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A Multi-Criteria Analysis GIS Tool for Measuring the Vulnerability of the Residential Stock Based on Multidimensional Indices

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Abstract: There is extensive scientific evidence showing that the characteristics of the urban and residential environment directly affect people's quality of life and health. In this framework, numerous building renovation policies have been developed in Europe, mainly focused on improving energy efficiency. However, we are dealing with a multifactorial and multicausal phenomenon of a complex system where competent institutions need quantitative diagnosis mechanisms that consider this holistic vision when making decisions and prioritizing interventions. Regarding this, the present research develops the potential of the multi-criteria methodology in a first proposal, which integrates social, energy, environmental and spatial aspects linked to the relationship between housing and the effects on the health of its inhabitants. It is a multidimensional method based on systematized and exportable vulnerability indices, which applies indicators that have been calculated using cadastral data and a typomorphological characterization of the residential stock. The analysis of the results through geostatistical techniques of autocorrelation and clustering applied to the case study of Donostia-San Sebastián shows that the proposed methodology is effective in achieving the objectives set. The associated GIS tool has proved to be agile and replicable.

Keywords: urban regeneration; housing and health; urban health; multi-criteria analysis; vulnerability assessment; geographic information system

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1. Introduction

Europe has an aged residential stock [1], as several European reports indicate, more than 40% of residential areas were built more than 50 years ago and around 85% of residential buildings are more than 25 years old [2,3]. The deterioration of the built environment is increasingly affecting the well-being and quality of life of citizens, especially the most vulnerable population [4–6]. In this context, numerous policies for building renovation have been developed in Europe. The objectives of these actions are related to the improvement of energy efficiency [7], in response to the COP (Climate Change Conference of the Parties) and the European Directive (EU 2018/844) on the retrofitting of buildings and the identification of energy poverty. However, the impact of inadequate housing goes beyond the energy field. The urban and residential environment features directly affect people's health and quality of life [8]. Currently, more than 20% of the population lacks adequate housing [9]. According to the WHO [10], improving housing conditions can save lives, prevent diseases, increase the quality of life, reduce poverty, help mitigate climate change and contribute to the achievement of the Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda [11], including those related to health (SDG 3) and sustainable cities (SDG 11).

Housing policies, which guarantee fundamental rights and the equitable distribution of public resources, should address this complexity in their rehabilitation strategies by prioritizing those areas or buildings with the greatest needs and difficulties in terms of transformation. However, current approaches are sectorial and lack this comprehensive vision. Therefore, there is a need for systematic diagnostic mechanisms that interrelate the multiple associated areas, assess the vulnerability of urban residential buildings and allow prioritizing interventions not only according to their impact on climate change but also consider variables from the perspective of people's health and well-being.

In this respect, and in order to contribute in this direction, the present research introduces a first multidimensional methodological proposal for the evaluation of vulnerability from a health perspective. The objective is not to obtain health results, but to diagnose housing vulnerability from this theoretical framework.

1.1. Analytical Framework

According to the literature review, some authors identify housing conditions as factors that generate vulnerability and urban marginalization [12,13]. Quantitative methods and indicators for assessing the vulnerability of the building stock are fundamental tools to facilitate decision-making in the definition of retrofitting policies and the prioritization of actions. The studies discussed below, demonstrate the usefulness of tackling the challenge of rehabilitating the building stock from different approaches: environmental quality and the habitability or spatiality of the dwellings, energy or the social vulnerability of their residents.

1.1.1. Environmental Vulnerability—Hygrothermal, Acoustic and Lighting Comfort

Environmental vulnerability is mainly associated with the physical structure of the dwelling itself and the deficiencies of insufficient comfort [14,15]. Scientific evidence shows that the quality of the indoor environment has a direct impact on the comfort of people living in dwellings and depends not only on thermal, but also on acoustic, visual and air quality levels [16,17].

Studies on the environmental quality of dwellings adopt two main approaches. On the one hand, hygrothermal measures are used to assess environmental quality using monitoring and quantitative methods [18,19]. On the other hand, studies based on qualitative aspects through surveys that focus on the perception of the inhabitants [20–22]. In the latter, as they employ subjective indicators, the results may differ from the established standards in terms of comfort, as they depend on the individual perception of the users [23], but in many cases, they complement the quantitative information.

1.1.2. Spatial Vulnerability—Habitability

The condition of spatial vulnerability is linked to the physical characteristics of the inhabited built environment since its poor conditions such as a low quality materials, a non-flexible housing layouts, a overcrowding, etc., will not allow a satisfactory development of everyday life [24]. Spatial characteristics can affect both physical and mental health, as well as well-being.

A particular layout can restrict or favor accessibility, humidity, natural lighting, ventilation, comfort and view availability-related aspects [25,26]. Furthermore, the fact that dwellings are flexible and adaptable over time is beneficial from the perspective of intergenerationality, social cohesion of the environment and a community sense of belonging [27,28]. The current pandemic caused by COVID-19 has highlighted, on a further basis, the deficiencies in the existing housing stock related to all of the above [29].

There are several reports and good practice [30–32] guides that, based to a greater or lesser extent on the available scientific evidence, propose design improvements aimed at the health and well-being of the inhabitants. Despite that, in terms of health, further research is needed to explore the role of the interior design of housing and buildings in assessing and quantifying spatial vulnerability [33].

1.1.3. Social Vulnerability—Social Profile

Social vulnerability represents a discriminatory factor that, among other aspects, increases the impact of vulnerability in people living in certain urban contexts, a situation that is aggravated when other vulnerability factors, such as gender, are added [34]. The integration of indicators and indices in this area in the overall assessment of vulnerability is extremely important, representing a cross-cutting axis in all the fields analyzed above.

