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Wind Farm Location Special Optimization Based on Grid GIS and Choquet Fuzzy Integral Method in Dalian City, China

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Abstract: Selecting an appropriate wind farm location must be specific to a particular administrative region, which involves restrictions balance and trade-offs. Multi-criteria decision making (MCDM) and GIS are widely used in wind energy planning, but have failed to achieve the selection of an optimal location and make it difficult to establish a set of independent factors. Fuzzy measurement is an effective method to evaluate intermediate synthesis and calculates the factor weight through fuzzy integrals. In this paper, optimal wind farm location is analyzed through coupling Grid GIS technique with λ fuzzy measure. Dalian City is selected as the study area for proving the feasibility of the proposed method. Typography, meteorological, transmission facilities, biological passage, and infrastructure are taken into the index system. All the indexes are specialized into victor grid cells which are taken as the base wind farm location alternative unit. The results indicate that the Grid GIS based λ fuzzy measure and Choquet fuzzy integral method could effectively deal with the special optimization problem and reflect optimal wind farm locations.

Keywords: wind farm; Grid GIS; λ fuzzy measure; optimization

Citation: Cui, L.; Xu, Y.; Xu, L.; Huang, G. Wind Farm Location Special Optimization Based on Grid GIS and Choquet Fuzzy Integral Method in Dalian City, China. *Energies* **2021**, *14*, 2454. https://doi.org/10.3390/en14092454

Academic Editor: Andrés Elías Feijóo Lorenzo

Received: 25 March 2021
Accepted: 19 April 2021
Published: 25 April 2021

1. Introduction

Currently, the world primary energy consumption has increased from 3701 Mtoe in 1965 to 13,511 Mtoe in 2017 [1]. At the global consumption level of 2017, coal, oil, and natural gas reserves are barely sufficient for a further 52.6, 50.2, or 134 years, respectively [2]. The international community is increasingly concerned about the influence of primary energy consumption on climate change and air pollution [3]. As well known, wind energy is a kind of renewable energy which could be sustainably utilized and doesn't bring any air pollution, and is expected to achieve extensive commercial success.

Selecting an appropriate wind farm location must be specific to a particular administrative region, which involves restrictions balance and trade-offs [4–6]. The location of a wind farm is very important to the feasibility of wind turbine investment, and it is also related to environmental impacts such as wildlife and socio-economic factors. Consequently, local planners should face dual challenges because they have to make plans for economy growth and reduce the environmental risk [7]. Therefore it is essential to indentify the optimal locations for wind farm development. Previously, many researchers analyzed offshore and onshore wind farm layout optimization [8,9]. For example, Mytilinou developed an optimization methodology based on life cycle cost analysis and used this in the offshore wind farms [10]. Nezhad assessed offshore wind farm sites in the Samothraki Islands and showed the OW energy potential per location [11]. Multi-criteria decision making (MCDM) has been widely used in energy planning [12]. For example, a hybrid MCDM model was proposed by Mehmet and Metin based on BOCR (Benefits, Opportunities, Costs and Risks) and ANP (Analytic Network Process) to research renewable energy alternative priorities [13]. A novel hybrid MCDM method was developed by Fetanat and Khorasaninejad based on the fuzzy analytic network method to find an offshore wind farm's best position in the southwest of Iran, and the results revealed robustness when the experts' opinions changed [14]. In general, this research was effective for evaluating wind farm locations.

In real-world problems, spatial data is very important for identifying optimal wind farm locations. The Geographic Information System (GIS) is an effective tool to deal with the problem of spatial planning and management [15]. As a result, from the 2000s a number of studies made efforts to estimate wind farm location priorities, and built alternatives by combining MCDM with GIS in several countries [16–19]. For example, Latinopoulos and Kechagia developed a multi-criterion evaluation method for wind farm location in Greece based on GIS, and the results showed that the method could provide suitable locations for future wind farm building [7]. Baseer et al. conducted a wind farm site suitability analysis using a MCDM approach based on GIS [20]. Konstantinos et al. presented a combination of AHP (Analytic Hierarchy Process) and GIS to determine the most suitable locations in Eastern Macedonia and the Thrace region, Greece [21]. Spyridonidou and Vagiona used GIS and Statistical Design Institute software to plan offshore wind farms in Greece under the national spatial planning scale [22]. However, the GIS based evaluation methods for wind farm site selection are mainly focused on spatial elements without considering a differentiated and precise evaluation of location suitability, and failed to achieve the optimal location.

When attempting to evaluate suitable wind farm locations a common feature is that almost all the MCDM methods assume that the evaluation factors are independent of each other. Therefore, for a complex system it is difficult to establish a set of independent factors [23,24]. For the MCDM method with interactive factors, fuzzy measure is an effective method to evaluate synthesizes intermediate and calculates the factor weight through fuzzy integral [25]. Fuzzy measure is obtained by replacing additivity with a weaker monotonicity, and it is a form of non-additive measure [26]. Previously, a number of studies were mainly focused on the theoretical development of fuzzy integrals and fuzzy measures [27,28]. The results showed that the fuzzy measure can effectively deal with the interaction between various factors [29]. However, the theory of fuzzy measure and its application in the integration of MCDM and GIS is very infrequent, especially in wind farm location optimization. The reason lies in that decides the fuzzy measure effectively is very complex. As a result, λ fuzzy measure is proposed to deal with this complex problem without expert opinion [30]. In particular, λ fuzzy measure is simple to interpret and easy to calculate, therefore it has gained great popularity.

