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A Multicriteria GIS-Based Assessment to Optimize Biomass Facility Sites with Parallel Environment—A Case Study in Spain

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Abstract: Optimizing a biomass facility site is a critical concern that is currently receiving an increased attention because of geographically spread biomass feedstock. This research presents a multicriteria GIS assessment with Weighted Linear Combination (WLC) (most suitable areas) and a sensitivity analysis (implementation strategies) applied to various disciplines using suitable criteria to optimize a biomass facility location in the context of renewable energies respecting the environment. The analyses of results with twelve criteria show the most suitable areas (9.25%) and constraints in a case study in Extremadura (Spain), where forest and agriculture are typical for land uses. Thus, the sensitivity analysis demonstrates the insight of the most influential criteria for supporting energy planning decisions. Therefore, this assessment could be used in studies to verify suitable biomass plants sites with corresponding geographical and spatial circumstances and available spatial data necessary in various governmental and industrial sectors.

Keywords: biomass plant location; sustainability; multicriteria spatial decision; WLC; fuzzy logic; sensitivity analysis

1. Introduction

Numerous researchers have studied on the suitability of the location of biomass facilities at different regional, national and international levels as part of the handling problems [1–4]. To assess the potentials of a biomass facility, its geographic and spatial distribution and dissemination is a vital feature to be investigated [1,5]. Here, the Geographic Information System (GIS) is considered as an important tool nevertheless of methods applied in the process of location optimization [6,7]. The GIS can investigate the location in depth enabling to analyze large spatial data volumes in order to visualize geographical expression of different societies' activities [8–11]. For example, the GIS allows to exhibit these spatial data in map format. Thus, with the combination of Multicriteria Decision Analysis (MCDA), decision-makers can distinguish the present state of matters and some notion of future settings in energy management [12–14]. According to Herrea-Seara et al. [15], MCDA was used to select the optimal biomass power facility location and the method of Analytic Hierarchy Process (AHP) and GIS as well in Granada province of Spain as a similar approach proposed in Valencia province (Spain) by Prepina et al. [16]. In Valencia province, it has been also made with different methodologies to combine GIS techniques and methods [7] on mathematical programming to optimize the location and size of a biomass facility [17].

For many decades, energy planning and management problems have been related with rapid economic development. This development represents a critical issue and concern of high energy request and environmental degradation at the various regional, national and international governments level [18,19]. This significant issue and concern has produced a new market of renewable energy and bioenergy to use biomass resources [18,20,21]. Producing energy with biomass materials has many benefits and provides crucial advantages for the parallel environment together with European renewable energy promotion strategy [22]. The European Union (EU) according to Directive 2009/28/EC has conceived a policy framework of renewable energies' sources until 2020 [23,24]. The Directive supports each EU member for developing their own renewable energy strategy for the period 2011–2020 [25]. Particularly, the Spanish Government concentrates on a low carbon economy, convinced of a more long-term sustainability by not using the former Feed-In-Tariff (FIT) [26]. In Spain, the Extremadura Bioenergy Plan 2015–2020 has been launched and has been contained in the smart specialization and adaptation like a key working axis in the energy development sector [27,28]. Therefore, a reliable and accurate assessment for optimal location of biomass facilities is still required.

The GIS-MCDA methods consider different factors, technological, political, natural, environmental and economic among others [29]. Normally, taking energy management decisions is a complicated process that requires knowledge from different disciplines [19,30]. This proposed methodology is one of the most effective ways to select suitable sites for potential biomass facilities. Here, the AHP method together with the GIS-MCDA method is the most dominant tools applied in the bioenergy and biomass division as renewable energy management for identifying potential facility locations. Thus, the Weighted Linear Combination (WLC) is a moderately easy-to-use analytical method that can be applied when dealing with the MCDA, and can be used in various conditions and situations. The WLC method is used to combine the standardized criteria values. Then, the sensitivity analysis is carried out as a work to check the stability solution, namely the alternative selected and the rank of the alternatives, to alternations in the input data [31,32]. So, the GIS-MCDA method as a reliable and accurate assessment supports the Energy Spatial Decision Support System (ESDSS) on land-use issues and further gets the final map for optimal biomass facility management and planning for renewable energy management in a long-term sustainability policy decisions.

The present study describes a multicriteria GIS-MCDA method to identify suitable areas for locating a biomass facility regarding the European, national and regional strategies and policies. The proposed method is implemented in a regional case study in Extremadura (Spain) that has abundant territory of agriculture and forest. Particular attention is paid to the selection of suitable location with a basis for the work provided by detailed evaluation criteria such as socio-economic, environmental and geophysical with an analytical procedure. Then, the proposed methodology herein uses the AHP and WLC functions of multicriteria decision modeling, which valuing the whole case study region by means of a common rating scale in an environment of GIS. The final stage consists in a sensitivity analysis of the criteria and their connected weights. This is to describe various and different decision choices and patterns, which evaluate a reasonable method for biomass facility integration.

