A holistic and multi-stakeholder methodology for vulnerability assessment of cities to flooding and extreme precipitation events

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Abstract

Over recent years, the frequency and intensity of torrential rain and flooding events linked to climate change have been impacting on cities throughout the world. Adaptation to climate change must therefore be integrated into urban planning and coupled with sustainable urban development and conservation policies. To do so, a good understanding of the vulnerability of cities to these extreme events is necessary, lending special attention to the specifics of the different urban areas, such as historic city centres.

In the present study, a vulnerability evaluation methodology is presented for cities against extreme rainfall and flooding, which follows a holistic and multi-stakeholder approach, integrating architectural, socio-economic, and cultural perspectives, that supports evidence-based decision-making for the sustainable development of the agents that intervene in the process. The MIVES method, based on a multiple criteria decision-analysis process and a CityGML-based data model are used for that purpose, with which a process for capturing, evaluating, and representing information in an objective, organized, and systematic way has been developed. These advantages are demonstrated through the application of that process to a case study in Donostia-San Sebastián (northern Spain), located on a river estuary in front of the sea, with a wide diversity of building styles.

Keywords: vulnerability assessment, urban areas, historic buildings, extreme events, MIVES, CityGML

1. Introduction

Climate change remains a major challenge for humankind despite the multiple actions that have taken place since the first World climate Conference in 1979. According to the IPCC [1] and the European Environmental Agency (EEA) [2], extreme climate-change events will intensify in frequency around the world, impacting on highly vulnerable human and natural systems, and they call for the implementation of adaptive actions.

Floods affect countries worldwide and their significant impacts, even in high-income countries contribute to 33% of average annual losses. Rivers, coastlines, rain and ground-water are all sources of flood water, due to meteorological and hydrological events and any combination of them will usually impact on cities. As an example, river flooding is said to have average global annual costs of US$104 billion [3].

City populations have increased the vulnerability of urban areas to extreme events, placing them in the focus of the fight against climate change, since they are facing not only physical, but also social, economic, and cultural challenges. Furthermore, many cities assign protection levels to areas of historic, architectonic and cultural value (historic city centres) that are woven into the identity of the local population and their sense of place. Historic cities are characterized by their architecture, high population densities, and availability of services. They promote tourism, increase investment and contribute to economic life. The current climate-change context, besides threatening cities in general, seriously threatens their cultural heritage. Its inclusion in adaptation plans for heritage preservation is fundamental for future generations. Nowhere has the impact of climate change on cultural heritage been analysed as much as in urban areas [4]. Despite the vulnerability of heritage sites exposed to natural hazards, existing action plans related to adaptation and response mechanisms, still do not include heritage as clear priority. [5]. While UNESCO started a dialogue to include heritage in disaster risk reduction policies and strengthen preparedness actions at World Heritage properties [6], most approaches remains vague on how to adopt adequate risk management procedures for cultural heritage protection and practical frameworks are still missing. In spite of some relevant example of integrated planning [7], many sites do not have specific procedures or plans aimed at reducing vulnerability or risk. The methodologies and the tools that support adaptation strategies have to address the historic city. Awareness must be raised of climate change impacts, both among urban planners and heritage managers, to promote conservation policies and to safeguard cultural heritage and cities sustainability [8-9].

The Effect-Vulnerability-Adaptation-Implementation (EVAI) model [10] is often used for adaptation planning. It follows a top-down approach that begins with a damage assessment of the adverse event, the identification of the vulnerability and the analysis of the coping capacity of the system to identify proper adaptation measures. Hence, the first step is to analyse the impact on urban elements and their vulnerability.

The impact or damage assessment will depend on the element under study, the geographical location, the time frame, and its final purpose, for which numerous methods and tools available [11]: expert and stakeholder led mapping/modelling and material specific studies. Damage models are extensively applied to evaluate losses due to flooding, among which flood depth-damage functions are a globally accepted means of assessing physical damage [12]. However, these functions only consider the economic costs of the building, although probabilistic approaches to structural assessment are beginning to emerge, following seismic vulnerability assessment processes [13]. Likewise, proper assessment of vulnerability can improve climate change risk management. Vulnerability to climate change in terms of its nature, magnitude and frequency will define the degree to which a system is susceptible to, and unable to cope with, adverse climate change events [1].

Aimed at facilitating decision-making process when various fields and criteria are involved, multiple-criteria decision analysis (MCDA) methodologies are suitable due to their multidisciplinary role which have already been applied in various field, e.g., energy, ecological-economics, resilience, sustainable urban development, etc. [14-19]. However, city vulnerability assessment methodologies to counter flooding and extreme precipitation events including buildings with different cultural value are still missing [20-22].

On the other hand, urban modelling is becoming a useful tool to represent the complex interrelations of a city. The implementation of vulnerability assessment methodologies in urban models can facilitate the visualization of the information and support the decision-making. Nevertheless, a compromise between data availability, modelling accuracy and computational cost should be attained [23]. The selection process of pertinent and precise indicators and data to model the behaviour of the urban system with respect to sustainability criteria is of increasing relevance [24]. Furthermore, an interdisciplinary focus is essential to address the climate change-cities binomial, comprising urban planning, building systems, and climate evolution, as well as to design sustainable cities and societies [25-29]. As those factors operate on different temporal horizons and spatial scales, efforts must be oriented towards the achievement of a comprehensible, accurate, manageable, predictive and low-cost model that can link various fields and facilitate the representation and understanding of their interactions [30].

Geographic Information Systems (GIS) are used for digital modelling of the terrain to estimate flooding depth and extension in case of flooding events [31-32]. Although, the analysis of the propagation and the impact of flooding can be improved through 3D city models [33], the limitations of these models are due to the lack of integration between the building and urban scale and the absence of interoperability between data formats at syntax level [34]. The latest studies on the flooding of urban areas are targeted at improving the visualization of flood depth and extension, without considering damage to buildings [35-36]. Few researchers have integrated BIM and GIS so that high-definition building models can be used for flood-impact assessments [37-38]. CityGML is an open data model and XML-based format for the storage and the exchange of virtual 3D city models issued by the Open Geospatial Consortium (OGC) and the ISOTC211. Although under exploited, it is a tool that promises to make urban planning and management easier by linking different disciplines. Its success among researchers

[39-41] is due to its potential to combine geometric data and building databases, its interoperability, and its options for detailed definitions at different levels. CityGML, with which many municipalities already work, has been used for disaster-risk management in indoor applications [36], and fire events [42].

2. Aim and methodological approach

The motivation behind this research work is the need to consider climate change risks and to mitigate its foreseeable impacts on cities. For this aim, prior to the incorporation of hazard and exposure components, considering climatic scenarios to assess the risk based on foreseen increase in precipitation patters and sea-level rise, a vulnerability assessment of the built environment is necessary. This article is focused on the development of a comprehensive pluvial and fluvial flooding vulnerability assessment methodology for cities, which also includes historic areas and a holistic perspective of the built environment in terms of its physical, socio-economic, and cultural singularities. Vulnerability has been addressed considering the local effects of climate change on the risk of flooding, according to developed projections for the 21st century with high spatial resolution (1km x 1 km), which show, in the Bay of Biscay, a consistent trend of the current and projected increase in sea level and an increase in extreme precipitation by 30% at the end of the century. The study shows that significant increases could occur in the maximum flood flows, along with the flooded surface area and with the speed and flow values [43-44]. The final aim is the promotion of holistic urban development policies to counter future flooding and extreme precipitation events through conservation-friendly and sustainable adaptation strategies. For this purpose, on the basis of this research work outputs, efforts should be oriented to the development of a risk assessment methodology, able to support the identification of main impacts derived from climate change and subsequent prioritization of adaptation actions that are essential for the conservation of the built environment and promotion of sustainable cities.

The first premise of the methodological approach is that the singularities of historic cities must be integrated into climate-change adaptation plans for the enhancement of sustainability within cities. Extended areas must be covered, to achieve a useful tool for urban planners, which leads to the need to identify a set of proper and effective indicators for multi-criteria decision-making.

The different perspectives or criteria involved required a methodology based on MCDA such as MIVES [the Spanish acronym for The Integrated Value Model for Sustainability Assessment], which provides a systemic and objective methodology for holistic and integrated vulnerability assessment. MIVES is used to include a multi-stakeholder perspective and to balance the identification of proper, traceable, and effective data with accurate results.

The application of MIVES has demonstrated its flexibility and soundness in various complex sustainability-related situations, covering different fields in the construction engineering area [45-50]. This methodology combines two analytical concepts: Multi-Criteria Decision-making Theory and Value Engineering [51]. MIVES transforms different types of hierarchized indicators into a dimensionless unit, a process that involves their comparison and the definition of their relative importance, integrating technical, environmental, economic, and social parameters into a single-value index. The greatest strength of the MIVES methodology is the objectivity of its decision-making process, as the alternatives are assessed by a panel of experts at an initial stage, minimizing any subjectivity in the process [52].

The next step of the methodological approach is to provide an information strategy to facilitate big data management and a multi-scale urban model. Hence, the methodology is supported by a CityGML data model, which was chosen due to its capacity to combine geometric and semantic data; represent 3D georeferenced information at different levels of detail that allows the multiscalability and because it is a standard defined by the OGC, which improves the later interoperability. The model allows the vulnerability assessment of the city by properly structuring all the information, so that it easily identifies most vulnerable assets and facilitates subsequent decision-making for adaptation strategies. To do so, a categorization process for the buildings is developed.

Finally, the results are implemented and validated for a real case study in an area of Donostia-San Sebastián (Spain).

3. A holistic and multi-stakeholder vulnerability assessment methodology

The assessment of vulnerability is the first stage for evidence-based decision-making, prior to the risk analysis stage and the development of adaptive strategies. In a climate-change context [1], vulnerability is the interrelation between system sensitiveness and adaptive capacity. In the case of buildings, sensitiveness is their susceptibility to the impact of an event and their adaptive capacity is the likelihood that they will be capable of withstanding an event. The methodology presented in this paper is focused on pluvial and fluvial flooding, exacerbated in many regions by climate extremes such as daily extreme or heavy precipitation events and sea-level rise and considering the response of buildings located in urban areas to these effects. Hence, the proposed vulnerability assessment methodology brings together parameters related to building sensitivity and adaptive capacity for buildings in urban areas, as well as the specific characteristics of historic buildings.

