Quantitative seismic risk evaluation and mapping: cases of schools and residential facilities in Lisbon and Algarve

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SUMMARY:
This contribution deals with activities within the framework of an EC-project, entitled "UPStrat-MAFA (Urban prevention strategies using macroseismic and fault sources)", emphasising the inventory, vulnerability and seismic risk of buildings. The cases considered deal with elementary and non-elementary public schools as well as the residential building stock in Lisbon and Algarve in mainland Portugal. A new concept of global disruption measures is introduced and discussed, with the objective of providing a systematic way to quantify earthquake impact in urban areas. This approach provides civil protection, the authorities and local decision makers with a new tool judged to be valuable in prioritizing mitigation measures and responses.

Keywords: inventory, public-school, seismic risk, vulnerability, UPStrat-MAFA

1. INTRODUCTION

This paper outlines and summarizes on-going activities especially related to the "vulnerability of buildings, urban infrastructures and systems" and "Quantitative risk evaluation and mapping" carried out within the framework of the project UPStrat-MAFA "Urban prevention strategies using macroseismic and fault sources" (Zonno et al., 2012). The study aims to construct measures of risk covering different seismic impacts, like physical damage, economic loss and social harm (including human loss, casualties and shelter requirements) and to develop an integrative measure of the global impact of earthquakes on society that supports mitigation practices. Risk analysis is performed for the housing stocks surveyed in different historical periods, in order to analyse the evolution of expected losses and to determine whether the natural regeneration of the building stock shows any trend towards seismic risk mitigation. Seismic risks in pilot regions are ranked according to some of the risk measures identified. The different risk measures are then critically reviewed and compared, stressing constraints and assumptions. Furthermore, the question on uniformity is addressed by identifying critical risk measures common to the studied areas dealt with, as well as those that are distinctive features of each of the studied areas. The dependence of average annual seismic risk on variables like seismic hazard and vulnerability is analysed in detail. Sensitivity analysis of the risk measures to governing quantities is carried out that, together with the ranking of seismic risk inside the pilot regions, provides information on risk mitigation priorities. Finally, a more comprehensive measure of impact is presented. The disruption index, a new concept, is introduced, with the objective of providing a systematic way to quantify earthquake impact in urban areas. A framework is stipulated where urbanized areas are seen as complex networks where nodal points have roles as sources and sinks, interacting interdependently. Furthermore, definition of a classification system for characterizing the exposed elements is introduced. – In the following the main emphasis is placed on vulnerability assessment of schools and residential houses in Lisbon and Algarve.

2. VULNERABILITY ASSESSMENT OF RESIDENTIAL BUILDINGS AND SCHOOLS

2.1 Steps for vulnerability assessment

Studying the seismic vulnerability of an urban region follows two main steps: (i) exposure of geo-referenced inventory and vulnerability classification of assets at risk; and (ii) vulnerability characterization according to damage models. Damage models will be selected in the next steps of the project in accordance with the macroseismic evaluation of the seismic hazard obtained in other tasks. In this stage of the UPStrat-MAFA project, a geo-referenced inventory and vulnerability classification (steps i and ii) were developed for two classes of assets at risk in Lisbon: (a) public-school facilities and (b) Lisbon and Algarve residential stock.

2.2 Inventory and vulnerability of Lisbon elementary public-school facilities

Lisbon elementary public schools serve a population of 15 800 children, with ages ranging from six to nine years old. The elementary educational school facilities include 93 buildings, most of them the property of the City Council of Lisbon (CCL), but a few are rented. This network presents construction characteristics divisible into four distinct periods (Raposo et al., 2007): before 1930, between 1930 and 1970, between the 1970s and 1980s, and after the 1980s.

Until 1930, buildings were designed as dwellings and were later adapted to be used as schools. Many of them are classified as part of municipal heritage or located in protected areas, in the oldest Lisbon neighbourhoods, presenting characteristics from the *Pombalino Period* (built after the 1755 earthquake). Generically they are 3-storey buildings plus mansards with high ceilings (4 meters) that present masonry and timber-framed vertical structures and horizontal structures and roofs also made of timber.

