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Social vulnerability assessment to seismic risk using multicriteria analysis: the case study of Vila Franca do Campo (São Miguel Island, Azores, Portugal)

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Abstract The increase in the frequency and magnitude of disasters triggered by earthquakes in different regions of the Earth is a major challenge to contemporary societies. The awareness that disasters and risk are processes structured on spatial–temporal interactions maintained at the social-ecological system between the natural hazards and the vulnerabilities of socioeconomic, political and physical nature becomes utterly important in the increase of social systems' resilience. Thus, the assessment of social vulnerability plays a decisive role in understanding the factors that distinguishes individuals, households and communities, in terms of their ability to anticipate, cope with, resist to and recover from the impact of disasters triggered by natural hazards. This article presents a geographic information system (GIS)-based approach model to assess the social vulnerability to seismic risk using multicriteria analysis (MCA) techniques, in a group decision-making process. The methodology applied to the municipality of Vila Franca do Campo (São Miguel Island, Azores, Portugal) identified moderate social vulnerability values at the neighbourhood level and higher social vulnerability values for the built environment and demographic characteristics of the social groups. The social vulnerability patterns make a clear distinction between the older/historical urban cores and the new urban areas. In the first case, the presence of ancient buildings constructed with materials of low resistance to earthquakes coupled with a higher population density and the traits of demographic and socioeconomic frailties of the social groups, results in higher vulnerability values. This pattern is common in the historic centre of S. Miguel district, Ribeira das Taínhas, northern areas of Água de Alto and western and eastern neighbourhoods of Ponta Garça. The new

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urban areas, mainly found in S. Pedro, central areas of Água de Alto, S. Miguel and Ponta Garça districts, have lower values of social vulnerability due to changes in the built, demographic and socioeconomic environments. Results recommend the integration of social vulnerability indexes into seismic risk mitigation policies and emergency management planning.

Keywords GIS · Multicriteria analysis · Social vulnerability assessment · Seismic risk

1 Introduction: theory and aim

The Earth's surface is abundant in the occurrence of hazardous phenomena with natural genesis. Their location, frequency and magnitude may impact the regular behaviour of social systems. There is, at least since the mid-twentieth century, a trend towards an increase in human loss, structural damage and social disruption as the consequence of disasters triggered by natural hazards (Renaud et al. 2010). The confrontation with such trend, jointly with the awareness of the unnaturalness of its causes, is at the basis of the questioning of dominant geophysical paradigm whose approach stands on one-dimensional physicalist conceptualizations of disaster (Hewitt 1983). Population growth, rapid urbanisation and massive occupation of hazardous areas are amongst the most common and visible human causes of recurrence of extreme events (Blaikie et al. 1994; Hewitt 1997; Bankoff 2004).

Indeed, disasters 'are multidimensional, all-encompassing occurrences that sweep across every aspect of human life' (Oliver-Smith 2004) and widely surpass the idiosyncrasies of physical environment. They outcome from the spatial–temporal interaction between natural hazards and vulnerabilities coupled to individuals and communities, which emerge and are reproduced in the socioeconomic, political, cultural and technological environments (Blaikie et al. 1994; Cardona 2004; Hilhorst and Bankoff 2004; Rodriguez and Russell 2006). Within this subject, one considers risk as the potential loss of elements or exposed systems, which results from the 'complex combination of vulnerability and hazard' (Blaikie et al. 1994).

Vulnerability is the key term in redefining two of the concepts considered previously—disaster and risk (Birkmann 2006). There are multiple definitions of vulnerability proposed by institutions (UNDP 2004; UNDRO 1982; UN/ISDR 2004) and authors (Blaikie et al. 1994; Watts and Bohle 1993; Turner et al. 2003; Cardona 2004; Adger 2005). In this article, vulnerability is considered 'as the susceptibility to experiencing negative outcomes as a consequence of a hazard event and reflects an individual's, community's, or a society's capacity, to prepare for, respond to, and recover from a disaster' (Wisner et al. 2004; Rodriguez and Russell 2006).

Social vulnerability is an outcome 'from the activity and circumstances of everyday life or its transformations' (Hewitt 1997; Cutter et al. 2000). According to Cutter et al. (2000), social vulnerability is based in several susceptibilities of the individuals, like the 'lack of access to resources, including information and well-being; limited access to political power and representation; certain beliefs and customs; weak buildings; infrastructures and lifelines'. Nevertheless, vulnerability is not exclusively related with individuals' inherent fragilities, but rather comprises others fragilities, namely the material form of a given place (Hewitt 1997; Morrow 1999; Cutter et al. 2000). Therefore, social vulnerability is constituted within an 'intrasocietal' realm (Rodriguez and Russell 2006), incorporating demographic, socioeconomic, political, cultural, institutional and physical factors, such as age, gender, race, disability, ethnicity, social class, type of occupation, unemployment rate, dependency on one single economic sector, immigrant status, political ideology, density and quality of built environment, land-use, housing tenancy, family and the presence of informal support networks. (Wisner and Luce 1993; Blaikie et al. 1994; Davidson 1997; Morrow 1999; Cutter et al. 2003; Dwyer et al. 2004).

Great part of the research on social vulnerability has been directed to the development of methods or quantitative techniques with the ability to translate an abstract concept into a practical tool. Cutter et al. (2003) proposed a Social Vulnerability Index for the United States by using social and economic vulnerability indicators, mapping highest vulnerability indexes in East and South Texas counties, and in the Mississippi Delta region. Kuhlicke et al. (2011) assessed the social vulnerability with quantitative and qualitative data, in three case studies linked to floods (Germany, Italy and U.K.), remarking that vulnerability is much a result of the socioeconomic, demographic, cultural and institutional context. Armas (2008) proposed a Normalised Composed Index to study the correlation between social vulnerability and the seismic risk perception in the historic centre of the municipality of Bucharest (Romania).

This article proposes a model of social vulnerability to seismic risk assessment using MCA techniques applied to the municipality of Vila Franca do Campo, located in the southern coast of S. Miguel island (Azores Archipelago, Portugal). The methodology was selected due to four reasons. First, it is a method oriented towards decision-making processes and the assessment of social vulnerability calls for risk management policies (Birkmann 2006). Second, through a group decision-making process, it is possible to understand the traces of social vulnerability in the study area, avoiding the processing of statistical data based exclusively in taxonomic methods, which revealed ‘pitfalls’ in previous studies (Kuhlicke et al. 2011). Third, it includes techniques that allow the hierarchical structuring of the conceptual understanding of the social vulnerability, the estimation of the criteria weights that define the social vulnerability to seismic risk and their aggregation with fuzzy operators. Fourth, as discussed by Rashed and Weeks (2003), the introduction of fuzzy logic operators in the vulnerability assessment considers uncertainty and imprecision as intrinsic components of vulnerability models becoming the ideal principle, and with the greater consistency, to deal with the uncertainty of such processes. The social vulnerability assessment is developed at the neighbourhood level, allowing the analysis of social vulnerability in three different spatial scales: inter-districts, intra-districts and municipality. The model is implemented through a group decision-making process, given the theoretical and practical decisions made throughout the different stages of MCA involved the three researchers of the project ‘Risk Governance: the case of seismic risk in Azores’ (Martins 2010; Silva et al. 2011).