Despite the interest in evaluating the social reality through an instrument that allows its measurement and quantification, the scientific literature shows that it is not easily measurable [35] since it is a complex and multifaceted system [36,37]. Nevertheless, there are different tools based on statistical data that quantify vulnerability among different population groups and places: some authors present approaches for the identification of disaster risk and juxtapose them with a local approach in order to examine the differences regarding the functions and purpose of the assessment, as well as its impact on policy development [38]; others identify the challenges in quality and acceptability based on a case study of a social vulnerability index of river flooding in Germany [39]; still other studies assess social vulnerability to flooding [40] focusing on the municipality of a Spanish medium-sized city highly exposed to flooding due to the possible breakage of the upstream dam. Finally, some authors review existing indicator methodologies in order to understand the breadth and depth of the practice [41].

Social indicators are configured as instruments capable of representing complex realities in a single number or general index [42].

Out of these tools, the quantitative indicator called the Social Vulnerability Index (So VI) is the most used one, constructed from a multivariate principal component analysis (PCA) [43,44]. While social vulnerability indices are widely used, none has been definitively validated, as social vulnerability encompasses a subjective component that is beyond the scope of this index [45].

1.1.4. Energy Vulnerability

Over the last decades, the scientific approach to energy poverty has gone through many definitions, being the one expressing the difficulty or inability of a household to adequately meet its domestic energy needs (heating and other energy services) the most shared one, due to three main components: high energy costs, low income and energy inefficiency of buildings [46,47]. In terms of methods for its assessment, the most recognized trends follow two approaches that mainly focus on economic aspects [48]: indicators based on household income/expenditure [49] and consensus indicators based on responses to material deprivation questionnaires such as not being able to afford to go on vacation at least one week a year, having arrears in the payment of expenses related to the main dwelling (mortgage or rent, gas bills, community, etc.), not being able to afford to have a car, not being able to afford a washing machine, etc. [50].

On a practical basis, the most widely used method to measure energy poverty is the one introduced by the United Kingdom, which considers poor household energy if, to reach an adequate level of thermal comfort in the home, it is obliged to spend more than 10% of its income on energy [51]. The scientific literature also includes other proposals [52]: methods that focus on economic aspects [53–55]; those that delve into the development of policy initiatives [56,57]; and finally, methods that emphasize the impact of energy poverty on spatial justice and energy inequality [58–61]. Extending the energy vulnerability approach, Sánchez-Guevara [62] developed an energy poverty methodology based on minimum conditions of thermal habitability that considers the climatic, building and socio-economic particularities of the country. The method focuses on the required energy expenditure to achieve minimum thermal habitability conditions in social housing. Furthermore, several authors propose the renovation of dwellings and the improvement of energy efficiency as an appropriate measure to reduce energy poverty [63–66].

1.1.5. The Multidimensional Approach—Integral Approach

Even though numerous studies highlight the importance of incorporating methods with a multifactorial approach through an integrative vision that characterizes the building stock [67], there has not been enough methodological development along these lines. The assessment methods linked to energy poverty, which combine environmental, energy and social vulnerability, stand out particularly [46,47,68].

In addition to these energy poverty studies, some authors go further and call for a more complex and holistic view of the analysis. For example, Lowe et al. (2017) study buildings as complex socio-technical systems with attention to the role of occupants in dwellings [69]. On the other hand, Doi et al. (2008) [66] address the multi-dimensionality by incorporating factors related to the quality of life, quality of space and social interaction into the method by developing an evaluation system based on the quantification and weighting of the multi-elements. However, there is not yet sufficient methodological development for assessment tools that take into account the holistic approach outlined above.

2. Materials and Methods

The main objective of this proposal is to create a multi-criteria analysis method to evaluate the priority of rehabilitation interventions from an integral perspective that brings together social, energy, environmental and spatial aspects by calculating indices for each area. At the same time, it aims to be an instrument to show the wide range of existing problems and vulnerabilities and provoke a reflection on the need to diversify strategies for the rehabilitation of the residential stock and serve as a diagnostic mechanism in decision-making for policymakers and stakeholders.

Therefore, a systematized and exportable method is proposed, implemented through a GIS (geographic information system) tool. As a basis, it uses georeferenced cadastral information, including both dimensional and geometric data at the building level and aggregated alphanumeric information. The unit of analysis is the building portal within the municipal scope of work.

Figure 1 shows the outline of the methodological approach, followed by a detailed description of the proposed methodology in its different phases.

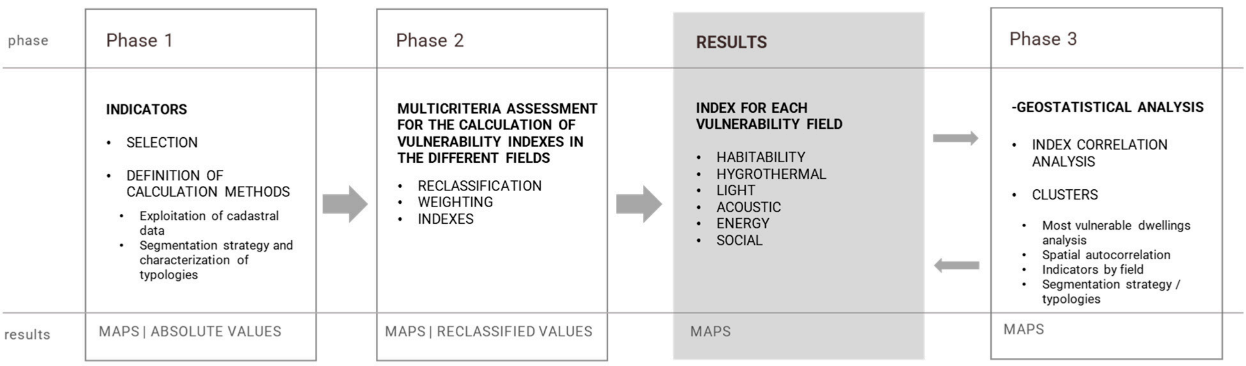

Figure 1. Diagram of method and phases. Own elaboration.

