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Vulnerability assessment of cultural heritage sites towards flooding events

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Abstract. Historic sites are threatened by diverse weather patterns, mainly due to global climate change, such as sea-level rise and increasing frequency of storms and other extreme precipitation events. As climate change is becoming an increasing urban problem, heritage located in this context is considered as a sensitive and vulnerable element of the city. Adaptation should be oriented to a sustainable transformation of the historic city, leading to more resilient and safe environments. Risk-based approaches should incorporate an assessment of sensitiveness and capacity to adapt to these hazards. Vulnerability is often assessed on a large scale (e.g. regional, local) and buildings are not considered as part of the urban environment, while conservation is often developed on the operational scale of a monument or site. Management of cultural heritage requires therefore for an urban approach, which considers all the elements and buildings as part of the urban environment. Research presented in this paper describes a methodological approach (MIVES - Integrated Value Model for Sustainability Assessment) for vulnerability assessment of historic sites, supported by multilevel indicators (urban, building, element), in order to provide an informed decision-making. The solution proposed in based on an organised and structures decision tree, which provides a comparable and unique vulnerability index on the building level.

1. Introduction

Climate change adaptation, disaster risk reduction and cultural heritage preservation respond to the objectives of urban sustainable development [1] and aim at giving priority to people's quality of life improvement. Even if the topics are related to different fields of knowledge and competences, sustainable development can be reached only through a holistic approach, which considers all transformations and processes of change. In this context, the Sendai Framework [2] discusses the importance of understanding disaster risk, in all of its dimensions of vulnerability, adaptive capacity and

exposure through the systematic evaluation of disaster losses and cultural heritage impacts, among others, in the context of event-specific hazard-exposure and vulnerability information.

The implementation of strategies related to cities' sustainable development, is a practice based on evidence based decision-making and information management. Data availability on the city level has been increasing in the last decades, leading to the development of diverse approaches. From one hand those requiring for a large amount of data and delivering highly accurate results and on the other hand those based in simple data but delivering generic results. Both approaches are not suitable for the strategic level of decision-making, which requires for a balance between data collection and accuracy of results in order to be cost-effective. Information should be organized and structured in order to be comprehensive and this can be supported by the use of proper data model. When dealing with vulnerability assessment, informed decisions are of the most relevant importance as the prioritization of interventions in the pre-disaster period is crucial to raise adaptation and decrease risk.

The use of value analysis methodologies can provide objective conclusions for establishing strategic priorities, in order to overcome the barrier of involving different stakeholders, with diverse profiles and needs.

2. Scope of the research

Main objective of the research presented is to develop a methodological framework for vulnerability assessment in historic areas against flooding events, through a decision-making methodology for the prioritization of adaptive and risk reduction interventions.

The methodology developed has the objective of evaluating the potential damage to historic buildings in case of flooding, where vulnerability is appraised and quantified by indicators, values functions and algorithms which delivers a vulnerability scoring based on a unique value index. The vulnerability assessment is supported by a multiscale urban model which standardize and synchronize geographic and semantic information. The research presented is therefore linked to different domains, namely climate change adaptation, disaster risk reduction and cultural heritage preservation.

The vulnerability assessment methodology applies the MIVES (Integrated Value Model for Sustainability Assessment) method through the definition of the decision-making process, the establishment of the information strategy for data acquirement and the development of a set of indicators sustained by the use of objective and justified calculation models.

Research is aligned with current scientific and political commitments, as climate change adaptation gains relevance and sets a new and emerging concern for public administrations. Some well-known organizations such as the European Commission, the United Nations, the World Bank, the IPCC, and UNESCO consider climate change impacts on urban areas as one of the strategic priorities which must be discussed internationally, leading to the launch of several initiatives at the local level [3], [4].

3. Methodological approach

Decision-making related to climate change adaptation at urban level should be based on an informed and evidence-based strategy implementation, especially if carried out on historic buildings. A building vulnerability assessment method is therefore the first step to be addressed. Flooding impacts should be determined in terms of the intrinsic conditions as well as social aspects of the area or building considered, as their characteristics makes them more susceptible to the effects of climate change or more capable of coping with them.

To be effective and in order to provide a solid basis for political and technical commitment, the method should find a balance between resources consume and results accuracy. Cities generate a large amount of heterogeneous data, at different scales, in different formats, and for different uses [5]. Many of these data can be used to determine to what extend a building is vulnerable to the effects of climate change, through the creation of representative typologies, by organising the building stock in categories with similar constructive elements and characteristics.

