>
<td>0 0 0 1 0 0 1</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1</td>
<td>0 0 0 0 0 1 1</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0</td>
<td>0 0 0 0 1 1 0</td>
</tr>
<tr>
<td>type\textmatrix -</td>
<td>type\textmatrix -</td>
</tr>
<tr>
<td>0 0 0 0 4 0 4</td>
<td>0 0 0 0 4 0 4</td>
</tr>
<tr>
<td>0 0 0 0 4 0 1</td>
<td>0 0 0 0 4 0 1</td>
</tr>
<tr>
<td>0 0 0 0 4 2 0</td>
<td>0 0 0 0 4 2 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 4</td>
<td>0 0 0 0 0 0 4</td>
</tr>
<tr>
<td>0 0 0 0 0 0 4</td>
<td>0 0 0 0 0 0 4</td>
</tr>
<tr>
<td>0 0 0 0 0 4 1</td>
<td>0 0 0 0 0 4 1</td>
</tr>
<tr>
<td>0 0 0 0 4 0 0 1</td>
<td>0 0 0 0 4 0 0 1</td>
</tr>
<tr>
<td>0 0 0 0 0 4 1</td>
<td>0 0 0 0 0 4 1</td>
</tr>
<tr>
<td>0 0 0 0 4 3 0</td>
<td>0 0 0 0 4 3 0</td>
</tr>
</tbody>
</table>

Figure 4.33 Position matrix C1 and type matrix between 150 and the 200 generation

<table>
<thead>
<tr>
<th>C1 =</th>
<th>typematrix =</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 1 0 1</td>
<td>0 0 0 0 4 0 4</td>
</tr>
<tr>
<td>0 0 0 0 1 0 1</td>
<td>0 0 0 0 4 0 1</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0</td>
<td>0 0 0 0 4 2 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1</td>
<td>0 0 0 0 0 0 4</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1</td>
<td>0 0 0 0 0 0 4</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0</td>
<td>0 0 0 0 0 4 1</td>
</tr>
<tr>
<td>0 0 0 1 0 0 1</td>
<td>0 0 0 0 4 0 0 1</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1</td>
<td>0 0 0 0 0 4 2</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0</td>
<td>0 0 0 0 4 3 0</td>
</tr>
</tbody>
</table>

Figure 4.34 Position matrix C1 and type matrix after 200 generations

Figure 4.34 is the representations of the position matrix with 1’s (C1) and its associated type matrix that represent the position and the WT Type after 200 generations.
Figure 4.33 is the representation of the position matrix with 1’s (C1) and it associated type matrix, that represent the position and it type, between 150 and the 200 generation. Objective values with maximum fitness along generations can be observed in Figure 4.36 to 4.38.

Figure 4.35 showed the fitness value along generations and is observed its variation between the 6 and 10 that is the maximum fitness value.

![Figure 4.35 Fitness along generations](image)

Figure 4.36 illustrates that there are significant discrepancies among generations. However, it is also indicated that the upward tendency can be observed. In other words, the efficiency is toward to the maximization direction.

Figure 4.37 showed the power value along generations and is observed its variation among generations but with an increased trend observing the higher values. A valley is observed close generation 120, but is because the cost is tried to be minimized.
Figure 4.36 Efficiency along generations

Figure 4.37 Power along generations

Figure 4.38 showed the cost value along generations and is observed its variation among
generations but with a decreased trend of values.

Figure 4.38 cost along generations

Figure 4.39 Pareto front 3D view, efficiency vs. power vs. cost of all generations together

Pareto front along generations can be observed in Figures 4.39 to 4.42.

Figure 4.39 showed a 3D view of the Pareto front of all generations, according the color code is observed a good diversity distance base, and the proximity tendency of every generation to the true Pareto.

Figure 4.40 showed a 2D view of the Pareto front power vs. efficiency of all generations,
according the color code is observed a good diversity distance base and the proximity tendency of every generation to the true Pareto with a clear tendency of maximized power and efficiency.

Figure 4.40 Pareto front 2D view, power (Kw) vs. efficiency of all generations together

Figure 4.41 Pareto front 2D view, cost (millions USD) vs. power (Kw) of all generations

Figure 4.41 showed a 2D view of the Pareto front cost vs. power of all generations, according the color code is observed a good diversity distance base and the proximity tendency of every generation to the true Pareto with a clear tendency of maximized power and minimized cost.
Figure 4.42 showed a 2D view of the Pareto front efficiency vs. power of all generations, according the color code is observed a good diversity distance base and the proximity tendency of every generation to the true Pareto with a clear tendency of maximized power and maximized efficiency.
Through observing the Pareto front 2D and 3D graphs along with different generations and the graphs with maximum fitness in the computational part (i.e., Figure 4.15 to 4.42), it appears that the tendencies of the objective values are improving along with the generations. Therefore, the Pareto set is closer to a “real” Pareto front in every generation. Moreover, the graph (Figure 4.43) of Pareto front 2D view shows the tendency along with generations in the power and efficiency categories. All in all, the remaining graphs illustrate the tendency to maximize power and efficiency and minimize cost which is the primary objective of the proposed methodology. It validates the goal that the better and quality solutions are acquired through each generation.
Chapter 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This chapter discusses the conclusions drawn from the study and also shows the direction for the future work.

5.1 Conclusions

- Most of the real-world wind farm design layout and the real terrain cases are not exactly as 2 dimensional as a wind farm installed off-shore and on flat terrain on-shore. In this study was developed and presented and approach for 3 dimensional terrain cases and it application through a cases study with the help of Cluster Identification Algorithm (CIA).

- Some cases demand dealing with simultaneously optimizing multi-objective problems, so the present work developed a methodology that integrated Multi- Objective Genetic Algorithm (MOGA) in order to solve the problem of determined the optimal position of wind turbines on a non-flat terrain (mountainous area) and at the same time maximize wind power that the wind farm is exposed to, efficiency of wind power and minimized cost.

- The function of CIA is to determined a cluster (sub-set) of suitable possible positions from a large-scale mountainous region that follows a path of heights from lower to higher according to the direction of the wind with the help of a previous classification of height using limit bins, and finally came out with a subset of position (cells) Matrix a.

- MOGA uses Matrix a as terrain input and developed a set of non-dominated solutions for a wind turbines’ positioning that search for maximized power, maximized efficiency
and minimized cost dealing with variables and complicated factors such different WT type, different WT quantity, Weibull wind data and the downstream wake decay model of aerodynamic losses including the new rotor 50% rule. The increased variables necessarily increased the computational effort.

- The methodology was applied step by step for a case study, with the purpose of showing its application with a well objective values tendency and the Pareto front along generation closer the real Pareto.

5.2 Future work

This work could be directed towards several other studies such as:

1. Part of the future word could be to create a sensitivity analysis for different case studies by varying the inputs and defining their relationship with the outputs;

2. Different problems of wind farm sizes could be conducted by considering wind farm's complexities as well as other options, such as variable bounds, estimation of objective function values, exact calculation that can be applied in different regions.

3. Inclusion of optimization techniques other than MOGA could also be interesting future works.
REFERENCES

2. URL http://www1.eere.energy.gov/windandhydro/wind_how.html#inside
20. URL http://www1.eere.energy.gov/windandhydro/wind_how.html#inside
APPENDIX I

VERTICAL AXIS WIND TURBINE COMPONENTS

Rotor:
The blades and the hub together are called the rotor.

Blades:
It’s what the wind moves when it blows over them. Most turbines have two or three blades.

Pitch:
In order to control the speed of the rotor when winds are too high or low the blades must be pitched in a certain angle.

