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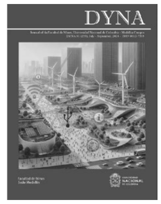

UNIVERSIDAD NACIONAL DE COLOMBIA

Selection of optimal areas for the installation of Wind Farms in the north-eastern part of Cuba

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Abstract
The present research aims to select optimal areas for the installation of wind farms in the north-eastern part of Cuba. The research is based on the free software QGIS, Hierarchical Process Analysis, databases of the information of the alternatives and criteria and Geographic Information Systems (GIS), which makes it possible to know the places where these farms will be installed. In addition, experts were consulted to obtain the weights or level of importance of the selected criteria, such as distance to ports, distances to common roads, distances to population centers, to electrical grids and finally the wind speed. As a result, a mathematical conceptual model was obtained for the selection of optimal zones for the installation of wind farms in the eastern north of Cuba, by means of the MCDM and GIS methods, where it was determined that, within the evaluated alternatives of wind farms, Gibara III is the optimal one. These models will allow the development of wind projects in the eastern region of Holguin, and to be able to manage human, financial and material resources.

Keywords: Geographic Information System (GIS); Multicriteria Decision Support Methods (MCDM); Decision Support Methods (MCDM); wind farms; multicriteria analysis; Hierarchical Process Analysis (AHP)

Selección de zonas óptimas para la instalación de Parques Eólicos en el norte Oriental de Cuba

Resumen
La presente investigación tiene como objetivo seleccionar áreas óptimas para la instalación de parques eólicos en la zona nororiental de Cuba. La investigación se basa en el software libre QGIS, Análisis Jerárquico de Procesos, bases de datos de la información de las alternativas y criterios y Sistemas de Información Geográfica (SIG), que permite conocer los lugares donde se instalarán estas granjas. Además, se consultó a expertos para obtener los pesos o nivel de importancia de los criterios seleccionados, como distancia a puertos, distancias a vías comunes, distancias a centros poblados, a redes eléctricas y finalmente la velocidad del viento. Como resultado se obtuvo un modelo conceptual matemático para la selección de zonas óptimas para la instalación de parques eólicos en el norte oriental de Cuba, mediante los métodos MCDM y GIS, donde se determinó que, dentro de las alternativas de energía eólica evaluadas fincas, Gibara III es la óptima. Estos modelos permitirán desarrollar proyectos eólicos en la región oriental de Holguín, y poder dirigir recursos humanos, financieros y materiales.

Palabras clave: Sistemas de Información Geográfica (SIG); Métodos de Soporte a la Decisión Multicriterio (MCDM); Métodos de Soporte a la Decisión (MCDM); parques eólicos; análisis multicriterio; Análisis Jerárquico de Procesos (AHP)

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1. Introduction

The most advantageous conditions for locating wind farms in Cuba are located in 21 zones near the northern coast, 13 zones for short and medium term installation of up to 600 MW of wind farms (including those already installed). There are also 6 zones suitable for installing up to 400 MW in the medium and long term.

For the installation of wind turbines, previous studies of the terrain are carried out, avoiding soft and unstable soils, which could cause damage to the structures due to the vibratory forces of the blades, although the new wind turbine technologies minimize these effects.

All this analysis leads to know the places where these farms will be installed, which will allow directing human, financial and material resources. The objective is to select optimal areas for the installation of wind farms in the north-eastern part of Cuba.

In the research work carried out by [1] in their recommendations, it is proposed to define the physical location of the equipment, the distances to be covered and the energy transmission lines within the territory and other complementary factors, so it will be sought, through the GIS, to find the best options of areas for the installation of Wind Projects, in the north of Holguín.

Applied [2] the IntiGIS model to define the most convenient technology to cover the electrification needs of Zapara Island. On the other hand, MDMC methods are based on explicit criteria, to evaluate several alternatives, it is used when a group of people must make an important decision in which different and complex aspects concur, especially in the stages of selection and evaluation of alternatives. In multi-criteria models, the decision-maker will be able to estimate the possible implications of each course of action, so that a better understanding of the links between his actions and his objectives can be obtained.