Once the building stock is organised and structured in a manageable number of categories, the value analysis method is applied and vulnerabilities are compared by using a unique index, thereby facilitating

the prioritisation of interventions in a specific area or building of the historic city and providing greater objectivity in decision-making.

The vulnerability assessment method proposed in this research has been applied to the case study of San Sebastian and it was supported by the use of an interoperable and multi-scalar data model, which had the objective of organising required data and providing a visual understanding of results.

3.1. Building stock categorization

Vulnerability is mainly obtained by using macro-scale information, which results in the determination of which area is more vulnerable with respect to another one. On contrary, information needed to obtain a building diagnosis, is performed on a micro-scale, using a one by one approach through field surveys. When assessing the vulnerability of cultural heritage located in urban areas, it is important to define which buildings are more vulnerable in order to provide and define which adaptation measures are required. The micro-scale approach is often too expensive and time consuming for local governments and thus a balance between the two approaches should be seek. The compromise can be found by modelling the historic city through a statistical distribution of the buildings characteristics in a determined area, starting from the sample concept [6].

Information available from public sources and information systems is grouped according to the building characteristics, creating a limited number of samples [7], which reflect almost the entire building stock. These groups should reflect the flooding vulnerabilities, the historic value and the constructive characteristics of the buildings. A second and more detailed level of information is collected for sample buildings and vulnerability calculated. Results are then extrapolated to other buildings within the same category, thereby obtaining an overall vulnerability assessment for the whole historic district.

3.2. Integrated value model for sustainable assessment

Among the multi-criteria approaches that have been developed in the last decades [8], the Integrated Value Model for Sustainable Assessment (MIVES) has demonstrated its applicability in diverse complex scenarios related to sustainability [9], [10].

MIVES has been developed by the Polytechnic University of Catalonia (UPC), Tecnalia and the University of the Basque Country (UPV/EHU) and combines two different concepts, the Multi-Criteria Decision-making Theory and Value Engineering [11]. The model is used to compare and give equality to variables with different units of measurements, either quantitative or qualitative, by providing a dimensionless unit. The relative importance of the aspects considered is taken into account, giving as a result a unique and comparable index. As the methodology establishes the evaluation prior to the generation of alternatives, subjectivity in the decision-making is avoided [12].

4. Decision-making process

MIVES established different steps for the methodology, which are the following:

- Definition of the problem and decision to be taken;
- Definition of the requirements tree though the establishment of the information hierarchy;
- Set of the value functions which transforms all the aspects considered in a variable with values comprised between 0 and 1;
- Assignment of weights to compare the importance of one aspect compared to another one;
- Evaluation of the alternatives to obtain the value index.

Buildings, located in urban areas which are subject to climate change impacts, play an important role in the selection of the adaptive measures, which can be implemented in both the urban as well as building level. Knowing their vulnerability, in an objective way, is essential for the strategic planning approach.

4.1. The vulnerability assessment requirement tree

The requirements tree for heritage buildings vulnerability assessment has been built considering the connection with other disciplines, such as climate change adaptation and considers as main

requirements, elements which traditionally compose vulnerability: sensitiveness and adaptive capacity [13].

The requirements tree proposed follows a hierarchical structure based on three levels: requirements, criteria, and indicators. In the first levels, namely the requirements and criteria, general and qualitative aspects are defined, while in the last level, the indicators, concrete and measurable aspects are considered.

The sensitiveness requirement has the objective of assessing the degree to which a building is affected by an event. Depending on the conditions, typology and characteristics of the structure that is considered, its response to climate impacts varies. Criteria related to this requirement are therefore associated to the current state of the building, constructive critical elements, envelope characteristics, main use, and structural material.

The requirement of adaptive capacity refers to the ability of a system to assume the potential effects of an event, overcoming its consequences. In this case, criteria refer to interventions, socio-economic conditions and the cultural value of the buildings.