Therefore, the research question of this paper is to develop a grid GIS based Choquet fuzzy integral method and find the optimal wind farm location in the Dalian City of China. All the data of the study area are specialized by Grid GIS which contains the raster forms and the victor attributes. The victor grid cell will be taken as the base wind farm alternative unit. The λ fuzzy measure will be used for weighting interactive factors and their coalitions. Marichal Entropy and Shapley Values will be used to determine the λ fuzzy measure. The Choquet fuzzy integral method will be used to find the optimal wind farm location in the study area. Compared with the traditional MCDM method, this paper could balance the trade-offs among the independent factors when finding an optimal wind farm location. Moreover, victor grids have an advantage over common raster data in former research. The obtained results of the paper will be useful for potential role planners when establishing effective wind farm building plans and improving local energy sustainability.

2. Methodology

In the context of finding an optimal wind farm location, there will be conflicts between different indexes. So as to deal with the complicated conflicts among the indexes, λ fuzzy measure is used to weight each index and the Choquet fuzzy integral method is used to combine the index values and weights. To deal with the wind farm location finding problem, the hybrids of GIS grids, Marichal Entropy and Shapley Values are put forward to calculate the fuzzy measures. Then, the optimal wind farm location is determined.

2.1. The Concept of the λ Fuzzy Measure

Sugeno first proposed the concept of the λ fuzzy measure [31]. It is a modeling of index set, which can express the importance of one or more indexes and describe the relationship between multiple indexes. Let $A = \{a_1, a_2, \ldots, a_m\}$ be a state space and $X = \{x_1, x_2, \ldots, x_n\}$ be the space of evaluation state. Dalian's wind farm alternative areas are presented as $x_1, x_2, \ldots, x_n \in X$. The options n $a_1, a_2, \ldots, a_n \in A$ would affect the states m, which define the m factors/index specific to the wind farm. For a given wind farm area $x_j \in X$, each index $a_i \in A$ the assessment value is expressed as $a_i(x_j)$.

Non-negative numbers are used to connect the state space $a_i(i = 1, 2, \ldots, m)$ with its combination to calculate the weight of each index in the wind farm location optimization process. λ fuzzy measure is used to calculate the significance of index a_i and its combination in respect of the potential interrelationship among constraints and indexes.

$P(a)$ implies the power set of A, and g: $P(A) \rightarrow IR$ implies the set function of λ fuzzy measure on set A which satisfy the following conditions:

(a) $g_\lambda(\phi) = 0, g_\lambda(A) = 1$;
(b) if $R \subseteq S$ then $g(R) \leq g(S)$, for any $R, S \in P(A)$;
(c) $g_\lambda(E \cup F) = g_\lambda(E) + g_\lambda(F) + \lambda g_\lambda(E)g(F)$ where $-1 < \lambda < \infty$ for $E, F \in P(A)$ and $E \cap F = \phi$

$$g(A) = \frac{1}{\lambda}[\prod_{a_i \in A} (1 + \lambda g_i) - 1] \quad (1)$$

where IR is the power set of $P(A)$, $g_\lambda(S)$ denotes the importance or weight of the set of index $S \in P(A)$, or the capability of S to find out the wind farm optimal location without considering any remaining indexes; and g is the g_λ fuzzy measure. If set $A = \{a_1, a_2, \ldots, a_m\}$ is finite, the mapping $a_i \rightarrow g_i(a_i)$, $i = 1, 2, \ldots, m$ is the fuzzy density function, and can be formulated as follow:

2.2. Choquet Fuzzy Integral Method

The Choquet fuzzy integral method is a most commonly used aggregation operator when there is interaction between indexes. Consider the given wind farm alternative as x_j, and the relevant stand of each index as a numerical value, shown as $a_1(x_1), a_2(x_2), \ldots, a_m(x_j)$. For the wind farm alternative question, A is the index set with the corresponding λ fuzzy measure μ. In order to compare different wind farm location optimization schemes, the general index score $a_1(x_1), a_2(x_2), \ldots, a_m(x_j)$ needs to be obtained. Assume that $a_1(x_1) \leq a_2(x_2) \leq \ldots \leq a_m(x_j)$, then the Choquet fuzzy integral measuring μ on X is defined as [32]:

$$\int x_j d\mu = \sum_{i=1}^{m} (a_i(x_j) - a_{i-1}(x_j))u(A_i) \quad (2)$$

The transfer of vector $x_j(a_i)$ is i, and $A_i = \{a_i, \ldots, a_m\}$, $a_0(x_j) = 0$, $\mu(A_0) = 0$.