In this article, two main objectives are aimed: (1) to assess social vulnerability through a group decision-making process, which will guide and structure the modelling process with all relevant theoretical aspects and avoiding a pure statistical approach and (2) to provide a method oriented to support risk reduction, allowing the mapping of social vulnerability at the neighbourhood level providing support for risk mitigation policies and emergency management planning.

2 Social vulnerability in the framework of seismic risk

The social vulnerability concept has been implemented in multiple forms. Common approaches include indicators of demographic order, more specifically age and gender, as well as socioeconomic, built environment and seismic hazard exposure dimensions (Cutter et al. 2000; Dwyer et al. 2004; Wisner et al. 2004; Bolin 2006; Enarson et al. 2006).

Groups located at both ends of the age spectrum are consensually referred as potentially more vulnerable. Such increased vulnerability may occur due to circumstances of potential dependency from others (Wisner and Luce 1993; Cutter et al. 2003; Dwyer et al. 2004). Particularly regarding elderly people, characteristics related with mobility constraints and greater dependency of the welfare state and the lack of informal support, networks (family, neighbours, friends) might negatively interfere both on the coping capacity and the post-disaster recovery (Cutter et al. 2000; Cutter et al. 2003). In young people, vulnerability 'is self-evident, especially those who lack adequate family support' (Morrow 1999). The condition of women is consensually referred to conferring potential vulnerability. This is especially evident on contexts where women paths of life are marked by deficits of integration in labour market or social roles that may convert into lower capacity to resist or recover from natural extremes (Wisner and Luce 1993; Blaikie et al. 1994; Enarson et al. 2006). Regarding the family structure, single-parent households and large households are pointed out as potentially more vulnerable when coupled with fragile socioeconomic conditions that obstruct them generating enough resources to support their dependents members (Morrow 1999; Cutter et al. 2003).

Indicators coupled with the socioeconomic dimension are key elements for the analysis of social vulnerability. Persons and households with more resources will have, a priori, a higher capacity to select and invest in safer housing solutions (Hewitt 1997; Morrow 1999; Cutter et al. 2000; Dwyer et al. 2004; Wisner et al. 2004). Socioeconomic status may be patterned by several indicators, including income, the type of occupation and the unemployment rate (Cutter et al. 2003; Dwyer et al. 2004). These indicators determine the resistance and recovery capacity of individuals to economic and structural damage induced by seismic events. Nevertheless, it is important to highlight that socioeconomic status is usually coupled to the individuals' education level (Wisner and Luce 1993; Morrow 1999; Cutter et al. 2000; Wisner et al. 2004; Armas 2008). Individuals with higher education levels have, in theory, better and more professional opportunities and, like so, may progress in their socioeconomic status (Morrow 1999; Cutter et al. 2003; Armas 2008). Besides, lower education levels may jeopardise 'the ability to understand warning information and access to recovery information' (Cutter et al. 2003).

Earthquakes are a major threat to human life due to the collapse of built structures. In effect, the built environment is the primary cause of damage and disruption of social life (Hewitt 1997). The most common indicators associated with this dimension are building construction year, type of building structure, quality of construction, number of floors, type of occupancy, roof cover, the occupancy rate and the density of adjacent buildings (Hewitt 1997; Sousa 2006; Afonso 2010; Martinelli et al. 2008; Sarris et al. 2009). The year of construction is a capital element as it allows the determination of the type of construction and materials in a certain area. Concerning the function of buildings, residential buildings are most commonly point out as more vulnerable because there is a greater chance of being occupied by residents during a seismic event (depending on the period of the day during which it occurs). Legal status towards housing is also considered, with renters being classified as potentially more vulnerable. They have, by principle, less freedom to invest on seismic rehabilitation of their own, by comparison with property owners (Morrow 1999; Cutter et al. 2003), and are more prone to post-disaster housing market inflationary surges.

The evaluation of social vulnerability to seismic risk is indissoluble from exposure to seismic hazard on the part of the elements at risk, and in this respect, one may consider the resident population, volume of buildings and housing (Davidson 1997; Sousa 2006).

A smaller or larger proportion of elements at risk is usually a challenge to emergency management planning. The land-use is an indicator that conditions the degree of vulnerability to seismic risk, given that densely built areas may hamper emergency operations (search and rescue; medical emergency), whilst dispersedly populated areas can be isolated in case of great damages to communication and transportation infrastructures (Morrow 1999; Cutter et al. 2003).

2.1 Case study: the municipality of Vila Franca do Campo

The Azores archipelago (Fig. 1) is located in the North Atlantic Ocean, in the Macaronesian biogeographical region, at a distance of 1,450 km from mainland Portugal. The archipelago is constituted by nine volcanic islands, alongside a NW–SE orientation with 600 km, and are assembled in three groups: Eastern group (Santa Maria and São Miguel islands), Central group (Terceira, Graciosa, São Jorge, Pico and Faial islands) and Western group (Flores and Corvo islands).

The municipality of Vila Franca do Campo is located at the island of S. Miguel, between parallels 37°42′–37°47′ N latitude and the meridian 25°20′–25°29′ W longitude (Fig. 1). With a territory of 77.9 km^2, the municipality is divided in 6 districts: Água de Alto, Ponta Garça, Ribeira das Taínhas, S. Miguel, S. Pedro and Ribeira Seca. Nevertheless, it is important to refer that on 2001, Ribeira Seca was not considered a district yet.