Having collected the heterogeneous information on cities (different format, scale, purpose, etc.), a value analysis method is used to compare building vulnerabilities on a unique index, consequently, supporting the prioritization of adaptative solutions within a precise building or group of buildings within the city. However, a methodology for collecting and structuring the data, at various hierarchical levels, is needed, due to the large amount of information that will be processed, and for objectivity in the decision-making process. Additionally, as a previous step, the available information should be linked to specific buildings by classifying building typologies that represent the existing stock. Hence, the first step in an assessment of the vulnerability of cities to flooding and extreme precipitation events is to categorize the building stock according to similarities and common constructive characteristics.

3.1. Building stock categorization

The selection of the parameters for the categorization of building categories is one of the core steps. The categorization process is not unique and depends on the urban area singularities, the characteristics of the buildings themselves and on data availability [53]. The number of categories, their representativeness and the relevance of the information that is gathered are the main aspects to be analysed. Precise thresholds are therefore required for dividing the different aspects into varied ranges and to discard the less representative categories. For each category, a reference building will be defined [54]. When a large building stock has to be analysed, only the most identifiable characteristics of a reference building will be categorized and later extrapolated to the whole building stock. The categorization of the buildings, based on both their constructive characteristics and their historic value, should therefore refer to the vulnerability of the buildings to flooding.

The following parameters were used for the categorization of the buildings: year of construction (buildings from the same period share similar construction details); use (an extreme event will have similar economic impacts on buildings); existence of a basement (the basement is the most sensitive part of the buildings to flooding); level of protection (indicating the historic value of the building and determining the possibility of installing specific adaptations); number of dwellings (establishing the number of owner occupants within the building to undertake adaptative solutions -the higher the number of owners, the higher the adaptation capacity); and socio-economic status (also a pointer to the economic means of the owners to undertake adaptive solutions). If all the parameters are considered, the number of categories would be too vast. Thus, in order to establish the final categories, parameters were divided into ranges by analysing the values concentration in the study area and discarding the less representative groups. In order to be representative, categories are defined according a threshold of 2% of the overall building stock.

3.2. Vulnerability assessment requirement tree

Having categorized the building stock, the selection of a set of indicators for the vulnerability assessment was carried out considering the balance between accuracy of the results and limited resources for their definition and processing in the model [55].

The MIVES methodology was applied in an objective way, to identify the most vulnerable buildings both to the effect of coastal and river flooding and to the impact of extreme precipitations within urban areas. The stages of the methodology are as follows: identification of the problem, definition of the decision support tree, setting of the value functions, weight assignment and alternative evaluation (together with a sensitive analysis) to obtain a value index.

The requirement tree that is the basis for future vulnerability assessment structures the data in a hierarchical manner, generally, at three levels [56] (see Figure 1): requirement level (the main criteria to make decision), criterion level, and indicator level (specific aspects to assess in detail the vulnerability of the buildings). Indicators must be representative, differentiating, complementary, quantifiable, precise, and traceable [57]. In this work, based on a definition of vulnerability to climate change, the requirements are sensitiveness and adaptive capacity. In the case of criteria and indicators, the tree is adapted to the buildings and cultural heritage perspective through the definition of criteria and indicators.

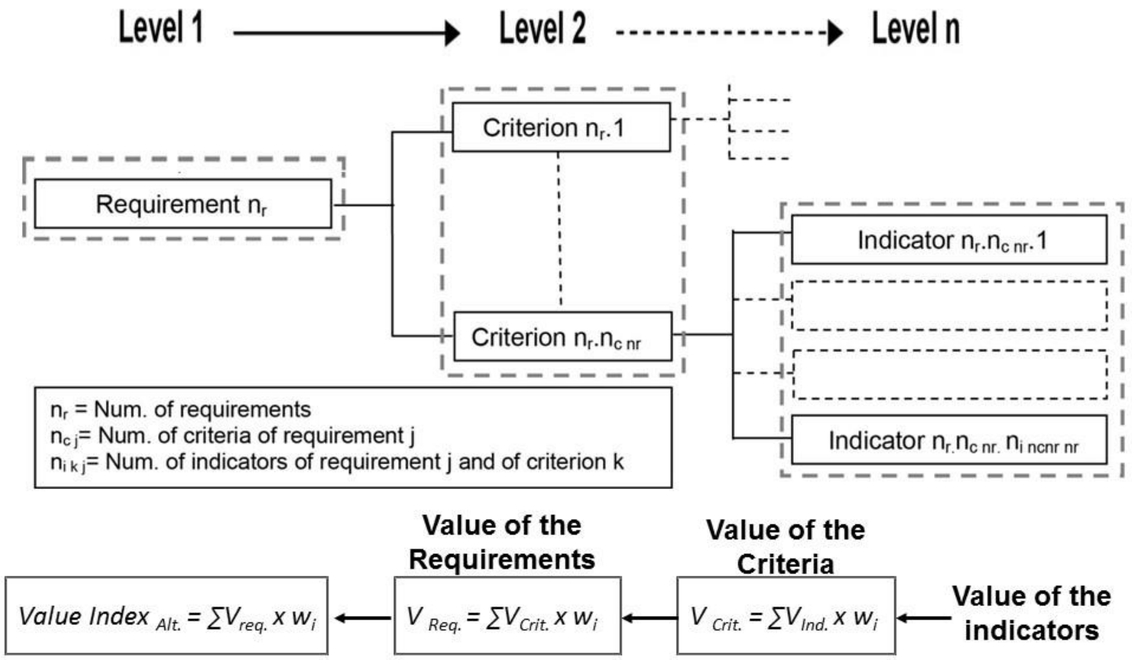

Figure 1: Requirement tree and formulation for calculating the Value Index in MIVES methodology (Source: Adapted from [52])

The requirement of sensitiveness involves an evaluation of the potential damage level caused to the building by the impact of the hazard, depending on its intrinsic characteristics. To do so, objective parameters are considered (see Figure 2): current state of the building, constructive critical elements, envelope characteristics, main use, and structural material are considered. The current state of the building indicates its state of conservation, the physical condition of the constructive solutions, and water-related damage. The constructive elements and the envelope of the building represents the most critical systems in case of flooding or extreme precipitation. Criticality is related to the use of the building and it influences the period of time it will remain after the event. Structure considers the performance of the structural material when exposed to water.

The requirement of adaptive capacity refers to the aptitude of a building to face and recover from the potential effects of an extreme event. In this case, three criteria are established: interventions, socio-economic conditions, and the cultural value of a building. Interventions refer to previous rehabilitation or maintenance interventions and the relevance and quality of available equipment for water drainage. Socio-economic conditions refer to the coping capacity of the inhabitants, considering their economic capacity, based on the history of interventions and the number of owners in a building. The cultural value of a building refers to the protection level provided by local government and related institutions, based on the historic, architectonic, and cultural value of the building.

As stated by some authors [58-61], when a large building inventory (typically heterogeneous) is to be analysed, reference or archetypal buildings can be described that also implies a categorization process. Therefore, reference buildings are “theoretical” buildings based on typical measurements of existing buildings and the indicators can be applied to every sample building. Whenever possible, datasets will be obtained from a public database, otherwise online visualisation maps and *in situ* inspections will be used.

3.3. Value functions of the indicators

A value function is a number that represents an objective assessment of either a qualitative or a quantitative indicator. It is included in a mathematical function that transforms different measurement units into a dimensionless variable. Graphically, while the vertical axis represents the minimum or the maximum satisfaction level (0 and 1, respectively), the horizontal axis represents the alternatives of the indicator. The most common value function shapes are concave, convex, linear, and S-shaped, depending on the nature of the indicator [62]. The value function for each indicator is defined in MIVES by [Eq. 1]. If the shape of the value function is unclear, it will be further defined by the expert panel. In this research, the expert panel is composed of specialists, professionals and researchers with either engineering and architectural backgrounds (some of them trained in MIVES methodology), working in the fields of design, execution and maintenance of buildings, conservation and risk management in construction, bringing together experience and knowledge of the challenges presented in the article, mainly focused on the urban environment. The panel of experts functions as a forum for debate to identify and to evaluate requirements, criteria and indicators.

$$V_{ind} = B * \left[1 - e^{-K*\left(\frac{|X - S_{min}|}{C}\right)^{P}}\right] \text{[Eq. 1]}$$

$$B = \frac{1}{\left[1 - e^{-K*\left(\frac{|S_{max} - S_{min}|}{C}\right)^{P}}\right]} \text{[Eq. 2]}$$

where, V_{ind} is the indicator value; S_{min} and S_{max} are the points of minimum and maximum satisfaction (0 and 1), respectively; X is the abscissa that generates a value equal to V_{ind}; P defines the shape of the curve (if $P< 1$ the curve is concave; if $P> 1$ the curve is convex or S-shaped; if $P = 1$ it is linear);C is the x-value of the point of inflexion for curves with $P> 1$; and, K is the y-value at point C.

When the relative importance of different parameters needs to be determined, the Analytical Hierarchy Process (AHP) is used. In this case, elements are compared in pairs to determine their relative importance. For this purpose, a comparison matrix is used, verifying the consistency of the matrix, which helps to verify the coherence of the values attributed by the experts [63-64]. These matrix calculations, as Dr. Piñero stated [47], are based on their specific vectors (auto-vector of weights) and the ratio of consistency (auto-value).

$$A = \begin{vmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} = \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} = \frac{1}{a_{1n}} & a_{n2} = \frac{1}{a_{2n}} & \dots & 1 \end{vmatrix} \textit{[Eq. 3]}$$

where, a_{ij} represents the relative importance of the variable I with respect to j, on a scale between 1 and 9.