The entire GIS requires the methods that will be used to complete tasks and procedures. To create maps, a raster format or a vector format can be used; The source of obtaining the maps can be: scanning images, purchasing the maps, through GPS, using remote sensing or using a web service; but it is important to define the methods to use in each process. Therefore, there are only two formats to represent and systematize GIS in a geographic database: the vector model and the raster model. [3] with GIS-AHP methods studied the wind potential, concluding that these methods are appropriate for the selection of wind power plants. Applied [4] GIS-AHP methods, in the Kozani Regional Unit, to study the wind and solar economic potential, with the social and environmental dimensions, showing that the study area is suitable for solar energy than for wind energy, and finally [5] and [6] propose that renewable energies are closely linked to issues such as energy decentralization and rural electrification, and affirm that this geographical dependence means that GIS They can play a very important role in site location, regional planning, impact assessment, socio-economic analysis, multi-criteria analysis, etc.The multicriteria evaluation technique (MCA) has been applied in different planning processes and at different scales: the location of landfills [7] environmental planning and management, the analysis and study of the territorial impact of wind farms in Cantabria under a GIS environment [8] the techniques of multicriteria evaluation, fuzzy logic and Geographic Information Systems as tools for land use planning [9] urban simulation scenarios using GIS and multicriteria analysis [10], GIS based sensitive analysis with multi-criteria decision [11] sustainable site selection using GIS and multi-criteria method [12] and multi-criteria decision for the location of renewable energy sources [13].To search for optimal solutions to multi-objective land use allocation problems, authors such as [14] used multi-objective optimization techniques. Other authors such as [15], incorporated genetic algorithms that explored and demonstrated the usefulness of different tools and approaches and finally [16] published in OLADE, an approach for rural electrification projects, where he raises the problems of renewable energy and its future solution.

2 Materials and methods

The research is based on the free software QGIS, Hierarchical Process Analysis and Databases of alternatives and criteria information. For its development, the work of [17] and [18] was taken as a reference, applied to 60 public agencies and 12 private companies in the wind energy sector in the United Kingdom, considering the following constraints:

- Optimal areas <10 km from the power grid,
- Avoid high hill ridge,
- Slope < 10%,
- Wind speeds greater than 5 m/s,
- 10 km to the road. 10 km to the power grid,
- 400 meters to aquifers,
- 1 km to area of ecological value or area of special scientific interest,
- Grade 1 or 2 soil.

The problem is restricted to the following conditions:

- Incompatibility in land use, protected space, or with high environmental value,
- Areas located less than 300 m from an urban or residential area, to minimize visual and acoustic impact,
- Area located less than 100 m from a forest mass, to avoid turbulences,
- Areas with aeronautical restrictions, taking into account air safety, radio-electric interference, civil and military security.
- A methodological proposal is made, which is based firstly on the application of the Hierarchical Analysis

Hierarchical Analysis (AHP) method, to find the weights of each criterion or constraint with a view to its evaluation within the GIS, where first the hierarchical structure is modeled, based on the model of [18]. Then, the priorities among the criteria are established (relative importance of evaluation). Here a priority vector is constructed for the evaluation of the importance given by each expert to each criterion, this numerical value should be as tight as possible, by direct assignment, through a scale.

The pairwise comparisons will determine the weights of each criterion and will be presented as a square matrix, where each element is compared with each other [19]. One of the drawbacks of this method is that there is not always consistency between the judgments issued by the decision maker, so it is necessary to measure the consistency of judgments, called consistency ratio (CR), because for this, first the consistency index (CI) is calculated, as shown in Eq.1:

$$CI = \frac{\lambda max - n}{n - 1} \quad (1)$$

Table 1.
Random consistency index (RI) as a function of the size of the n matrix

n	1	2	3	4	5	6	7	8
RI	0	0	0,52	0,88	1,11	1,25	1,8	1,4
n	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
RI	1,45	1,48	1,51	1,53	1,55	1,57	1,5	1,5

Source: Saaty Thomas, L.2015

And where, for the improvement of the consistency of the judgments, the random consistency index (RI) is compared with the size of the n matrix, as can be seen in Table 1.