The requirement tree proposed is therefore defined by two requirements, eight criteria and fourteen indicators, as presented in the following Figure.
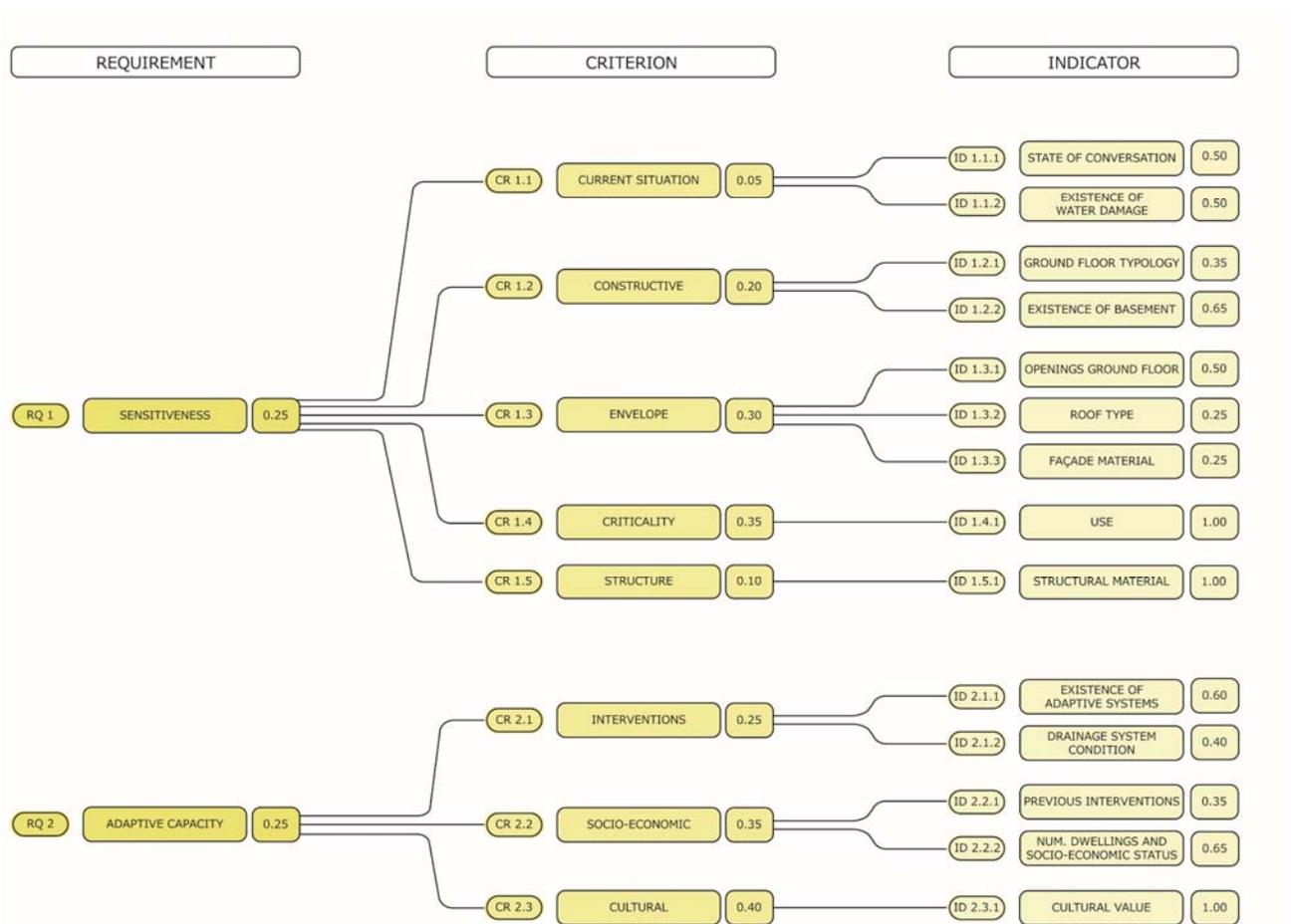

Figure 1. Requirements tree and overall weighting for the vulnerability assessment

Weights have been assigned by member of an expert panel, starting from the calculation of the γ weights of the indicators, followed by the β weights of the criteria, and lastly by the α weights of the requirements. Weight assignment is performed by comparing elements at the same level and in the same

branch of the requirements tree. Thus, the indicator weights are calculated according to other indicators belonging to the same criterion. In the same manner, a criterion weight is calculated by other criteria belonging to the same requirement.

Requirements, criteria and indicators have the objective of representing what we want to evaluate, avoiding the repetition of certain aspects or avoiding the use aspects which are out of scope. Indicators selected should therefore be representative, differentiating, complementary, relative, quantifiable and traceable [14].

Analytic Hierarchy Process (AHP) [15] was used for the weights assignment, by establishing the relative importance of each branch of the requirements tree. An adjustment was made of the final results, considering the opinion of each member of the expert panel.