Wind direction:
This is an "upwind" turbine, since it operates facing into the wind; other turbines are designed to work "downwind," facing away from the wind.

Nacelle:
The nacelle sits atop the tower and contains the generator along with other parts to keep them safe from the weather. Some nacelles are large enough for a helicopter to land on.

Brake:
In cases of emergencies were the rotor must be stopped the wind turbines have a disc brake which can be applied mechanically, electrically, or hydraulically.

Low-speed shaft:
The rotor turns the low-speed shaft at about 30 to 60 RPM’s.

Gear box:
In this part of the wind turbine two gears connect the low speed shaft to the high speed shaft, whit this, the RPM’s are triplicate (that the low speed shaft turns about 30 to 60 RPM’s ,the high
speed shaft turns about 1000 to 1800) in order to get the rotational speed required by the generator.

**Generator:**

An electric generator is a device that converts mechanical energy to electrical energy. A generator forces electric charge (usually carried by electrons) to flow through an external electrical circuit.

**High-speed shaft:**

Is the part that is responsible of moving the generator.

**Controller:**

Is the part of the wind turbine that starts it up at wind speeds of about 8 to 16 mph and shuts it off the machine at about 55 mph since the turbine may be damaged when operating at high speed winds.

**Anemometer:**

As a part of the controller system it is connected directly to it and measures the wind speed.

**Wind vane:**

It measures the direction of the wind and transmits the information to the yaw drive in order to adjust the turbine accurately with respect to the wind.

**Tower:**

It is the main structure of a wind turbine, which is fabricated from tubular steel, concrete, or steel lattice.

**Yaw drive:**

Being this an upwind turbine the wind must blow directly in front of the rotor so the yaw drive with the information of the wind vane keep the rotor facing the wind as it changes its direction
**Yaw motor:**

It supplies the energy for the yaw drive.

In the Figures A and B it could observe a Horizontal Axis wind turbine and Vertical Axis wind turbine.

![Figure A. HAWT [20]](image1)

![Figure B. VAWT [20]](image2)
On-shore wind farms

In this scenario the wind turbines are located in mountainous areas that are around three kilometers from the nearest shore; all this to abuse the “topographic acceleration” as the wind quickens over the hill.

In this layout, the wind turbines obtain additional wind speeds, meaning that the amount of energy produced increases; never the less, studies need to be perform in the area regarding to local wind by analyzing the vegetation in the zone or historical data, since in this particular kind of layout a difference of 30 cm. might duplicate the output [20 ]. (See Figure C)

Near-shore wind farms

This layout consists on installing wind turbines within ten Km. of land when in water and/or 3 Km. of a shoreline when in land. Near-shore layouts are considered a good spot to mount wind turbines since the convection that occurs each day because of the differential heating of land and sea [20]. (See Figure D)

Offshore wind farms

Offshore wind farms can be located 10 Km. or more from the coast, one of their main advantage is that in this layout the wind turbines do not interfere with the landscape and the noise is reduced as the distance from the shore increases. The advantages of this layout are that the wind speed is high on the open sea due the fact that water has less surface roughness than land. On the other hand it is more expensive to build a off-shore wind farm since the towers need to be taller than the ones on land if you include the portion of the tower that is submerged, the foundations are more expensive since they have to withstand the currents, the transmission lines cost more
since the length is increased, and finally, the repair is even more costly and more frequent because of corrosion. This kind of wind farm will continue growing since the energy production overcomes the installation costs [20]. (See Figure E)

**Airborne wind farms**

New prototypes are being generated like the airborne wind farms on which winds generated by the uneven heating of the atmosphere and the roughness/uneven terrain of earth surface play an important role. These prototypes are still on the development stage and will be available in future years [20]. (See Figure F).
APPENDIX III

WAKE DECAY MODEL

A wake model is used for simplification of the wind field calculations. This wake analysis is based on the assumption that momentum is conserved inside the wake. In the analysis of a single wake, the near field behind the wind turbine is neglected making it possible to model the resulting wake as a turbulent wake or a negative jet. At the turbine, the wake has a radius equal to the turbine radius, $r_t$. As the wake propagates downstream, the radius of the wake, $r_1$, increases linearly, proportional to the downstream distance, $x$, as shown in Figure I. [21].

![Figure I. Wake decay model Sketch](image)

A set of formulas can be used to model a wind farm. Different calculations are used to find out the values for the wind speed downstream, the downstream rotor radius; turbine thrust coefficient, entrainment constant, velocity downstream, and the cost function. The following formula describes the wind speed downstream of the turbine:
Where:

\[ U = U_0 \left[ 1 - \frac{2a}{\left( 1 + \alpha \left( \frac{x}{r_1} \right) \right)^2} \right] \]

- \( u \): wind speed downstream from the turbine
- \( u_0 \): initial wind speed
- \( \alpha \): entertainment constant
- \( a \): axial induction
- \( r_1 \): downstream rotor radius
- \( x \): distance downstream the turbine

The downstream radius, \( r_1 \), is related to the rotor radius, \( r \), by the following formula:

\[ r_1 = R_r \sqrt{\frac{1 - a}{1 - 2a}} \]

Where:

- \( r_1 \): is the downstream rotor radius
- \( r_r \): rotor radius
- \( a \): axial induction factor

The turbine thrust coefficient, \( CT \), is related to the axial induction factor in the following relation:
The entrainment constant, $a$, is empirically given as:

$$C_T = 4a(1 - a)$$

The entrainment constant, $a$, is empirically given as:

$$
\alpha = \frac{0.5}{\left(\ln \left(\frac{Z}{Z_0}\right)\right)}
$$

Where:

- $\alpha = $ entertainment constant
- $Z = $ hub height
- $Z_0 = $ surface roughness

In the instance of a wind turbine encountering multiple wakes, the kinetic energy of the mixed wake can be assumed to be equal to the sum of the kinetic energy deficits. This results in the following expression for the velocity downstream of $N$ turbines:

$$
(1 - \frac{U_{avg}}{U_0}) = \sum_{i=1}^{n} \left(1 - \frac{U_i}{U_0}\right)^2
$$

Then we get the next equation

$$
U_{avg} = \left[1 - \left(\sum_{i=1}^{n} \left(1 - \frac{U_i}{U_0}\right)^2\right)\right] U_0
$$
APPENDIX IV