2.1. *Phase 1—Selection and Calculation Methods for Indicators*

The selection is made through an exhaustive analysis of the literature [70–74] (See Supplementary Material S1 for more references), which identifies housing-related health factors collected by authors from multiple disciplines. Through a first selection process, 32 indicators are considered. After studying redundancies, calculation feasibility, data existence, spatial scale, processing needs and consistency, both the final set of 24 indicators and their incidence in each of the vulnerability fields under study are established: spatial, environmental, energy and social. The environmental area is divided into three fields: hygrothermal, lighting and acoustic. For each indicator, a generic sheet that brings the definition of characteristics and the calculation method together is developed, in order to obtain ranges of absolute values and detailed graphic analysis, subsequently applied to the case study.

Figure 2 presents the 24 categorized indicators according to the four themes of vulnerability. The colors indicate the indicators involved in each index. There are indicators involved in different fields.

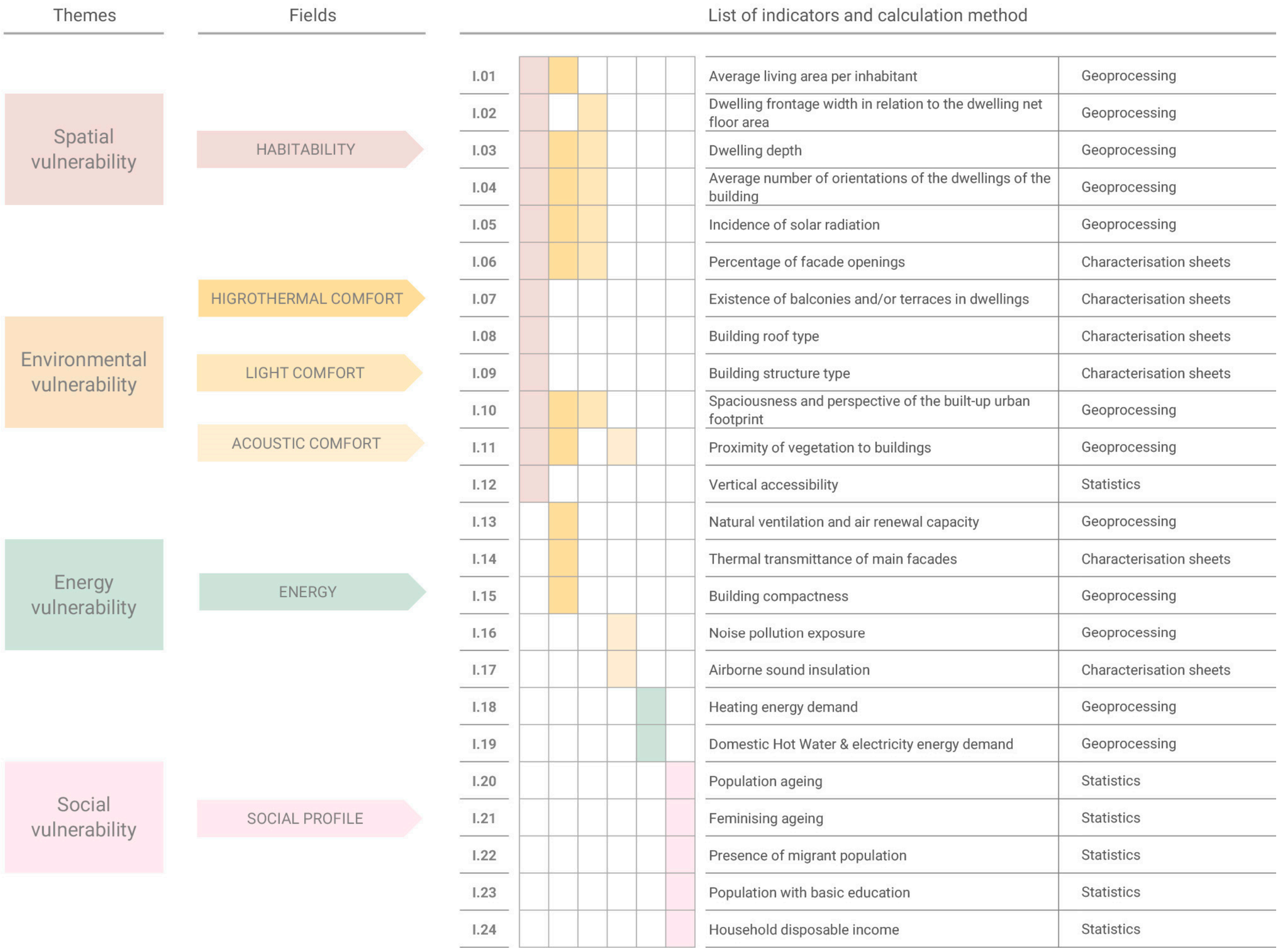

Figure 2. Diagram of indicators for each vulnerable area and method of calculation. Own elaboration.

Each indicator is implemented in GIS using two main methods.