4.2. Indicators value functions

Indicators are of different nature and present diverse units of measure. The different variables can be transformed into comparable and dimensionless units through the use of value functions, resulting in a value comprised between 0 and 1. Different value functions (concave, convex, linear, S-shaped) have been used for this purpose, where the vertical axis represents the minimum (0) or the maximum (1) level of satisfaction and the abscissa represents the variable of the indicator.
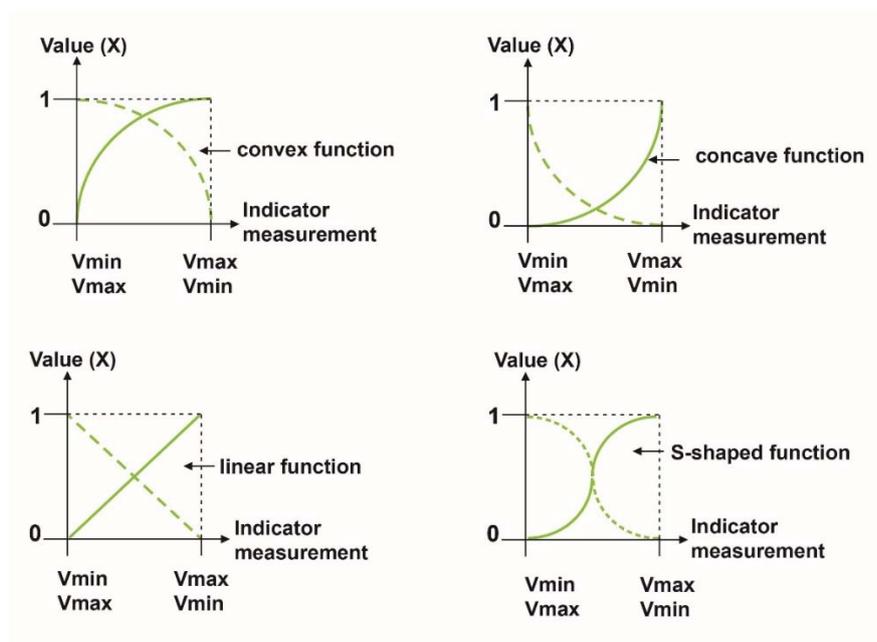

Figure 2. Different shapes of the value functions. Source:[16]

MIVES use the following equation as a mathematical model, in order to define the different value functions of each indicator,

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

Where,

V_{ind} is the value of the indicator under evaluation.

B is a factor that allows the function to remain within the range from 0 to 1. It is assumed that the highest level of satisfaction has a value of 1.

For each indicator a value function has been created, to evaluate the different alternatives. In cases where the value function was not clear, it was defined by a working group. The following Figure shows the indicators selected for the vulnerability assessment and their relative values:

INDICATOR CODE	INDICATOR MEANING	VALUE MEANING	VALUE
ID 1.1.1	STATE OF CONSERVATION	GOOD	0.00
		FAIR	0.18
		POOR	0.73
		VERY BAD	1.00
ID 1.1.2	EXISTENCE OF WATER DAMAGE	NO EXISTING WATER DAMAGE ON THE BUILDING	0.00
		PRESENCE OF WATER DAMAGE ON THE BUILDING	1.00
ID 1.2.1	GROUND FLOOR TYPOLOGY	PORTICO STRUCTURE	0.00
		CLOSED STRUCTURE WITH NO ACTIVITY	0.50
		CLOSED STRUCTURE WITH ACTIVITY	1.00
ID 1.2.2	EXISTENCE OF BASEMENT	NO BASEMENT NOR SEMI-BASEMENT	0.00
		EXISTENCE OF BASEMENT OR SEMI-BASEMENT	1.00
ID 1.3.1	OPENINGS GROUND FLOOR	NO OPENINGS	0.00
		SMALL OPENINGS	0.49
		LARGE OPENINGS	1.00
ID 1.3.2	ROOF TYPE	PITCHED	0.00
		FLAT	1.00
ID 1.3.3	FAÇADE MATERIAL	BRICK/NON POROUS STONE	0.00
		MORTAR	0.38
		STEEL	0.62
		CONCRETE	0.82
		POROUS STONE	1.00
ID 1.4.1	USE	CULTURAL CENTRES, PUBLIC EQUIPMENT WITHOUT PRIORITY USE	0.00
		COMMERCE	0.22
		RESIDENCE	0.69
		EMERGENCY AND SANITARY	1.00
ID 1.5.1	STRUCTURAL MATERIAL	STONE	0.00
		BRICK	0.33
		STEEL	0.60
		CONCRETE	0.82
		WOOD	1.00
ID 2.1.1	EXISTENCE OF ADAPTIVE SYSTEMS	EXISTENCE OF ADAPTIVE SYSTEMS	1.00
		ABSENCE OF ADAPTIVE SYSTEMS	0.00
ID 2.1.2	DRAINAGE SYSTEM CONDITION	GOOD	1.00
		FAIR	0.78
		POOR	0.29
		VERY BAD	0.00
ID 2.2.1	PREVIOUS INTERVENTIONS	PREVIOUS INTERVENTIONS	1.00
		NO INTERVENTIONS MADE	0.00
ID 2.2.2	NUM. OF DWELLINGS AND SOCIO-ECONOMIC STATUS	X DWELLINGS, Y AVERAGE STATUS	Y*0.7+(X*0.0244)*0.3
ID 2.3.1	CULTURAL VALUE	GRADE I	1.00
		GRADE II	0.86
		GRADE III	0.61
		GRADE IV	0.27
		NONE	0.00