2.3. The Determination of λ Fuzzy Measure

Before applying the Choquet integral method to get the optimal alternative of the wind farm, it is necessary to calculate the λ fuzzy measure of each index. Shapley value is used to insure the weight of each index is calculated objectively. The role of index $a_i(a_i \in A)$ played in the wind farm alternatives process can not only be described by g_λ (a_i), but the weights of all set index $S(\{S|a_i \in S, S \in P(A)\})$ must also be examined. Grabisch defined the Shapley value based on the fuzzy measure of general finite discrete set [33]. If g_λ is the λ fuzzy measure of $P(A)$, for any $a_i \in A$, the Shapley value can be defined as:

$$I(a_i) = \sum_{k=0}^{m-1} \frac{(m-k-1)!k!}{m!} \times \sum_{Q \subseteq A \backslash a_i, |Q|=k} (g_\lambda(Q \cup a_i) - g_\lambda(Q)) \tag{3}$$

where $I(a_i)$ is the contribution of index a_i in wind farm alternative, $\sum_{i=1}^{m} I(a_i) = 1$. If all indexes in set A are independent of each other, that $g_\lambda(a_i) = I(a_i)$. The contribution of $a_i(a_i \in A)$ could then be calculated through the following formulation:

$$w_j = \frac{1 - E(a_j)}{m - \sum_{i=1}^{m} E(a_j)}, j = 1, 2, \ldots, m \tag{4}$$

where $0 \leq w_j \leq 1$ and $\sum_{j=1}^{m} w_j = 1$.

Marichal Entropy is used to calculate the fuzzy measure of indexes in this research. Marichal Entropy was defined by Marichal and proved that it is similar to the Shannon Entropy [34]. Fuzzy measure of from Marichal Entropy satisfies the boundary conditions, maximization, decisiveness, expandability, symmetry and strictly monotonic increasing is the typical property of the effective entropy measure. When the Shapley value of the wind farm index is given, λ fuzzy measure can be computed through Equation (5).

$$\underset{\lambda, g_\lambda}{Max}\ H_M(g_\lambda) = \sum_{i=1}^{n} \sum_{S \subseteq X \backslash a_i} \gamma_s(n) h[g_\lambda(S \cup a_i) - g_\lambda(S)] \tag{5a}$$

subject to

$$\begin{cases} I(a_i) = \sum\limits_{k=0}^{n-1} \frac{(n-k-1)!k!}{n!} \sum\limits_{\substack{Q \subseteq X \backslash a_i \\ |Q| = k}} [g_\lambda(Q \cup a_i) - g_\lambda(Q)] \\ g_\lambda(A) = 1 \\ g_\lambda(E \cup F) = g_\lambda(E) + g_\lambda(F) + \lambda g_\lambda(E) g(F) \\ g_\lambda(S) \in (0,1), \forall S \in P(A) \\ \lambda \in (-1, \infty) \end{cases} \tag{5b}$$

As $h(x) = \begin{cases} -x \ln x & if\ x > 0 \\ 0 & if\ x = 0 \end{cases}$, $\gamma_s[M] = \frac{(m-|S|-1)!|S|!}{m!}$, and $|S|$ is the potential of index S.

By calculating the model of Equation (5), the λ value and the λ fuzzy measure are acquired. Take g_λ (a_i) and λ into the Equation (1), λ fuzzy measure of all the indexes of the wind farm can be solved.

2.4. Natural Breaks

The ranking of the results is based on the natural breaks method [35]. The Natural breaks method finds "the optimal" way to cut apart the ranges, which means the ranges where like areas exist are grouped together. The variation is minimized by the Natural breaks method. Therefore, the areas within each color are as close as possible in value to each other.

3. Study Area

The study is carried out in Dalian City, which is located in the northeast of Liaoning province, China. The total area is 13,237 km^2, with 5,952,000 residents (census of 2018). The typography is dominated by hills with altitudes ranging from 0 m to 476 m. The study area is situated in a peninsula, and protrudes into the sea (as shown in Figure 1). Dalian City is situated in the transition zone from the Bohai Sea to the Mongolia plateau, and is affected by the humid air from the ocean and the cold air from the north [36]. As a result it is characterized by rich wind resources. According to the 13th five-year plan of Dalian energy development, the installed capacity of wind energy in the city will reach 1.9 million kilowatts in 2020.