2.1.1. Exploitation of Cadastral Data

The potential of the cadastral database lies in the amount of information gathered and structured uniformly for the whole territory. It consists of graphic (cartographic) and literal/descriptive (alphanumeric) information. The vector information is used to calculate geometric variables utilizing geoprocessing in the GIS itself, while the descriptive information on each building is obtained by performing statistical operations in a spreadsheet that is spatially associated with the cartography. Full cadastral integration is completed with the sum of cartographic and alphanumeric information.

2.1.2. Strategy for the Segmentation and Characterization of Typologies

A method for the segmentation and characterization of residential typologies is proposed for the calculation of vulnerability indicators that cannot be extracted from cadastral information. Similar studies rely on only two variables (building height and year of construction) to conduct the classification [75]. In this case, in order to perform a more rigorous analysis, two other variables have been included in the analysis. On the one hand, given that physical density is a determinant in the identification of urban structure and form, measure such as the gross floor area [76], a variable that distinguishes structures at a district or census tract scale, is introduced. On the other hand, each building block is parameterized according to its aspect ratio, which represents the relation between the two main dimensions of the polygon and the circularity index, and shape factor that measures the degree of deviation from the ideal figure. Then, the two variables are visualized in a scatter plot, identifying clusters corresponding to an existing residential building type in the literature.

The typomorphological matrix is obtained from the combination of the four defined variables, which exhaustively classifies the residential park in terms of typomorphologies in the urban context. Subsequently, the most common architectural and constructive characteristics are determined for each of the segments. In this way, the indicators associated with architectural form or composition, difficult to calculate without fieldwork, can be obtained through association with the typologies.

2.2. Phase 2—Multi-Criteria Assessment for the Calculation of Vulnerability Indices in the Different Fields

The generic concept of multi-criteria assessment is determined as the set of spatial operations to achieve an objective based on a series of criteria, whose intensity and thresholds are variable, somehow affecting the assessed activity and overlapping spatially in the typical way of geographical information [77,78]. It is a method that allows a holistic assessment of the vulnerability phenomenon from an integral and complex perspective. The implementation of the multi-criteria method in conjunction with fuzzy logic through GIS presents a high potential for modelling vulnerability in a multidimensional way. The method is applied according to the following processes.

2.2.1. Reclassification of Absolute Values According to Fuzzy Logic

The theory of fuzzy logic is designed to deal with problems without well-defined boundaries, as opposed to binary logic (true and false), and is based on the idea that the world is not composed of indivisible and discrete elements, but is a continuum with different properties in different locations [79].

First of all, the initial absolute value ranges of the indicators are transformed into reclassified factors in fuzzy membership layers using a specific mathematical function, that is, providing intermediate values between a zero vulnerability level (0) that will increase in intensity up to a maximum vulnerability value (1).

To reclassify the absolute values of the indicator in each area, thresholds composed of statistical, normative and spatial criteria are defined. These, when combined, set reference values or control points and justify the growth trend of the estimated membership function.

Once the nature of the vulnerability to be modeled is known through the aforementioned criteria, it is expressed mathematically by means of fuzzy membership functions, which can be combined with each other, each indicator. The functions implemented in a spreadsheet have been linear, small sigmoid, exponential and Gaussian.

This process has been summarized in Figure 3.

2.2.2. Weighting of the Indicators for Each of the Vulnerability Indices

The procedure used for assigning weights to subject matter experts is based on Saaty's pairwise comparison method, also known as the Analytical Hierarchy Process (AHP) [80]. It establishes, from the calculation of the dominant eigenvector of a matrix of binary comparisons of the factors, a reciprocal square matrix where the number of rows and columns are defined by the number of factors to be weighted. In this matrix, the relative importance is assigned, where, comparing the criteria one by one, the formalization of the value judgements is made on a continuous scale ranging from 1 to 9 (from equal importance to extreme difference).

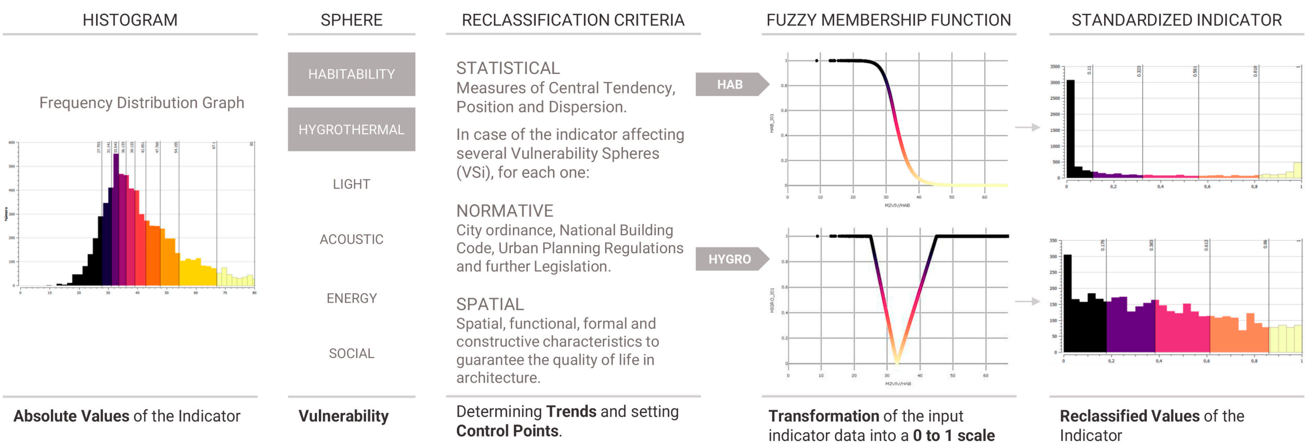

Figure 3. Methodological scheme of reclassification. Example indicator I.01. Average surface area of dwellings per inhabitant. Own elaboration.