The Azorean people have, since archipelago’s settlement in fifteenth century, a long history of cohabitation with seismic risk. Historical records allow an estimation of the number of casualties caused by earthquakes on the archipelago: between 5,345 and 6,350 individuals, causing massive destructions in built structures and cyclical shakes in Azorean social structures (Nunes 2008). The most catastrophic event witnessed in the Azores, the earthquake of 22nd October 1522, infamously hit Vila Franca do Campo. This earthquake triggered a landslide, which hit the village existing at that time, causing 4,000–5,000

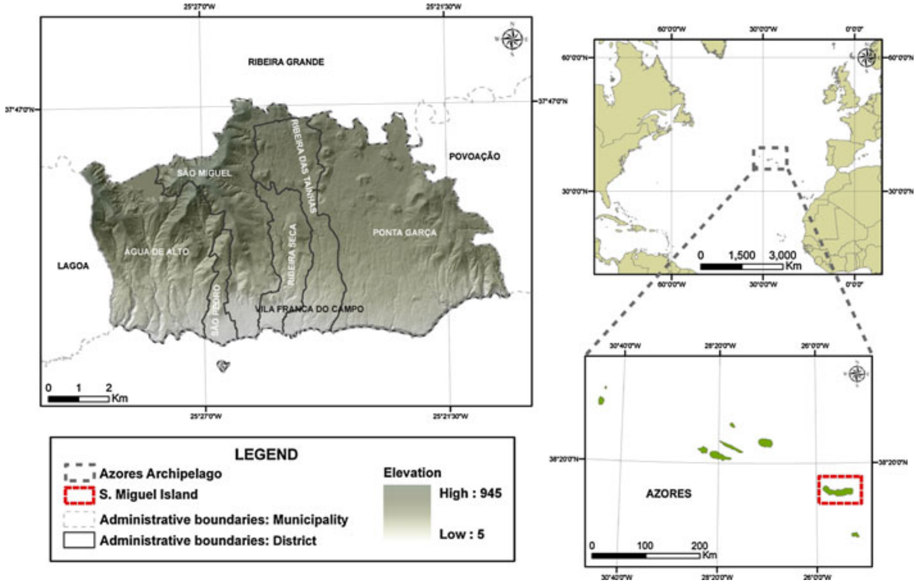

Fig. 1 General location of the study area

casualties. Since then, the municipality suffered five more disaster episodes, as a consequence of the earthquakes of 1591, 1852, 1932, 1935 and 1952 (Nunes et al. 2004). Nevertheless, these events caused no human losses, only material damages.

The municipality of Vila Franca do Campo has some important social vulnerability traits. Demographically, there was a high proportion of young (<14-year-old) population (24.7%) residing in the municipality in 2001. The elderly (>65-year-old) population is less representative (11.7%), although the percentage increased between census 1991 and census 2001 (variation rate 13.1%). Large households are dominant in the municipality, 41.0% of households have 3 or 4 elements, whilst those composed by 5 or more elements represent a proportion of 32%. The districts of Ponta Garça (77.1%), S. Pedro (75.4%) and Ribeira das Taínhas (75.0%) have the leading percentage of households with 3 or more individuals.

Regarding the socioeconomic condition, the rate of potential dependency in Vila Franca do Campo was at 82.5% in 2001, although some districts had bigger dependency rates: Ponta Garça (83.2%), S. Pedro (82.7%) and S. Miguel (82.5%). Illiteracy rates were 15.6% on the municipality, but Ponta Garça (18.6%), Ribeira das Taínhas (15.8%) districts presented even higher values. It is worthwhile mentioning that there was a high percentage of the population residing on the municipality with only elementary school (57.0%) and only a sparse percentage of people with graduate education levels (4.6%). On these two indicators, Água de Alto, Ribeira das Taínhas and Ponta Garça have low education levels when compared to S. Miguel and S. Pedro.

In the built environment, it is noteworthy that, in 2001, 60.0% of the constructions had 40 or more years. The districts of Água de Alto (53.1%), Ribeira das Taínhas (52.3%) and Ponta Garça (50.3%) have the highest percentages of old buildings ($\geq$50 years), whilst S. Pedro (50.0%) and S. Miguel (45.8%) have a higher proportion of more recent buildings ($\leq$30 years). Within the municipality in 2001, only 42.7% of the buildings had reinforced concrete structures, whilst 42.1% had masonry/mortared structures and 5.2% were of adobe, rammed earth or stone masonry structures. These two types of building solutions, which theoretically imply greater vulnerability, are common in Ponta Garça (60.4%), Ribeira das Taínhas (48.5%) and S. Miguel (47.9%).

3 Methodology

3.1 The multicriteria evaluation approach

The assessment of social vulnerability to seismic risk is carried out using MCA, a method composed of techniques that support the decision-making process based on multiple criteria (Voogd 1983). Decision-making processes are based on theoretical assumptions with considerable uncertainty and subjectivity (Eakin and Bojorquez-Tapia 2008), and in this context, MCA incorporates techniques that allow to structure in the theoretical principles and operational dimension, the vulnerability models which support the decision-making processes.

At this stage, it is important to define the key concepts associated with MCA. *Criterion* is a means of judgment or rules that test the degree of appropriateness of the different alternatives to the decision process, being structured in *objectives* and *attributes* (Hansen 2005). *Objectives* describe the condition of a system, being related and/or derived from *attributes* and indicating which *objectives* are essential for the decision process (Malczewski 1999). The optimisation of the *objective* happens with the definition of a set of *attributes*, given that these characterise the proprieties of the process being assessed (in this case, social vulnerability). Attributes are normally classified in two groups: *factors* and *restrictions*. *Factors* are social vulnerability *attributes* that are considered in the assessment process and reflect the variation of the vulnerability of a given *objective* of the model. *Restrictions* are *exclusionary factors* when aggregate the alternatives.

The assessment of social vulnerability with MCA is a methodological process structured in four stages: (1) hierarchical structure of the social vulnerability model, (2) standardisation of *criteria*, (3) *criteria* weighting and (4) decision rules. The first phase includes the layout of the hierarchical structure of the social vulnerability model, defining their *objectives* and *factors*. The next phase aims to standardise the numerical scale of social vulnerability *factors* into a common scale, using fuzzy set membership functions. According to Malczewski (1999), a fuzzy set is ‘a category of elements or objects that have no clearly defined boundaries between those objects which belong to a class and those who do not belong, allowing an object to belong simultaneously to multiple sets’. During the third stage, the relative weight of the social vulnerability *criterion* is estimated. The decision rule, the fourth stage of MCA, consists in aggregating the social vulnerability *criteria*, in this case, using an ordered weighted average (OWA). This technique allows relating the typical fuzzy aggregation operators, such as intersection and union, with the order weighted average combinations (Malczewski 1999).

3.2 Hierarchical structure of the social vulnerability model

The hierarchical structure of the proposed model results from the examination of relevant literature, which allowed the identification of *criteria* that reflect the multidimensional concept of social vulnerability to seismic risk. Statistical data from the Portuguese Census of Population and Housing 2001 (INE 2001) and land-use data (Martins 2010) were used to define the hierarchical structure.