2. Materials and Methods

To optimally integrate a biomass facility, the proposed methodology is applied in a case study region and is for the management and planning on renewable energy in a long-term sustainability perspective. In this process, with the case study region rasterized into 10 m $\times$ 10 m grid cells, the assessment framework combines geospatial data as authentic information with criteria weightings as a worth-based information and applies the multicriteria GIS-MCDA technique. Subsequently, for the final optimization map calculation of a biomass facility, the WLC method and the sensitivity analysis are reflected. Here, the ArcGIS 10.2 software as a module builder with inbuilt tools is used to build the optimization assignment and transformation process and analyzes the results based on the various source data [33,34].

2.1. Proposed Case Study Area

Agro-forest resources as an extensively existing source on sustainable and renewable biomass held a promise with energy development and production of Extremadura. Specifically, Extremadura province (Spain) has extensive agricultural and forestal resources that specifically are 30% of its agricultural land area and 68% of its forestal land area as shown in Table 1 [35,36]. However, 96% of total biomass resources are currently not used, consequently energy production substitution needs to be imported. Extremadura Government, therefore, is rising the energy and power production, mostly heating, with biomass and biogas as an effective alternative for reducing fossil fuels' usage in many divisions such as housing, industry, public facilities, etc. The region is selected to apply the established methodology below since more than 4 million tons of raw materials of Extremadura Province can be transformed into biomass [36].

Table 1. Territorial distribution of Extremadura province (Spain) [35,36].

Territorial Type	Surface (ha.)	Percentage (%)
Reservoir and urban area	66,646	1.60
Agricultural area	938,368	22.54
Peripheral agricultural area	326,792	7.84
Forest area	2,831,651	68.02

The case study region selected is Hervas situated in Ambroz Valley region of Extremadura Province on the border of the Salamanca Province (Castilla and Leon) and in the foothills of the Bejar and Gredos Mountain in terms of geographical features as depicted in Figure 1. This region as one of 8 municipalities is the pivot of commerce and administration in the Ambroz Valley because of its geographical and social situation. It has abundant and plentiful wetlands and rivers as water resources, essential for agrarian activities. The region covers a multifunctional Agro-Silvo-Pastoral System (ASPS) that is a land-sue system implying the deliberate association of wood components, deciduous forest predominated with the chestnut tree, with cattle and pre-existing agricultural activities in the same site.

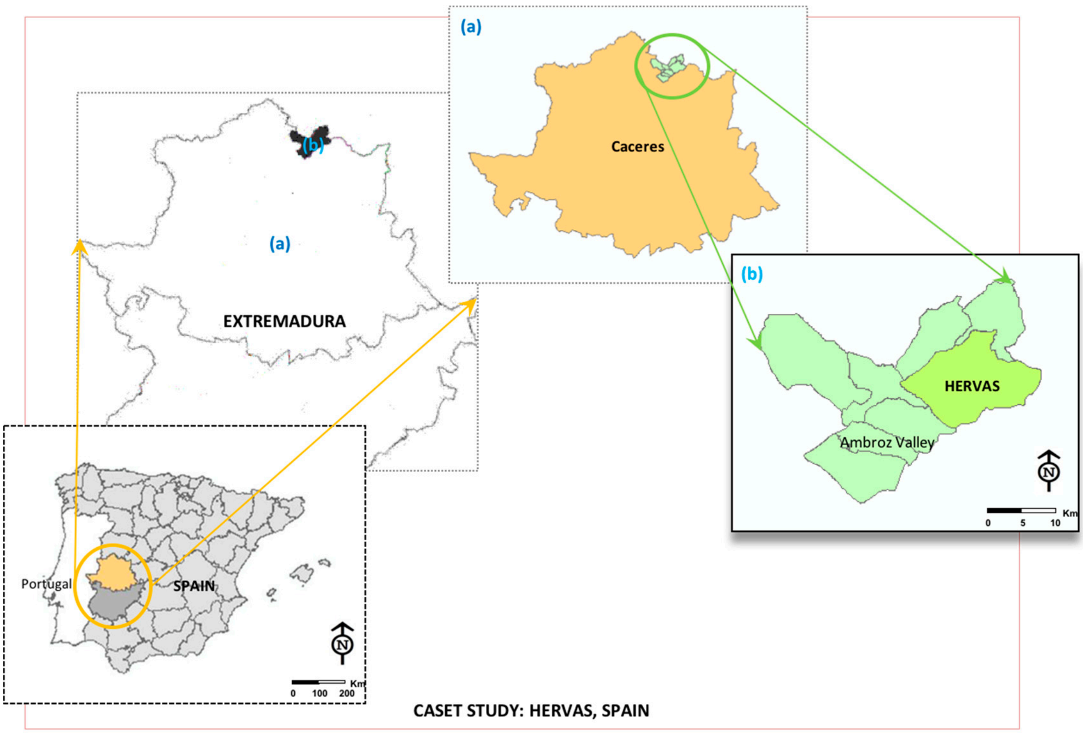

Figure 1. The case study area proposed (Hervas, Spain) for biomass facility site.