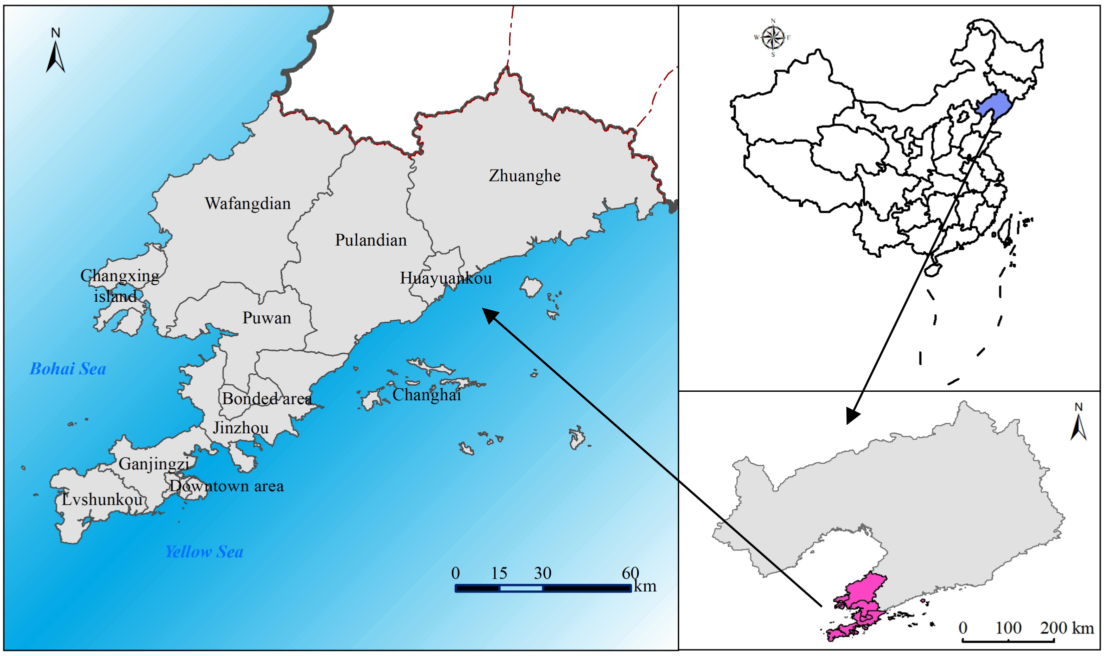

Figure 1. The location of the study area.

The importance of the study area lies in the fact that the potential of wind energy is very high and has potentially suitable alternatives for the development of a wind farm. As a famous harbor and industrial city in China there are many infrastructures in Dalian, such as shipbuilding, petrochemical, equipment manufacturing and high-tech industry. Therefore, the demand for electricity is very large in this area. Dalian is an important routine for migratory birds in northeast Asia. Routes for migratory birds through Dalian can be divided into three: the east, middle, and the west [37]. Approximately 10 million migratory birds are foraged, stopped, and replenished their physical strength in this area each year according to the statistics [38]. Therefore, all kinds of natural conditions and socio-economic conditions will cause conflicts between wind energy exploration and environmental protection. To make full use of the considerable wind resources, it is a considerable challenge for the local government to management the wind energy more efficiently.

4. The Frame Work of the Wind Farm Location Special Optimization Model

In order to solve the wind farm location optimization problem, it is necessary to establish an index system to determine the wind farm alternatives. The Chinese government provided a number of the indexes that should be required when making efforts to find a suitable location for a wind farm. The indexes are categorized as natural factors such as typography, landform and geological conditions. Socio-economic factors should also be considered in the wind farm selection process as presented in the introduction section. Therefore, the index system taken into consideration can be summarized as typography, meteorological, transmission facilities, biological passage, and infrastructure (as presented in Table 1). The data of daily average wind speed in Dalian City from 1 January 2010 to 31 December 2018 are collected. The data's altitude and slope are calculated from DEM which is download from http://www.gscloud.cn/ accessed on 23 November 2019. Transmission lines, major roads, the infrastructures, bird ways and bird sanctuary are collected from the Bureau of Natural Resources, Dalian, China.

Table 1. Index system for finding the optimal location of wind farm.

First Level Index	Second Level Index	Third Level Index
Natural factors	Typography	Altitude Slope
	Meteorological	Accumulated wind speed
Socio-economic factors	Transmission facilities	Distances to roads Transmission lines
	Biological passage	Bird way Bird sanctuary
	Infrastructure	Building area Power plant Chemical plant

Natural factors are spatial data and the research scale in previous studies is most based on administrative region. In this study the Dalian City is disaggregated into 1844 small victor grids based on Grid GIS. Ii is the integration of the grid and GIS, and it both has the raster forms and victor attributes. Natural factors and socio-economic factors are specialized into the grid cells, and take the victor grid cell as the base wind farm alternative unit. The resolving of the grid is 2000 m.

For the typography data layers, a digital elevation model (DEM) is used to create the slope layer of the area in percent, and the original resolution of the DEM is 30 m. Since wind energy decreases with the elevations as air density decreases, DEM is also used to define suitable sites of the wind farm based on elevation. For the meteorological data, the kriging interpolation method is used to generate the layer map with the resolution of 2000 m. For the transmission facilities, biological passage and infrastructure, 500 m buffer zones were created individually. Finally all the indexes are specialized into each grid which is the base wind farm alternative unit.

As the index value in each alternative farm alternative is expressed in different measurement units, the standardization process is used to render the index commensurate. The detailed processes for the wind farm alternatives optimization is generalized as the following step:

- Step 1: Build the grid cells in the study area.
- Step 2: Build the index system for wind farm location optimization system to the study area.
- Step 3: Calculate each index of each grid cell, and take the gird cell as the wind farm alternative.
- Step 4: Standardized the values of index.
- Step 5: Calculate the importance of index according to Formulas (3) and (4).
- Step 6: Determine the λ fuzzy measure of the index based on Model (5).
- Step 7: Value wind farm potential location based on the Choquet integral according to Equation (2) and determines the optimal grid for the wind farm location.