In the second group, buildings were designed as schools and were built during the so-called *Estado Novo* (the political regime in Portugal before 1974). Initially (until the 1950s) the structure of these buildings is characterized by pavements in timber girders resting on masonry walls, sometimes with reinforced concrete slabs in the WCs and common areas. These are two-storey facilities and have two separate areas, with a symmetrical plant, for female and male students. From the 1950s to the 1970s, the use of reinforced concrete structures became standard, using light prefabricated slabs, horizontal roofing with fibrocement sheets or waterproofing as cladding, and double walls in brick masonry.
The buildings of the third group were based on a “Standard Project for Elementary Schools”, later known as type P3 schools. They have a heavy prefabricated design, composed of modular blocks up to two stories high. The standard structural solution was not always used, and there are schools with the same modular typology, but with a structure of concrete cast *in situ*.

Finally, buildings from the end of the 1990s and early 2000s seem to offer good conditions, both in terms of construction and functional spaces. The structure of these buildings is usually made of reinforced concrete, sometimes with mixed structures of concrete and steel, never exceeding three floors. Fig. 2.1 shows the geo-referenced distribution of schools in Lisbon, surveyed in 2007 and classified by construction period.

In 2007, it was found that 14% of the student population had classes in the oldest buildings in the most ancient districts of Lisbon (grandchildren of the inhabitants of these old districts that present worrying ageing and desertion ratios). The majority of pupils (44%) had classes in the buildings of the 3rd construction period, which represents 41% of the school building stock. Table 2.1 presents a summary of the characteristics of Lisbon elementary public schools.

In 2003, the CCL evaluated 30 of the older buildings, to check and identify aspects related to structural safety, service safety and fire safety. Walls out-of-level due to deformation, buckling walls, punching effects in walls and racking of stone window frames and doors were some of the aspects considered. In 2006 with the elaboration of the Lisbon Educational Chart, an evaluation of the condition of all school buildings was made. It was found that 56% of schools needed major repairs (score of 3 in 4 levels).

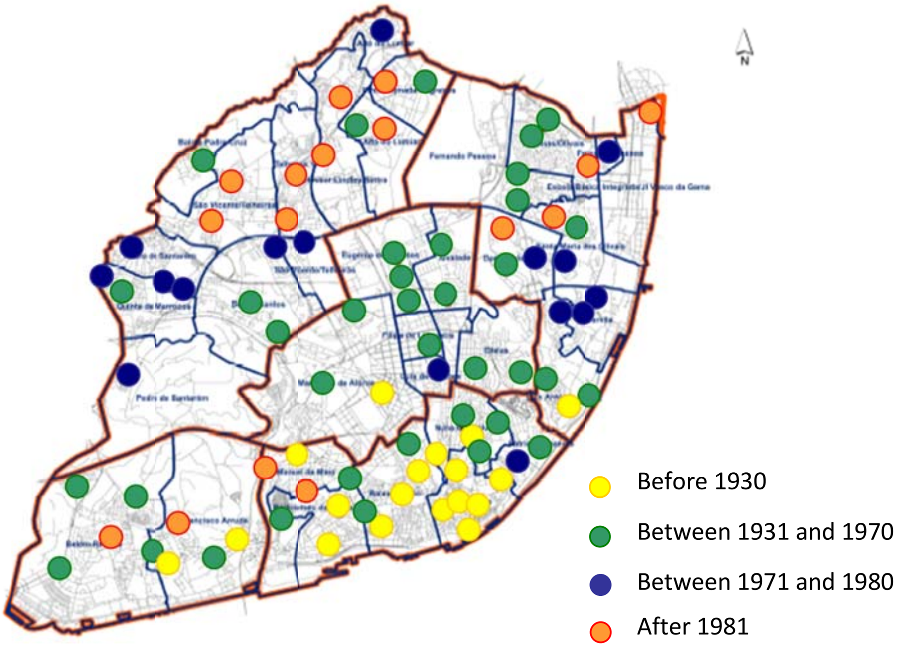


Figure 2.1. Distribution of the schools in the City of Lisbon classified by construction period; 2007 survey (Raposo, et al., 2007).