2.2. Spatial Criteria and Constraints Selection and Description

The selecting and determining criteria was decided by the decision-makers with the real data such as the relevant literatures, regional policies and EU directives. Here, particularly, the authors are the decision-makers who make the innovation of the evaluation criteria used, which are objectively based on real data. Thus, the decision-making process considers always the recommendations of an expert panel, which is consisting of academics, architects, planners, local authorities, and local authorities. The multicriteria GIS-MCDA method provides apparent approaches to classify and analyze decision-making problems and supports the derivation of decision-making preferences within a structured framework (see Figures 2 and 3). In this study, extensive criteria and evaluation processes are organized into three main criteria involved in the computation procedure as follows: first, socio-economic criteria are (1) transport cost, (2) economic area, (3) potential demand and (4) site access; second, environmental criteria are (1) agricultural area, (2) vegetation cover, (3) hydrology and (4) ecological condition; and, third, geophysical criteria are (1) geology and soil, (2) geomorphology, (3) orientation and (4) visibility. Then, the constraints point out to limit the particular territory containing both natural and artificial areas in the present study: sensitive ecosystem, building ordinance, national heritage, ground use regulation, artificial element, hydrographical network and other installation. Particularly, the four levels of hierarchical structure were used for the decision evaluation process. The first level, biomass facility location suitability, represents the decision-making goal, the second level describes three different criteria to obtain the first level, the third level shows each criterion's sub-criteria and the fourth level embodies each sub-criterion's spatial attributes. The following states a full account of the criteria selected.

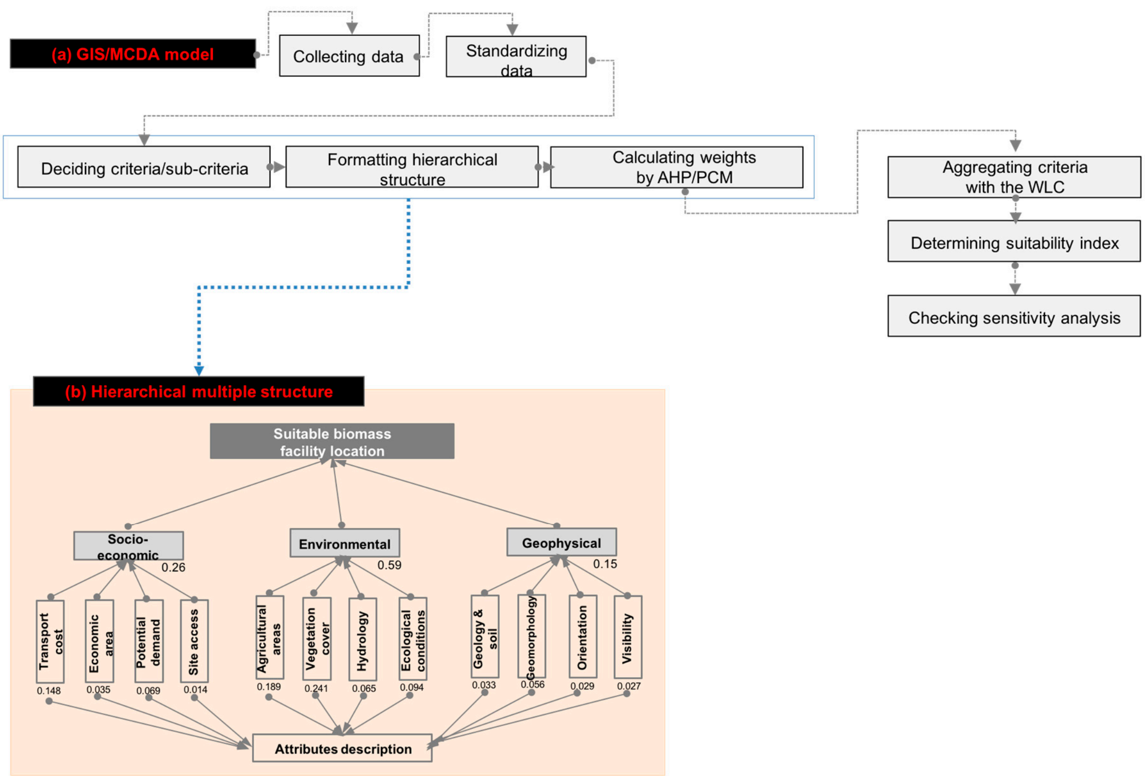

Figure 2. Schematic diagram for biomass facility location optimization.