MATLAB CODE FOR MOGA

```matlab
% double direction
function [R,C,G,P]=windfarm3d(nt,tc,n,m,A,X)

start=input('enter the initial quatity of
turbines:');

ending=input('enter the final quatity of
turbines:');

iterations=input('enter the number of
evaluations (number of lay out for each
nt) you want to performed:');

generation_number=input('enter the
number of generations you want to
perfomed:');

range=iterations

K1_total=input('enter the maximum
quantity of turbines Type 1:');

K2_total=input('enter the maximum
quantity of turbines Type 2:');

K3_total=input('enter the maximum
quantity of turbines Type 3:');

K4_total=input('enter the maximum
quantity of turbines Type 4:');

n=input('enter the number of rows in
units of 5 diameter of rotor:');

m=input('enter the number of columns in
units of 5 diamenter of rotor:');

elitism=input('enter the ELITISM YOU
WANT SENT TO NEW
POPULATION:');

probabilityXover=input('enter the
Percentage of crommosomes of non
nomintated solutions for create the Cross
over solutions (Suggested 70%):')

% creates and Array to enter the
efficiency
objectiveMatrix=zeros (range*(ending-
start+1),5);%paraobtener los
nondominated values
fitnessarray=zeros (1,range*(ending-
start+1));

populationlayout=zeros (range*(ending-
start+1),n*m);

populationtypelayout=zeros
(range*(ending-start+1),n*m);
fitness_graph=zeros
(5,generation_number);

V3avg=682; % power average only to
get and stimations
Pavg=0.5*1.125*V3avg;

for nt=start:ending;
    for K2=1:range;
        randturbine=nt; %ceil(rand(1)*nt);
        V = [ones(1,randturbine) zeros(1,n*m-
randturbine)];
        P1 = V(randperm(n*m));
        populationlayout (counter,1:m*n)
        =P1(1,:);
        C1=zeros (n,m);
        p=0;
        for K3=1:n;
            C1(K3,1:m)=P1(1,p*m+1:K3*m);
            p=p+1;
        end
        %typematrix
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        type1=0;
        type2=0;
        type3=0;
        type4=0;
        typematrix=zeros (n,m);
        for i=1:n;
            for j=1:m;
                if C1(i,j)==1;
                    Ciclo20=0;
                    while Ciclo20==0;
                        randomtype=randi([1, 4]);
                        if randomtype==1;
                            if type1<K1_total;
                                type1=type1+1;
                                typematrix (i,j)=randomtype;
                                Ciclo20=1;
                            end
                        end
                        if randomtype==2;
                            if type2<K2_total;
                                type2=type2+1;
                                typematrix (i,j)=randomtype;
                                Ciclo20=1;
                            end
                        end
                        if randomtype==3;
                            if type3<K3_total;
                                type3=type3+1;
                                typematrix (i,j)=randomtype;
                                Ciclo20=1;
                            end
                        end
                        if randomtype==4;
                            if type4<K4_total;
                                type4=type4+1;
                                typematrix (i,j)=randomtype;
                                Ciclo20=1;
                            end
                        end
                    end
                end
            end
        end
        for i=0:n-1;
            populationtypelayout
            (counter,i*m+1:m*(i+1))=typematrix
            (i+1,:);
        end
        end
    end
end
end
end
end
end

load HeightMatrix.mat
load turbinedatamatrix.mat
H=10;
alpha=0.4; % large city with tall
buildings
Pmatrix=zeros (n*m,1);
row=1; % is necessary to store the Pij
values
for i=1:n;
    for j=1:m;
        k=typematrix(i,j); % Turbine type
        matriz that obteina from a matrix same
random as the lay out configuration
create Rando from previus 2D work
if k>0;
    Y=HeightMatrix(i,j);% terrain cell
    height
    L=turbinedatamatrix(k,3);% Hub
    heigth that depend the turbine type
    X=C1(i,j);% 1 or 0 depend the lay out
    configuration create Rando from previus
    2D work, the layout matrix is C1
    A=turbinedatamatrix(k,2);% Rotor
    Area that depend the turbine type
    Altura_total=Y+L;
    Correlacion_de_altura=(Altura_total/H)^
    (1.2)

    P=Pavg*Correlacion_de_altura*X*A/10
    00; % Power (Pij) by a turbine in the ij
    position in kilowatts
    %U1= (((Y+L)/H)^(alpha))*10;
    %V0 = 10
    %P=0.5*1.125*U1^3*X*A/1000*1.7;
    Pmatrix(row,1)=P; % is necessary to
    store the Pij values
    row=row+1;
end
end
end

Ptotal_theorical=sum (Pmatrix);

end
end
end
end

Ptotal_theorical=sum (Pmatrix);
end
end
end
end
end
end

end
```
Vo = 8.80;
turbina = 0;
for i = 1:n;
    for j = 1:m;
        if turbina == 0;
            X = C1(i,j); % layout matrix
            if X == 1;
                Y = HeightMatrix(i,j);
                k = typematrix(i,j);
                A = turbinedatamatrix(k,2);
                L = turbinedatamatrix(k,3);
                X50 = i;
                Y50 = j;
                Uo = ((Y + L)/H)^(alpha)*Vo;
                U = Uo;
                Power = 0.5*1.125*U^3*X*A/1000;
                PowerMatriz(i,j) = Power;
                X50 = i;
                Y50 = j;
                Column = j;
                Uo = U;
                X50 = i;
                Y50 = j;
                end
        end
    end
end
if j = m;
    turbina = 0;
end
end
if turbina > 0;
    X = C1(i,j);
    k = typematrix(X50,Y50);
    Rr = turbinedatamatrix(k,4);
    entertainmentconstant = turbinedatamatrix(k,6);
    axialinduction = turbinedatamatrix(k,7);
    L0 = turbinedatamatrix(k,3);
    Y0 = HeightMatrix(X50,Y50);
    Y1 = HeightMatrix(i,j);
    Y = HeightMatrix(i,j);
    k = typematrix(i,j);
    L1 = turbinedatamatrix(k,3);
    Y0_con_turbina = Y0 + L0;
    Y1_con_turbina = Y1 + L1;
    pos = HeightMatrix(n+1,j);
    x = (pos - column)*5*rotoraverage;
    r1 = entertainmentconstant*x*Rr;
    U = ((Y + L)/H)^(alpha)*Vo;
    if Y1_con_turbina > Y0_con_turbina;
        if r1 >= (Y0_con_turbina - Y1_con_turbina);
            U = Uo*(1 - (2*axialinduction)/(1 + entertainmentconstant* tart*x/r1))^2);
            if k > 0;
                cost = turbinedatamatrix(k,5);
                costmatrix(row,1) = cost; % is necessary to store the costij values
                row = row + 1;
            end
        end
        end
    end
    if Y1_con_turbina < Y0_con_turbina;
        if r1 >= (Y0_con_turbina - Y1_con_turbina);
            U = Uo*(1 - (2*axialinduction)/(1 + entertainmentconstant* tart*x/r1))^2);
            if k > 0;
                cost = turbinedatamatrix(k,5);
                costmatrix(row,2) = cost; % is necessary to store the costij values
                row = row + 1;
            end
        end
        end
    end
    end
    end
end
end

objectiveMatrix(:,5) = X3(:,5);

% stop = input('stop para ver non

dominated');

COUNTER

%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%

X2 = objectiveMatrix;

for K30 = 1:range*(ending-start+1);

Counter20 = 0;

for K31 = 1:range*(ending-start+1);

Xprima = zeros(1, 6);

if X2(K30,1) <= X2(K31,1);

Xprima(1,1) = 1;
endif

if X2(K30,2) <= X2(K31,2);

Xprima(1,2) = 1;
endif

if X2(K30,3) <= X2(K31,3);

Xprima(1,3) = 1;
endif

if X2(K30,4) < X2(K31,4);

Xprima(1,4) = 1;
endif

if X2(K30,5) < X2(K31,5);

Xprima(1,5) = 1;
endif

if X2(K30,6) < X2(K31,6);

Xprima(1,6) = 1;
endif

if Xprima(1,1) + Xprima(1,2) + Xprima(1,3)

== 3;

if Xprima(1,4) + Xprima(1,5) + Xprima(1,6)

>= 1;

Counter20 = Counter20 + 1;
endif
endif

del X2(K30,1) <= X2(K31,1);

Xprima(1,1) = 1;
end
endif

if X2(K30,2) <= X2(K31,2);

Xprima(1,2) = 1;
endif

if X2(K30,3) <= X2(K31,3);

Xprima(1,3) = 1;
endif

if X2(K30,4) <= X2(K31,4);

Xprima(1,4) = 1;
endif

if X2(K30,5) <= X2(K31,5);

Xprima(1,5) = 1;
endif

if X2(K30,6) <= X2(K31,6);