The model of social vulnerability to seismic risk is hierarchically structured in three disaggregation levels (Fig. 2). The 1st level comprises the four *objectives* that allow the multidimensional assessment of social vulnerability: demography, socioeconomic, built environment, seismic hazard exposure (Wisner and Luce 1993; Blaikie et al. 1994; Davidson 1997; Hewitt 1997; Morrow 1999; Cutter et al. 2000, 2003; Dwyer et al. 2004; Bolin 2006; Armas 2008; Martinelli et al. 2008; Sarris et al. 2009).

The 2nd level of the demography *objective* considers age structure, gender, family structure and population density (inh/ha). The 3rd level of the age structure is divided into three categories, to differentiate the levels of vulnerability between age groups (Wisner and Luce 1993; Cutter et al. 2003). The same procedure is applied regarding gender, by distinguishing the vulnerability between genders (Blaikie et al. 1994; Enarson et al. 2006). Concerning family structure, the 3rd level distinguishes the households according to the number of elements, allowing to measure the vulnerability of households according to the number of dependent members (Morrow 1999; Cutter et al. 2003). Population density is a continuous variable, and for this reason, it does not have a 3rd level of hierarchy, given the possibility to associate the values to the vulnerability scale during the standardisation phase.

The socioeconomic vulnerability is assessed in four 2nd level *factors*: social dependency rate, illiteracy rate, level of education and unemployment rate. The level of education *factor* is divided into three 3rd level categories, enabling to scale the vulnerability according the highest education level of the population (Cutter et al. 2003; Armas 2008). The remaining *factors* comprise continuous values, and for this reason, it does not have a 3rd level of disaggregation.

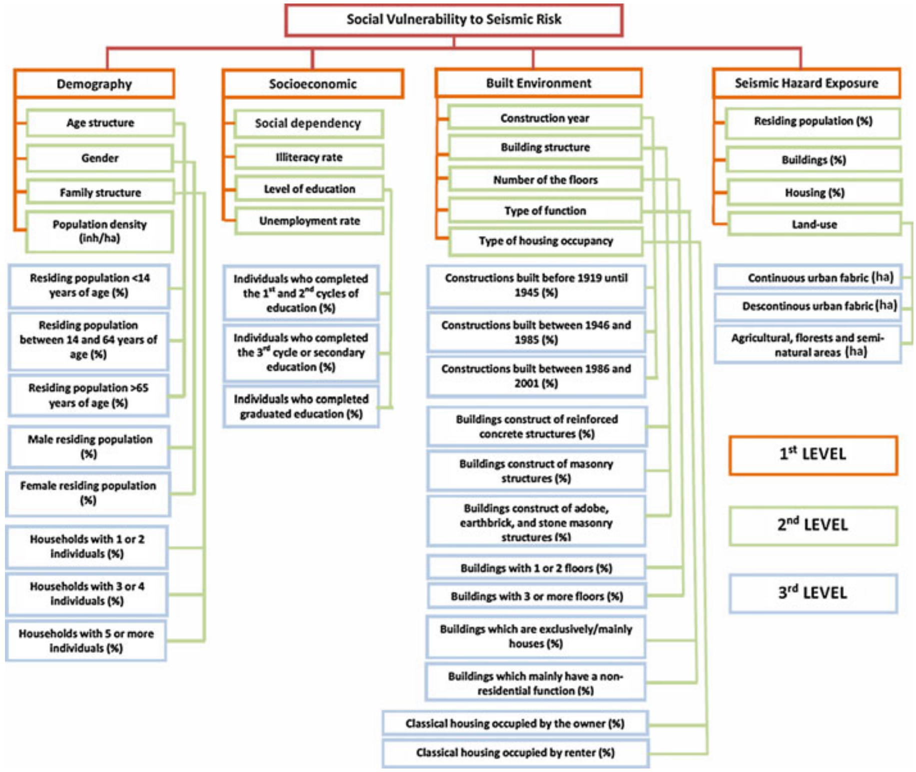

Fig. 2 Hierarchical structure of the social vulnerability model

The vulnerability associated with the built environment is evaluated by five *factors:* construction year, building structure, number of the floors, type of function and type of housing occupancy. As far as the year of construction is concerned, three 3rd level categories are proposed (Fig. 2), associating the age of the building to a lesser or greater vulnerability (Teramo et al. 2005; Sarris et al. 2009). The structure of construction *factor* makes the distinction between the types of material used in the construction of the building, since the materials have different resistance to the travelling of seismic waves, and thus, different indexes of vulnerability (Hewitt 1997; Sarris et al. 2009; Martinelli et al. 2008). The number of floors distinguishes the proportion of buildings with one or two floors from those that have 3 or more floors, whilst the 3rd level of the buildings function distinguishes exclusively/mainly residential buildings from non-residential buildings (Cutter et al. 2000). Finally, the type of occupancy of buildings differentiates, in the 3rd level, owners from renters (Morrow 1999; Cutter et al. 2003).

Seismic hazard exposure incorporates three 2nd level *factors*: resident population, buildings and housing (Davidson 1997; Sousa 2006). These *factors* are continuous values and, therefore, may be directly associated with vulnerability scale during the standardisation stage. Land-use is structured into three 3rd level categories, since the density of urban settlements represents different vulnerabilities to natural hazards (Cutter et al. 2003). Land-use maps production was based on visual interpretation of orthophotomaps of year 2005. The extraction of land-use data followed the technical specifications defined by the Corine Land Cover programme (EEA 2000). These included, for a 3rd level nomenclature, the definition of a minimum mapping unit of 2 ha and a reference scale of 1:5,000. In the modelling process, one needs to *exclude* neighbourhoods without population or buildings from the social vulnerability assessment, in order to prevent result bias. Therefore, 45 of the 235 neighbourhoods of Vila Franca do Campo were excluded.

3.3 Standardisation of social vulnerability criteria

The standardisation of *criteria* values is required because they usually have different measurement scales. Re-scaling the *criteria* is also needed for the decision rules stage. This process is similar to the process of fuzzification, introduced by fuzzy logic, according to which, a set of *criteria* values in a certain scale is converted into another comparable, expressing a fuzzy standardised scale of values (Eastman 2006). The results will indicate the ‘relative degree of belonging (membership) to a set, ranging from 0.0 to 1.0, indicating a continuous growth from not belonging up to total belonging’ (Hansen 2005). Within this framework, the vulnerability *criteria* data sets were standardised using a fuzzy membership function. Then, an 8 byte scale (0–255) transformation was developed in order to optimise the radiometric spectrum of the raster data (Kienberger et al. 2009). In this fuzzy standardised scale, 0 corresponds to total absence of vulnerability and 255 represent the total presence of vulnerability.