Finally, the consistency ratio (CR) is calculated by the following Eq.2:

$$RC = \frac{CI}{RI} \quad (2)$$

This term must be less than 0,10 for the results to be reliable and to be recognized as acceptable [14]. After the consistency analysis, if the condition is met, we proceed with the method, evaluating in a paired way each criterion, and arriving at a weighting that provides the degree of importance of one criterion over another, actually what the expert choice software does, is after obtaining the score of the experts, it normalizes by the sum of the columns, then dividing each element xij, on the sum, In this way each criterion is left in a single range, to be able to operate each criterion, then, the normalized values of each criterion are added, becoming the weighting of the same, in the same way, the normalized values of each column are added, obtaining the weight of each alternative, finally each alternative is operated by the weights of each criterion, and the alternative that has the highest value, will be the best.

Procedure to implement the GIS method

The remarkable thing about GIS is that they allow working with georeferenced spatial information. That is, they can present a digital map, in which all objects have a common identifier and their own attributes. This allows the information to be separated and stored independently by thematic layers, which with their superposition (always under the same reference system) make up the digital map. This makes it possible to work with the information in a very versatile way, with easy access and facilitating the user to generate new information related to the existing one Fig. 1.

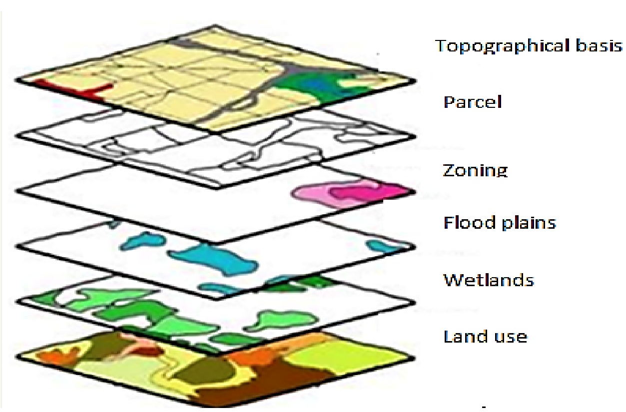

Figure 1. Capable overlay in GIS systems.
Source: García-Cascales, 2013.

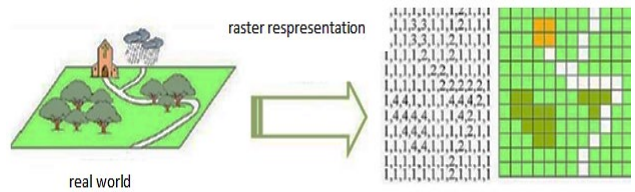

Figure 2. The vector geometric elements used are: points, lines, polygons and multipolygons.
Source: Self-made Imagen.

3 Vector data

ESRI Shapefile (SHP) format. In order to maintain the geometric characteristics of the elements of a digital map, its boundaries are defined by vectors. This makes it possible to process geographic information with high spatial accuracy Fig. 2.

3.1 Characterization of the alternatives to be evaluated

Alternatives to be studied:

1. **Gibara III Wind Power Plant**: it is located in Gibara municipality, 40 km northeast of Holguin province, it is expected to generate 51 MW and its start-up is planned for the year 2022, according to two UNE statistics.
2. **Cabo de Lucrecia Wind Power Plant**: Located in Punta de Mula, Banes municipality, Holguin province, it comprises a half moon from Cabo Lucrecia almost at the latitude of Cabo Lucrecia, to Punta de Mula to the Northwest, from 200 m from the coast and up to 2 km in depth, with an estimated length of 6 km and an approximate surface extension of 13 km2, it has sustained winds throughout the day, This condition differentiates this territory from the southern coast, because the arrival of the trade winds is not affected by the mountains and also, during the daytime period the wind direction coincides with the sea breeze, which contributes to increase the wind speed, results obtained from the database studied, the average winds at Cape Lucrecia are 17 km / h (4,7 m/s), a favorable condition to obtain electrical energy from the wind using low (less than 100 kW) and moderate power (100-500 kW) machines.
3. **Punta de Mula Wind Power Plant**: Located in Puerto Rico Libre beach, Banes municipality, Holguin province.
4. **Rio Seco I Wind Farm**: Located in Punta Caleta Honda, in Banes municipality, Holguin province, the Rio Seco Wind Farm will have a power of 51 MW and will have 34 GAs of 1.5 to 2 MW, with a configuration in 2 rows almost parallel to the coast and no less than 300 m from it, with its GAs in the most advantageous positions to avoid unfavorable geotechnical conditions.

4 Results and discussion

Results of the application of the Hierarchical Process Analysis method.

To check the consistency of the experts' evaluation, the Expert software was used, in its small configuration, in case it does not exist, the process is performed again, Table 2.