Table 2.1. Elementary public schools' characteristics - Lisbon

Construction period	Buildings (%)	Pupils (%)	No. of floors (typically)	Structural type
Pre-1930	22 (24%)	2212 (14%)	3	Pombalino period; masonry before 1960
1931 to 1970	38 (41%)	6952 (44%)	2	Masonry before 1960 + RC before 1960; RC 1961-1985
1971 to 1980	13 (14%)	2528 (16%)	2	Heavy prefabrication or RC cast in situ
After 1981	20 (21%)	4108 (26%)	2 (rarely 3)	RC 1986-2001 and RC + Steel structure

Later in the UPStrat-MAFA project, the geo-referenced database will be updated in order to characterize building and population vulnerability in Lisbon elementary schools in 2011/2012, and elementary schools will be classified using a vulnerability index, as was already done for non-elementary school facilities (see section 2.2).

2.3 Inventory and vulnerability of Greater Lisbon Metropolitan Area non-elementary public school facilities

In 2005, the General Secretariat of the Portuguese Education Ministry (DG/ME) and ICIST/IST had developed the Programme for Seismic Risk Reduction of Educational Facilities (PRRSIE) (Proença et al., 2005; Ferreira et al., 2007). This programme was restricted to the existing educational facilities within the Greater Lisbon Metropolitan Area (GLMA), namely in the district of Lisbon (Amadora, Cascais, Loures, Oeiras and Sintra counties) and in the district of Setúbal (Alcochete, Almada, Barreiro, Moita, Montijo and Seixal counties). Public schools directly supervised by the Ministry of Education (public primary schools, supervised by municipalities, and non-state-owned schools were not considered). A total of 53 schools (of the 211 identified according to the former criteria — see Fig. 2.2) were directly surveyed. Of these, 157 and 54 school facilities are located in the districts of Lisbon and Setúbal, respectively. These school facilities comprise a total of 169 745 students, with ages varying from 8 to 18 years (or more).

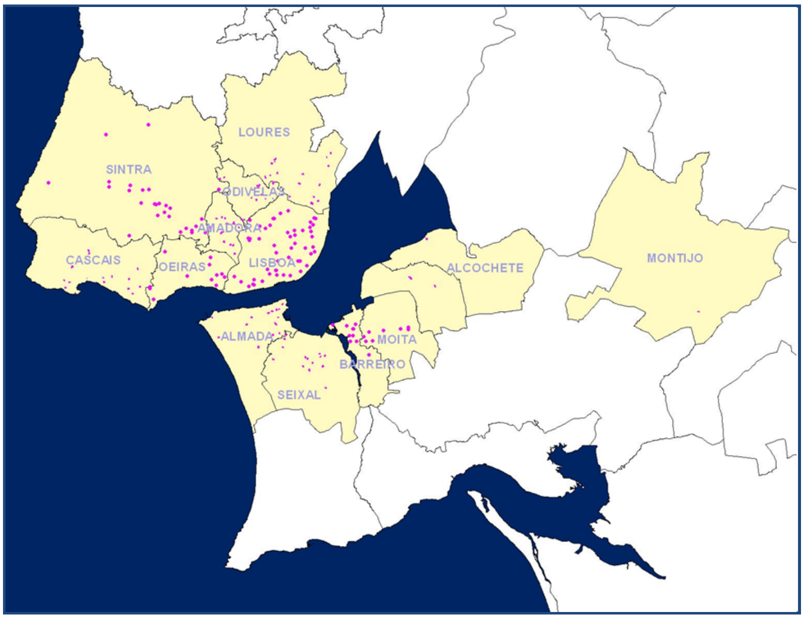


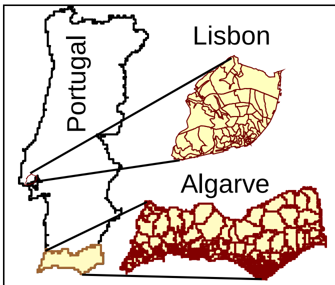
Figure 2.2 Location of educational buildings considered in the PRRSIE project.