The *factors* that generated the hierarchy within the social vulnerability model were standardised through a linear fuzzy set membership function, in which the vulnerability varied linearly between minimum and maximum values in the scale for each *factor*. This prevented the introduction of abrupt changes in the vulnerability values of each *factor*, decreasing the likelihood of error propagation within the model. It is possible to distinguish the *factors* that were standardised by the standardisation function (Table 1), with an increasing or decreasing type, according to the direction of the vulnerability variation within a given *factor*. As an example, regarding the proportion of buildings constructed between 1986 and 2001, which are theoretically less vulnerable, a decreasing function was applied, since the maximum vulnerability happens to the proportion of 0%, the value from which vulnerability starts to decrease being minimum in the proportion of 100%. In the percentage of construction built before 1919 until 1945, theoretically with greatest vulnerability, the function’s form is increasing, given that vulnerability increases from the minimal value of 0% and achieves maximum value at 100%.

3.4 Criteria weights estimation

A challenge in decision-making processes involving multiple *criteria* is how to measure the relative importance of each *criterion* amongst a group of *criteria*, besides being necessary to consider that they reflect different levels of significance to the decision-makers (Eastman 2006). Thus, assigning weights to each *criterion* is a key step in the decision process, aiming to determine and distinguish the relative importance of each one. MCA incorporates different methods for the estimation of *criteria* weight; however, an option was made by the method developed by Saaty (1980), the analytical hierarchy process (AHP). This method allows the management of the subjectivity of the judgment associated with the estimation weighting of the vulnerability *factors*, thus diminishing the uncertainty and error associated with the assessment process (Eakin and Bojorquez-Tapia 2008).

The AHP method depends on the construction of a comparison matrix to evaluate *criteria*, according to the relative importance of the pairwise of *factors* being estimated (Valente and Vettorazzi 2005; Eastman 2006). The calculus of the *criteria* weight is

Table 1 Vulnerability *criteria*, type of the standardisation function and *criteria* weights

Hierarchy level	Vulnerability criteria	Type of the standardisation function	Weights
1st	Demography		
2nd	Age structure		(0.3210)
3rd	Residing population <14 years of age (%)	Increasing	0.4545
3rd	Residing population between 14 and 64 years of age (%)	Decreasing	0.0909
3rd	Residing population >65 years of age (%)	Increasing	0.4545
2nd	Gender		(0.0736)
3rd	Male residing population (%)	Decreasing	0.2890
3rd	Female residing population (%)	Increasing	0.7110
2nd	Family structure	Increasing	(0.3210)
3rd	Households with 1 or 2 individuals (%)	Increasing	0.4286
3rd	Households with 3 or 4 individuals (%)	Increasing	0.1429
3rd	Households with 5 or more individuals (%)	Increasing	0.4286
2nd	Population density (inh/ha)		(0.2845)
1st	Socioeconomic		
2nd	Social dependency rate	Increasing	(0.2085)
2nd	Illiteracy rate	Increasing	(0.4874)
2nd	Level of education		(0.0956)
3rd	Individuals who completed the 1st and 2nd cycles of education (%)	Increasing	0.6370
3rd	Individuals who completed the 3rd cycle or secondary education (%)	Decreasing	0.2583
3rd	Individuals who completed graduated education (%)	Decreasing	0.1047
2nd	Unemployment rate	Increasing	(0.2085)
1st	Built environment		
2nd	Construction year		(0.2364)
3rd	Constructions built before 1919 until 1945 (%)	Increasing	0.6370
3rd	Constructions built between 1946 and 1985 (%)	Increasing	0.2583
3rd	Constructions built between 1986 and 2001 (%)	Decreasing	0.1047
2nd	Building structure		(0.5007)
3rd	Buildings construct of reinforced concrete structures (%)	Decreasing	0.1047
3rd	Buildings construct of masonry structures (%)	Increasing	0.2583
3rd	Buildings construct of adobe, earthbrick and stone masonry structures (%)	Increasing	0.6370
2nd	Number of the floors		(0.0876)
3rd	Buildings with 1 or 2 floors (%)	Decreasing	0.3790
3rd	Buildings with 3 or more floors (%)	Increasing	0.6210
2nd	Type of function		(0.0876)
3rd	Buildings which are exclusively/mainly houses (%)	Increasing	0.6210
3rd	Buildings which mainly have a non-residential function (%)	Decreasing	0.3790
2nd	Type of housing occupancy		(0.0876)
3rd	Classical housing occupied by the owner (%)	Decreasing	0.3790
3rd	Classical housing occupied by renter (%)	Increasing	0.6210

Table 1 continued

Hierarchy level	Vulnerability criteria	Type of the standardisation function	Weights
1st	Seismic hazard exposure		
2nd	Residing population (%)	Increasing	(0.1250)
2nd	Buildings (%)	Increasing	(0.3750)
2nd	Housing (%)	Increasing	(0.1250)
2nd	Land-use		(0.3750)
3rd	Continuous urban fabric (ha)	Increasing	0.6370
3rd	Discontinuous urban fabric (ha)	Increasing	0.2583
3rd	Agricultural, florests and semi-natural areas (ha)	Decreasing	0.1047

performed by creating a hierarchy of the pairwise *factors*, using a continuous quantitative scale of 9 points in two diametrically opposed amplitudes: one amplitude of lesser importance and another one of greater importance. To ensure that the weighting of the *criteria* pairwise is not made randomly, AHP incorporates the calculus of consistency ratio that should be inferior to 0.1. Considering the hierarchical structure of the model (Fig. 2), the weight of each *criterion* was assessed according to three levels hierarchy. The 3rd level *factors* weights were estimated individually, with correspondence to the above *factors* of 2nd level (Fig. 2). The pairwise comparisons of 2nd level *factors* followed the same logic, considering each 1st level *factor* (Fig. 2).

The *criterion* weighting process was oriented by the authors judgments, considering four premises (Martins 2010): (1) the differentiation of the *criteria* relative importance considered the theoretical principles found on surveyed literature; (2) the empirical knowledge of the target area, particularly the characteristics of social vulnerability, conditioned the weights estimation; (3) factors with limited theoretical consistency, namely those that did not related the gender or family structure to economic resources, and the intrinsic subjectivity related to the weighting evaluation process, led to assign small differences in the estimation weights of the *factors* and (4) only 3rd and 2nd level *factors* were subjected to *criterion* weighting (Table 1), since there were no solid theoretical assumptions to differentiate the relative importance of the 1st level *objectives*.