Xprima(1,6) = 1;
endif

if Xprima(1,1) + Xprima(1,2) + Xprima(1,3)

== 3;

if Xprima(1,4) + Xprima(1,5) + Xprima(1,6)

>= 1;

Counter20 = Counter20 + 1;
endif
endif

end

X2(K30,4) = Counter20;  // means that some K31 dominated K30

end

end

objectiveMatrix(:,4) = X2(:,4);

end

Q100 = zeros(C12, n*m);  // create sub type population matrix
with non dominated
Q1 = zeros(C12, 5);  // create the sub objective matrix

counter3 = 1;

for K15 = 1:range*(ending-start+1);

if objectiveMatrix(K15, 5) == 1;

%==1;  // change

Q(counter3,:) = populationlayout(K15,:);

Q100(counter3,:) = populationtypelayout(K15,:);

Q1(counter3,:) = objectiveMatrix(K15,:);

counter3 = counter3 + 1;
endif
endif

Q2 = zeros(C12, 3);  // is the normalized objective values

Q6 = Q1;

Q6(:,1) = Q6(:,1)*-1

Q6(:,2) = Q6(:,2)*-1

for K16 = 1:C12;

Q2(K16,1) = (Q6(K16,1) - min(Q6(:,1)))/(max(Q6(:,1)) - min(Q6(:,1)));

Q2(K16,2) = (Q6(K16,2) - min(Q6(:,2)))/(max(Q6(:,2)) - min(Q6(:,2)));

Q2(K16,3) = (Q6(K16,3) - min(Q6(:,3)))/(max(Q6(:,3)) - min(Q6(:,3)));
end

fitnessMatrix = zeros(C12+2, C12);

for K17 = 1:C12;

for K18 = 1:C12;

Q3 = Q2(K17,1:3) - Q2(K18,1:3);

S1 = sum(Q3.*Q3);

S2 = sqrt(S1);

fitnessMatrix(K18,K17) = S2;

fitnessMatrix(K17,K18) = S2;
end
endif

for H19 = 1:C12;

fitnessMatrix(C12+1,H19) = sum(fitnessMatrix(1:C12,H19));
end

fitness_value_f1_row = fitnessMatrix(C12+2,:);

%% fitness 2

fitness_values_total = zeros(3, C12);

fitness_values_total(1,:) = fitness_value_f1_row;

fitnessMatrix2 = Q1';

min3 = min(objectiveMatrix2(4,:));

max3 = max(objectiveMatrix2(4,:));

range3 = max3-min3;

segment = range3/5;

for H20 = 1:C12;

if objectiveMatrix2(4,H20) == min3;

if objectiveMatrix2(4,H20) <= (min3 + segment);

if fitnessMatrix(C12+1,H20) <= (min2 + 2*segment);

if fitnessMatrix(C12+1,H20) <= (min2 + 3*segment);

circular(12,12)

end
endif
endif
end
end
if objectiveMatrix2(4,H20)<=min3+2*segment;
    fitness_values_total (2,H20)=3;
end
if objectiveMatrix2(4,H20)<min3+3*segment;
    fitness_values_total (2,H20)=3;
end
if objectiveMatrix2(4,H20)>=min3+3*segment;
    if objectiveMatrix2(4,H20)<min3+4*segment;
        fitness_values_total (2,H20)=4;
    end
end
if objectiveMatrix2(4,H20)>=min3+4*segment;
    if objectiveMatrix2(4,H20)<=min3+5*segment;
        fitness_values_total (2,H20)=5;
    end
end
for H21=1:C12
    fitness_values_total (3,H21)=fitness_values_total (1,H21)+fitness_values_total (2,H21);
end
for H21=1:C12
    fitness_values_total (1,H21)=fitness_values_total (2,H21);
end
for H21=1:C12
    fitness_values_total (2,H21)=fitness_values_total (1,H21);
end
for H21=1:C12
    fitness_values_total (3,H21)=fitness_values_total (1,H21)+fitness_values_total (2,H21);
end

for K23=1:C12-1;
    K24=K23+1;
    random1=ceil(rand(1)*m*n);
    Xoverparent1A= Qnew(K23,1:random1)
    Xoverparent1B= Qnew(K23,random1+1:n*m)
    Xoverparent2A= Qnew(K24,1:random1)
    Xoverparent2B= Qnew(K24,random1+1:n*m)
    stop=input('cromosoems Xover')
    Xoverparent1A100= Qnew100(K23,1:random1)
    Xoverparent1B100= Qnew100(K23,random1+1:n*m)
    Xoverparent2A100= Qnew100(K24,1:random1)
    Xoverparent2B100= Qnew100(K24,random1+1:n*m)
    Qxover(position,1:random1)=Xoverparent1A;
    Qxover(position,random1+1:n*m)=Xoverparent2B;
    Qxover(position2,1:random1)=Xoverparent2A;
    Qxover(position2,random1+1:n*m)=Xoverparent1B;
    Qxover100(position,1:random1)=Xoverparent1A100;
    Qxover100(position,random1+1:n*m)=Xoverparent1B100;
    Qxover100(position2,1:random1)=Xoverparent2A100;
    Qxover100(position2,random1+1:n*m)=Xoverparent2B100;
end
Qxovermutation = Qxover;
newpopulation (K26,:)= Qxovermutation(1:VARIABLE3,:);
for K27=1:VARIABLE3:
    newpopulationtype (K27,:)=Qxovermutation100(1:VARIABLE3,:);
end
newpopulation = newpopulation;
newpopulationtype = newpopulationtype;
for K28=1:VARIABLE3:
    Qxovermutation = Qxovermutation;
    Qxovermutation100= Qxovermutation100;
    contador100=contador100+1
end
for K29=1:range*(ending-start+1);
    out=ceil(start +(ending-start)*rand() )
    V = [ones(1,out) zeros(1,n*m-out)];
    newpopulation (K26,:) = V(1:);
    %typematriz
    for K30=1:VARIABLE3:
        factor=ceil(range*(ending-start+1)/VARIABLE3);
        Qxover100=Qxovermutation100(factor*VARIABLE3,:,:);
    end
end
for K31=1:VARIABLE3:
    factor=ceil(range*(ending-start+1)/VARIABLE3);
    Qxover100=Qxovermutation100(factor*VARIABLE3,:,:);
    out=ceil(start +(ending-start)*rand() )
    V = [ones(1,out) zeros(1,n*m-out)];
    newpopulation (K26,:) = V(1:);
    %typematriz
    for K32=1:VARIABLE3:
        factor=ceil(range*(ending-start+1)/VARIABLE3);
        Qxover100=Qxovermutation100(factor*VARIABLE3,:,:);
    end
end
type1=0;
type2=0;
type3=0;
type4=0;
typematrixcromosome=zeros (1,n*m);
for j=1:n*m;
if P1(1,j)==1;
Ciclo20=0;
while Ciclo20==0;
randomtype=randi([1, 4]);
if randomtype==1;
if type1<K1_total;
type1=type1+1;
typematrixcromosome(1,j)=randomtype;
Ciclo20=1;
end
if randomtype==2;
if type2<K2_total;
type2=type2+1;
typematrixcromosome(1,j)=randomtype;
Ciclo20=1;
end
if randomtype==3;
if type3<K3_total;
type3=type3+1;
typematrixcromosome(1,j)=randomtype;
Ciclo20=1;
end
if randomtype==4;
if type4<K4_total;
type4=type4+1;
typematrixcromosome(1,j)=randomtype;
Ciclo20=1;
end
end
end
for generation=2:generation_number;
for k1000=1:range*(ending-start+1);
if sum(newpopulation(k1000,:))==0;
out= randi([start, ending]);
V = [ones(1,out) zeros(1,n*m-out)];
random number
P1 = V(randperm(n*m));
newpopulation(k1000,:)= P1(1,:);
typematriz
% generationsXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
for k1000=1:range*(ending-start+1);
if sum(newpopulation(k1000,:))==0;
out= randi([start, ending]);
V = [ones(1,out) zeros(1,n*m-out)];
random number
P1 = V(randperm(n*m));
newpopulation(k1000,:)= P1(1,:);
end
end
end
efficiency_fitness = Qnew2(1,1)*-1;
power_fitness= Qnew2(1,2)*-1;
cost_fitness=Qnew2(1,3);
max_fitness=sorted(1,1);
fitness_graph( 1,1)=efficiency_fitness;
fitness_graph( 2,1)=power_fitness;
fitness_graph( 3,1)=cost_fitness;
fitness_graph( 4,1)=max_fitness;
fitness_graph( 5,1)=1;
end
}
end
end
for generation=2:generation_number;
for k1000=1:range*(ending-start+1);
if sum(newpopulation(k1000,:))==0;
out= randi([start, ending]);
V = [ones(1,out) zeros(1,n*m-out)];
random number
P1 = V(randperm(n*m));
newpopulation(k1000,:)= P1(1,:);
typematriz
% generationsXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
for k1000=1:range*(ending-start+1);
if sum(newpopulation(k1000,:))==0;
out= randi([start, ending]);
V = [ones(1,out) zeros(1,n*m-out)];
random number
P1 = V(randperm(n*m));
newpopulation(k1000,:)= P1(1,:);
end
end
end
end
newpopulationtype (K26,:)=
typematrixcromosome (1,:);
% Turbine type
% matrix that obtains from a matrix same random as the lay out configuration
% create Rando from previous 2D work
if k>0;