As previously stated, the vulnerability assessment in the climate change context involves the assessment of sensitiveness and adaptation capacity. In this research work, in total, eight criterion and fourteen indicators were identified and analyzed. With respect to the assessment of sensitiveness, the following five criterion and nine indicators were evaluated through a value function or pair-wise comparison using AHP. When detailed information is unavailable or a large number of buildings are to be assessed over a short period, a simplified method may be used for the evaluation of indicators. The vulnerability decision tree is shown in Figure 2 and final values are shown in Figure 6.

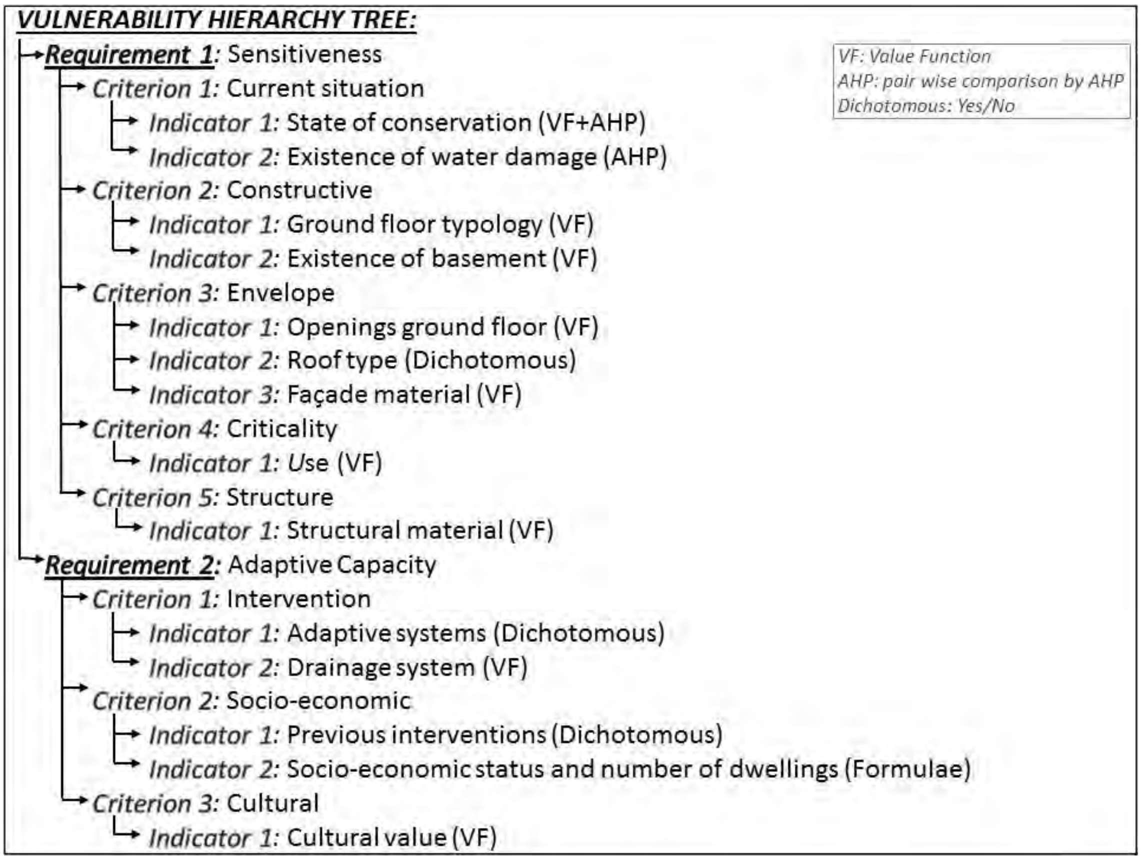

Figure 2: Vulnerability assessment decision tree. In brackets, the method used to obtain the value of the indicator.

<u>State of conservation</u> (Figure 3A and 3B) of the building, especially, of the structure, roof, and façade consists of four alternatives. i) Good: no damage present in the building and the three elements are in good or fair condition; ii) Fair: occasional damage is present, but no significant damage is detected on the three elements; iii) Poor: general deterioration is detected in the buildings and interventions are needed; and, iv) Very bad:

buildings with high levels of deterioration. This indicator was assessed by means of a value function for the four alternatives and then, by the definition of the relative importance of the three constructive elements with a pair-wise comparison using AHP. The final value of the indicator was generated by a matrix combining the three constructive elements and the four conservation alternatives. The simplified method determines damage to the structure and the roof through the assessment of the façade, as it was considered the most relevant constructive element in this situation.

Existence of water damage (Figure 3C and 3D) is an evaluation of the type of damage (filtrations, humidity, erosion) combined with the constructive element (foundations, structure above ground, façade, roof). The result is a compound indicator that the expert panel assesses, through pairwise comparison matrixes. The simplified method is only used to evaluate the existence of water damage in the building, considering only two alternatives: yes (maximum value, 1) or no (minimum value, 0).

Ground floor typology (Figure 3E) and its activity, which influences both the economic and the social impact is used to evaluate the sensitiveness. A linear value function was defined for this indicator, giving the maximum value (1) to ground floors with commercial or residential activity and the minimum value (0) to portico structures without activity. A medium value was given to closed ground floors with no activity.

Existence of a basement or a semi-basement (Figure 3F), due to the sensitiveness of such areas to flooding events, is another indicator. This indicator has two alternatives (yes/no) and the maximum value (1) is attached to buildings with (semi-)basement with direct access. The information on the basement can be obtained from the land registry, but the type of access often cannot be so easily obtained, so *in situ* inspections are necessary. A value function is proposed for those cases that also assess the type of access to the (semi-) basement.

Openings on the ground floor (Figure 3G) is an indicator to evaluate the sensitiveness of the building to flooding or intense rainfall, due to possible filtrations based on the existence of the openings in the building and their typology. Three alternatives were selected for this indicator: no openings (>25%), small openings (25-50%) and large openings (>50%). The value function that is defined gives the maximum value to buildings with large openings or glass fronted shop windows on the ground floor and the minimum value to those with no windows.

Roof type is used to assess the sensitiveness of the buildings to potential filtrations in case of intense rainfall. It is a dichotomous indicator with two alternatives, flat and pitched roof. The former has the maximum value as they are more disposed to damage derived from poor water evacuation and, consequently, possible filtrations.

The finishing material of the façade (Figure 3H) is assessed to gauge the short-term effects of the water (dirt, deterioration, filtration, corrosion, cracks, detachments, deformations etc.). If various materials coexist in the façade, the material with highest presence is selected. The maximum value goes to those materials that are more porous or more sensitive to degradation.

Building use (Figure 3I) is an indicator that analyses the impact of any potential disruption, if the building had to remain out of use. Four alternatives were defined. i) Buildings which can be out of service for long periods, because their activity is not fundamental (cultural centres, recreational facilities, parking, etc.); ii) Buildings that can be out of service for medium periods, as their activity has some relevance, mainly for economic recovery (offices, restaurants, shops, etc.); iii) Buildings that can be out of service for short periods, because they hold a relevant activity for the society (residential buildings); and, iv) Buildings that cannot be out of service, because their function is fundamental in an emergency, (hospitals, emergency services, pharmacies, first-aid clinics, etc.).The value function that is defined gives the maximum value to the last alternative and the minimum value to the first one.

The type of structural material (Figure 3J) reflects the sensitiveness of the building to water absorption or filtration following its exposure to a flooding event. The most common five structural materials (stone, brick, steel, concrete and wood) are considered as alternatives and the value function defined gives the maximum value to materials that are most easily damaged in contact with water such as wood. The minimum value is for stone.

In the case of adaptive capacity indicators, three criterion and five indicators were considered. The value is attached in the opposite way to sensitiveness indicators, which means that the maximum value (1) is given to the best alternative as the adaptative capacity of the building indicates its coping capacity in case of an event.

Existence of adaptative systems (e.g. temporary shield panels, sealants, etc.), which means that buildings have higher protection against a flooding or intense rainfall events. It is a dichotomous indicator that gives the maximum value to buildings with previously implemented adaptative solutions.

Drainage system condition (Figure 3K) is a measure of the capacity to evacuate rainwater from the building. Four alternatives were defined. i) Good: the drainage system and other related components are in good condition; ii) Fair: in general the system is in good condition, but is isolated and no immediate repairs are necessary; iii) Poor: the system is in poor condition with risk of collapse and requires immediate repair; iii) Very bad: the system is completely damaged and needs complete renovation. The first alternative has the maximum value while the last one, has the minimum value.

Previous interventions during the service life of the building analyses the capacity of the owners to support future interventions. Owners who undertook rehabilitation works are usually more diligent with regard to maintenance works. This a dichotomous indicator and the maximum value is given when previous interventions exist.

Number of dwellings and socio-economic status of the owners also implies assessing the social adaptation capacity. On the one hand, it is frequently established that, as the intervention cost can be shared among owners, the adaptative capacity of the building increases with the number of dwellings. In this case, a linear function was used, giving the maximum value for 40 or more dwelling in the same block. On the other hand, the socio-economic status is evaluated considering the occupation category of the inhabitants. Based on [65], three status levels were defined with a linear value: high, medium and low. The average status is calculated by the sum of the percentage of each category multiplied by its value. Finally, the indicator value is the combination of both aspects, given a weight of 70% to the average status and 30% to the number of dwellings.

Cultural value (Figure 3L) refers to the degree of protection of the buildings established by the Administration. Five alternatives were identified. i) Without protection: the building is not included in any list of protected buildings and, consequently, no restrictions on interventions are defined; ii) Grade IV: buildings of recognizable value with respect to their environment deserving protection, mainly of external elements; iii) Grade III: buildings of recognized individual value, with protection of the external envelope and restrictions on interventions; iv) Grade II: buildings of recognized individual value where both the exterior and the interior envelopes are protected, limiting future interventions; v) Grade I: buildings declared of special interest and subjected to obligatory consultations and authorization of supra-municipal level. This last alternative has the maximum value, as it is considered that the higher the protection level, the higher the investment will be both for maintenance and for adaptation.