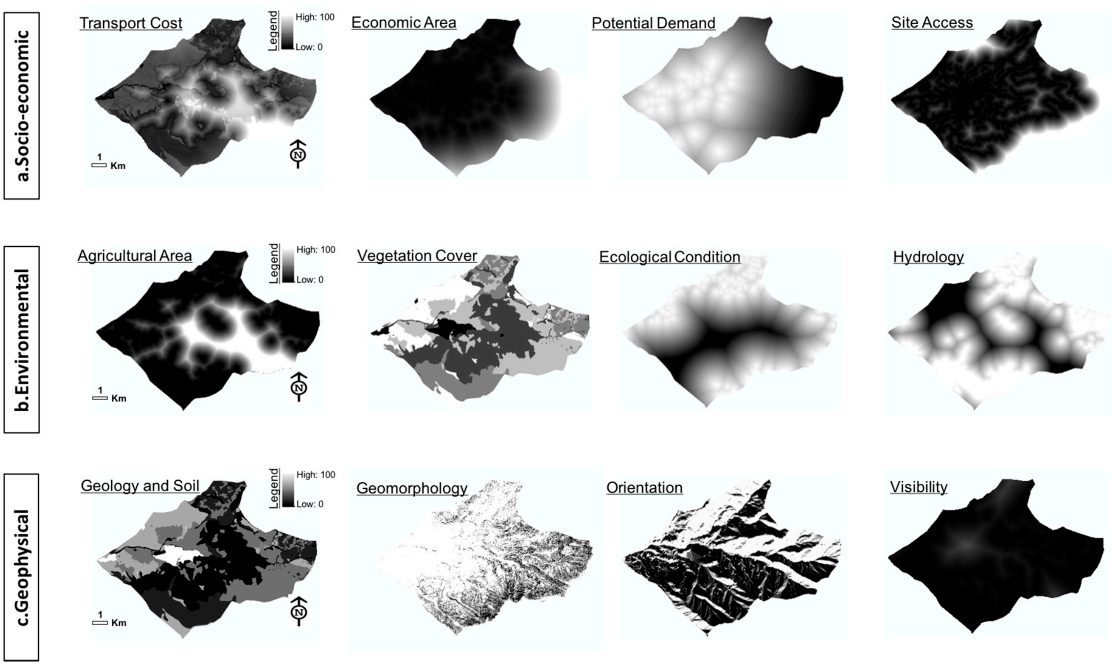

Figure 3. Analyzed maps of each sub-criterion: (**a**) Socio-economic; (**b**) Environmental and (**c**) Geophysical.

2.2.1. Socio-Economic Criteria

First group comprises the four sub-criteria, specifically transport cost, economic area, potential demand and site access, which are related to the socio-economic evaluation of the selected case study area (see Figure 3a):

- Transport cost: Transport cost is spatial spread classification of biomass collection and distribution cost. The spatial representation of transport cost with the sub-criterion weight is 0.148.
- Economic area: Economic area is spatial spread classification of economic activities and population density. The spatial representation of economic area with the sub-criterion weight is 0.035.
- Potential demand: Potential demand is spatial spread classification of energy consumption and demand. The spatial representation of potential demand with the sub-criterion weight is 0.069.
- Site access: Site access is spatial spread classification of transport networks, highways, local roads and railways. The spatial representation of site access with the sub-criterion weight is 0.014.

2.2.2. Environmental Criteria

Second group comprises the following four sub-criteria: agricultural area, vegetation cover, hydrology and ecological condition, which are related to the environmental evaluation of the selected case study area (see Figure 3b):

- Agricultural area: Agricultural area is spatial spread classification preserving certain land types. The spatial representation of agricultural area with the sub-criterion weight is 0.189.
- Vegetation cover: Vegetation cover is spatial spread classification conserving natural formations. The spatial representation of vegetation cover with the sub-criterion weight is 0.241.
- Hydrology: Hydrology is spatial spread classification of water bodies and main/second streams of water. The spatial representation of hydrology with the sub-criterion weight is 0.065.
- Ecological condition: Ecological condition is spatial spread classification based on NATURA 2000. The spatial representation of ecological condition with the sub-criterion weight is 0.094.

2.2.3. Geophysical Criteria

Third group comprises the four sub-criteria, specifically geology and soil, geomorphology, orientation and visibility, which are related to the geophysical evaluation of the selected case study area (see Figure 3c):

- Geology and soil: Geology and soil is spatial spread classification of earth components diversity. The spatial representation of geology and soil with the sub-criterion weight is 0.033.
- Geomorphology: Geomorphology is spatial spread classification of slope and elevation of land surface flow. The spatial representation of geomorphology with the sub-criterion weight is 0.056.
- Orientation: Orientation is spatial spread classification of better aspect for aesthetical reason. The spatial representation of orientation with the sub-criterion weight is 0.029.
- Visibility: Visibility is spatial spread classification of aesthetic protection and valuation. The spatial representation of visibility with the sub-criterion weight is 0.027.

2.3. Multicriteria GIS-MCDA Approach

With the extensive selected criteria based on the 10 m × 10 m raster format grid cells, fuzzy logic set is herein used to standardize the criteria and sub-criteria data. Each pixel potential fitting to fuzzy logic is evaluated by the concept proposed to calculate any series of the membership function of fuzzy logic set. In this setting, a Triangular Fuzzy Number (TFN) is simply articulated as a triplet (l, m, u) in which parameters l, m and u, respectively, represent lower, medium and upper values. These values describe a fuzzy set ($x \leq y \leq z$) [37,38]. Figure 4a in consideration of above shows a TFN. It can be decided the linguistic terms and values related, and triangular fuzzy numbers in terms of Table 2. Also, ratings and membership on fuzzy function are explained as shown in Figure 4b.