5. Results and Discussion

5.1. Determine the Shapley Value and Fuzzy Measures

All the index values are numerated from 0 to 1 according to the minimum index value and maximum index value. The index system for finding the wind farm optimal location can be classified as two categories: the positive and the negative due to the characteristics of each index. Positive means the bigger the better, and negative means the smaller the better. Meteorological and transmission facilities are classified as positive indexes, and typography, biological passage, infrastructure are classified as negative indexes. Based on Equation (4), the entropy weight of each index is obtained. Then, based on entropy weight of each index the Shapley value of each index is obtained. The optimization system involves three levels, and Table 2 presents the Shapley of the second level index. The results of the Choquet fuzzy integral method are calculated through Python code which was developed by the author.

Table 2. The Shapley value of the first and second level index.

First Level Index	Shapley Value	Second Level Index	Shapley Value
Natural factors	0.8	Typography	0.125
		Meteorological	0.875
Socio-economic factors	0.2	Transmission facilities	0.264
		Biological passage	0.055
		Infrastructure	0.681

Each index and its combined λ fuzzy measure g_λ can be calculated through Equation (5) with the Shapley values of all the indexes. The results of λ value and λ fuzzy measure in the third level index are shown in Table 3. The result is finding that all the λ values are positive, which implies there exists a complementary relationship between the indexes except distances to roads and transmission lines. With the λ fuzzy measure and λ value of the third level indexes, the Choquet fuzzy integral method can act as a region group. The λ fuzzy measure and λ value and of the first level indexes and second level indexes can also be calculated.

Table 3. The λ values and λ fuzzy measure of the third level index.

<table>
<tr><th>First Level Index</th><th>Second Level Index</th><th>Third Level Index</th><th>λ Fuzzy Measure</th><th>λ Value</th></tr>
<tr><td rowspan="3">Natural factors</td><td rowspan="2">Typography</td><td>Altitude</td><td>0.491</td><td rowspan="2">0.075</td></tr>
<tr><td>Slope</td><td>0.491</td></tr>
<tr><td>Meteorological</td><td>Accumulated wind speed</td><td>0.870</td><td></td></tr>
<tr><td rowspan="7">Socio-economic factors</td><td rowspan="2">Transmission facilities</td><td>Distances to roads</td><td>0.167</td><td rowspan="2">0.000</td></tr>
<tr><td>Transmission lines</td><td>0.833</td></tr>
<tr><td rowspan="2">Biological passage</td><td>Bird way</td><td>0.491</td><td rowspan="2">0.075</td></tr>
<tr><td>Bird sanctuary</td><td>0.491</td></tr>
<tr><td rowspan="3">Infrastructure</td><td>Building area</td><td>1.000</td><td rowspan="3">0.344</td></tr>
<tr><td>Power plant</td><td>0.133</td></tr>
<tr><td>Chemical plant</td><td>0.047</td></tr>
</table>

5.2. Wind Farm Location Based on Shapley Value

According to the Shapley value shown in Table 2, all the indexes' aggregate values can be employed to each grid cell that serves as the basis for alternative wind farm units. The ranking of the results is based on natural breaks method. Figure 2 presents the different land suitability levels of the wind farm alternatives in the study area. The results are divided into five categories: very suitable, suitable, commonly, unsuitable, and very unsuitable. The very suitable regions are mainly located around the downtown of Dalian City, whereas most very unsuitable and unsuitable areas are those found in the urban area. The commonly and suitable areas are mainly in the middle of Dalian City.

The reason the wind farm location is based on Shapley value is that the Shapley value of meteorological index is 0.875 and the Shapley value of natural factors is 0.8; the Shapley value of infrastructure index is 0.681 and the Shapley value of socio-economic factors is 0.8. Therefore, the meteorological index is the most important index in the entire optimization process based on Shapley value. The optimal grid cell for the wind farm location is a region where accumulated wind speed has a high value, and the socio-economic factors are neglected by this calculation process. The average accumulated wind speed of Dalian City from 2010–2018 is shown in Figure 3. The places with high accumulated wind speed are located around the downtown area which is consistent with very suitable areas. In contrast, the places with low accumulated wind speed are located in the north of the study area, which is consistent with unsuitable areas.