In fact, from this series of value judgements between pairs of factors, after carrying out the described process, the values of the weights of each factor are obtained and shown in Figure 4. Therefore, each factor assumes a relative weight that will make certain variables have a greater influence on the final suitability for the proposed objective. The multi-criteria evaluation, in addition to considering degrees of suitability, allows the factors to be considered as having different relative importance.

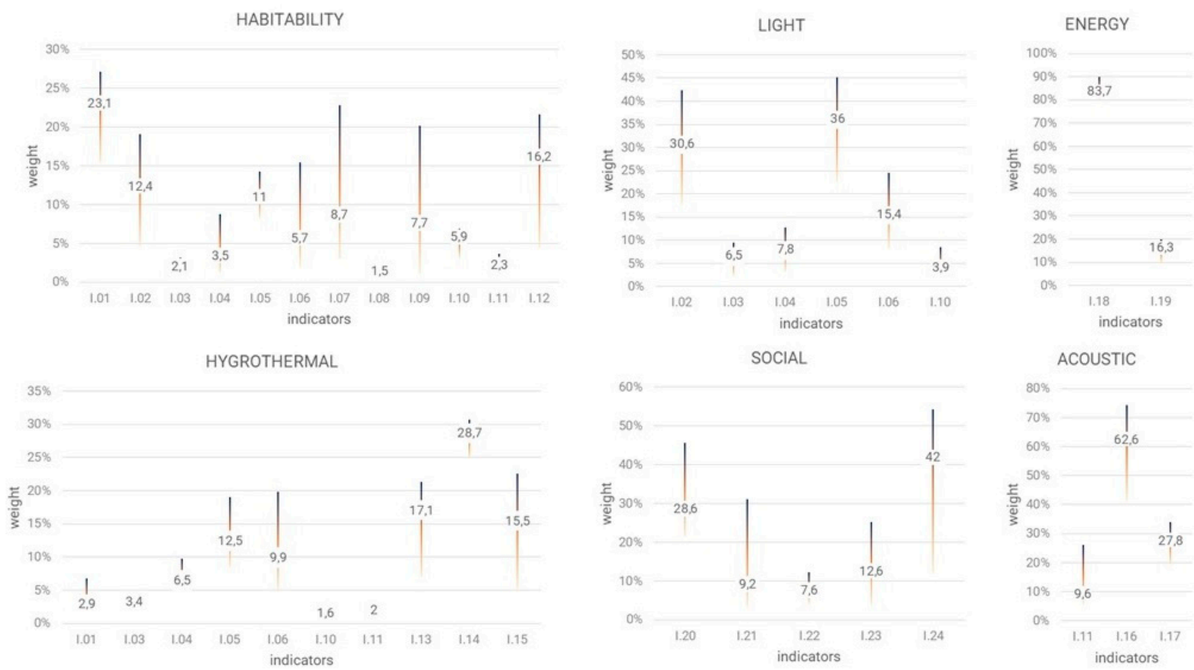

Figure 4. Confidence interval graph of the weighting resulting from the pairwise comparison of the team of experts according to Saaty's methodology. Own elaboration.

2.2.3. Calculation of the Vulnerability Indices: Weighted Linear Combination

Vulnerability modeling through the multi-criteria procedure of Weighted Linear Combination (WLC) [81] contributes decisively to highlighting the graded spatial model of vulnerability at the municipal level, based on the principles of an absence of categorical limits and the necessary combination and compensation of factors through the establishment of a system of weights expressed as a percent of one.

In other words, it is an additive procedure calculated as a product of the criterion's weight and its scores. So, the high weight of a factor would imply a higher influence of that feature in the final vulnerability model. This implies that buildings with deficiencies in any of the factors are not excluded in the case of having a better rating in other high relative weight factors, avoiding the loss of nuances and information.

The compensation system plays an important role in the combination of the factors, where the relative weights of the factors have a decisive influence, with the most vulnerable areas having a maximum value of 1 on this scale, and unsuitable areas being close to 0.

The calculation for each vulnerability index in each area associated with each building is carried out using the following expression:

$$I_{j,A} = \sum P_{i,A} \cdot Z_{ij,A} \leq 1 \quad (1)$$

where:

A = Vulnerable area;
P = Weighting;
Z = Reclassification score;
i = Indicator;
j = Building.

After carrying out the WLC for the total building stock and integrating the indicators corresponding to each area, maps with vulnerability gradations by the criteria and their relative importance are obtained. This way, it is possible to characterize several profiles according to the affected area considered. Given that the values of the indices per se lack categorical meaning, a classification using natural breaks (Jenks) [81] was chosen, in such a way that five groupings with similar values are generated and the differences between classes are maximized.

2.3. Phase 3—Geostatistical Analysis

The following methodologies are used to analyze the spatial distribution of vulnerability in the city.

2.3.1. Correlation Analysis of the Indices

This multi-criteria and multi-axial approach is expressed in the bivariate statistical analysis of the indices by calculating Pearson's statistical correlation coefficient [82].

2.3.2. Analysis of the Most Vulnerable Dwellings (Clusters)

The aim is to detect, on the one hand, areas with a higher concentration of highly vulnerable buildings (hotspots). This is achieved through spatial autocorrelation techniques that do not consider each vulnerability value of each building in isolation, but in relation to the locations of its surroundings. Moran Global Index [83] is calculated and a Getis–Ord Gi* analysis [84] is performed to identify spatial clusters. While the Moran Global Index describes the general pattern of location of vulnerability values, whether dispersed, random or concentrated, the Getis–Ord Index measures the concentration of high or low values at three levels of significance, which can form several clusters or tend to monopolize in the study area. Thus, the analysis is carried out using Voronoi polygons and a Queen-type contiguity criterion.