Table 2.
Expert choice evaluation.

Hierarchieze criteria for the evaluation of areas to install wind farms Pairwise comparations Matrix					
	Distance ports	**Distance of roads(Railway)**	**Distance to communication**	**Distance to electrical network**	**Wind speeds**
Distance ports	1	5	1/5	1/3	1/7
Distance of roads(Railway)	1/5	1	1/3	1/3	1/5
Distance to communication	5	3	1	4	1/3
Distance to electrical network	3	3	1/4	1	1/5
Wind speeds	**7**	**5**	**3**	**5**	**1**

Source: Own elaboration.

Table 3.
Consistency analysis.

AHP		**Consistency check**	**AHP-1**	**CA**	**Lambda**	**Ci**	**CI/RI**
0.101	10.1 %		0.101	1.6363	5.9706445	0.2427361	0.2167286
0.056	5.6 %	**Check your results 22 %**	0.056	0.9476	**Randomness index, RI**		
0.249	24.9 %		0.249	1.19281	3	0.58	1.12
0.123	12.3 %		0.123	1.31044	4	0.9	
0.471	47.1 %		0.471	0.88374	5	1.12	

Source: Own elaboration.

Table 4.
Relative weights found for the evaluation of areas to install wind farms.

Objective: To prioritize criteria for the evaluation of areas to install wind farms.							
#	**Criteria**	**C1**	**C2**	**C3**	**C4**	**C5**	
C1	Distance Ports	1	5	⅕	⅓	1⁄7	
C2	Distance of roads (Railway, Highway)	⅕	1	⅓	⅓	⅕	
C3	Distance to population center	5	3	1	4	⅓	
C4	Distance to electrical networks	3	3	0.25	1	⅕	
C5	Wind speeds	7	5	3	5	1	
	Addition.	16.00	17.00	4.25	10.00	1.00	
#	**Criteria**	**C1**	**C2**	**C3**	**C4**	**C5**	
C1	Distance Ports	1	5	0.2	0.333	0.142	
C2	Distance of roads (Railway, Highway)	0.2	1	0.333	0.333	0.2	
C3	Distance to population center	5	3	1	4	0.333	
C4	Distance to electrical networks	3	3	0.25	1	0.2	
C5	Wind speeds	7	5	3	5	1	
	Addition.	16.20	17.00	4.78	10.67	1.88	
	Normalized						**Average**
C1	Distance Ports	0.062	0.294	0.042	0.031	0.076	0.101
C2	Distance of roads (Railway, Highway)	0.012	0.059	0.070	0.031	0.107	0.056
C3	Distance to population center	0.309	0.176	0.209	0.375	0.178	0.249
C4	Distance to electrical networks	0.185	0.176	0.052	0.094	0.107	0.123
C5	Wind speeds	0.432	0.294	0.627	0.469	0.533	0.471

Source: Own elaboration.

Likewise, the result of the consistency analysis, equal to 0.21, slightly higher than 0.10, which is ideal, but can be considered for this study, Table 3.

Summarizing the application of the AHP method, Fig. 4 shows the weights of each criterion to be taken into account in the process. each criterion to be taken into account in the process are shown in Table 4.

As can be seen in Table 4, the wind speed criterion was the most weighted by the experts; if there were no acceptable speeds, it would be impossible to operate the turbine, followed by the distance to populated communities, which would benefit from the energy produced, and finally the electrical grids and communication routes for installation logistics.

The criteria or restrictions that were taken into account in the GIS modeling are shown below. Are shown below:

4.1 Variable criteria

1.That they are located in the strata Gibara III, Rio Seco I, Punta de Lucrecia and Punta de Mula,

2.That the ports are close to the areas of location to guarantee the transfer of the resources imported by the country, distance of 40 km, considering that this will be the optimum with a value equal to 5, between 40 and 50 km value equal to 3, and more than 60 km, value equal to 1, to be taken into account for the buffers,

3.That the future facilities are close to communication lines such as roads and railways, also to ensure that inputs reach the installation site, between 0 and 3 km, value of 5, between 3 and 5 km value of 3, and more than 5 km value of 1.