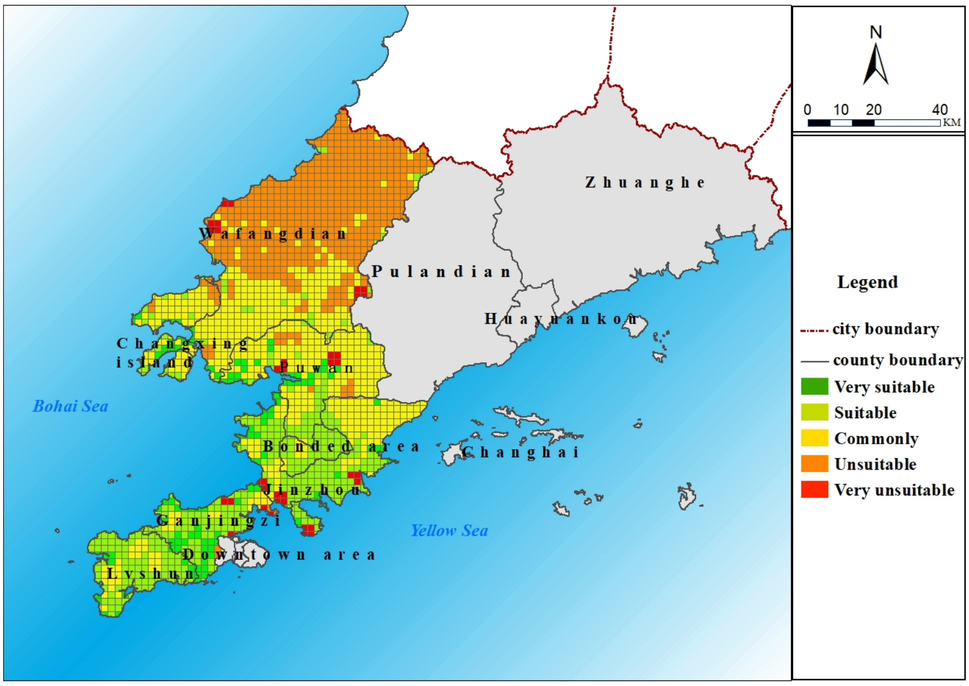

Figure 2. Wind farm suitability area based on Shapley value.

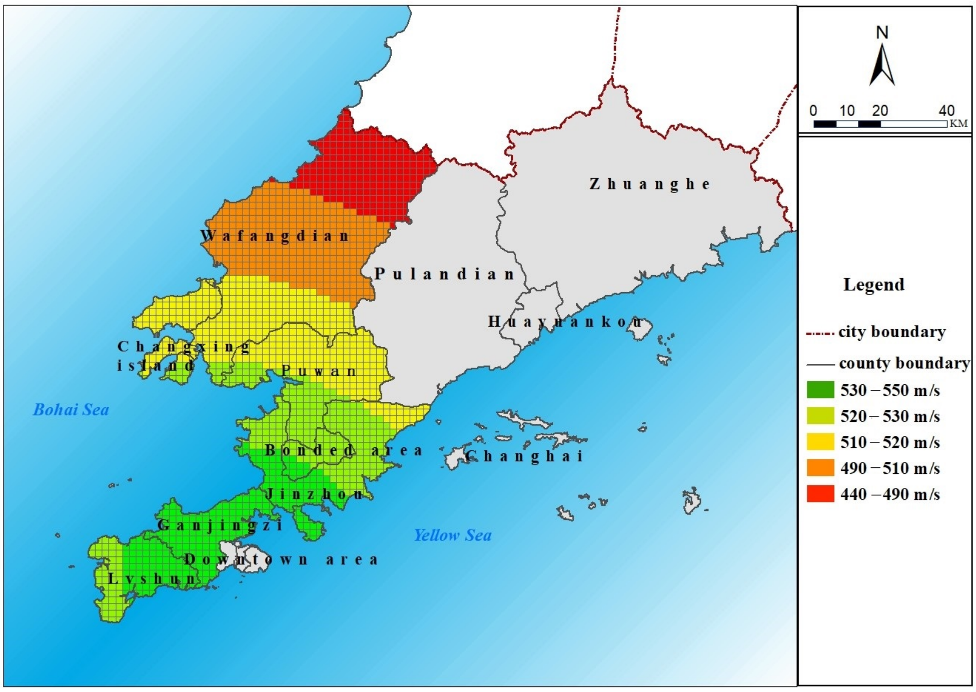

Figure 3. The average accumulated wind speed of Dalian City from 2010–2018.

5.3. The Optimal Wind Farm Location Based on Choquet Fuzzy Integral Method

Based on the λ value and λ fuzzy measure shown in Table 3, all the indexes' aggregate values for each grid cell can be calculated through the Choquet fuzzy integral method. This procedure provides a general measurement standard for each grid cell, so that the specific alternative wind farms in Dalian City can be optimized accordingly. The ranking of the result is based on the natural breaks method. Similar to the result from the Shapley value, the result is divided into five categories: very suitable, suitable, commonly, unsuitable, and very unsuitable. Figure 4 shows the wind farm suitability areas based on the Choquet fuzzy integral method. The very suitable regions are mainly located in Changxing Island and Jinzhou near the Yellow Sea. The very unsuitable and unsuitable areas are mainly located in the north of Wafangdian.