This study was divided into the following stages: (i) Review of national and international earthquake performance of educational facilities. Identification of different building typologies in terms of the expected, a priori, earthquake performance. Amongst other factors, identification of these typologies takes into account the building construction period (and, indirectly, the applicable earthquake-resistant design codes), building material, location and conservation. (ii) Development of a GIS-based simulator to predict expected damage distribution for each of the recognized building typologies.

Table 2.2 identifies the most representative building typologies and associates a vulnerability index with each building (dependent on its typology, construction materials and the level of ERD features), based on empirical methods developed by Giovinazzi and Lagomarsino (2002 and 2003) and adapted in successive stages (Oliveira et al., 2004(a) and 2004(b)). The aforementioned method was adjusted to the existing building typologies and extended to consider two extra typologies. These two extra typologies, identified as RC2- and RC2+, refer to reinforced concrete buildings built between 1958 and 1983 or after 1983, respectively. These periods reflect the dates applying to the Portuguese seismic codes. The first Portuguese seismic code dates from 1958 (RSCCS, 1958), and it was successively updated and substituted in 1961 (RSEP, 1961), and in 1983 (RSA, 1983).

2.4 Inventory and vulnerability of Lisbon and Algarve residential stock

The geographic location of Lisbon and Algarve in the Portuguese mainland territory is presented in Fig. 2.3 together with its aggregate exposure statistics. The figures for the inventories of Lisbon and Algarve housing stock and their inhabitants are based in the Portuguese Census survey, where some variables representing structural characteristics expected to affect the seismic vulnerability of buildings were cross-referenced, simultaneously.



Statistics	Lisbon	Algarve
Parishes	53	83 (2%)
No. Of soil profiles	10	49
No. of geog. units: parishes & soil profiles	74	222
Building classes	315	315
Residential buildings	53 387 (1.8%)	160 543 (5.4%)
Dwellings	288 481 (6.0%)	276 093 (5.7%)
Population	553 113 (5.7%)	390 310 (4.0%)

Figure 2.3 Geographic location of Lisbon and Algarve and statistics (adapted from Sousa et al., 2010a and b)

Table 2.2. Vulnerability of non-elementary public school facilities - Greater Lisbon Metropolitan Area.

Architect project	**Construction period**					**Structural type**
	1881-1940	1941-1958	1958-1970	1970-1973	>1983	
«Proj. especial» (séc. XIX)	0.700					Load-bearing masonry walls with RC storey slabs until 1950s and integrally made with RC (frame structure, low ERD) until 1970.
«Proj. especial» < 1945	0.616					
«Proj. especial» / MOP		0.716	0.669	0.467	0.386	
MOP			0.532			
Lyceum buildings			0.553	0.454		RC frame buildings built in the 1960s and early 1970s. Low ERD features
Block buildings (28mx28m)			0.553			RC frame buildings built in the 1960s
«Conjunto de pavilhões – Brandão»			0.553	0.447		RC frame buildings built in the 1960s and early 1970s. Low ERD features
«Pré-fabricado de madeira»			0.644			Timber frame building
Block build. 3 × 3 compact			0.447	0.447	0.373	RC frame buildings built in the 1960s, 1970s and after 1980 (these could be considered to present some ERD)
Prefabricated Proclasp				0.573		RC precast panel
Prefabricated RC				0.553		RC precast
Block buildings (21m × 21m)				0.454	0.382	RC frame buildings built in the 1970s and after 1980 (these could be considered to present some ERD)
«Proj. Luís Pacheco»					0.373	RC frame buildings
Prefabricated lightweight timber			0.553	0.553		Timber frame building