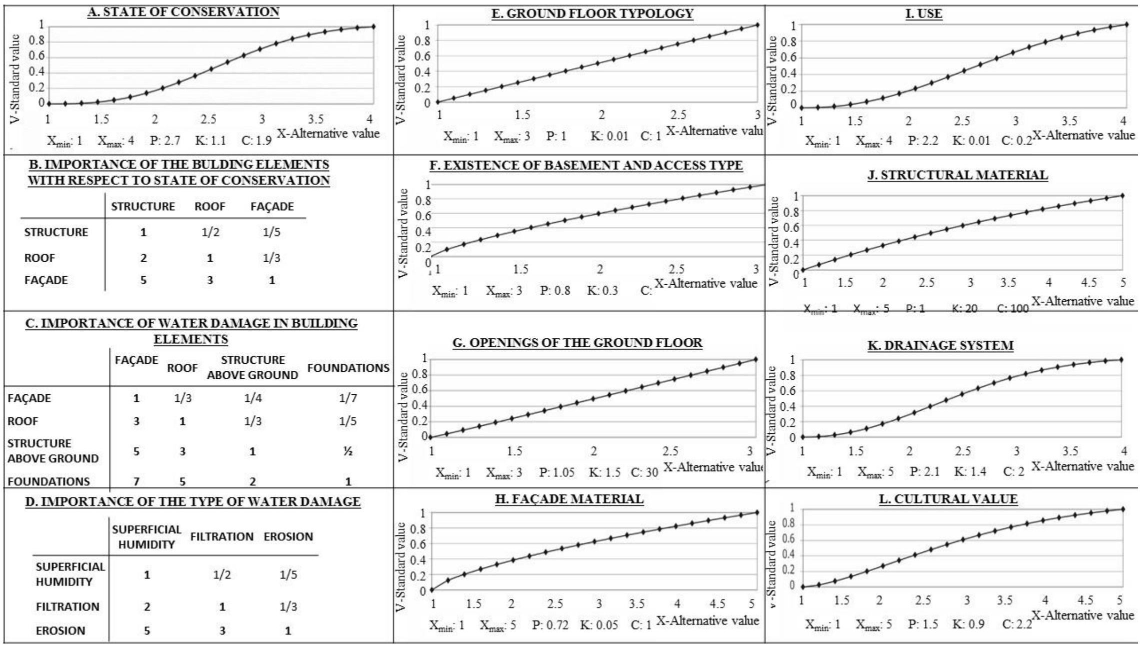

Figure 3: Assessment of the indicator alternatives. Value functions and comparison matrixes.

3.3. Weight assignment.

Depending on the final objective of the analysis, some parameters of the multi-criteria analysis may be more relevant than others. Therefore, the relative importance of the parameters at the same level is established through the assignment of weights to each one. Weights can be given through a direct score, when few elements have to be compared and the weight of each element is clear, or through the Analytical Hierarchy Process (AHP), verifying its consistency by means of the comparison matrix. In some cases, an adjustment of the final weight was made according to the expert panel opinion. When a unique parameter is at a level, a weight of 1 is assigned. In some cases, such as the socio-economic, and sensitiveness, indicators, and the adaptive capacity criterion, an adjustment was made to their final values, which were rounded, following discussion in the expert panel opinion. The final values of the value functions and weights are summarized in Figure 6.

With regard to the two sensitiveness indicators (Figure 4left), the panel of experts considered that both indicators could affect the vulnerability of the structure against flooding and extreme precipitation in the same way, which was not the case for constructive and envelope criterion indicators, to which different weights were assigned. In reference to the assessment of criteria, building criticality is considered as the most important parameter for vulnerability assessment, as buildings with critical use should remain in service after the event. Constructive aspects and the envelope are the next most relevant criterion as they can lead to water filtration. The structure is given a lower weight as the damage is usually in the long-term. According to the expert panel, the last one on the list is the state of the building.

CURRENT SITUATION

	STATE OF CONSERVATION	EXISTENCE OF WATER DAMAGE	WEIGHTS AHP
STATE OF CONSERVATION	1	1	0.50
EXISTENCE OF WATER DAMAGE	1	1	0.50

CONSTRUCTIVE

	GROUND FLOOR TYPOLOGY	EXISTENCE OF BASEMENT	WEIGHTS AHP
GROUND FLOOR TYPOLOGY	1	1/2	0.33
EXISTENCE OF BASEMENT	2	1	0.67

ENVELOPE

	NUMBER OF OPENINGS	ROOF TYPE	FAÇADE MATERIAL	WEIGHTS AHP
NUMBER OF OPENINGS	1	2	2	0.50
ROOF TYPE	1/2	1	1	0.25
FAÇADE MATERIAL	1/2	1	1	0.25

INTERVENTIONS

	EXISTENCE OF ADAPTIVE SYST.	DRAINAGE SYST. CONDITION	WEIGHTS AHP
EXISTENCE OF ADAPTIVE SYST.	1	1.50	0.60
DRAINAGE SYSTEM CONDITION	0.67	1	0.40

SOCIO ECONOMIC

	PREVIOUS INTERVENTIONS	NUM. DWELLING & ECONOMIC STATUS	WEIGHTS AHP
PREVIOUS INTERVENTIONS	1	1/2	0.33
NUM. DWELLING & ECONOMIC STATUS	2	1	0.67

Figure 4: Indicator weight assignments for sensitiveness (left) and adaptative capacity (right) from the comparison matrixes and their consistency validation.

Adaptative capacity indicators are evaluated as follows (Figure 4right). The existence of adaptative systems is valued higher than the drainage system, as buildings including adaptive interventions that have previously been damaged will supposedly be better prepared for future events. In the case of the socio-economic criterion, the number of dwellings and the socio-economic status of inhabitants are more positively evaluated, as they have a more of a direct relation with the economic capacity of inhabitants. With regard to adaptative capacity criteria, the cultural value has the highest value, as it characterizes the historic relevance and constrains the implementation of specific adaptative measures, while the intervention criterion has the lowest.

Finally, the sensitiveness and the adaptive capacity requirements have equal values for the vulnerability assessment of the building, in case of extreme precipitation and flooding events (Figure 5).

SENTSITIVENESS

	CURRENT SITUATION	CONSTRUCTIVE	ENVELOPE	CRITICALITY	STRUCTURAL MATERIAL	WEIGHTS AHP
CURRENT SITUATION	1	1/4	1/6	1/7	1/2	0.05
CONSTRUCTIVE	4	1	1/2	1/3	3	0.18
ENVELOPE	6	2	1	2	3	0.32
CRITICALITY	7	3	1	1	3	0.35
STRUCTURAL MATERIAL	2	1/3	1/3	1/3	1	0.10

ADAPTIVE CAPACITY

	INTERVENTIONS	SOCIO-ECONOMIC	CULTURAL	WEIGHTS AHP
INTERVENTIONS	1	1	1/2	0.26
SOCIO-ECONOMIC	1	1	1	0.33
CULTURAL	2	1	1	0.41

Figure 5: Sensitiveness and adaptive capacity criterion weight assignments from comparison matrixes and their consistency validation.

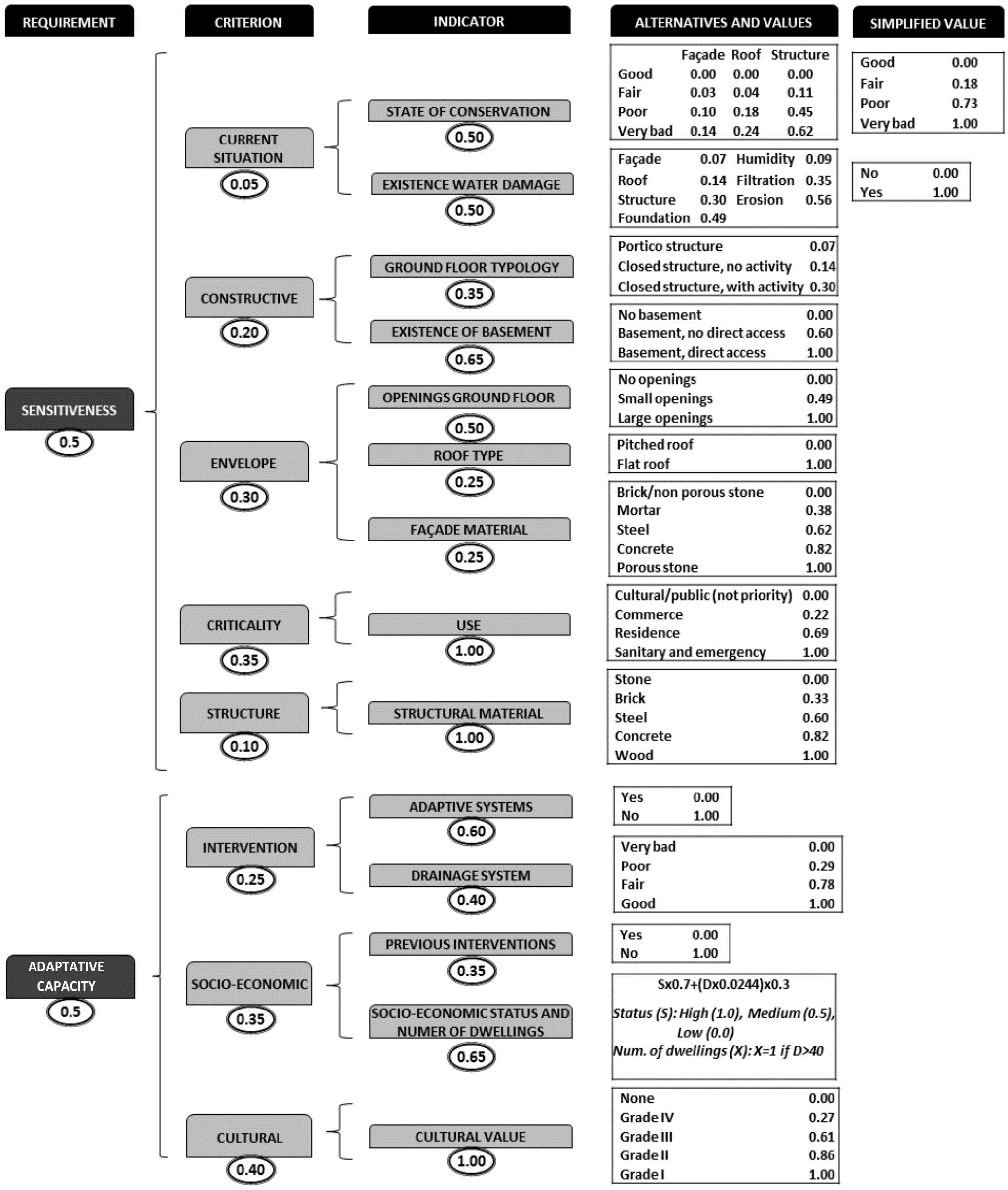

Figure 6: Value of requirements, criteria, and indicators of the vulnerability decision tree.