4.That future installations are close to population centers (potential consumers) and not only in isolated communities, because the energy generated must be consumed or transferred to the grid, for a distance of 2 km, value of 5, from 2 km to 3 km value of 3, more than 3 km value of 1,

5.That future facilities are close to the grid to reduce the levelized energy costs, value of 5, for distance of 5 km, between 5 and 8 km, value of 3 and more than 8 km, value of 1,

6.That the future installations wind speeds are optimal, based on a wind study, based on the wind map of Cuba, for speeds between 5 and 6 m/s, value of 1, for speeds between 6.5 and 7 m/s, values of 3 and greater than 7 m/s, values of 5,

7. That future installations do not intercept migratory air corridors of birds,

That future facilities do not intercept areas of flora and fauna reserves.

Data source for conceptual modeling through GIS Table 5.

4.2 Making Buffers

With the data obtained, the buffers of each variable are made in the QGIS software. Fig. 3, shows the buffers made to the wind speed polygonal, wind speed polygonal area with a criterion of 5, 1 km buffer with a criterion of 3 and 2 km buffer evaluated with a criterion of 1.

Fig. 4 shows the buffers made to the polygon shapefiles of the population centers. The 2 km buffer was given a criterion of 5, the 3 km buffer a criterion of 3 and the 5 km buffer a criterion of 1.

Table 5.
Data origin for GIS modeling.

Supplies	Type of data
Stratum 1,2,3 y 4	Poligon shapefile
Position	Poligon shapefile
Road mesh	line shapefile
Population core	Poligon shapefile
Electrical line meshes	line shapefile
Wind speed	Wind map of Cuba
Migratory flyways	Google earth

Source: Own elaboration.

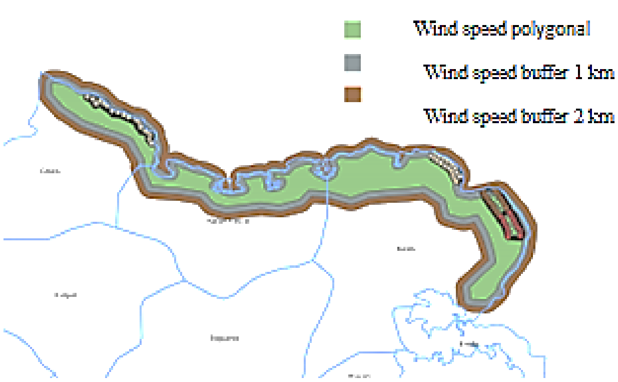

Figure 3.
Buffer to wind speed, source: Own elaboration.
Source: Self-made Imagen