3.5 Decision rules: aggregation of criteria

Decision rules comprise the stage in which social vulnerability *criteria* are aggregated using the OWA technique (Yager 1988). According to Malczewski (2006a), in a certain set of *n criterion* maps, OWA is defined as a map aggregation operator that associates with an *i*th location a set of order weights, $v = v_1, v_2, \ldots, v_n (v_j \varepsilon [0, 1], j = 1, 2, \ldots, n$ and $\sum_{j=1}^{n} vj = 1)$ and a set of *criterion* weights $w = w_1, w_2, \ldots, w_n (w_j \varepsilon [0, 1])$ and $\sum_{j=1}^{n} wj = 1$. Considering the *attributes* values $a_{i1} a_{i2}, \ldots, a_{in}$ at the *i*th location (Malczewski 2006a):

$$\mathrm{OWA}_i = \sum_{j=1}^{n} u_j z_{ij,} u_j = \frac{v_j w_{j(*)}}{\sum_{j=1}^{n} v_j w_{j(*)}}$$

where $z_{i1} \geq z_{i2} \geq \ldots \geq z_{in}$ is the order resulting from reordering the *attributes* values $a_{i1}, a_{i2}, \ldots, a_{in}$; and $w_{j(*)}$ is the reordered *j*th *criterion* weight w_j It is worthwhile to mention that *criterion* weights are reordered according to $z_{i1} \geq z_{i2} \geq \ldots \geq z_{in}$. This method aggregates social vulnerability *criteria* considering both *criterion* weights and order weights (Valente and Vettorazzi 2005; Eastman 2006; Malczewski 2006b); however, *criterion* weights define the trade-off degree amongst *criteria*, where all the locations on the jth *criterion* map are linked to the same weight of w_j order weights are connected to the *criterion* values on a location-by-location approach (Malczewski 2006a), being assigned to the ith location *attribute* in a decreasing order and not considering from which *criterion* map the values result.

The most common OWA operators to aggregate *criteria* during the evaluation process are weighted linear combination (WLC) and the Boolean overlay operations, as intersection (AND) and union (OR) (Eastman 2006), as they both allow to define the trade-off degree between *criteria* and the accepted risk (or uncertainty) within the decision strategy space (Fig. 3). Eastman (2006) states that risk adverse decisions result from the introduction of the logical AND of fuzzy sets, whereas the risk acceptance decisions occur by using the logical OR operator. Trade-off is an intermediate solution, since it allows compensating the importance of each *criterion* within the process. The weights order were defined in a group decision-making process, which was based in the fluctuation degree of ANDness/ORness (to define the risk degree) and trade-off (through WLC operator) within the decision strategy space (Eastman 2006; Malczewski 2006a) (Fig. 3).

To implement OWA into the social vulnerability assessment, six scenarios were defined (Fig. 3): (i) neutral risk, maximum trade-off; (ii) minimum risk, no trade-off; (iii) maximum risk, no trade-off; (iv) low risk, partial trade-off; (v) high risk, partial trade-off and (vi) neutral risk, partial trade-off. Scenarios ii and iv (Fig. 3) intended to simulate lower values of social vulnerability, therefore, being classified as optimistic scenarios and lower risk taking within the decision strategy space. Whilst the neutral scenarios (i and vi) aimed to set an equilibrium between *criteria* during the aggregation stage, the scenarios iii and v (Fig. 3) extrapolate the increase of social vulnerability values along the scale range, clearly representing a pessimistic scenario and higher risk taking.

Once the OWA premises were established, the social vulnerability *factors* were aggregated in three independent stages. In the first stage, the 3rd level *factors* aggregation lead to the 2nd level *factors* (with 3rd level disaggregation). The second stage aimed to aggregate the 2nd level *factors* resulting from the 3rd level aggregation process and the 2nd level *factors* that did not derived from the decision rules phase (Fig. 2), originating four 1st

Fig. 3 Location of social vulnerability scenarios within the decision strategy space

level *factors*. In the third and final stage, the four *objectives* of the 1st level were aggregated and a final social vulnerability scenario was created.

4 Results

The results discussion is centred on the aggregation levels of the *criteria.* Emphasis is given to the 2nd and 1st level aggregation operations, since they provide a comprehensive analysis of the social vulnerability focusing, respectively, in their multidimensional aspects (demographic, socioeconomic, built environment and seismic hazard exposure) and overall vulnerability. The aggregation of *criteria* results varies in a continuous scale ranging from 0 to 255 using five equal-interval classes of vulnerability (0–51: very reduced, 52–102: reduced, 103–153: moderate, 154–204: high and 205–255: very high).

In the aggregation of 3rd level factors, an option by a neutral risk and maximum trade-off scenario (Fig. 3) was made. Given that the 3rd level *factors* represent the maximum disaggregation of vulnerability *criteria*, there is a greater theoretical support to estimate *criteria* weights, whilst ensuring their relative importance. Therefore, the chosen scenario (i) establishes the maximum equilibrium between the *factors* relative importance.

Regarding the 2nd level aggregations, in demography, a high-risk scenario was admitted together with a partial trade-off between vulnerability *factors* (Fig. 3). A greater order weight to 2nd level *factors* was also considered, which already had a higher estimation weight (Table 1). It was notorious, an overvaluation of social vulnerability in scenario iii results, whilst in scenarios ii and iv, the situation was the opposite (Table 2). In the former, it occurs due to an excessive importance given to *factors* of a greater relative importance (age structure and family structure), leading to an overestimation situation. In the latter, it results from the importance given to a *factor* of reduced importance, i.e., population according to gender (Table 1).

In the socioeconomic *objective,* a high-risk and partial trade-off scenario is adopted. The greatest weight is assigned to the literacy rate, which is, in itself, the most important *factor* for the vulnerability associated with this *objective* (Table 1).

In the built environment, a high-risk and partial trade-off scenario was adopted between the vulnerability *factors*. The highest weight value was given to the most important vulnerability *factor*, in this particular case, the building structure (Table 1). Thus, partial compensations were admitted between *factors*, avoiding the overestimation (scenario iii) of vulnerability whilst giving a greater importance to *factors* that represented a higher vulnerability in this *objective* (year and materials of construction). Selecting scenarios of low or neutral risk within the decision strategy space would have lead to the reduction in social vulnerability values in this dimension (Table 2).

Regarding seismic hazard exposure, a neutral risk and partial trade-off scenario was adopted (Fig. 3). This scenario was the most indicated to represent the vulnerability of this *objective* because the *factors* had similar weights (Table 1) and the order of weights should follow the same trend, justifying the option for a neutral scenario (Table 2).