On the other hand, we identify the typomorphologies whose percentages are significantly higher than the case study sample average. To do this, we contrast whether the values of very high vulnerability by area for the entire sample are significantly different from what is observed in each typomorphology. Thus, the percentage of very vulnerable buildings by area and segment is calculated to show the intensification of the most representative cases on a color scale.

Additionally, a cluster analysis of the categories with very high vulnerability by area is carried out, so that these buildings can be catalogued and grouped according to the causes of their vulnerability, identifying a pattern according to the indicators that cause this situation. The k-means clustering algorithm is used [85].

3. Results and Discussion

The present research has been developed in the framework of the project RISAV, funded by Diputación Foral de Gipuzkoa. Therefore, pursuing the application of the method in the local reality, the case study selected for the validation of the method is the city of Donostia-San Sebastián, a Spanish municipality, a coastal city in the North of Spain. The population of the municipality is 188,240 inhabitants (2020) [86] and the surface area is 60.89 km^2. The population density is 3060.77 inhabitants/km^2. It has 10,717 buildings (2020) comprising 93,818 dwellings, of which 4704 are single-family and the remaining 89,114 are multi-family [87].

The final analysis sample of this research consists of a total of 6757 buildings and 80,336 dwellings. Given the objective of developing a method for prioritizing renovation interventions, periods after 2007 have been excluded from the study; construction standards have been considered adequate since the implementation of the Technical Building Code (CTE 2006), which is the main set of regulations governing the construction of buildings in Spain since 2006.

First, the data and maps resulting from the calculation of the vulnerability indices are presented, followed by the correlation analysis that validates the selection of indicators, and finally, the results are analyzed with the aim of identifying patterns that can serve as a basis for the design of municipal rehabilitation strategies. In addition, an interactive web viewer (https://atlasak.datuak.net/risav/index.html (accessed on 3 August 2023)) has been developed to facilitate the visualization of the results (indicator and index data, hotspots and additional building related data).

3.1. Index Maps

The resulting vulnerability model reflects the graded reality of the spatial, environmental, energy and social factors that buildings present in relation to this concept. Table 1 quantifies the results in absolute and relative terms for buildings and dwellings for each vulnerability degree.

Table 1. Data resulting from the indices by vulnerable areas for the case study of Donostia-San Sebastián. Absolute and relative data for buildings and dwellings. Own elaboration.

	Habitability		Hygrothermal		Light		Acoustic		Energy		Social	
Vulnerability level	N.build.	N.dw.	N.build.	N.dw.	N.build.	N.dw.	N.build.	N.dw.	N.build.	N.dw.	N.build.	N.dw.
very low	620	9097	40	1694	1463	16,293	316	2880	3073	45,087	1910	20,027
low	1748	25,466	2674	35,352	2193	20,930	ejes	14,696	1882	19,055	1448	16,391
medium	1510	21,170	1411	19,010	869	12,425	1915	24,360	884	9120	1701	23,885
high	1307	13,690	1370	15,626	946	16,712	1194	16,892	614	5617	1011	10,408
very high	**667**	**5844**	**357**	**3585**	**382**	**8910**	**937**	**16,923**	**193**	**1453**	**682**	**9621**
Total	5852	75,267	5852	75,267	5853	75,270	5985	75,751	6646	80,332	6752	80,332
	Habitability		Hygrothermal		Light		Acoustic		Energy		Social	
Vulnerability level	% build.	% dw.	% build.	% dw.	% build.	% dw.	% build.	% dw.	% build.	% dw.	% build.	% dw.
very low	10.59%	12.09%	0.68%	2.25%	25.00%	21.65%	5.28%	3.80%	46.24%	56.13%	28.29%	24.93%
low	29.87%	33.83%	45.69%	46.97%	37.47%	27.81%	27.12%	19.40%	28.32%	23.72%	21.45%	20.40%
medium	25.80%	28.13%	24.11%	25.26%	14.85%	16.51%	32.00%	32.16%	13.30%	11.35%	25.19%	29.73%
high	22.33%	18.19%	23.41%	20.76%	16.16%	22.20%	19.95%	22.30%	9.24%	6.99%	14.97%	12.96%
very high	**11.40%**	**7.76%**	**6.10%**	**4.76%**	**6.53%**	**11.84%**	**15.66%**	**22.34%**	**2.90%**	**1.81%**	**10.10%**	**11.98%**

The level of detail and expressiveness of the resulting cartography allows us to perceive important inequalities in relation to the vulnerability degree. Thus, it highlights the spatial variation of vulnerability in the city, even differentiating the areas within the census boundaries themselves that should be the object of specific rehabilitation policies. Figure 5 presents these results, which are the basis for the analysis presented below.