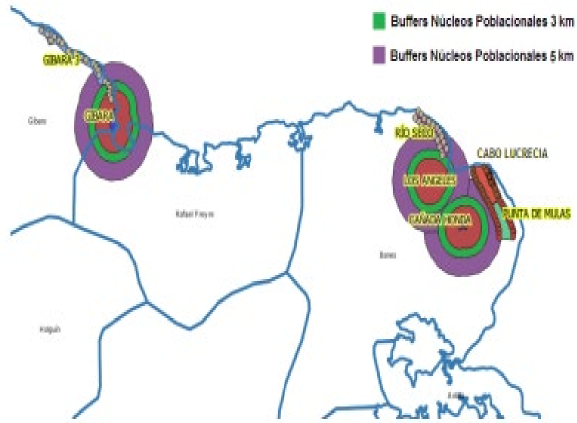

Figure 4. Buffers of population centers.
Source: Self-made Imagen

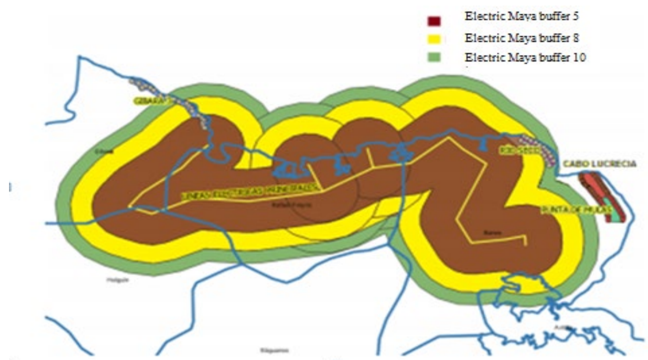

Figure 5. Electrical line buffers
Source: Self-made Imagen

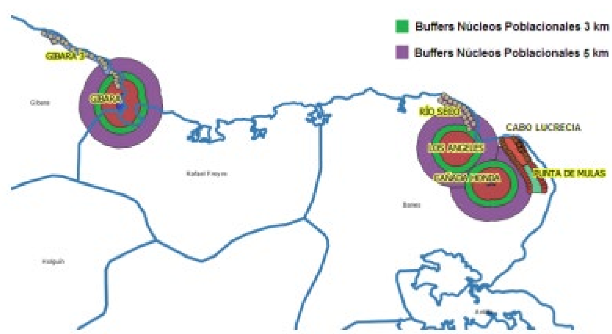

Figure 6.
Buffers of population centers.
Source: Authors

Fig. 5 shows the buffers made to the shapefiles of the electric grid lines, giving a criterion of 5 to the buffer of 5 km, a criterion of 3 to the buffer of 8 km and a criterion of 1 to the buffer of 10 km.

Fig. 6 shows the buffers made to the polygon shapefiles of the population centers. The 2 km buffer was given a criterion of 5, the 3 km buffer a criterion of 3 and the 5 km buffer a criterion of 1.

Fig. 7 shows the buffers made to the shapefiles of the electric grid lines, giving a criterion of 5 to the buffer of 5 km, a criterion of 3 to the buffer of 8 km and a criterion of 1 to the buffer of 10 km.

Fig. 9 shows the buffers made to the shapefiles of the road map lines, the 3 km buffer was given a criterion of 5, the 5 km buffer was given a criterion of 3 and the 8 km buffer was given a criterion of 1.

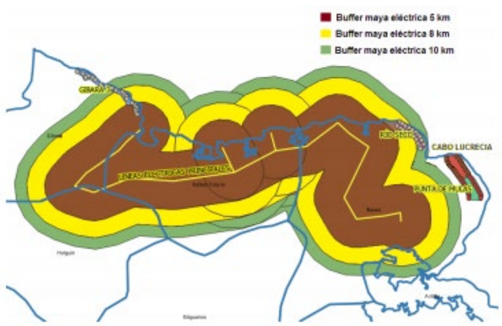

Figure 7.
Power line buffers. Sources: own elaboration.
Source: Authors

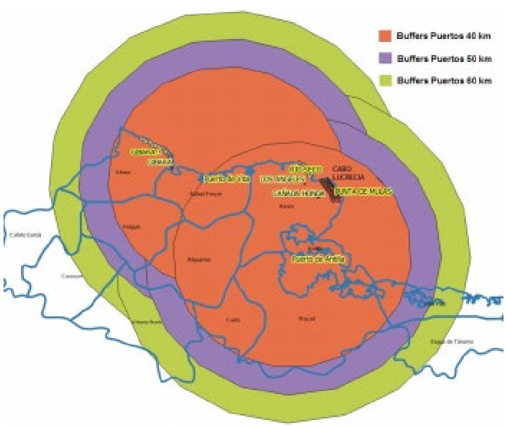

Figure 8.
Buffers of the ports
Source: Self-made Imagen.

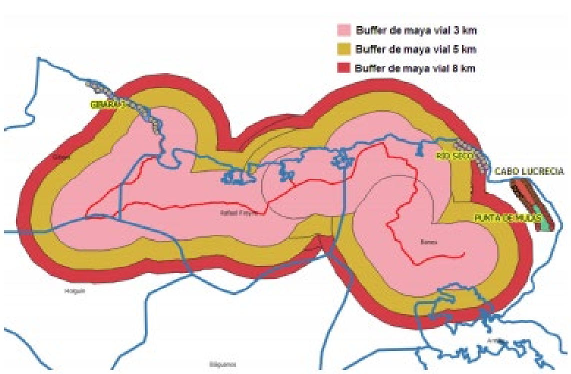

Figura 9.
Topes de la calzada
Source: Authors

Figure 10. 2 km raster of the population centers.
Source: Self-made Imagen.