Considering the previous options, the built environment had the highest social vulnerability values within the four *objectives*. The average vulnerability is moderate (137.8) at the municipality scale, being that the neighbourhoods classified with moderate, high or very high vulnerability are located in the eastern and western area of Ponta Garça, on Ribeira das Taínhas, eastern border of S. Miguel and northern neighbourhoods of Água de Alto (Fig. 4c). In S. Pedro and central neighbourhoods of Água de Alto e S. Miguel, very reduced or reduced vulnerability values were identified (Fig. 4c). The relevance of higher

Table 2 Statistical data related to 1st level scenarios results, by social vulnerability dimensions

	Demography	Socioeconomic	Built environment	Seismic hazard exposure
Scenario i				
Minimum	5.0	9.0	47.0	35.0
Maximum	180.0	102.0	172.0	170.0
Average	97.7	39.8	76.1	90.1
Scenario ii				
Minimum	1.0	4.0	5.0	1.0
Maximum	128.0	33.0	66.0	112.0
Average	26.9	17.0	22.1	27.4
Scenario iii				
Minimum	40.0	43.0	93.0	128.0
Maximum	255.0	214.0	255.0	255.0
Average	166.7	117.8	184.1	203.1
Scenario iv				
Minimum	3.0	5.0	22.0	23.0
Maximum	149.0	70.0	117.0	157.0
Average	62.3	28.2	51.8	64.2
Scenario v				
Minimum	20.0	28.0	85.0	75.0
Maximum	227.0	136.0	241.0	217.0
Average	130.3	67.1	137.8	147.3
Scenario vi				
Minimum	5.0	8.0	33.0	40.0
Maximum	192.0	99.0	196.0	190.0
Average	99.7	41.5	81.0	94.0

vulnerability values reproduces the vulnerability features of the municipality's constructions, highlighting the predominance of buildings with more than 40 years and with structural systems of low resistance to earthquakes. It is also important to note the differences in vulnerability on the intra-district analysis, namely in S. Pedro, S. Miguel and Ponta Garça. The variation of vulnerability is quite evident on the neighbourhoods of each district, with less vulnerable neighbourhoods corresponding to newly built areas, whilst the most vulnerable correspond to the older urban cores or historical centres.

Demographic vulnerability is the second greatest at the Vila Franca do Campo municipality, being averagely assessed as moderate (130.3). The moderate and high vulnerability values are presented on the eastern and western border neighbourhoods of the district of Ponta Garça, in some western neighbourhoods of Ribeira das Taínhas, on the historical centre of S. Miguel and the northern neighbourhoods of Água de Alto (Fig. 4a). The most significant values are derived from the higher proportion of large families, the significant presence of age groups constituted by youngsters and elderly, and also the utmost population density, especially in the historical centre of S. Miguel and Ponta Garça. In the intra-district analysis, several neighbourhoods of reduced vulnerability were identified, corresponding to newly urban areas. In these areas, the reduced vulnerability results from changes in the demographic structure of the population.

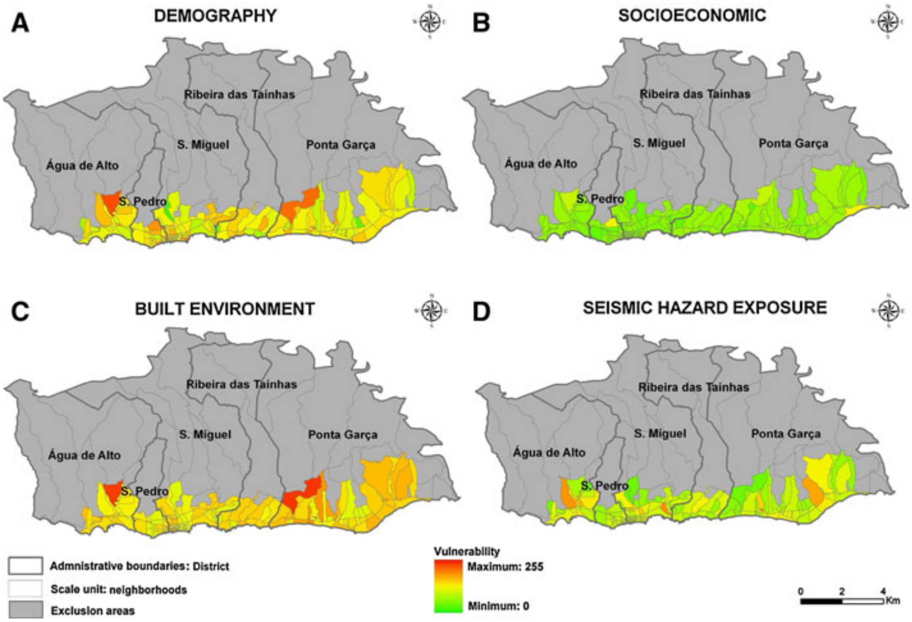

Fig. 4 Social vulnerability related with the four *objectives*

Regarding seismic hazard exposure, vulnerability values are lower than those of both indicators already analysed, presenting an average reduced vulnerability (94.0). In this domain, it is possible to make a clear distinction between the average values of greater vulnerability in Água de Alto (100.4), S. Miguel (100.4) and Ponta Garça (97.6) when compared with the lower average values of Ribeira das Taínhas (88.8) and S. Pedro (85.5). It is necessary to stress the moderate vulnerability of S. Miguel, Água de Alto and eastern sector of Ponta Garça (Fig. 4d), given that in these areas, there is a predominance of continuous urban fabric territories and the largest proportion of residing population, buildings and housing. The neighbourhoods with very reduced or reduced vulnerability comprise discontinuous urban fabric territories, thus slightly diminishing the vulnerability associated with the land-use, which also have an inferior percentage of residing population, buildings and housing. In this case, the vulnerability varies depending on the degree of urbanisation.

Socioeconomic dimension has an average reduced vulnerability (67.1) (Fig. 4b). The districts of Ponta Garça (68.1), Água de Alto (64.3) and Ribeira das Taínhas (59.8) are residually more vulnerable on the socioeconomic scope than S. Miguel (57.9) and S. Pedro (57.4), considering their average values; one should also highlight the inter-districts variation of vulnerability. This is explained by the high illiteracy rates and low educational levels in Ponta Garça, S. Pedro and Ribeira das Taínhas, since the potential dependency rate and unemployment rate are quite similar across the five districts.