Y=HeightMatrix(i,j);% terrain cell
height
L=turbinedatamatrix(k,3);% Hub height that depend the turbine type
X=C1(i,j);% 1 or 0 depend the lay out configuration create Rando from previous
2D work, the layout matrix is C1
A=turbinedatamatrix(k,2);% Rotor Area that depend the turbine type

Altura_total=Y+L;

Correlacion_de_altura=(Altura_total/H)^ (1.2);
P=Pavg*Correlacion_de_altura*X*A/1000; % Power (Pij) by a turbine in the ij
position in kilowatts

if turbina==0;
X=C1(i,j);
if X==1;
   k=typematrix(X50,Y50);
   Rr=turbinedatamatrix(k,4);
   entertainmentconstant=turbinedatamatrix(k,6);
   axialinduction=turbinedatamatrix(k,7);
   L0=turbinedatamatrix(k,3);
   Y0=HeightMatrix(X50, Y50);
   Y1=HeightMatrix(i, j);
   if Y1>Y0_con_turbina;
      if r1 >= (Y1_con_turbina - Y0_con_turbina);
         U=Uo*(1-(2*axialinduction)/(1+entertainmentconstant*(x/r1))^2);% the axial induction is
called a , probabiy i need Ct to calculate
end

P=0.5*1.125*U^3*X*A/1000*1.7;
else if Y1<Y0_con_turbina;
   if r1 >= (Y0_con_turbina - Y1_con_turbina);
         U=Uo*(1-(2*axialinduction)/(1+entertainmentconstant*(x/r1))^2);% the axial induction is
called a , probabiy i need Ct to calculate
end

A=turbinedatamatrix(k,2);

Power=0.5*1.125*U^3*X*A/1000;
PowerMatriz (i,j)=Power;
if j==m;
turbina=0;
end
end

PowerMatriz;
C1;
typematrix;
Potal_with_downstream_per columnist=sum (PowerMatriz);
Potal_with_downstream=sum (Potal_with_downstream_per column);

%VelocityMatriz=zeros (n,m);
%PowerMatriz=zeros (n,m);
 rotoraverage=100;
Vo=8.80;
turbina=0;
for i=1:n;
   for j=1:m;
      k=typematrix(i,j);
      if k>0;
         cost=turbinedatamatrix(k,5);
         costmatrix(row,1)=cost; % is necessary to store the costij values
         row=row+1;
      end
   end
end

V1=(((Y+L)/H)^(alpha))*Vo;
U1=Uo;
Power=0.5*1.125*U^3*X*A/1000;
PowerMatriz (i,j)=Power;
if j==m;
turbina=0;
end
end
end
end
end
end
end
end

total_cost=sum (costmatrix);

% store the results
% objectiveMatrix (counter,1)=efficiency;
% objectiveMatrix (counter,2)=output;
% objectiveMatrix (counter,3)=total_cost;
% counter=counter+1;
end % comes from the main cycle

% PARETO SET
X3=objectiveMatrix;
for K35=1:range*(ending-start+1)
   X3(K35,5)=1;
end

end

90
X3

%stop=input('stop para ver objective matrix');

for K30=1:range*(ending-start+1);
for K31=1:range*(ending-start+1);
Xprima=zeros(1,6);
if X3(K31,1)<=X3(K30,1);
    Xprima(1,1)=1;
end
if X3(K31,2)<=X3(K30,2);
    Xprima(1,2)=1;
end
if X3(K31,3)<=X3(K30,3);
    Xprima(1,3)=1;
end
if X3(K31,4)<=X3(K30,4);
    Xprima(1,4)=1;
end
if X3(K31,5)<=X3(K30,5);
    Xprima(1,5)=1;
end
if X3(K31,6)<=X3(K30,6);
    Xprima(1,6)=1;
end
end
end

if Xprima(1,1)+Xprima(1,2)+Xprima(1,3)==3;
    if Xprima(1,4)+Xprima(1,5)+Xprima(1,6) >=1;
    Counter20= Counter20+1;
    X3(K30,4)= Counter20; %means that some K31 dominated K30
end
end
end
end

objectiveMatrix(:,5) =X3(:,5) ;

X2=objectiveMatrix;

for K30=1:range*(ending-start+1);
for K31=1:range*(ending-start+1);
    Xprima=zeros(1,6);
    if X2(K31,1)<=X2(K30,1);
        Xprima(1,1)=1;
    end
    if X2(K31,2)<=X2(K30,2);
        Xprima(1,2)=1;
    end
    if X2(K31,3)<=X2(K30,3);
        Xprima(1,3)=1;
    end
    if X2(K31,4)<=X2(K30,4);
        Xprima(1,4)=1;
    end
    if X2(K31,5)<=X2(K30,5);
        Xprima(1,5)=1;
    end
    if X2(K31,6)<=X2(K30,6);
        Xprima(1,6)=1;
    end
end
end
end
end

objectiveMatrix(:,4) =X2(:,4) ;

%% FITNESS 1 PART 1
Reenglones=(range*(ending-start+1))
C12=sum (objectiveMatrix(:,5));

Q=zeros(C12,n*m); %CREATE SUB POPULATION MATRIX WITH NON DOMINATED
Q100=zeros(C12,n*m); %CREATE SUB TYPEPOPULATION MATRIX WITH NON DOMINATED
Q1=zeros(C12,5); %CREATE THE SUB OBJECTIVE MATRIX

for K15=1:range*(ending-start+1);
    if objectiveMatrix(K15,5)==1; %==1;
        Q(counter3,:)=populationlayout(K15,:);
        Q100(counter3,:)=populationtypelayout(K15,:);
        Q1(counter3,:)=objectiveMatrix(K15,:);
        counter3=counter3+1;
    end
end