3.4. Final vulnerability index.

According to MIVES methodology, the sensitiveness and the adaptive capacity value is obtained by the addition of the criteria values multiplied by their respective weight. Furthermore, in a normal situation, the final vulnerability index will be given by subtracting the index of adaptive capacity from the index of sensitiveness, as sensitiveness is a negative parameter and the adaptive capacity is a positive one, the vulnerability index indicating a higher vulnerability of the building.

However, as low sensitive elements can have a low adaptative capacity and are more vulnerable than high sensitive elements with a high adaptative capacity, the previous linear calculation procedure is insufficient. Therefore, the calculation is adapted following the approach generally used in climate-change contexts, by dividing various ranges for the sensitiveness (S) and adaptive capacity (AC) indexes. The ranges are based on the work by Kleinfelder [66], which modifies the qualitative ICLEI proposal and are used to calculate the vulnerability (V) level. Table 1 shows the sensitiveness and the adaptative indexes and then the resulting six vulnerability levels according to a colour scale (V0 is the least vulnerable and V5 is the most vulnerable) based on the proposal in [67]. Highest vulnerability corresponds to categories which showed highest sensitiveness values and lowest adaptative capacity values, while lowest vulnerability corresponds to categories which showed low sensitiveness values and high adaptive capacity values.

Table 1: Levels of sensitivity, adaptive capacity and vulnerability.

		SENSITIVITY				
		S0 S0≤0.10	**S1** 0.10<S1≤0.40	**S2** 0.40<S2≤0.60	**S3** 0.60<S3≤0.90	**S4** 0.90<S4≤1.00
ADAPTIVE CAPACITY	**AC0** AC0≤0.33	**V2**	**V3**	**V4**	**V5**	**V5**
	AC1 0.33<AC1≤0.75	**V1**	**V1**	**V2**	**V3**	**V4**
	AC2 0.75<AC2≤1.00	**V0**	**V0**	**V0**	**V1**	**V2**

4.Multiscale data model creation: the case study of Donostia-San Sebastián

4.1. <u>Model definition</u>

The vulnerability assessment methodology was implemented in four districts of Donostia-San Sebastián (northern Spain): Centre, Gross, Egia, Alde zaharra (Old part) situated in front of the sea and next to the boundaries of the Urumea river (see Figure 7).

As previously stated, the CityGML data model was used in this research work. It combines the necessary geometric and semantic data. Firstly, the geometric model of the city was created in an efficient and semi-automatic way [68] with the data from the land registry linked with, LiDAR and the Digital Terrain Model to map the height and the altitude of each building. Secondly, the semantic data organized by the six parameters identified for the building categorization were introduced in an automatic way through a semantic process, so as to establish categories and select sample buildings. In order to define the right number of categories for the building stock under analysis, a statistical overview of the parameters was carried out, discarding those representing less than 2% of the overall building stock analysed, as explained in section 3.1. The analysis led to the selection of the following four parameters out of a possible six: the use, level of protection, existence of a basement, and status. Additionally, 1950 was selected as the limit to distinguish between historic and new buildings, mainly due to construction singularities. These parameters led to the definition of 15 categories, representing around the 80% of the stock and in consequence, 15reference buildings representing each category.

Figure 7: Categorization of the reference buildings in the four districts in Donostia-San Sebastián.

Thirdly, the model was completed with the introduction of the indicator values, in order to calculate the vulnerability index for each reference building, and then to extrapolate the result to all buildings of the same category, achieving the vulnerability of the studied area.

Table 2: Vulnerability value for each reference building.

CATEGORY	SENSITIVITY INDEX		ADAPTATIVE CAP. INDEX		VULNERABILITY INDEX
1	0.64	S3	0.22	A0	**V5**
2	0.70	S3	0.32	A1	**V3**
3	0.75	S3	0.35	A1	**V3**
4	0.75	S3	0.21	A0	**V5**
5	0.73	S3	0.29	A0	**V5**
6	0.67	S3	0.24	A0	**V5**
7	0.72	S3	0.22	A0	**V5**
8	0.50	S2	0.35	A1	**V2**
9	0.50	S2	0.22	A0	**V4**
10	0.65	S3	0.35	A1	**V3**
11	0.67	S3	0.46	A1	**V3**
12	0.82	S3	0.60	A1	**V3**
13	0.79	S3	0.48	A1	**V3**
14	0.79	S3	0.61	A1	**V3**
15	0.79	S3	0.47	A1	**V3**

Table 2 shows the sensitiveness and the adaptative capacity indexes according to the criteria established in Table 1. Figure 8 shows the graphical representation of the vulnerability of the studied area. Buildings in no category that represent less than 2% of the overall building stock are coloured in white.

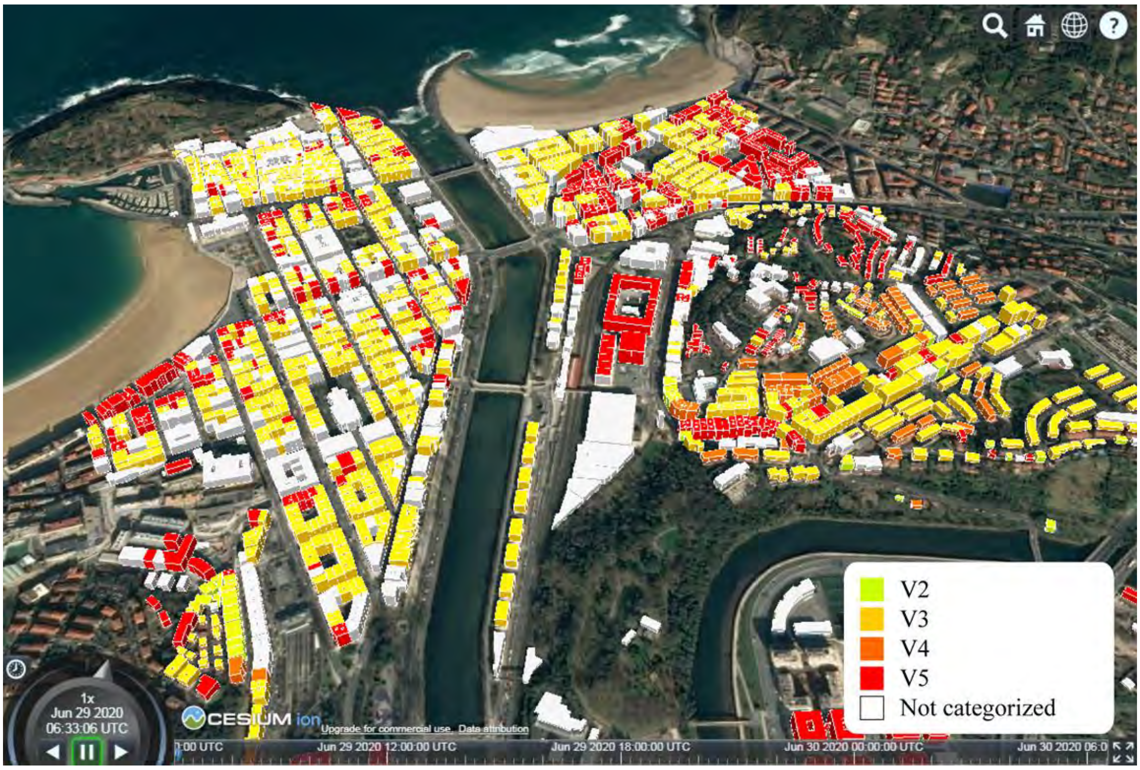

Figure 8: Vulnerability modelling of the districts of Alde zaharra, Centre, Egia, and Gross.

Some blocks from the district of Gross and Alde zaharra were analysed in detail, in order to validate the results. In total, engineers and architects carried out onsite inspections of 83 buildings, to collect data for the indicators. A technical datasheet prepared for this purpose in advance was filled in. The vulnerability index was then determined in the office. The following data shows a comparison between the vulnerability value provided by the data model using building categories and onsite inspections.

Of the 83 buildings that were analysed, only 3 of them presented (3.6%) the vulnerability level obtained from the building categorizations, which more often than not differed from the level obtained by onsite inspections (see Appendix A), mainly due to variations in the adaptative capacity level. This discrepancy was because many adaptation measures are not updated in the public open-data sources, and because some buildings have less homogeneous characteristics than the category under analysis.

5. Conclusions

This research work has presented a vulnerability assessment methodology to facilitate decision-making in case of flooding and extreme precipitation events in cities, with a special focus on the identification of cultural heritage values aimed at integrating the procedure into a wider framework of climate change adaptation plans and policies.

The approach is based on a multicriteria analysis with an integrated and holistic perspective following MIVES methodology. With it, all the available data are organized in a structured way and used to evaluate different indicators, criteria and requirements in an objective manner, based on a value analysis. The methodological approach demonstrated a successful balance between the accuracy of the results and necessary resources for the assessment.

The data modelling tool CityGML can be used to combine geometric and semantic data, facilitating the management of big data, as well as providing graphical representations to support decision-making for sustainable development.

As demonstrated in the case study, the success of the methodology is its balanced identification of proper, traceable, and effective indicators, and its accurate results, which make possible its replication in other cities and countries with similar characteristics and issues. Furthermore, when large numbers of buildings in an extended area need to be analysed, the use of the building categorization strategy has shown that it is an effective approach to scale the vulnerability index of a sample of reference buildings to the whole study area.