Based on the Building Questionnaire of the 2001 Portuguese Census it was possible to classify the housing stock into 315 different typologies, considering 9 periods of construction, for 5 classes of structural type and 7 classes, based on the number of floors. Following previous research projects, (LESSLOSS – Spence, 2007 and SHARE - Sousa and Carvalho, 2012), and with the main goal of simplifying the analysis of results, the original 315 typologies obtained from Census 2001 were aggregated in 7 typological classes, taking into consideration two vulnerability factors, period of construction or reconstruction and structural type. The 7 adopted typological classes are: adobe and rubble stone (all periods), masonry before 1960, masonry 1961-1985, masonry 1986-2001, reinforced concrete (RC) before 1960, RC 1961-1985 and RC 1986-2001. Each typological class was then subdivided into 7 classes for the number of floors, obtaining a total of 49 vulnerability classes. The Portuguese Census also surveyed the population present in residential buildings with the above-mentioned vulnerability characteristics. Fig. 2.4 and Fig. 2.5, (a) to (g), map the geo-referenced database characterizing the building inventory and main vulnerability factors of Lisbon and Algarve housing stock, surveyed in 2001.

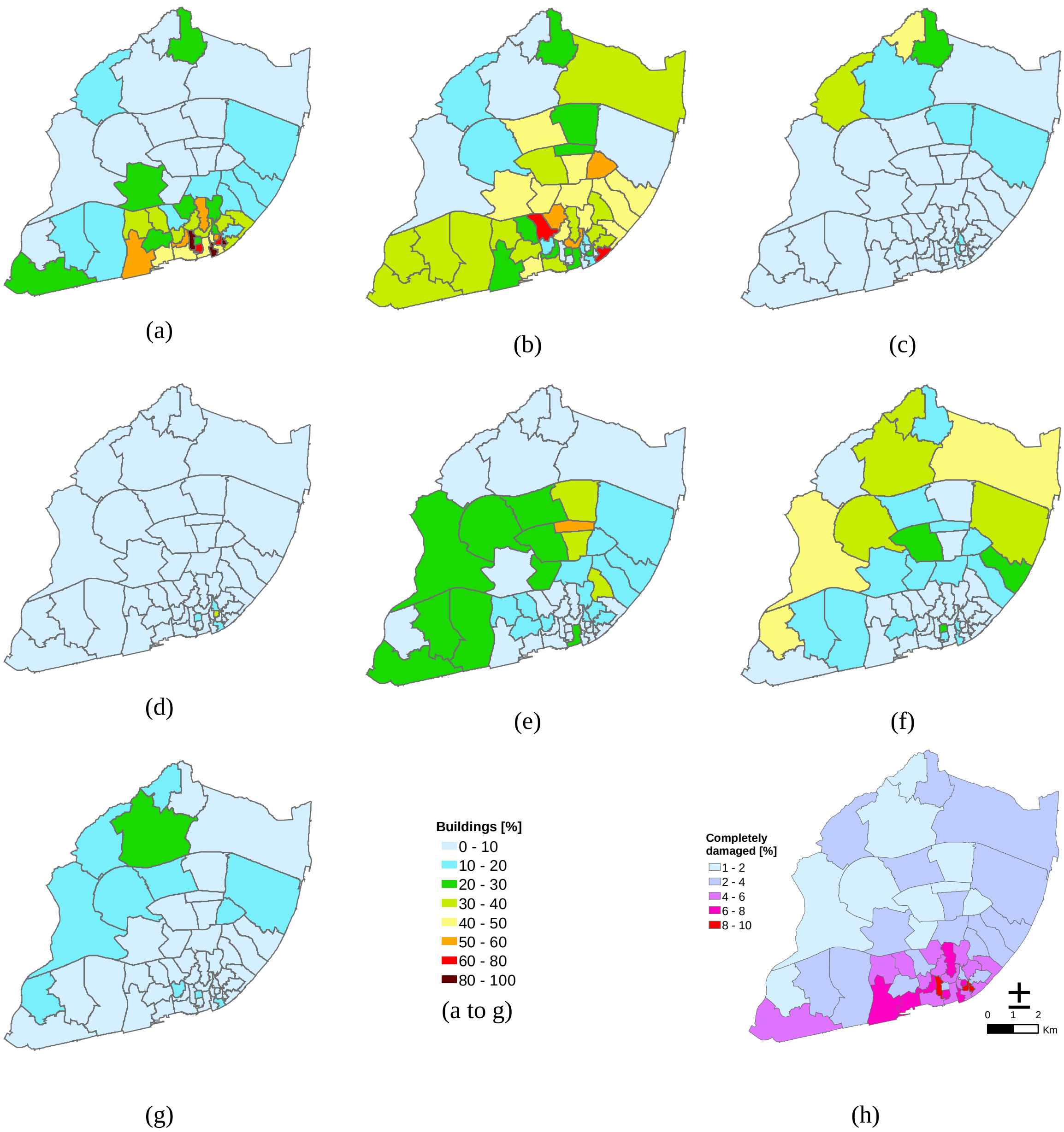


Figure 2.4 Exposure maps for Lisbon ((a)-(g) adapted from Sousa et al., 2010a); percentages of buildings, per parish, in each vulnerability class: (a) adobe and rubble stone; (b) masonry before 1960; (c) masonry 1961-1985; (d) masonry 1986-2001; (e) RC before 1960; (f) RC 1961-1985; (g) RC 1986-2001; (h) Vulnerability map.