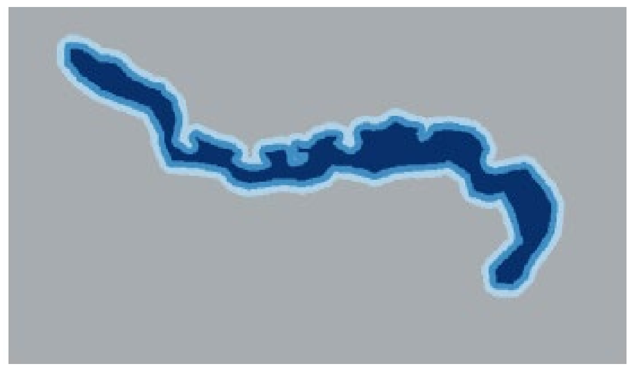

Figure 11. Raster sum of wind speed
Source: Self-made Imagen.

4.3 Rasterization of buffers

Each buffer is converted to a raster image with the value reached according to its criteria, this operation is performed with the conversion tool of this software, which is called rasterize. Fig. 10 shows an example of the rasterization of the 2 km buffer of the population centers.

4.4 Sum of the raster images of each variable

The raster images of each variable are added in the QGIS software tool, called raster calculator. Fig. 11 shows the raster calculator in the procedure of adding the raster images made to the buffers of the population cores. Fig. 12 shows the result of the sum of the raster images of the wind speed variable.

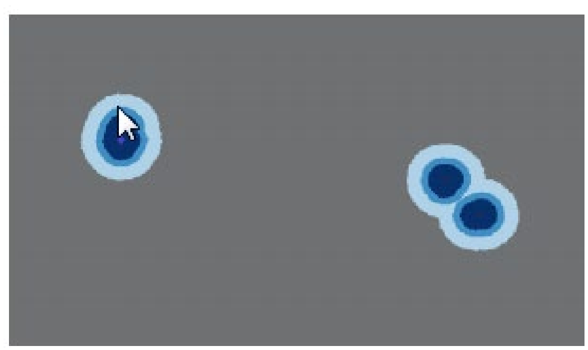

Figure. 12. Shows the result.
Source: Self-made Imagen

Likewise, Fig. 12 shows the result of the sum of the raster images of the population core variables.

Figs. 13 and 14 shows the result of the raster sum of the population centers variable.

4.5 *Sum of all raster*

With the raster sums of each variable, we proceed to add them all, each one multiplied by the weight of its variable obtained by the AHP method, to obtain a raster image of all the variables.

Fig. 15, shows the raster image of the sum of all the rosters of each variable, where the areas with the highest concentration of variables with their best criteria can be seen in dark blue.

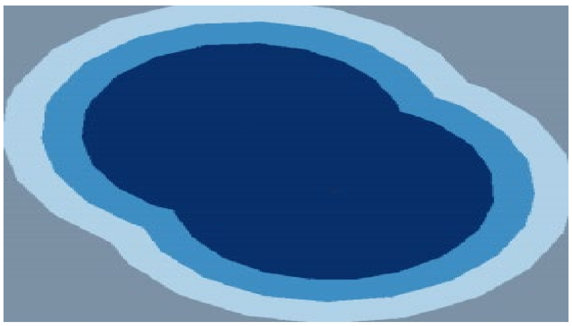

Figure 13. Raster sum of population centers.
Source: Self-made Imagen

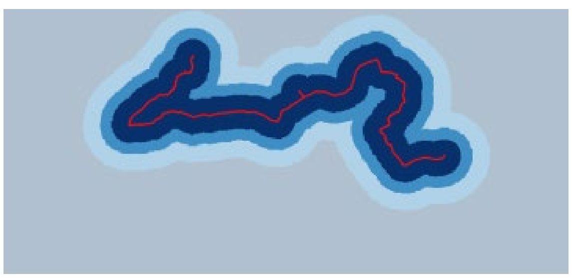

Figure 14. Shows the result of the raster sum of the Power lines variable.
Source: Self-made Imagen.

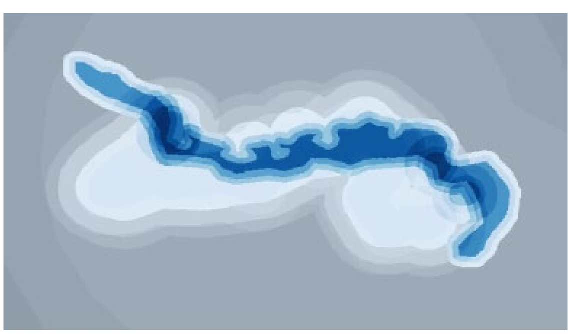

Figure 15. Shows the raster image of the sum of all the rosters.
Source: Self-made Imagen.