Q2=zeros(C12,3); % IS THE NORMALIZED OBJECTIVE VALUES
Q6= Q1
Q6(1,:)=Q6(:,1)^-1
Q6(2,:)=Q6(:,2)^-1
for K16=1:C12;
Q2(K16,1)=Q6(K16,1)-min(Q6(:,1))/(max(Q6(:,1))-min(Q6(:,1)));
Q2(K16,2)=Q6(K16,2)-min(Q6(:,2))/(max(Q6(:,2))-min(Q6(:,2)));
Q2(K16,3)=Q6(K16,3)-min(Q6(:,3))/(max(Q6(:,3))-min(Q6(:,3)));
end

Q2(:,1);
Q2(:,2);
Q2(:,3);
Q1(:,4);

C12;

Q= zeros (C12,n*m); %CREATE SUB POPULATION MATRIX WITH NON DOMINATED
Q100= zeros (C12,n*m); %CREATE SUB TYPEPOPULATION MATRIX WITH NON DOMINATED
Q1= zeros (C12,5); %CREATE THE SUB OBJECTIVE MATRIX

for K17=1:C12;
    for K18=1:C12;
        Q3=Q(K17,1:3)-Q(K18,1:3);
        S1= sum (Q3.*Q3);
        S2= sqrt(S1);
        fitnessMatrix(K18,K17)=S2;
        fitnessMatrix(K17,K18)=S2;
    end
end

fitnessMatrix=C12+1,H19)=sum(fitness Matrix (C12,H19));

end

%evaluacion de fitness con valores de part1

C12;
min2= min(fitnessMatrix(C12+1,:));
max2= max(fitnessMatrix(C12+1,:));
range2= max2-min2;
segment= range2/5;
for H20=1:C12;
    if fitnessMatrix(C12+1,H20)>=min2;
        if fitnessMatrix(C12+1,H20)<(min2+segment);
            fitnessMatrix(C12+1,H20)=1;
        end
    end
    if fitnessMatrix(C12+1,H20)>(min2+segment);
        if fitnessMatrix(C12+1,H20)<(min2+2*segment);
            fitnessMatrix(C12+1,H20)=2;
        end
    end
    if fitnessMatrix(C12+1,H20)>(min2+2*segment);
        if fitnessMatrix(C12+1,H20)<(min2+3*segment);
            fitnessMatrix(C12+1,H20)=3;
        end
    end
    if fitnessMatrix(C12+1,H20)>(min2+3*segment);
        if fitnessMatrix(C12+1,H20)<(min2+4*segment);
            fitnessMatrix(C12+1,H20)=4;
        end
    end
    if fitnessMatrix(C12+1,H20)>(min2+4*segment);
        if fitnessMatrix(C12+1,H20)<(min2+5*segment);
            fitnessMatrix(C12+1,H20)=5;
        end
    end
end
end

end
fitnessMatrix;
fitness_value_f1_row=fitnessMatrix(C1 2+2,:);

%% FITNESS 2

fitness_values_total=zeros(3,C12);
fitness_values_total (1,:)=fitness_value_f1_row;
objectiveMatrix2= Q1';
min3= min(objectiveMatrix2(4,:));
max3= max(objectiveMatrix2(4,:));
range3=max3-min3;
segment= range3/5;
for H20=1:C12;
if objectiveMatrix2(4,H20)>=min3;
if objectiveMatrix2(4,H20)<
min3+segment;
fitness_values_total (2,H20)=1;
end
if
objectiveMatrix2(4,H20)>=min3+segment;
if objectiveMatrix2(4,H20)<
min3+2*segment;
fitness_values_total (2,H20)=2;
end
if
objectiveMatrix2(4,H20)>=
min3+2*segment;
if
objectiveMatrix2(4,H20)<min3+3*segment;
fitness_values_total (2,H20)=3;
end
if
objectiveMatrix2(4,H20)>=
min3+3*segment;
if
objectiveMatrix2(4,H20)<
min3+4*segment;
fitness_values_total (2,H20)=4;
end
end
if
objectiveMatrix2(4,H20)>=
min3+4*segment;
if
objectiveMatrix2(4,H20)<=min3+5*segment;
fitness_values_total (2,H20)=5;
end
end
for H21=1:C12
fitness_values_total (3,H21)=fitness_values_total (1,H21)+fitness_values_total (2,H21);
end

% SORTED DESCENDING

columnf1f2=C12;
for H20=1:C12;
if columnf1f2(H20,4)>=min3;
if columnf1f2(H20,4)<
min3+segment;
fitness_values_total (3,H20)=1;
end
if
columnf1f2(H20,4)>=min3+segment;
if columnf1f2(H20,4)<
min3+2*segment;
fitness_values_total (3,H20)=2;
end
if
columnf1f2(H20,4)>=
min3+2*segment;
if columnf1f2(H20,4)<min3+3*segment;
fitness_values_total (3,H20)=3;
end
if
columnf1f2(H20,4)>=
min3+3*segment;
if
columnf1f2(H20,4)<min3+4*segment;
fitness_values_total (3,H20)=4;
end
end
if
columnf1f2(H20,4)>=
min3+4*segment;
if
columnf1f2(H20,4)<=min3+5*segment;
fitness_values_total (3,H20)=5;
end
end

generation30=C'
EfficiencyX1=columnf1f2(1,:)*-1
PowerY1=columnf1f2(2,:)*-1
CostZ1=columnf1f2(3,:)
% Auto-generated by MATLAB on 14-Oct-2012 16:55:49
% Create figure
figure = figure('Name','Fitness Plot Efficiency Vs Powe Vs Cost',
'Color',[0.678431391716003 0.921568632125854 1]);
colorbar('hot');

% Create axes
axes1 = axes('Parent',figure,'FontSize',14,'Font Name','Times New Roman',
'Color',[0.905882358551025 0.905882358551025 0.905882358551025]);
view(axes1,[-43.5 34]);
grid(axes1,'on');
hold(axes1,'all');

% Create scatter3
scatter3(EfficiencyX1,PowerY1,CostZ1, S1,ColorC1,...
'MarkerFaceColor',[0.078431375324726 0.168627455830574 0.549019634723663],...
'Marker','.',
'Parent',axes1,
'DisplayName','Efficiency.');

% Create xlabel
xlabel({'Efficiency'},'FontWeight','bold','FontSize',16,
'FontName','Times New Roman');

% Create ylabel
ylabel({'Power Kw'},'LineWidth',1,'HorizontalAlignment','center',
'FontWeight','bold','FontSize',16,
'FontName','Times New Roman');

% Create zlabel
zlabel('Cost USD','FontWeight','bold','FontSize',16,
'FontName','Times New Roman');

% Create title
title({'Efficiency Vs Power Vs Cost'},'FontWeight','bold','FontSize',16,
'FontName','Times New Roman');