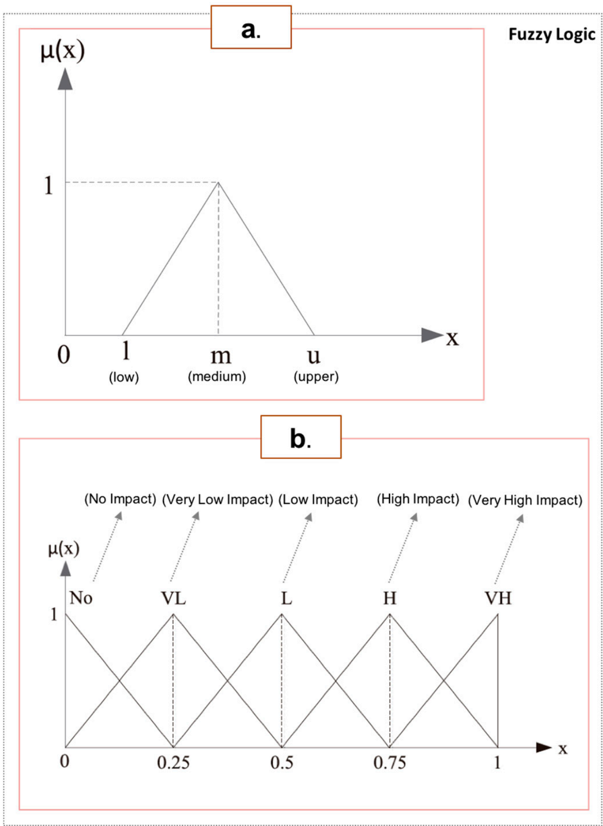

Figure 4. The fuzzy logic diagrams: (**a**) Triangular Fuzzy Number (TFN) diagram and (**b**) Fuzzy memberships and ratings function diagram [37,38].

Table 2. Correlation on fuzzified Likert measure in place of measuring the criteria' weights.

Linguistic Terms	Linguistic Values	Triangular Fuzzy Numbers
No impact	0.00	(0.00, 0.00, 0.25)
Very low impact	0.25	(0.00, 0.25, 0.50)
Low impact	0.50	(0.25, 0.50, 0.75)
High impact	0.75	(0.50, 0.75, 1.00)
Very high impact	1.00	(0.75, 1.00, 1.00)

To excerpt the relative criteria weight according to their importance, the AHP method is applied. The method is an efficient approach to take out the relative importance weights of the criteria in a specified decision-making problem and process. One of the most important steps in any multiple criteria problem and process is the precise estimation of the proper and pertinent data. Although qualitative information about the criterion and sub-criterion importance can be encountered, it is hard to quantify it properly. The method has varied steps containing to stipulating the hierarchical structure, deciding the relative and absolute importance weights of the criteria and sub-criteria, arranging required weights of each alternative and determining the final score. Also, this method has various phases to denote the hierarchical framework allocating favored weights of each alternative and defining the final weights based on the Pair-wise Comparison Matrix (PCM). Here, decision-makers will quantify their attitudes to the magnitude of criteria as comparing criteria pairs at a time and a scale expression. The PCM functioned by the decision-makers is relating on the perceived importance of each criterion using particular predetermined points of scale [39]. In this work, a 9-point scale was used and must follow the regarding attributes, a_{ii} = 1 and $a_{ij} = 1/a_{ji}$. The estimations and calculations of criteria' relative and absolute importance weights are the next step, which is inferred by the former comparisons. The estimation and calculation of the right primary eigenvector of the PCM can be approximated with the geometric mean of each row of the PCM [40]. If the PCM is completely consistent, $a_{ij} = a_{ik} \times a_{kj}$ for all potential mixtures of comparisons in the PCM. It is uncommon to have a completely consistent PCM. The AHP method contains an indexing named Consistency Ratio (CR) that reveals the all-round consistency of the PCM. According to Saaty [40], the CR must have a value of less than 10%, telling consistency of the matrix. Then, the application of WLC method estimates the suitability index, which is a widely utilize method for calculating final rating values of multicriteria problems. So, it is to compute the suitability value in multicriteria decision problems according to the grading scale used for the suitability index 0 to 100, which is, the higher score is the more suitable zone, as shown in Equation (1) [6,32]:

$$SI = \sum_{j=1}^{n} w_i x_{ij} \tag{1}$$

where SI is the value of suitability index; n is number of factors; w_i is the normalized score of weight factor i and x_{ij} is the criterion value of weight factor i.