Fig. 2.4 and Fig. 2.5 (h) show vulnerability maps for the region resulting from simulating damages (total and partial collapses) in residential building stock using the LNECloss tool (Campos Costa et al., 2010). LNECloss is an automatic tool, comprising several modules simulating: (i) seismic action at bedrock and at surface level, (ii) earthquake damage to buildings and (iii) social and economic losses. In the present simulation, the adopted ground motion scenario is constant along both regions, aiming at studying the regional variation of the vulnerability of their building stock. For example, the intermediate long distance seismic scenario existing in the Portuguese National Annex of Eurocode 8 – part 1 (zone 1.3, 475 years return period - NP EN 1998-1: 2010) was chosen. In this context, the heterogeneity of seismic ground motion was removed in Fig. 2.4 (h) and Fig. 2.5 (h). The effect of building exposure was also controlled, as the number of completely damaged buildings was normalized by each parish building toll. The damage model used in the simulation is based on the capacity spectrum method (ATC, 1996) further developed in LNECloss (Campos Costa, 2010). In the vulnerability maps shown in Fig. 2.4 (h) and Fig. 2.5 (h), it is clear that: (i) residential buildings located in Lisbon's Old Centre are more vulnerable than the remaining building stock; (ii) residential buildings located in Algarve's up-country and on its West Coast are more vulnerable than the remaining building stock (Sousa et al., 2010b) and (iii) residential buildings located in Lisbon Old Centre are more vulnerable than residential buildings located in Algarve's up-country. These results were already expected because buildings in central parishes of Lisbon are mainly old masonry buildings (see Fig. 2.4 (a) and Fig. 2.4 (g)), whereas recent RC buildings are located in main urban centres in the Southern littoral region of Algarve (see Fig. 2.5 (f) and Fig. 2.4 (g)).