For the aggregation of the 1st level *factors*, a neutral risk and maximum trade-off scenarios were defined keeping an equal importance between all *factors*. The social vulnerability resulting from this aggregation was assessed as moderate (133.0). Moderate and high vulnerability values are present on the majority of neighbourhoods of Água de Alto, on the eastern and western borders of Ponta Garça and western area of S. Miguel. Instead,

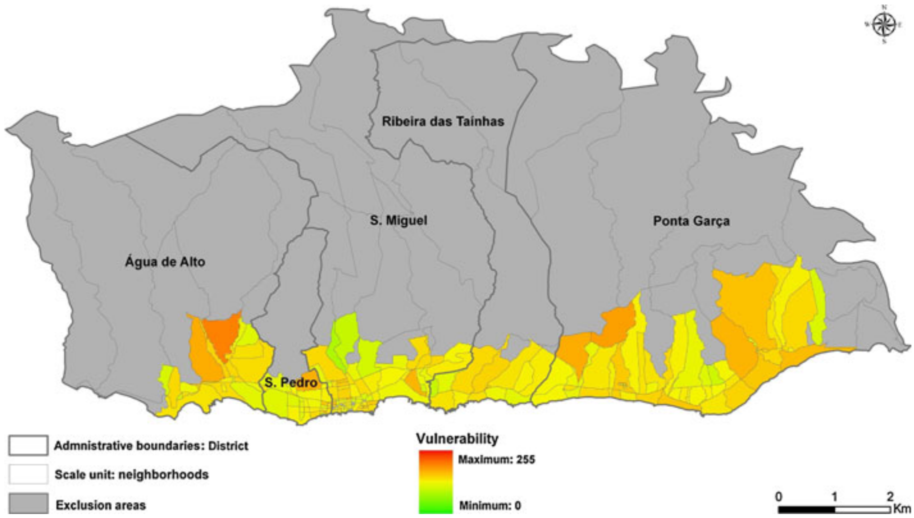

Fig. 5 Social vulnerability to seismic risk on Vila Franca do Campo

the values of reduced vulnerability are located in the vast majority of neighbourhoods on the western area of S. Pedro, central area of the districts of S. Miguel and Ribeira das Taínhas (Fig. 5). These results converge with the foregoing analysis, both from inter and intra-district point of view, and follows from the characteristics associated with the built environment, demography and exposure to seismic risk, although the socioeconomic dimension has a reduced importance.

5 Discussion and conclusions

The ancient cohabitation of Vila Franca do Campo community with seismic hazard calls for the need to assess the social vulnerability of individuals, households and built environment. This study used MCA techniques in a GIS-based approach. The modelling process was developed under a group decision-making process with strengths and weaknesses that should be discussed. The MCA allows categorising the collection of *criteria* that structures the social vulnerability model, differentiating the relative importance of each *criterion* and aggregating them in order to obtain a social vulnerability assessment. Thus, each neighbourhood has a social vulnerability membership in the scale range between 0 and 255, being that the portrayal of their inherent susceptibilities in concern to the dimensions of social vulnerability.

MCA is an effective method to arrange the conceptual understanding of social vulnerability since it decomposes its complexity into a hierarchical structure. We proposed a three-level disaggregation hierarchy that aimed to comprise the social vulnerability dimensions (demography, socioeconomic, built environment and seismic hazard exposure). A group of indicators were selected to provide a comprehensive assessment of each dimension. Since the hierarchy structure of the model is simplified, it is easier to apply the standardisation procedure, to define the *criteria* weights and their aggregation with OWA. Instead of proposing a single social vulnerability index, which in terms of risk management could be less efficient, the definition of a hierarchical structure allowed a multidimensional interpretation of the results. Its effectiveness can be measured in the built environment dimension. For example, in the identification of highly vulnerable neighbourhoods, it allows the convergence of the risk mitigation policies, namely the ones regarding the anti-seismic building codes, the rehabilitation of buildings and emergency management plans. A general vulnerability index will disable this approach since it simplifies social vulnerability issues and hampers the targeting of risk mitigation policies.

The weighting of *criteria* with AHP is a sensitive aspect. It involves judgments about the relative importance of the *criteria,* which has an undeniable subjective nature. This can be overcome if aspects like the input data consistency and a strong theoretical background to support the modelling process are taken in consideration. Nevertheless, future works should include more specialists in this field to obtain a more accurate and comprehensive evaluation process. The vulnerability *criteria* weighting allows assigning different influences to each indicator. This is very important for assessing the seismic hazard vulnerability, since the social vulnerability indicators are not of equal importance. For example, the ancient buildings constructed with low anti-seismic resistance materials have, in theory, a higher vulnerability when compared to the new buildings that used anti-seismic codes. Thus, the vulnerability weight of both variables is not the same.

The aggregation of vulnerability *criteria* with OWA aimed the development of multiple scenarios based on the optimisation of their fuzzy properties. The variation degrees of the ANDness/ORness operators provided different levels of risk and trade-offs between *criteria* within the decision strategy space. Therefore, it was possible to visualise the spatial behaviour of social vulnerability in the established conditions and gain knowledge about the phenomenon. In general, scenarios of low, minimum and neutral risk corresponded to a decrease in social vulnerability values within the neighbourhoods, underestimating the intensity of the phenomenon. In the seismic hazard exposure, the option by a neutral scenario was made given the equilibrium in the relative importance of each *criterion* in the evaluation. The high-risk scenarios maintained the social vulnerability spatial patterns but increased their values when a higher importance to the most relevant *factors* in each dimension was given (demography, socioeconomic and built environment). The maximum risk scenarios led to an overvaluation of the vulnerability.

The pitfalls of the statistical data used can produce ‘false positives’ in the vulnerability assessment process (Kuhlicke et al. 2011). The model represents the social vulnerability of Vila Franca do Campo in 2001 when indeed one is analysing a dynamic phenomenon. The absence of socioeconomic indicators in the statistical data reduced the model capacity in assessing this vulnerability dimension. The statistical data enabled the identification of the potentially vulnerable social groups (young, elderly, women, larger households) and the old buildings constructed with low resistance materials to seismic activity. However, not all women and elderly people are vulnerable to the seismic risk. Additionally, it is also impossible to conclude whether the old buildings had been reinforced with anti-seismic buildings codes or not.

Future works using this methodology should include a sensitivity analysis to be acquainted with the uncertainty related with the input data and to estimate the error propagation through the model. However, this requires the application of the model to a test area that has experienced a disaster event (e.g. an earthquake), quantifying the social vulnerability before the disaster and correlating with the social disruption and built environment damage induced by disaster. This could have been tested on the neighbouring island of Faial, which was the last of Azores to suffer a disruptive earthquake on 9 July 1998. However, the inoperability of statistical data from Census 1991 prevented such validation test.

Finally, the model results allowed the identification of the built environment and the demography as the dimensions of higher vulnerability at the neighbourhood scale within Vila Franca do Campo, being the overall social vulnerability classified as moderate. We have identified a social vulnerability pattern in which the old urban cores have higher vulnerability due to: (i) the presence of old buildings and structures that are unfit to the levels of seismic risk and (2) the presence of vulnerable social groups. Newer urban areas have lower vulnerability since they present changes in the built, demographic and socio-economic environment. These findings are consistent with the empirical knowledge of the area and are crucial elements to define seismic risk mitigation policies and emergency planning by the local authorities.

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