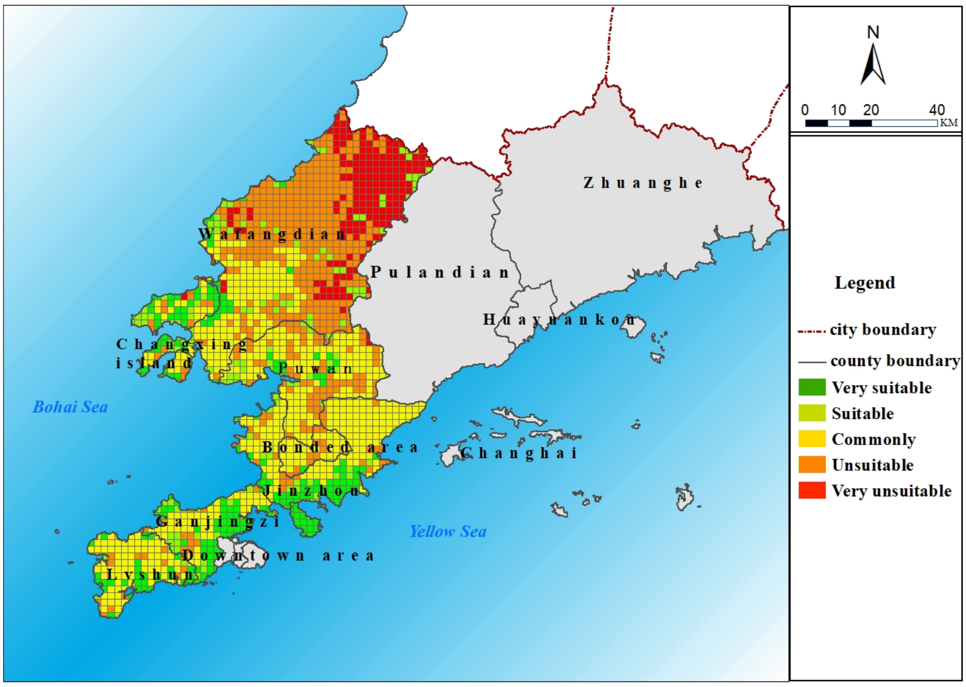

Figure 4. Wind farm suitability area based on the Choquet fuzzy integral method.

As presented in Figure 5, a large portion of the study area corresponds to the existing wind farms in the study area. From the result, 23.9% of the existing wind farm land is located in suitable or very suitable areas. The existing wind farm land located in the common area is 57.7%, and only 1.2% of the existing wind farm land is located in very unsuitable areas. This demonstrates the accuracy of the results from the Choquet fuzzy integral method.

The wind farm projects with construction permits in Dalian City are far below the wind energy capacity of the region. The actual production capacity of the study area is only 23.2% on average, which corresponds to about 179.2 km^2. The total land area that is suitable for wind farm development is the “very suitable” area based on the Choquet fuzzy integral method, which is 771.7 km^2. This means that about 592.6 km^2 can be used for wind farm development. Therefore, the optimal selection of wind farm location is very important, especially in the downtown area where a significant part of their territory seems to be more appropriate for the construction of a wind farm.

However, the existing wind farms in the study area do not all meet the crucial index systems. The existing wind farm in Wafangdian is located in the bird passage, which is not suitable. From the Choquet fuzzy integral method, there are quite a number of potential grids that can be used to build wind farms. Most very suitable grids are located at the southeast boundary of the study area, where the indexes exhibit high satisfaction degrees. The reason is that the transmission facilities and infrastructure are very excellent around the downtown region, which indicates that the selected socio-economic factors are more difficult to meet, especially for the mountain region in the north. This could be to the reason that the optimization results of wind farm spatial pattern presented in Figure 4 strongly represent the potential wind energy impaction.

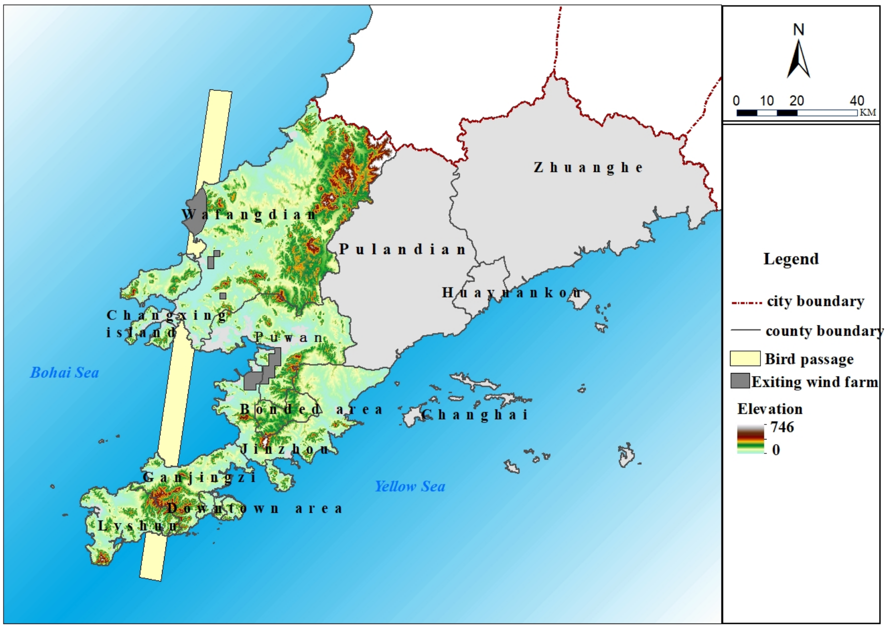

Figure 5. Existing wind farm in the study area.