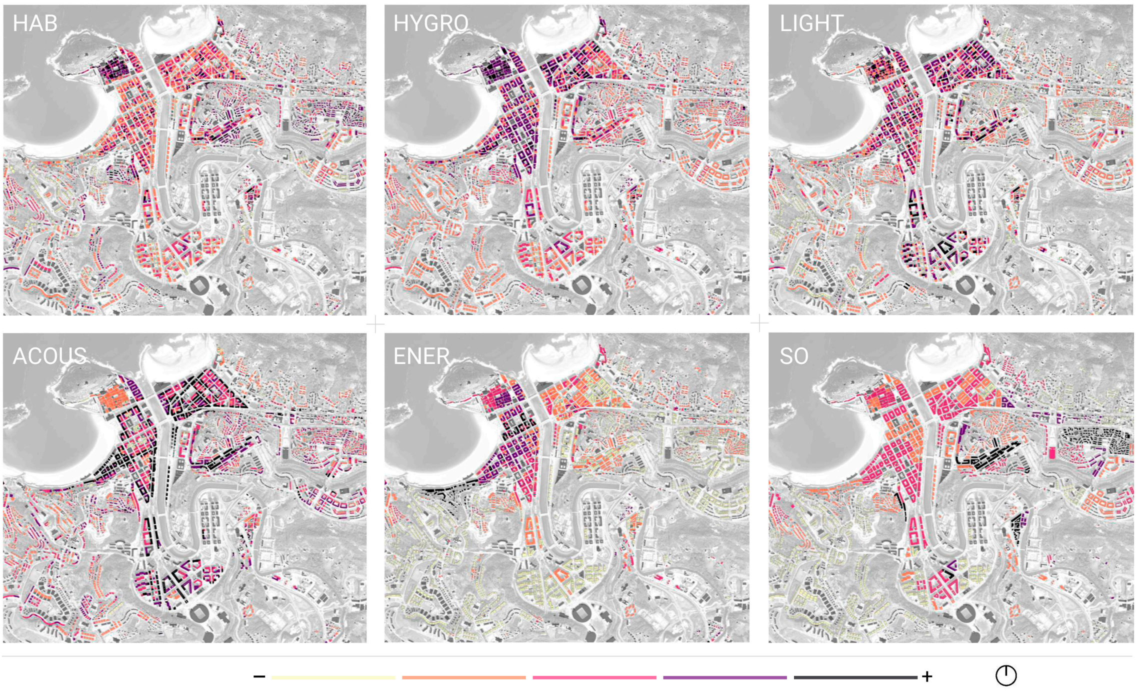

Figure 5. Plans resulting from the indices by areas of vulnerability. Own elaboration. The results for each area, both absolute values and reclassified values, as well as the resulting enlarged maps, are annexed in detail (see Supplementary Material S2 for maps and results).

3.2. Correlation Analysis of the Indices

The strongest correlations (r > 0.5) are between the indices of habitability with hygrothermal and hygrothermal with lighting. There is also a moderate correlation (0.3 > r > 0.5) between hygrothermal with energy, habitability with lighting and hygrothermal with acoustics. In any case, the coefficients are low enough to guarantee the independence of the indices. This is, in part, due to the reclassification process characteristic of the indicator according to the health condition estimated for each area of vulnerability, which produces a difference in results for the same initial indicator.

3.3. Analysis of the Most Vulnerable Dwellings—CLUSTERS

Once the different vulnerabilities have been analyzed, the three geostatistical analyses focused on the spatial concentration and characterization of the phenomena are performed.

3.3.1. Spatial Autocorrelation

The Moran Global Index shows a significant positive spatial autocorrelation in all cases (0.455 in Habitability; 0.499 in Hygrothermal; 0.578 in Acoustic and 0.489 in Light), but much higher in the Social (0.897) and Energy (0.764) indices, which is consistent with the calculation process of the indicators that compose them, in which the aggregated data by census section exacerbate an already pronounced phenomenon of spatial concentration. These spatial autocorrelation patterns are shown in Figure 6.

The habitability index presents a marked duality, with four vulnerability hotspots, being the historic center and the eastern axis of the locations with the highest concentration of buildings with very high values, while in the western part of the city the opposite situation is found, with concentrations of low values. A similar situation, although more intense, occurs in the case of the social index. In the case of the hygrothermal index, the concentration of very high values is found in the historic center and the suburbs. In the energy index, there is a great contrast, where the area of the historic center, expansion and waterfront tend to form a single hotspot, as opposed to the coldspots of more modern developments. The concentration of high values of the light index follows the axis of the Urumea river, similar to the acoustic index, although the latter is more axial.