% Create light
light('Parent',axes1,...
'Position',[-0.584254012643499 -0.106263835031555 0.804583962310622],
'Color',[0.678431391716003 0.921568632125854 1]);
Stop = input('continue with next generations');

if generation == 50;
    Stop = input('set of solution of turbine placement of Pareto set');
    A = Q(numpop(1:ceil(C12)), :)
    Stop = input('set of solution of turbine placement by type of turbine');
    B = Q100(numpop(1:ceil(C12)), :)
    Stop = input('set of solutions of Pareto optimal');
    C = Q1(numpop(1:ceil(C12)), 1:4);
    C(1:C12, 4) = sorted(:, 1);
    format shortg
    C
    Stop = input('see graphic Pareto set');
    generacion30 = C'
    EfficiencyX1 = generacion30(1, :)*-1
    PowerY1 = generacion30(2, :)*-1
    CostZ1 = generacion30(3, :)
    Stop = input('to see efficiency power and cost');
    S1 = 500;
    S2 = 60;
    ColorC1 = zeros(1, size(C, 1));
    for K32 = 1:size(C, 1);
        ColorC1(1, K32) = K2;
    end
end

if generation == 100;
    Stop = input('set of solution of turbine placement of Pareto set');
    A = Q(numpop(1:ceil(C12)), :)
    Stop = input('set of solution of turbine placement by type of turbine');
    B = Q100(numpop(1:ceil(C12)), :)
    Stop = input('set of solutions of Pareto optimal');
    C = Q1(numpop(1:ceil(C12)), 1:4);
    C(1:C12, 4) = sorted(:, 1);
    format shortg
    C
    Stop = input('see graphic Pareto set');
    generacion30 = C'
    EfficiencyX1 = generacion30(1, :) * -1
    PowerY1 = generacion30(2, :) * -1
    CostZ1 = generacion30(3, :)
    Stop = input('to see efficiency power and cost');
    S1 = 500;
    S2 = 60;
    ColorC1 = zeros(1, size(C, 1));
    for K32 = 1:size(C, 1);
        ColorC1(1, K32) = K2;
    end
end

% Auto-generated by MATLAB on 14-Oct-2012 16:35:49

% Create figure
figure1 = figure('Name', 'Fitness Plot Efficiency Vs Power Vs Cost', ...'
    'Color', [0.678431391716003 0.921568632158541 1]);
colorbar('hot');
% Create xlabel
xlabel({'Efficiency'},'FontWeight','bold',
'FontSize',16,...
'FontName','Times New Roman');

% Create ylabel
ylabel({'Power
Kw'},'LineWidth',1,'HorizontalAlignme
nt','center',
'FontWeight','bold',...
'FontSize',16,...
'FontName','Times New Roman');

% Create zlabel
zlabel('Cost
USD','FontWeight','bold','FontSize',16,...
'FontName','Times New Roman');

% Create title
title({'Efficiency Vs Power Vs
Cost'},'FontWeight','bold','FontSize',16,..
'.
'FontName','Times New Roman');

% Create light
light('Parent',axes1,...
'Position',[-0.584254012643499 -
0.106263835031555
0.804583896231062]);

% Create colorbar
colorbar('peer',axes1);

Stop=input('continue with next
generations');

if generation ==200;
    Stop=input('set of solution of turbine
placement of Pareto set');
    A=Q(numpop(1:ceil(C12)),:);
    Stop=input('set of solution of turbine
placement by type of turbine');
    B=Q100(numpop(1:ceil(C12)),:);
    Stop=input('set of solutions of Pareto
optimal');
    C=Q1(numpop(1:ceil(C12)),1:4);
    C(1:C12,4)=sorted(:,1);
    format shortg
    C
    Stop=input('see graphic Pareto set');
    generacion30=C*
    EfficiencyX1=generacion30(1,:)*1
    PowerY1=generacion30(2,:)*1
    CostZ1=generacion30(3,);
    Stop=input('to see efficiency power and
cost');
    S1=500;
    S2=60;
    ColorC1 = zeros( 1,size(C,1));
    for K32=1:size(C,1);
    ColorC1(1,K32)= K2;
    end

end

if generation ==300;
    Stop=input('set of solution of turbine
placement by type of turbine');
    B=Q100(numpop(1:ceil(C12)),:);
    Stop=input('set of solutions of Pareto
optimal');
    C=Q1(numpop(1:ceil(C12)),1:4);
    C(1:C12,4)=sorted(:,1);
    format shortg
    C
    Stop=input('see graphic Pareto set');
    generacion30=C*
    EfficiencyX1=generacion30(1,:)*1
    PowerY1=generacion30(2,:)*1
    CostZ1=generacion30(3,);
    Stop=input('to see efficiency power and
cost');
    S1=500;
    S2=60;
    ColorC1 = zeros( 1,size(C,1));
    for K32=1:size(C,1);
    ColorC1(1,K32)= K2;
    end

end

% Create figure
figure1 = figure('Name','Fitness Plot
Efficiency Vs Power Vs Cost',...
'Color',[0.678431391716003
0.921568632125854 1]);
colormap('hot');

% Create axes
axes1 = axes('Parent',figure1,'FontSize',14,'Font
Name','Times New Roman',...
'Color',[0.905882358551025
0.905882358551025
0.905882358551025]);
view(axes1,[-43.5 34]);
grid(axes1,'on');
hold(axes1,'all');

% Create scatter3
scatter3(EfficiencyX1,PowerY1,CostZ1,
S1,ColorC1,...
'MarkerFaceColor',[0.078431375324726
1 0.168627455830574
0.549019634723663],...,
'Marker','.',...
'Parent',axes1,...
'DisplayName','Efficiency');

% Create xlabel
xlabel({'Efficiency'},'FontWeight','bold',
'FontSize',16,...
'FontName','Times New Roman');

% Create ylabel
ylabel({'Power
Kw'},'LineWidth',1,'HorizontalAlignme
nt','center',
'FontWeight','bold',...
'FontSize',16,...
'FontName','Times New Roman');

% Create zlabel
zlabel('Cost
USD','FontWeight','bold','FontSize',16,...
'FontName','Times New Roman');

% Create title
title({'Efficiency Vs Power Vs
Cost'},'FontWeight','bold','FontSize',16,..
'.
'FontName','Times New Roman');

% Create light
light('Parent',axes1,...
'Position',[-0.584254012643499 -
0.106263835031555
0.804583896231062]);

% Create colorbar
colorbar('peer',axes1);

Stop=input('continue with next
generations');

if generation ==300;
    Stop=input('set of solution of turbine
placement by type of turbine');
    B=Q100(numpop(1:ceil(C12)),:);
    Stop=input('set of solutions of Pareto
optimal');
    C=Q1(numpop(1:ceil(C12)),1:4);
    C(1:C12,4)=sorted(:,1);
    format shortg
    C
    Stop=input('see graphic Pareto set');
    generacion30=C*
    EfficiencyX1=generacion30(1,:)*1
    PowerY1=generacion30(2,:)*1
    CostZ1=generacion30(3,);
    Stop=input('to see efficiency power and
cost');
    S1=500;
    S2=60;
    ColorC1 = zeros( 1,size(C,1));
    for K32=1:size(C,1);
    ColorC1(1,K32)= K2;
    end

end

% Create figure
figure1 = figure('Name','Fitness Plot
Efficiency Vs Power Vs Cost',...
'Color',[0.678431391716003
0.921568632125854 1]);
colormap('hot');
% Create axes
axes1 = axes('Parent',figure1,'FontSize',14,'Font Name','Times New Roman',...
'Color',[0.905882358551025 0.905882358551025 0.905882358551025];
view(axes1,[-43.5 34]);
grid(axes1,'on');
hold(axes1,'all');

% Create scatter3
scatter3(EfficiencyX1,PowerY1,CostZ1,
S1,ColorC1,...
'MarkerFaceColor',[0.078431375324726 1 0.168627455830574 0.549019634723663],...'
'Marker','.',...
'Parent',axes1,
'DisplayName','Efficiency,');

% Create xlabel
xlabel({'Efficiency'},'FontWeight','bold','
FontSize',16,...
'FontName','Times New Roman');