In the group of each criterion, their weights were arranged according to how important each criterion was deemed to be. Given the attribute values' set $a_{i1}, a_{i2}, \ldots, a_{in}$ at the i-th location of a set of n criterion maps was described by raster representation. Constraints obtained can showed the case study region in the land as two types: index suitability 1 stands for suitable; and index suitability 0 stands for unsuitable. For selecting land, the mathematical equation with constraints is in Equation (2) where SI_i is overall suitability index value; w_j is weight of factor j; x_{ij} is criterion score of factor j; y_k is criterion score of constraint k; n is number of factors; l is number of constraints:

$$SI_i = \sum_{j=1}^{n} w_i x_{ij} \cdot \prod_{k=1}^{l} y_k \tag{2}$$

This aggregation technique multiplies factor scores by their factor weight and then sums the products to yield the suitability score as described by Equation (2).

A sensitivity analysis is to check the stability solution, which is the alternative selected and the rank of alternatives, to alternations in the input data. The sensitivity analysis is applied to change weights of input criteria that can be seen what effect creates on the output as the visualization of the final results. The sensitivity analysis is a study that is to check the stability of the solutions gotten against the subjectivity of the decision-makers [41]. For that reason, sensitivity analysis is completed where weight values of GIS layers are altered to assess the differences in the biomass facility suitability map. To evaluate the sensitivity, a criterion weight w_i at a certain Percent Change (*PC*) standard level could be figured as follows in Equation (3) [31,32,41–47]:

$$w_i = w_{i\pm} w_{i0} \times PC \quad (3)$$

where w_i is the criterion weight *i* at a certain PC level; w_{i0} is the core adjusting criterion weight at the base run. The other criterion weight w_j is changed proportionally according to w_i derived in the Equation (4). In this study, the results of sensitivity analysis of suitability map with various scenarios used index value in Table 3.

$$w_j = (1 - w_i) \times \frac{w_{j0}}{1 - w_{i0}} \quad (4)$$

where w_j is the new weight value allocated to the criterion *j* and w_i is the criterion weight *i* at a certain PC standard level. So, w_{i0} and w_{j0} are criteria *i* and *j* weight values at the base run.

Table 3. Index of suitability value for classifying biomass facility location.

Suitability Value Index	Score	Description
Not suitable	0–20	Suitable location for biomass facility is not existed
Slightly suitable	20–40	Suitable location for biomass facility is low
Moderately suitable	40–60	Suitable location for biomass facility is medium
Suitable	60–80	Suitable location for biomass facility is high
Highly suitable	80–100	Suitable location for biomass facility is very high

3. Results and Discussion

Figures 5 and 6 present the final suitability map (S) with various phases for biomass facility location of the proposed case study region. These maps show consistent process for deciding the land optimization satisfying the research goals. First of all, three intermediate suitability maps as the preemptive results are analyzed and combined. The intermediate results of three criteria are shown in Figure 5a. Second, the definitive suitability map is shaped along with the intermediate results through the WLC method combination as depicted in Figure 5b. The final suitability map is produced by aggregating with the WLC method having a low level of risk. Here, based on the aforementioned participatory weighting allocation, we find out decision-makers' attitude regarding the specific criteria allocation. The final suitability map is made as the weighting functions as follows: 0.25 for socio-economic; 0.59 for environmental; 0.15 for geophysical. All maps are identified with the suitability index 0–100 as the most suitable with the highest values indicated in blue, to the least suitable areas with the lowest values indicated in brown. The analyses of results with twelve criteria conclude that the most suitable locations are close to forest and agricultural areas with 9.25% of the case study area with the most influential criteria: vegetation type under environmental criteria. Third, the constraints were excluded from the suitability map as shown in Figure 6a. The constraints left always like Boolean masks. They were actually not related with any procedure of weight allocation. In Figure 6b, it shows the five maps according to the five different categorical values aforementioned in Table 3. Therefore, we can see how to deal with the location problems and what directly bond to shaping the highly suitable (*hS*) and favorable areas for a biomass facility locally built.

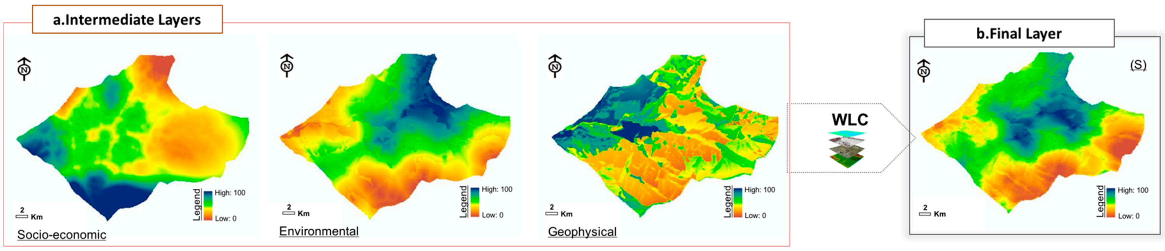

Figure 5. Process of final suitability map (S) with multicriteria GIS-MCDA evaluation of location optimization for biomass facility in the case study region: (**a**) Intermediate layers and (**b**) Final layer.