Finally, the inclusion of the multi-stakeholder perspective within the methodology ensures and enhance the interdisciplinary work of the agents involved in the climate change, urban planning and cultural heritage fields. The next step to ensure the adequate management of the impact of flooding and extreme precipitation events, in the built environment, is the identification of potential risks through the consideration of climate change scenarios. This further step will subsequently allow the design of effective adaptive solutions. An adequate selection of effective, low carbon and compatible solutions with the built environment will minimize the risk and lead to a sustainable conservation of our cities.

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Appendix A:

Comparison of the sensitiveness, adaptative capacity, and vulnerability levels given by real data obtained through onsite inspections and the building characterization data model

CATEGORY	REF.*	SENSITIVENESS		ADAPTATIVE CAPACITY		VULNERABILITY	
		INSPECTION	CATEGORIES	INSPECTION	CATEGORIES	INSPECTION	CATEGORIES

12	8297159	S3	S3	A1	A1	V3	V3
12	8297001	S3	S3	A1	A1	V3	V3
12	8297002	S3	S3	A1	A1	V3	V3
12	8297003	S3	S3	A1	A1	V3	V3
12	8297004	S3	S3	A1	A1	V3	V3
12	8297005	S3	S3	A1	A1	V3	V3
12	8297006	S3	S3	A1	A1	V3	V3
12	8297007	S3	S3	A1	A1	V3	V3
12	8297008	S3	S3	A1	A1	V3	V3
12	8297009	S3	S3	A1	A1	V3	V3
12	8297010	S3	S3	A1	A1	V3	V3
12	8297011	S3	S3	A1	A1	V3	V3
12	8297013	S3	S3	A1	A1	V3	V3
12	8297014	S3	S3	A1	A1	V3	V3
12	8297015	S3	S3	A1	A1	V3	V3
12	8297017	S3	S3	A1	A1	V3	V3
12	8297018	S3	S3	A1	A1	V3	V3
12	8297020	S3	S3	A1	A1	V3	V3
6	8297021	S3	S3	A1	A0	V3	V5
12	8297024	S3	S3	A1	A1	V3	V3
12	8297032	S3	S3	A1	A1	V3	V3
12	8297034	S3	S3	A1	A1	V3	V3
12	8297035	S3	S3	A1	A1	V3	V3
12	8297044	S3	S3	A0	A1	V5	V3
12	8297045	S3	S3	A1	A1	V3	V3
12	8297046	S3	S3	A1	A1	V3	V3
12	8297047	S3	S3	A1	A1	V3	V3
12	8297082	S3	S3	A1	A1	V3	V3
6	8297117	S3	S3	A0	A0	V5	V5
14	8297166	S3	S3	A1	A1	V3	V3
14	8297168	S3	S3	A1	A1	V3	V3
14	8297169	S3	S3	A1	A1	V3	V3
14	8297171	S3	S3	A1	A1	V3	V3
5	8297172	S3	S3	A0	A0	V5	V5
12	8297173	S3	S3	A1	A1	V3	V3
12	8297174	S3	S3	A1	A1	V3	V3
12	8297175	S3	S3	A1	A1	V3	V3
12	8297176	S3	S3	A1	A1	V3	V3
12	8297177	S3	S3	A1	A1	V3	V3
12	8297178	S3	S3	A1	A1	V3	V3
12	8297186	S3	S3	A1	A1	V3	V3
14	8297193	S3	S3	A1	A1	V3	V3
14	8297194	S3	S3	A1	A1	V3	V3
14	8297195	S3	S3	A1	A1	V3	V3

14	8297197	S3	S3	A1	A1	V3	V3
12	8297199	S3	S3	A1	A1	V3	V3
12	8297201	S3	S3	A1	A1	V3	V3
14	8297202	S3	S3	A1	A1	V3	V3
14	8297204	S2	S3	A1	A1	V2	V3
6	8297205	S3	S3	A0	A0	**V5**	**V5**
12	8297212	S3	S3	A1	A1	V3	V3
12	8297575	S3	S3	A1	A1	V3	V3
12	8297579	S3	S3	A1	A1	V3	V3
12	8297584	S3	S3	A1	A1	V3	V3
12	8297585	S3	S3	A1	A1	V3	V3
12	8297586	S3	S3	A1	A1	V3	V3
12	8297587	S3	S3	A1	A1	V3	V3
12	8297588	S3	S3	A1	A1	V3	V3
12	8297590	S3	S3	A1	A1	V3	V3
12	8297603	S3	S3	A1	A1	V3	V3
12	8397200	S3	S3	A1	A1	V3	V3
12	8397242	S3	S3	A1	A1	V3	V3
12	8397337	S3	S3	A1	A1	V3	V3
12	8397338	S3	S3	A1	A1	V3	V3
12	8397339	S3	S3	A1	A1	V3	V3
12	8397340	S3	S3	A1	A1	V3	V3
12	8397341	S3	S3	A1	A1	V3	V3
14	8397365	S3	S3	A1	A1	V3	V3
12	8397366	S3	S3	A1	A1	V3	V3
12	8397367	S3	S3	A1	A1	V3	V3
14	8397369	S3	S3	A1	A1	V3	V3
14	8397377	S3	S3	A1	A1	V3	V3
12	8397380	S3	S3	A1	A1	V3	V3
12	8397383	S3	S3	A1	A1	V3	V3
12	8397384	S3	S3	A1	A1	V3	V3
12	8397389	S3	S3	A1	A1	V3	V3
12	8397390	S3	S3	A1	A1	V3	V3
12	8397716	S3	S3	A1	A1	V3	V3
12	8397717	S3	S3	A1	A1	V3	V3
12	8397718	S3	S3	A1	A1	V3	V3
12	8397719	S3	S3	A1	A1	V3	V3
12	8397720	S3	S3	A1	A1	V3	V3
12	8397728	S3	S3	A1	A1	V3	V3

REF: refers to the numbering of the buildings used in the CityGML model.

Figure 1: Requirement tree and formulation for calculating the Value Index in MIVES methodology (Source: Adapted from [52])

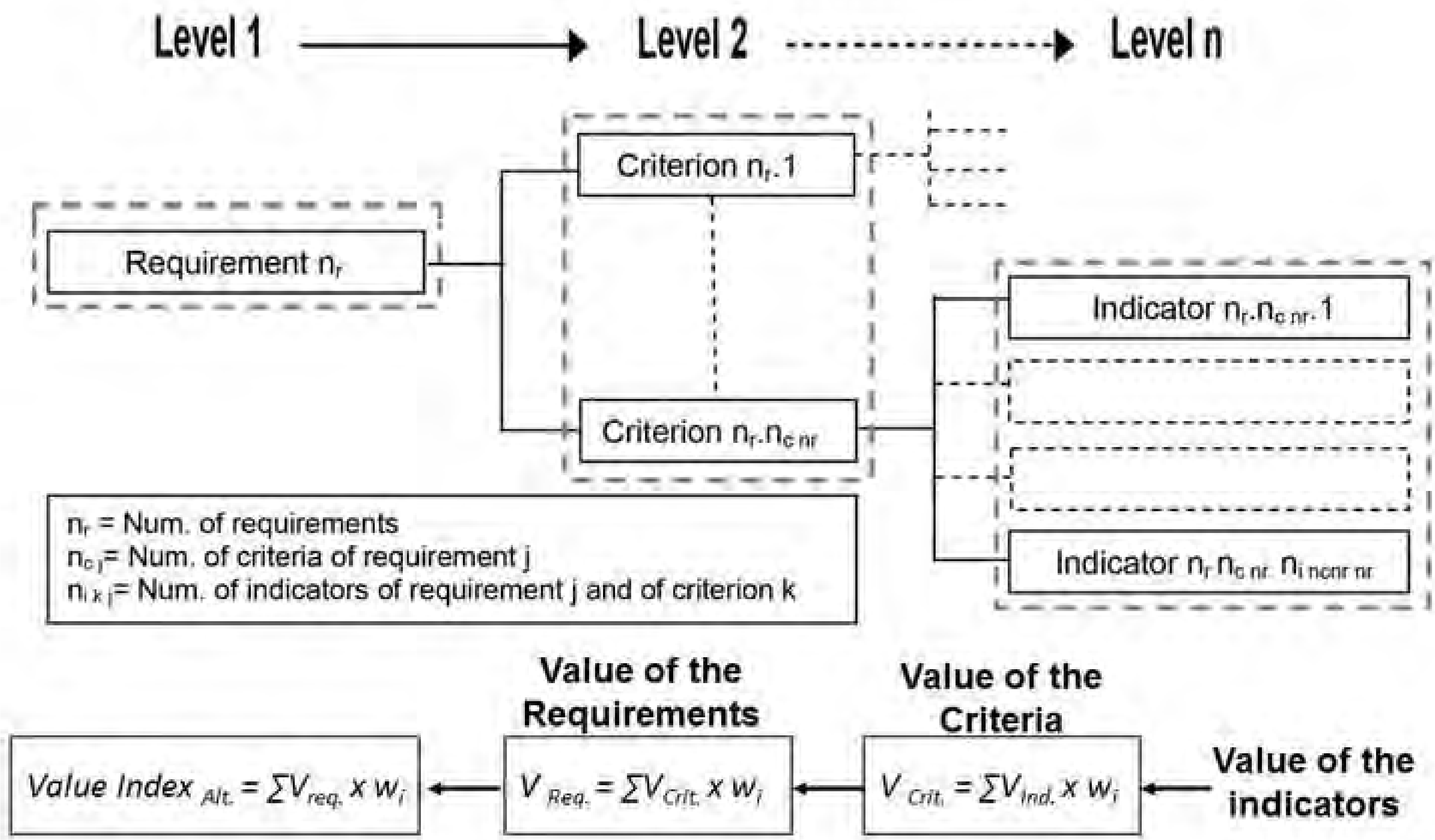


Figure 2: Vulnerability assessment decision tree. In brackets, the method used to obtain the value of the indicator.