% Create ylabel
ylabel({'Power
Kw'},'LineWidth',1,'HorizontalAlignme
nt','center',...
'FontWeight','bold',...
'FontSize',16,...
'FontName','Times New Roman');

% Create zlabel
zlabel('Cost
USD','FontWeight','bold','FontSize',16,...
'FontName','Times New Roman');

% Create title
title({'Efficiency Vs Power Vs
Cost'},'FontWeight','bold','FontSize',16,..
'.
'FontName','Times New Roman');

% Create light
light('Parent',axes1,...
'Position',[-0.584254012643499 -0.106263835031555 0.804583896231062]);

% Create colorbar
colorbar('peer',axes1);

Stop=input('continue with next
generations');

%%%%%%populationtype matrix
Qnew100= Q100(numpop(1:C12),:);
Qxover=zeros((C12*2-2),n*m);
C12
size(Qxover,1)
%stop=input('values of C12 y el :');
VARIABLE2= ceil((C12*2-
2)*probabilityXover);
VARIABLE3= VARIABLE1 +
VARIABLE2;
Qxover100= zeros ((C12*2-2),n*m);
%code for populationtype matrix
position1=1;
position2=2;
for K23=1:C12-1;
K24=K23+1;
random1=ceil(rand(1)*m*n);
Xoverparent1A= Qnew(K23,1:random1)
Xoverparent1B=
Qnew(K23,random1+1:n*m)
Xoverparent2A= Qnew(K24,1:random1)
Xoverparent2B=
Qnew(K24,random1+1:n*m)
%stop=input('cromosoems Xover');
Xoverparent1A100=
Qnew100(K23,1:random1);
Xoverparent1B100=
Qnew100(K23,random1+1:n*m);
Xoverparent2A100=
Qnew100(K24,1:random1);
Xoverparent2B100=
Qnew100(K24,random1+1:n*m);
Qxovermutation = Qxover;
Qxovermutation100 = Qxover100;
contador100=1
K30=VARIABLE1+1;
for K26=K30:VARIABLE3;
newpopulation(K26,:)=Qxovermutation(contador100,:);
newpopulationtype(K26,:)=Qxovermutation100(contador100,:);
contador100=contador100+1
end
for K26= VARIABLE3+1:
range=((ending-start+1));
%out=ceil(start +(ending-start)*rand() )
out= randi([start, ending]);
V = [ones(1,out), zeros(1,n*m-
out)];
newpopulation(K26,:)=P1(out,:);
%typematriz
%type1=0;
type2=0;
type3=0;
type4=0;
typematrixcromosome=zeros (1,n\*m);
for j=1:n\*m;
if P1(1,j)==1;
Ciclo20=0;
while Ciclo20==0;
randomtype=randi([1, 4]);
%randomtype=ceil(rand(1,4))
if randomtype==1;
if type1<K1_total;
    type1=type1+1;
typematrixcromosome(1,j)=randomtype;
    Ciclo20=1;
end
if randomtype==2;
if type2<K2_total;
    type2=type2+1;
typematrixcromosome(1,j)=randomtype;
    Ciclo20=1;
end
if randomtype==3;
if type3<K3_total;
    type3=type3+1;
typematrixcromosome(1,j)=randomtype;
    Ciclo20=1;
end
if randomtype==4;
if type4<K4_total;
    type4=type4+1;
typematrixcromosome(1,j)=randomtype;
    Ciclo20=1;
end
end
end
end
end
end
end
end
end
newpopulationtype (K26,:)=
typematrixcromosome (1,:);

% Create ylabel
ylabel({'Efficiency'},'FontSize',16,'Font Name','High Tower Text');

% Create title
title('Efficiency along Generations','FontSize',20,...
'FontName','High Tower Text');

% Create plot
plot(fitness_graph(1,:),'Parent',axes1,...
'MarkerFaceColor',[0.501960813999176 0.501960813999176 0.501960813999176],...
'Marker',',','LineWidth',3,'Color',[0.498039215803146 0.498039215803146 0.498039215803146]...
'DisplayName','fitness_graph(1,:);

% Create legend
legend(axes1,'show');

%CREATEFIGURE(FITNESS_GRAPH H1)
% FITNESS_GRAPH1: vector of y data
% Auto-generated by MATLAB on 22-Sep-2012 17:12:11
%
% Create figure
figure1 = figure;
% Create axes
axes1 = axes('Parent',figure1);
box(axes1,'on');
hold(axes1,'all');
% Create title
title({'Power along Generations','FontSize',20,...
'FontName','High Tower Text');

% Create plot
plot(fitness_graph(2,:),'LineWidth',3,...
'Color',[0.87058824300766 0.490196079015732 0.490196079015732],...
'DisplayName','fitness_graph(2,:);

% Create xlabel
xlabel({'Generation Number','FontSize',14,'FontName','High Tower Text');

% Create ylabel
ylabel({'Power from wind KW'},'FontSize',14,'Font Name','High Tower Text');

% Create title
title({'Power from wind KW','FontSize',20,...
'FontName','High Tower Text');

% Create plot
plot(fitness_graph(2,:),'LineWidth',3,...
'Color',[0.87058824300766 0.490196079015732 0.490196079015732],...
'DisplayName','fitness_graph(2,:);

% Create xlabel
xlabel({'Generation Number','FontSize',14,'FontName','High Tower Text');

% Create ylabel
ylabel({'Power from wind KW'},'FontSize',14,'Font Name','High Tower Text');
% Create axes
axes1 = axes('Parent',figure1,'FontSize',14,'Font Name','Times New Roman',
'Color',[0.905882358551025 0.905882358551025 0.905882358551025]);
view(axes1,[-43.5 34]);
grid(axes1,'on');
hold(axes1,'all');

% Create scatter3
scatter3(EfficiencyX1,PowerY1,CostZ1, S1,ColorC1,...
'MarkerFaceColor',[0.078431375324726 1 0.168627455830574 0.549019634723663],...
'Marker','.',...
'Parent',axes1,...
'DisplayName','Efficiency');

% Create xlabel
xlabel({'Efficiency'},'FontWeight','bold',
'FontSize',16,...
'FontName','Times New Roman');

% Create ylabel
ylabel({'Power kW'},'LineWidth',1,'HorizontalAlignme n','center',...
'FontWeight','bold',...
'FontSize',16,...
'FontName','Times New Roman');

% Create zlabel
zlabel('Cost USD','FontWeight','bold','FontSize',16,...
'FontName','Times New Roman');

% Create title
title({'Efficiency Vs Power Vs Cost'},'FontWeight','bold','FontSize',16,...
'FontName','Times New Roman');

% Create light
light('Parent',axes1,...
'Position',[-0.584254012643499 -0.106263835031555 0.804583896231062]);

% Create colorbar
colorbar('peer',ax)
CURRICULUM VITA

Carlos Alejandro García Rosales was born in Ciudad Juárez, México. The first son of Carlos García and Petra Rosales, he graduated from Preparatoria Del Chamizal High School in Ciudad Juárez, Mexico, in the spring of 2002 and entered The Instituto Tecnologico de Cd. Juarez in the fall. While pursuing a bachelor’s degree in Electro-mechanic Engineering, he has been working in industry since 2005, starting in electronic industry as assistance in the engineering department. He received his Bachelor of Science degree from The Instituto Tecnologico de Cd Juarez in the summer of 2008. From 2008 until 2012, he has been working as Process Engineer in the lighting industry. In the spring of 2010, he entered the Graduate School manufacturing program at The University of Texas at El Paso.

Permanent Address: Marcelo Caraveo #54-68.

Ciudad Juárez, México 32170.