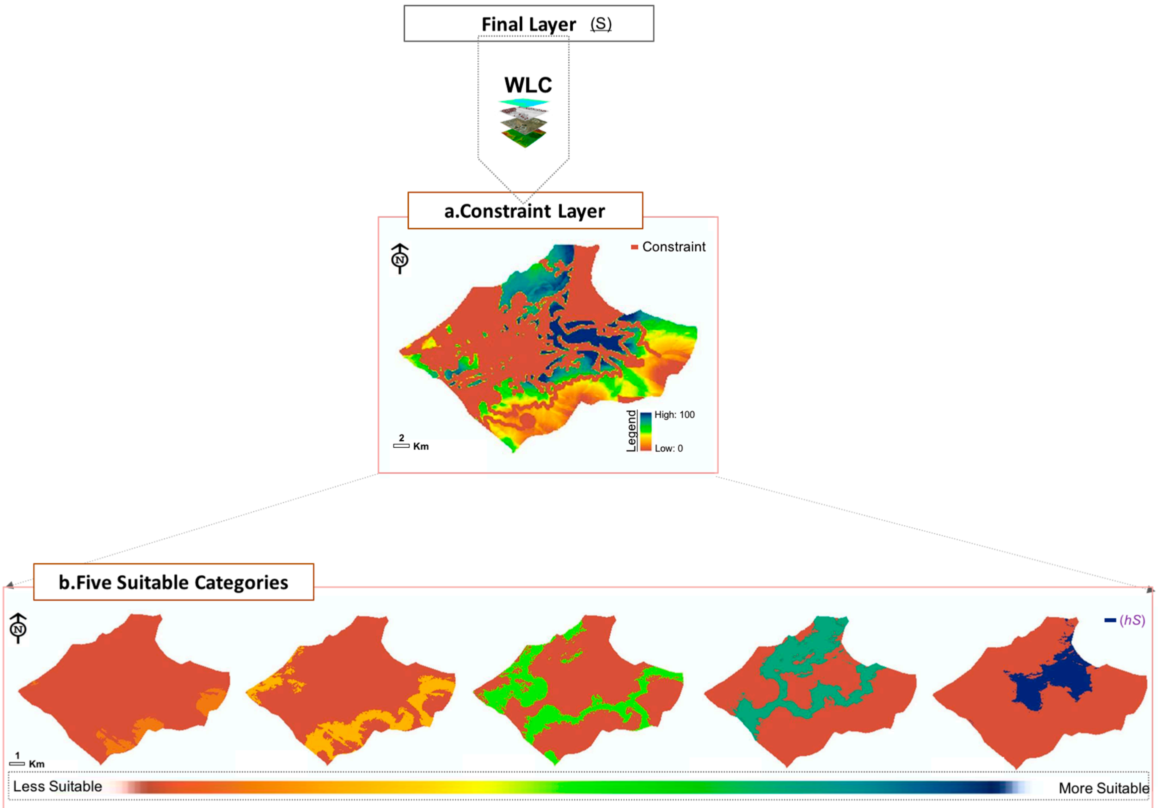

Figure 6. Constraints and five categorical values of final suitability map (S) with multicriteria GIS-MCDA evaluation: (**a**) Constraint layers and (**b**) Five suitable layers.

The Figure 7 presents different suitability maps for identifying suitable areas of biomass facility in the case study area proposed. The maps use the various criteria weights of WLC method and sensitivity analysis continuously changing from −15% to +15% variations. Here, ±5% increments were applied to the final suitability layer (S). The analysis of sensitivity is carried out within the range of −15% as the first run to +15% as the last run from the value of initial weight in suitability GIS-layers. Particularly, each run creates the suitability map of a distinct new biomass facility site. The main aim of this sensitivity analysis is to examine the suitability areas for biomass facility under criteria weights' percentage changes. The sensitivity analysis is conducted within the continuous ranges of the initial weight value from suitability GIS layer. Each run creates a single new biomass facility suitability map (A, A-1, A-2, B, B-1 and B-2).