4.6 *Vectorization*

The raster image was vectorized to find the polygons with the highest variable content and their criteria, where the polygons were labeled with their values, from 1 with the lowest variable content to 9 with the highest variable content, Fig. 16.

Fig. 17 shows an enlarged image of the vectorization, where the polygon of the Gibara III wind farm project can be seen, which encloses in its area a polygon with a value of 9, that is, it meets all the variables in its highest criterion.

Fig. 18 shows an enlarged image of the vectorization, where the polygons of the wind farm projects in the municipality of Banes can be seen. It can be observed that the Río Seco wind farm project has a polygon with a value of 7 and in the areas of Cabo Lucrecia and Punta de Mulas, the polygon with the best value is 6.

From the analysis it was obtained that the Gibara III Wind Farm project was the project with the optimal zones in the eastern region of Holguin, since it encloses in its stratum, zones with all the variables and its best criteria with a value of 9. The Rio Seco project enclosed in its stratum zones with a maximum value of 7, this means that it does not comply with all the variables in its best criteria, as well as Cabo Lucrecia and Punta de Mulas, with zones with a maximum value of 6.

Table 6 shows the Wind Farm projects, in what could be an order of priority in their construction for their optimal zones, according to the variables and criteria evaluated in the research.

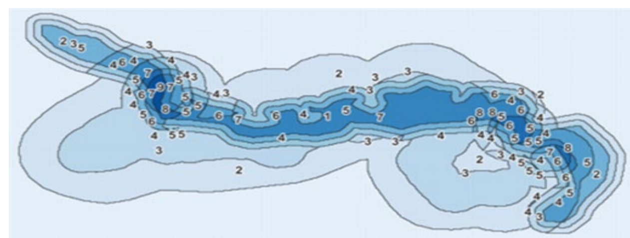

Figure 16. Vectorization of the total raster.
Source: Self-made Imagen

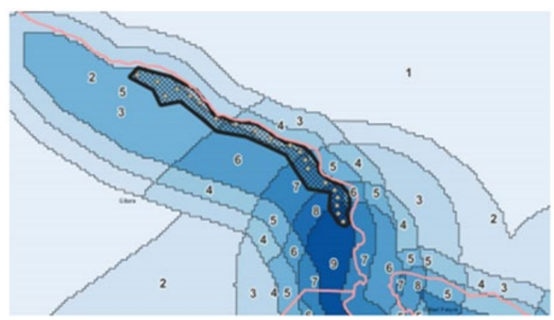

Figure 17. Gibara III in vectorization
Source: Self-made Imagen.

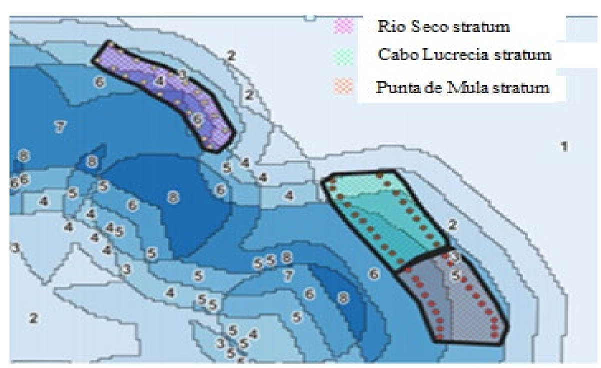

Figure 18. Dry river, Cape Lucrecia and Punta de Mulas in the vectorization
Source: Self-made Imagen

Table 6.
Results of the research

Wind Farm Projects	Priority
Gibara III	1
Rio Seco	2
Cabo Lucrecia	3
Punta de Mulas	4

Source: Own elaboration

5 Conclusions

1. With the research carried out, it was possible to elaborate, for the first time, a mathematical conceptual model for the selection of optimal zones for the installation of wind farms in the eastern north of Cuba, by means of the multicriteria and GIS methods, where it was determined that, within the evaluated alternatives of wind farms, Gibara III is the optimal one.
2. As a result of the combination of Multicriteria Decision Support Methods (MCDM) and Geographic Information Systems (GIS), a procedure was obtained that can be generalized for the optimal selection of areas in different fields of science.
3. These models will allow the development of wind projects in the eastern region of Holguin, and to be able to manage human, financial and material resources.

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