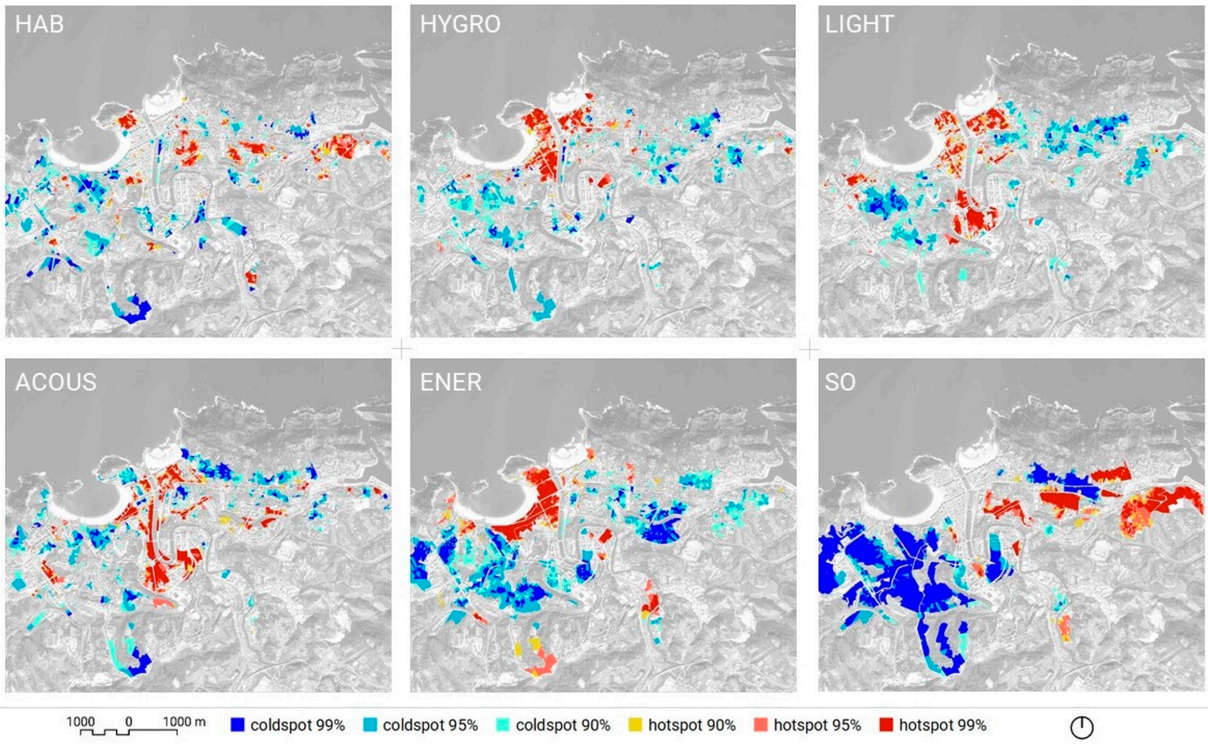

Figure 6. Plans resulting from the hotspot analysis (Getis–Ord Gi*) at different confidence intervals. Own elaboration.

3.3.2. Clusters by Segmentation Strategy—Typologies

The results obtained for each field are listed below. In the case of habitability, the linear blocks of the period 1941–1960 appear in various forms, as well as the historic center. In the hygrothermal area, again, the historic center appears, in addition to a series of varied typomorphologies from the period 1901–1940. In the light field, the historic center and some blocks in high-density environments relatively recent/post 1960s. On the other hand, in the acoustic area, no pattern is detected since the distribution is balanced. However, for the energy case, there is only one representative case corresponding to the nineteenth-century expansion. Finally, social vulnerability is manifested in the linear block and open block typologies.

3.3.3. Clusters of Vulnerability Indicators by Field

From the cluster analysis of the categories with very high vulnerability by area, the following patterns are identified are shown in Figure 7

By way of illustration, the case of the spatial area (habitability) is described, where five well-differentiated clusters were detected, which are described below:

The first of them agglutinates dwellings that have little surface area, bright with a high percentage of openings in the facade and in general have balconies and/or terraces and a type of structure that fits into the appropriate standards. In general, they are not located close to vegetation, and vertical accessibility is not guaranteed due to the existence of a community elevator in the building.

Figure 7. Composition of clusters according to incident indicators. Own elaboration.

The homes in the second cluster have a minimum of two orientations that guarantee adequate sunlight as well as a link to green areas and open spaces. In general, they tend to respond to a mixed structure that is within the standard; however, the roofs are sloped, which conditions the possibility of its use. The surface area of the dwellings is small, and they generally do not have balconies and have a low percentage of openings in the façade. The houses in cluster five share many of the same characteristics, with the difference that many of them do not have balconies or nearby vegetation.

The dwellings in the third cluster have a good rate of sunlight incidence throughout the day because of their high percentage of openings in the façade, although there is no significant representation of dwellings with balconies. However, the surface area of the dwellings is scarce and the type of structure and roofing is far from adequate standards, affecting its durability.

The houses in the fourth cluster have a large surface area and an acceptable solar radiation index throughout the day, although they are not characterized by the possession of balconies or terraces. On the other hand, the ratio between the length of the façade front with respect to the built surface is in the range of vulnerable values due to the reduced building depth. This could be interpreted as, although the house is spacious, it does not achieve a hierarchy of spaces, affecting the amplitude and perspective. Also, the type of structure and roof do not correspond to adequate standards, and its durability is affected, a fact that is aggravated by the lack of proximity to vegetation and the lack of vertical accessibility.

4. Conclusions

There is wide scientific evidence that quantitative methods using indicators are a fundamental tool in the evaluation of vulnerability that facilitate the decision-making process and the definition of rehabilitation strategies by the competent institutions, prioritizing those who are in a situation of higher vulnerability. It is necessary to develop methods that consider the multifactorial approach through an integrative and holistic vision that can characterize the building stock. In this regard, the present research of vulnerability develops a first innovative and complex methodological proposal, which integrates social, energy, environmental and spatial aspects through the calculation of indices for each area. The methodology presented has proven to be effective in achieving the objectives proposed and the associated GIS tool has proved to be agile and exportable, despite the large amount of data used.

Among the difficulties encountered, it should be noted that the element of analysis in the proposal presented is the dwelling and the aim is to determine the vulnerability of each housing unit. Evidently, the same building may contain dwellings with different characteristics that may have disparate conditions in the proposed indicators. However, characterizing the dwellings with the information currently available in the accessible sources is impossible in work carried out at the municipal level. The information associated with dwellings requires more specific approaches, which would require a larger scale of approximation, such as an analysis of a group of buildings or a neighborhood. In the method developed, the results are disaggregated at the building scale, which makes it possible to identify the areas or buildings with the greatest vulnerability.

The work developed in this project lays the foundations for an area of research of great interest and opens new lines of work, deepening some indicators that, although they have been defined in the methodological proposal in this project, still have a long way to go in terms of possibilities for development.

The proposed method aims to be a tool that makes visible the variety of problems associated with housing and provokes a reflection on the suitability of the rehabilitation strategies currently promoted by the public administration. It can be, in turn, an instrument to elaborate diagnoses and medium- to long-term intervention plans on a municipal or regional scale, where policies are designed to deal in a varied way with the multiple vulnerabilities existing in the building stock of each municipality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12081551/s1, S1: Analytical framework Indicators reference list; S2: maps and results: resulting maps of absolute values as reclassified values and the resulting expanded plans.

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