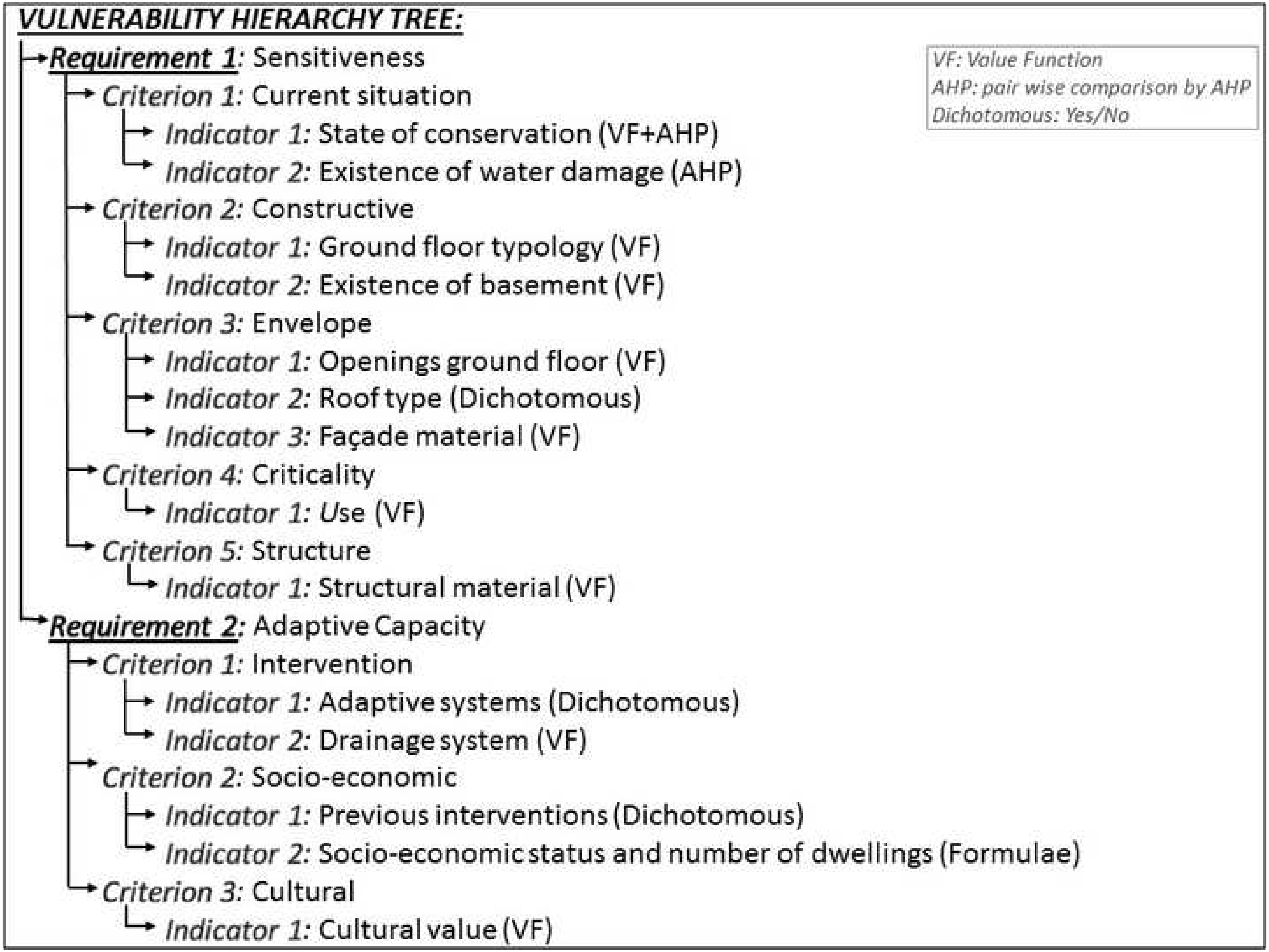
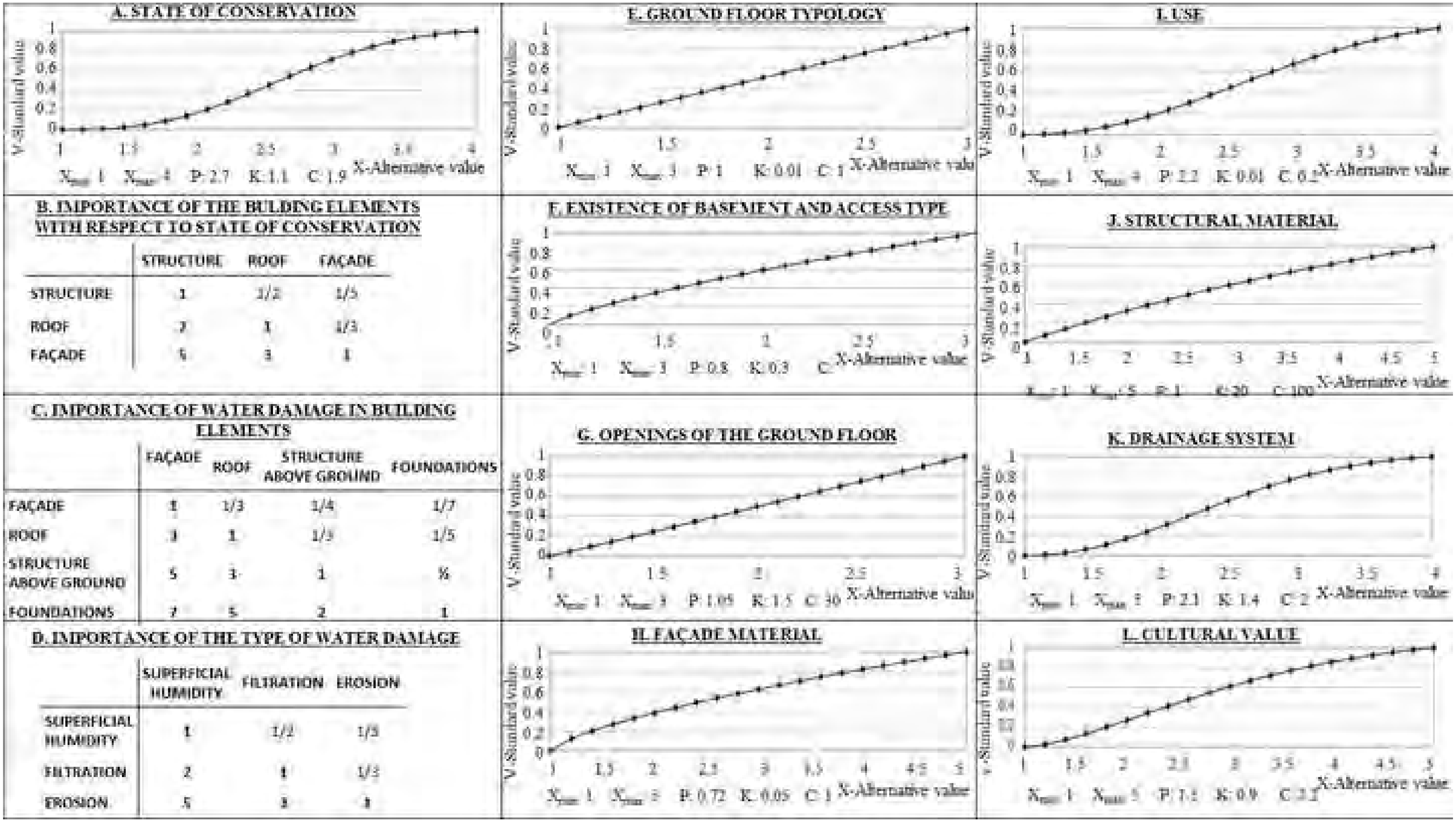


Figure 3: Assessment of the indicator alternatives. Value functions and comparison matrixes.



B. IMPORTANCE OF THE BULDING ELEMENTS WITH RESPECT TO STATE OF CONSERVATION

	STRUCTURE	ROOF	FAÇADE
STRUCTURE	1	1/2	1/5
ROOF	2	1	1/3
FAÇADE	5	3	1

C. IMPORTANCE OF WATER DAMAGE IN BUILDING ELEMENTS

	FAÇADE	ROOF	STRUCTURE ABOVE GROUND	FOUNDATIONS
FAÇADE	1	1/3	1/4	1/7
ROOF	3	1	1/3	1/5
STRUCTURE ABOVE GROUND	5	3	1	½
FOUNDATIONS	7	5	2	1

D. IMPORTANCE OF THE TYPE OF WATER DAMAGE

	SUPERFICIAL HUMIDITY	FILTRATION	EROSION
SUPERFICIAL HUMIDITY	1	1/2	1/5
FILTRATION	2	1	1/3
EROSION	5	3	1

Figure 4: Indicator weight assignments for sensitiveness (left) and adaptative capacity (right) from the comparison matrixes and their consistency validation.

Click here to access/download;Figure;Figure 4.png

CURRENT SITUATION

	STATE OF CONSERVATION	EXISTENCE OF WATER DAMAGE	WEIGHTS AHP
STATE OF CONSERVATION	1	1	0.50
EXISTENCE OF WATER DAMAGE	1	1	0.50

CONSTRUCTIVE

	GROUND FLOOR TYPOLOGY	EXISTENCE OF BASEMENT	WEIGHTS AHP
GROUND FLOOR TYPOLOGY	1	1/2	0.33
EXISTENCE OF BASEMENT	2	1	0.67

ENVELOPE

	NUMBER OF OPENINGS	ROOF TYPE	FAÇADE MATERIAL	WEIGHTS AHP
NUMBER OF OPENINGS	1	2	2	0.50
ROOF TYPE	1/2	1	1	0.25
FAÇADE MATERIAL	1/2	1	1	0.25

INTERVENTIONS

	EXISTENCE OF ADAPTIVE SYST.	DRAINAGE SYST. CONDITION	WEIGHTS AHP
EXISTENCE OF ADAPTIVE SYST.	1	1.50	0.60
DRAINAGE SYSTEM CONDITION	0.67	1	0.40

SOCIO ECONOMIC

	PREVIOUS INTERVENTIONS	NUM. DWELLING & ECONOMIC STATUS	WEIGHTS AHP
PREVIOUS INTERVENTIONS	1	1/2	0.33
NUM. DWELLING & ECONOMIC STATUS	2	1	0.67

Figure 5: Sensitiveness and adaptive capacity criterion weight assignments from comparison matrixes and their consistency validation.