In addition, the influence of the other factors, such as typography and biological passage, are also apparent but not as important as accumulated wind speed. According to the results present in Figures 2–4, accumulated wind speed is the primary factor for any wind farm built in Dalian City. However, future wind farm development policies are also supposed to take all of the above wind farm optimization factors into account, as they play a significant role in determining potential grid priorities for future wind farm planning. As presented in Figure 6, significant differences can be found between the Shapley value and Choquet fuzzy integral method concerning very suitable grids in the study area. Additionally, the areas of the same category in the Choquet fuzzy integral method and Sharpley value are shown in Table 4. The results indicates the very suitable area is bigger than that from Shapley value, which implies that the Choquet fuzzy integral method obtained the optimized wind farm location. The result also shows that cumulative wind speed is not the unique critical factor and other factors play an important part in the final determination of the most suitable location. Furthermore, when the Sharpley value is quite different, it is able to deduce that the final results would change greatly, which reveals that the determination of weight of the factors ought to be regarded as a detailed and in-depth optimization process. In summary, the Choquet fuzzy integral method can maximize the area of potential wind farm locations for obtaining an optimized wind farm location.

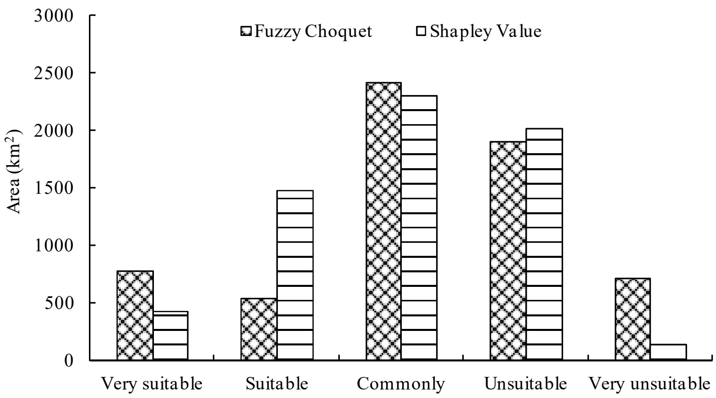

Figure 6. The area of wind farm alternative comparison between Choquet fuzzy integral method and Sharpley value.

Table 4. The area of the same category by Choquet fuzzy integral method and Sharpley value (km^2).

Very Suitable	Suitable	Commonly	Unsuitable	Very Unsuitable
67.64	112.01	1420.69	1043.47	0.97

6. Conclusions

Energy production in China is bringing more and more pressure on the environment, society, and economy. The topic of wind farm location selection can be considered as the decision making problem under complexity which includes all kind of indexes and various interactions between the indexes. This research has reported the design and application of a framework for the complex problem of wind farm location optimization through multiple mutually dependent indexes. A Grid GIS-based λ fuzzy measure and the Choquet fuzzy integral method were developed to optimize the location of a wind farm in Dalian City, China. The Shapley value was used to calculate the significance of the indexes. Furthermore, this system was good at handling multiple and usually conflicting planning objectives when selecting an optimized location for a new wind farm. Particularly, the traditional expert opinions were often inevitably affected by human preferences and difficult to obtain as demonstrated in this research. The optimization process was performed at a victor grid abided by the procurable map layers of the entire index. The final optimization map was obtained from the Choquet fuzzy integral method based on Grid GIS.

The results defined the optimal location of a wind farm along with the applicability of existing word farm projects. The very suitable grids are most located along southeast borders of the study area; in contrast the very unsuitable and unsuitable areas are mainly located in the north of Wafangdian. Based on above results, the location of the existing wind farms are mainly demonstrated as acceptable. However, only 23.2% of the actual capacity is reached in the study area, which corresponds to about 179.2 km^2. The existing wind farms in Dalian City were below the capacity of the area which means about 592.6 km^2 is still available for wind farm development. The results obtained can be used for planners to establish effective wind farm build plans and improve the local energy sustainability.

The research found that fuzzy measure is an effective method to evaluate intermediate synthesis and calculate the factor weight through fuzzy integral. Compared with the traditional MCDM method, the Grid GIS based λ fuzzy measure and Choquet fuzzy integral method could balance the trade-offs among independent factors when finding a wind farm location, and realize an optimal location. Furthermore, victor grids have an advantage over common raster data in the former research. The obtained results of the paper were useful for planners to establish wind farm built plans and improve local energy sustainability. When wind farm developers choose areas for new wind farm developments, it is better to use the results from the Choquet fuzzy integral method, which is more efficient at dealing with the optimization problem. The very suitable and suitable areas calculated by the Choquet fuzzy integral method are very suitable for the construction of a wind farm. On the contrary, the unsuitable and very unsuitable should be forbidden for wind farm construction.

The results indicate that the Grid GIS-based λ fuzzy measure and Choquet fuzzy integral method could effectively deal with the special optimization problem and reflect optimal wind farm sites. However, there are still some extensive works to be done in future research. A number of important factors such as land use, geological conditions and archeological sites should be considered, and the long term energy plan of the government should also be considered. The study also involves a variety of indexes and their interaction, which is a potential future research topic.

Author Contributions: Conceptualization, L.C. and Y.X.; methodology; validation, L.X.; investigation, L.X.; writing—original draft preparation, L.C. writing—review and editing, L.C. and G.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 41901251.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to the editors and all the reviewers for their insightful review.

Conflicts of Interest: The authors declare no conflict of interest.

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