Figure 3. Values attached to each alternative of the sensitiveness and adaptive capacity indicators

5. Implementation

The methodological approach was applied to the city of San Sebastian, located on the northern coast of Spain. The area selected comprises 6 districts, each with its different characteristics, situated next to the boundaries of the Urumea river. The geometry of the 3D urban model was generated using the CityGML standard [17] and semantic properties for the categorization process added, as referenced in the Spanish cadaster. Following the statistical overview of the study area, it was considered that use, level of protection, existence of a basement and socio-economic status had to be taken into account, with regard to all their variables, as primary parameters and the threshold of minimum representation was established at 2%. The categorization process lead to a generation of 15 categories, representing the 76% of the total building stock. Sample buildings were then selected according to the representativeness of

the parameters compared to the whole category and the availability of relevant information and semantic information completed and extrapolated to the whole category. As a result, the vulnerability index was calculated according to the values assigned to the variables of each indicator and the weights attached to each branch of the requirement tree.
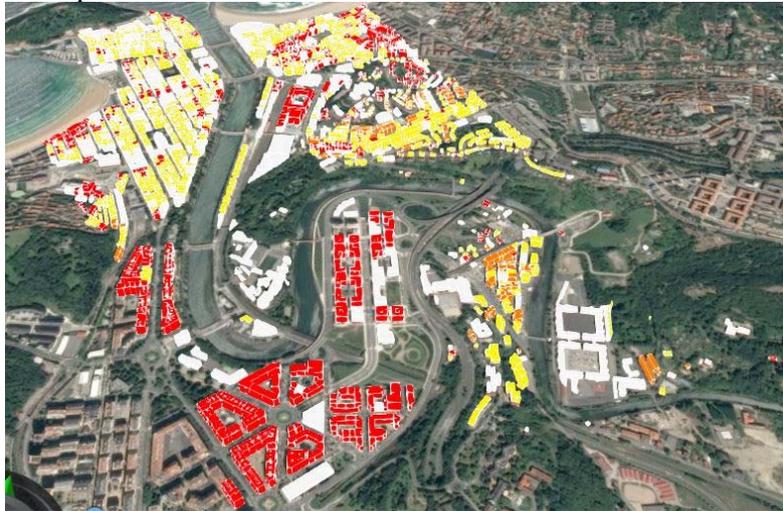

Figure 4. Graphical representation of the lots' vulnerabilities

In order to verify the accuracy of the results of the methodology proposed, a survey campaign was carried out on 100 buildings with the objective of comparing results given by real data and the categorization method. The margin of error resulted in a 9% and the largest difference was appreciated in one of the districts, which is mainly characterized by single-family houses of diverse characteristics, while the methodology shows its highest potential on districts which have been characterized by a smooth development and present similarities.

6. Conclusions

In vulnerability assessment of historic buildings towards flooding, decision-making is a complex process in which several disciplines and interests intervene, leading to a difficult exercise of comparison and evaluation. Local governments are more and more keen to have accurate results with the minimum efforts. A balance among data acquisition and accuracy of results to include the relevant information in a unique model or platform is essential for the decision-making process. Furthermore, multiple criteria decision analysis (MCDA) process helps decision-maker in improving the objectivity and quality of results by providing a systemic and organised way of thinking. Research proposed has established a hierarchic structure based on a requirements tree, in order to provide decision-making with an objective intervention priority index, in which the characteristics of the vulnerability assessment are defined, displayed and organized. A method for the fine-tuning of the methodology, on the one hand, considering the sensitiveness index and, on the other hand, the adaptive capacity index, has been established, providing vulnerability levels defined by these parameters.

7. Acknowledgements

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