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SENTSITIVENESS

	CURRENT SITUATION	CONSTRUCTIVE	ENVELOPE	CRITICALITY	STRUCTURAL MATERIAL	WEIGHTS AHP
CURRENT SITUATION	1	1/4	1/6	1/7	1/2	0.05
CONSTRUCTIVE	4	1	1/2	1/3	3	0.18
ENVELOPE	6	2	1	2	3	0.32
CRITICALITY	7	3	1	1	3	0.35
STRUCTURAL MATERIAL	2	1/3	1/3	1/3	1	0.10

ADAPTIVE CAPACITY

	INTERVENTIONS	SOCIO-ECONOMIC	CULTURAL	WEIGHTS AHP
INTERVENTIONS	1	1	1/2	0.26
SOCIO-ECONOMIC	1	1	1	0.33
CULTURAL	2	1	1	0.41

Figure 6: Value of requirements, criteria, and indicators of the vulnerability decision tree. Click here to access/download;Figure;Figure 6.png

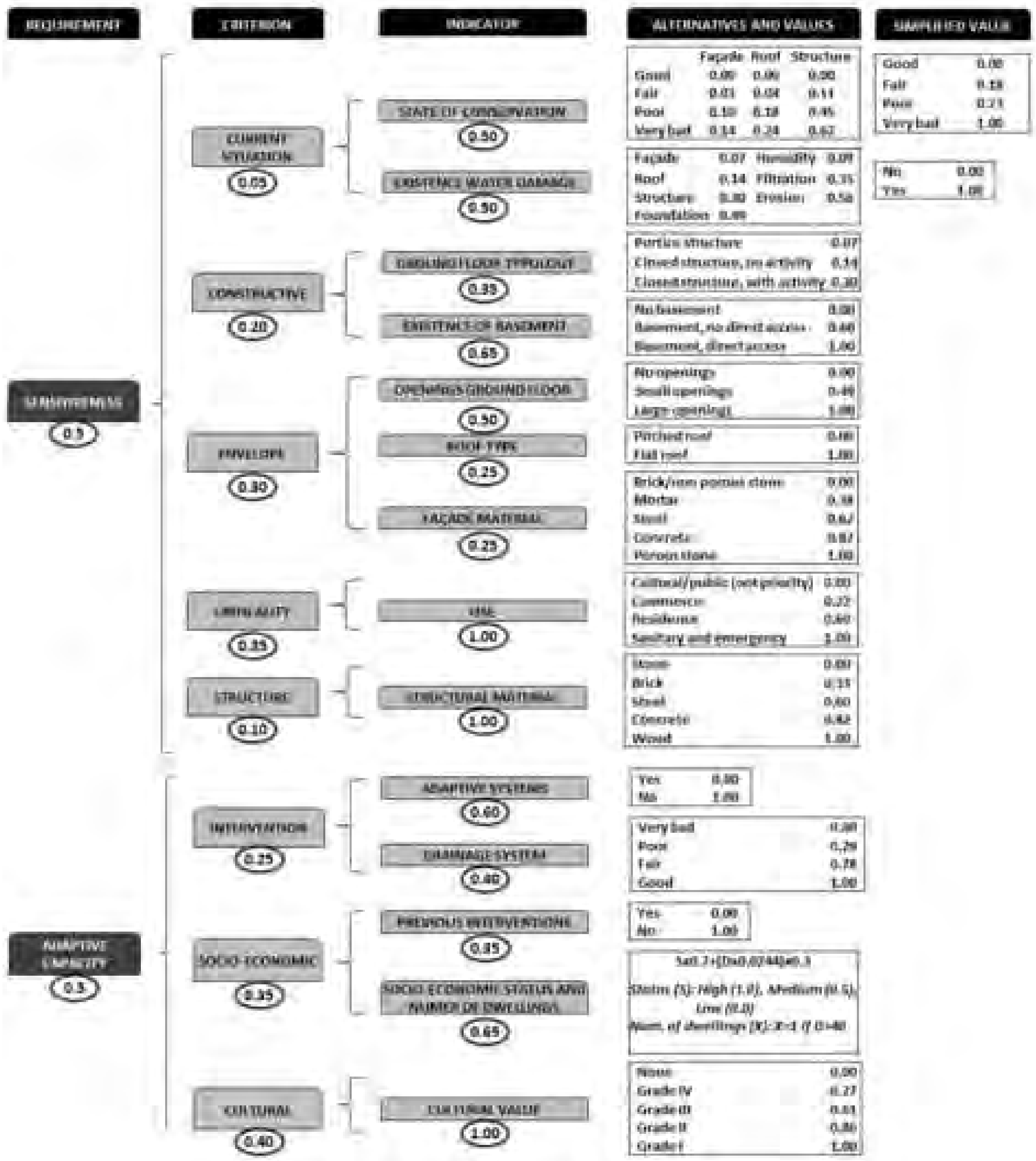

Figure 7: Categorization of the reference buildings in the four districts in Donostia-San Sebastián.

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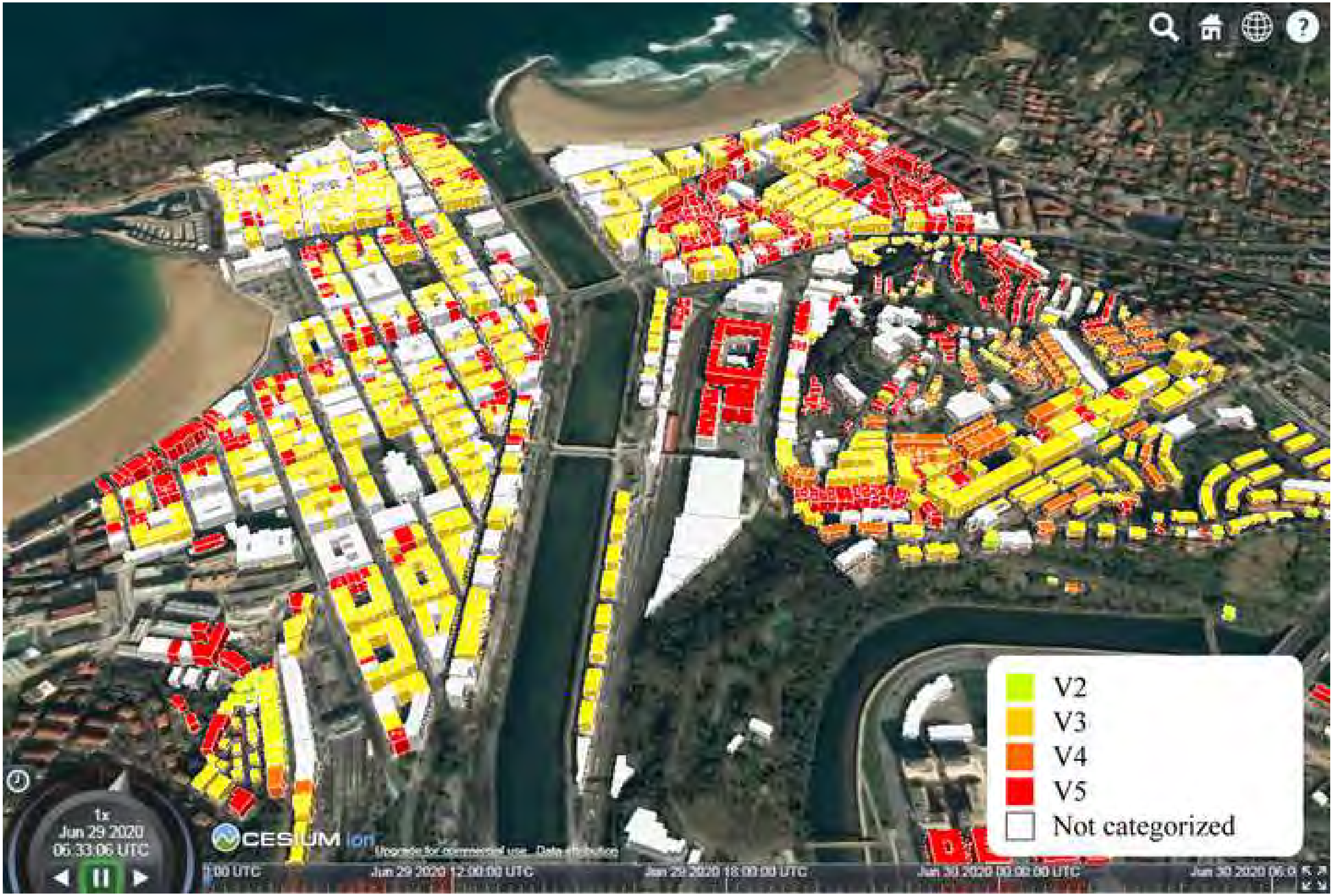
Figure 8: Vulnerability modelling of the districts of Alde zaharra, Centre, Egia, and Gross.

Click here to access/download;Figure;Figure 8.JPG



Authorship & Conflicts of Interest Statement

Manuscript title: A holistic and multi-stakeholder methodology for vulnerability assessment of cities to flooding and extreme precipitation events

AUTHORSHIP

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication.

In the table below, indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., Y.L. Chang) to the submitted manuscript. A check mark (÷) must appear against the name of each author at least once in each of the three categories below.

Author name	**Category 1**			**Category 2**	**Category 3**
	Conception and design of study	*Acquisition of data (laboratory or clinical)*	*Data analysis and/or interpretation*	*Drafting of manuscript and/or critical revision*	*Approval of final version of manuscript*
EXAMPLE: Y.L. Chang	÷		÷	÷	÷
A. Gandini	x		x	x	x
L. Garmendia	x		x	x	x
I. Prieto		x	x	x	x
I. Álvarez		x	x	x	x
J.T. San-José	x		x	x	x

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