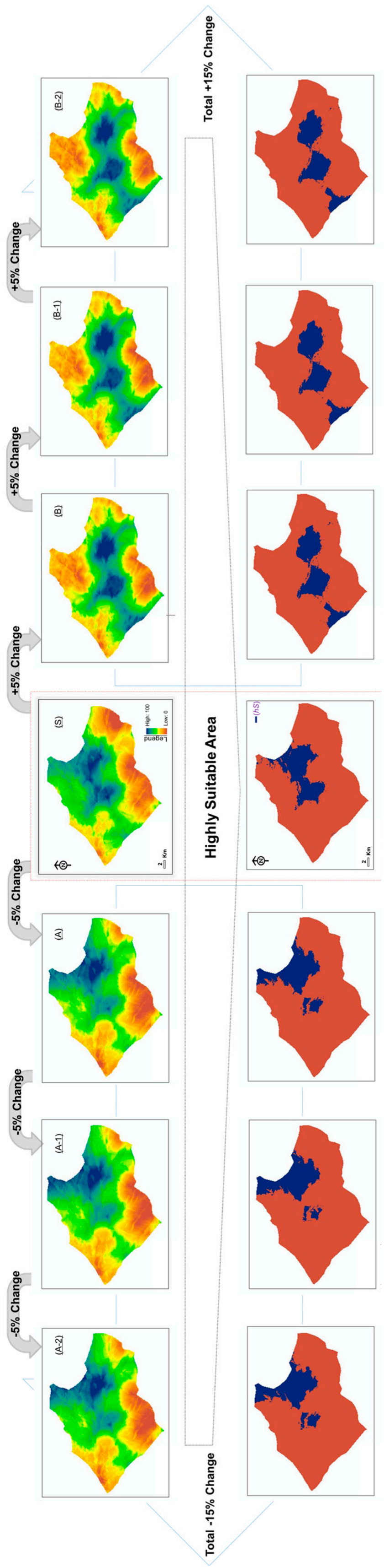

Figure 7. Various sensitivity analysis under continuously changing ±5% variations from final suitability map.

The application of multicriteria GIS-MCDA model for identifying suitable areas of biomass facility verifies as positive and justified, because based on the adopted criteria, in sustainable environment. Sensitivity analysis by altering the criteria weight reveals a high degree of model stability. Therefore, this methodology can be used for renewable and sustainable energy planning policy at all governmental and industrial sectors for solving decision problems due to the flexible character of the methodology proposed. Thus, this approach lets to use individual advantages, which making a much more holistic view of certain decision-making process.

4. Conclusions

Energy generation using biomass feedstock has many benefits and supplies important advantages that reducing reliance on the fossil fuels imported and alleviating Greenhouse Gas (GHG) emissions. The suitable and favorable location selection of biomass plants becomes a crucial issue and concern due to biomass feedstock dispersed geographically and spatially. Here, the combination of GIS and MCDA methods as a powerful and effective application can consequently be regarded to answer renewable and sustainable energy problems. This study focused on optimizing the locations of biomass facilities in a long-period sustainability and resilience. Thus, to select the weight coefficients of criteria and/or the comparable importance of criteria/sub-criteria, the multicriteria GIS-MCDA method is employed with decision-makers aforementioned. Then, with the WLC and sensitivity analysis, the criteria weight and final suitability locations classification summarize as suggested on a grading scale of 0 to 100. So, this study aims to integrate optimally the biomass facility location planning in the proposed case study region.

This paper presents an operative multicriteria GIS-MCDA approach that identifies biomass facility locations, which contribute to solve sustainable energy and logistics problems for the renewable energy sector. The approach utilized a structured MCDA framework in a GIS environment to evaluate biomass facility into a proposed case study area of an empirical region, Hervas (Spain). First, the study established the evaluation criteria and sub-criteria, which are twelve criteria, categorized into three groups, namely socio-economic, environmental and geophysical aspects. Specifically, they are reported on a grading scale from 0 to 100, from the least suitable areas to the most suitable area. The AHP method is offered as the assignment practice of objective weights with the PCM. Furthermore, the employment of WLC method and sensitivity analysis provides great flexibility in the combination process, which giving the ranking-based weights. The analysis of results concludes that the most suitable locations areas are very close to forestal and agricultural areas with 9.25% of the proposed case study region being the vegetation type under the environmental criteria as the most influential one. The final suitability map was validated through a sensitivity analysis by changing weights from −15% to +15% in 5% intervals confirming the proposed final suitability map. Through this analysis, it should be recommended to construct new biomass plants alternatively in the highly suitable area and directly connect to decide their location optimization. Seeing the location problem dealt with in this study is directly connected to deciding the highly suitable areas for optimizing the location of a local biomass plant. The findings of this research point out the effectiveness and mechanism of method proposed behind decision-makers' intention for identifying suitable areas for a biomass facility in the case study area. Additionally, the employment of WLC method and sensitivity analysis as the second set of weighs gives high adaptability in the combination layout of criteria.

For evaluating the potentials of biomass facility planning, the application of multicriteria GIS-MCDA model verifies its justification and positivity in terms of the criteria and sub-criteria adopted. Successfully, it differentiates space parts, which are highly favorable and suitable for planning biomass facilities in a long-term sustainability and resilience. By shifting the weight coefficients of criteria, the analysis of sensitivity reveals a high stability degree of the proposed model. Thus, it shows the possibility to influence to define the problems of current and future location optimization for a biomass facility. Consequently, this methodology can be used in studies to verify suitable biomass facility sites in this case as the ESDSS with similar geographical circumstances and conditions in the available data of spatial-GIS required. Also, the approach can support to take decisions of biomass plant location optimization in this case as the ESDSS in a long-term policy decisions and sustainability. It could fill a niche of decision-making method for biomass plant planning behind their intention and influence. For the planning policy of renewable and sustainable energy management at all private sectors, government levels and various industrial parts, it can be employed for solving decision-problems due to the pliable and adaptable characteristic of the methodology proposed. Thus, this approach lets to use individual advantages, which makes a much more holistic and seamless aspect of a certain procedure in the process of decision-makings.

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