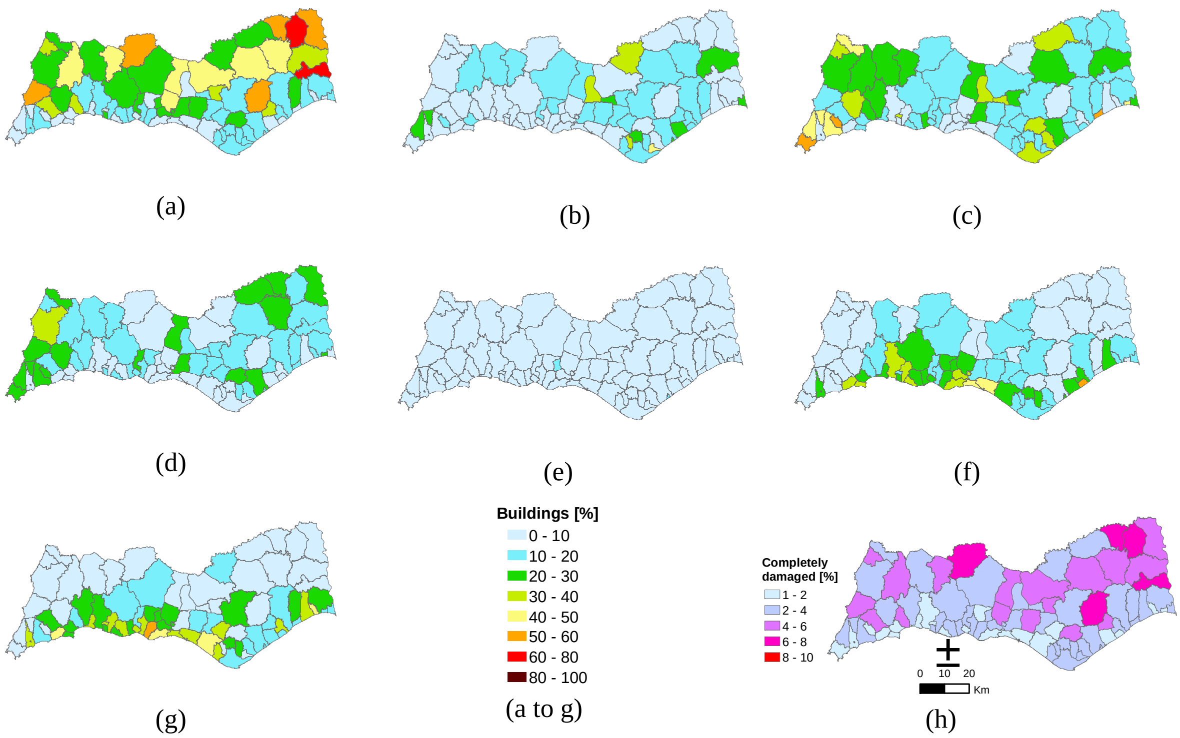


Figure 2.5. Exposure maps for Algarve ((a)-(g) adapted from Sousa et al., 2010b); percentages of buildings, per parish, in each vulnerability class (a) adobe and rubble stone; (b) masonry before 1960; (c) masonry 1961-1985; (d) masonry 1986-2001; (e) RC before 1960; (f) RC 1961-1985; (g) RC 1986-2001; (h) Vulnerability map.

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3. SEISMIC RISK ANALYSIS

3.1 Steps for risk analysis

As the UPStrat-MAFA project evolves, the analysis of risk for an urban region will follow five main steps: (i) the updating of the geo-referenced database in order to characterize building and population vulnerability in Lisbon and the Algarve in 1991 and 2011, corresponding to two additional different surveys of Portuguese Census; (ii) the characterization of the vulnerability of the analysed urban regions following a systemic approach; (iii) the definition of different measures of risk that cover different impacts, like average annualized economic and social losses (casualties, shelter requirements, etc.); (iv) the analysis of risk in 3 different moments, 1991, 2001 and 2011, aiming at studying how the natural renovation of the building stock contributes to mitigating the risk; (v) the definition of comprehensive measures of impact and risk criteria according to the methodology presented in the following section.

3.2. Definition of comprehensive measures of impact and risk criteria

This section will explore two problems that must be solved regarding seismic risk: (i) identifying and measuring human values – we have to deal with intangible values, leading us to the domains of weak preferences, incomparability, intransitivity and ordinal scales, and because modern society is mostly characterized by multiple interdependencies, it becomes difficult not to violate constraints of preference and additive independence, so qualitative analysis becomes necessary. (ii) measuring risk – on the other side, resources allocation and strategic decisions in the field of risk reduction may require assessment of value functions and trade-offs, mostly supported by quantitative risk analysis

Over the past four years, a major effort was made to identify and measure risk (Mota de Sá, 2012). From the examination of (i) several seismic simulators and (ii) extensive bibliographical research about physical and social impacts of severe events, and (iii) from the in-situ observation of regions and towns hit by recent major seismic episodes, more than 70 “primary concerns” or “criteria” were found to be systematically present in all texts and reports (Ferreira, 2012). Following some fundamental rules on decision problem structuring, these primary elements were aggregated into about 14 “fundamental criteria” translating critical dimensions (urban functions) interacting to produce an urban system's ability or inability to respond to a disruptive event. These dimensions encompass six fundamental human needs: “environment, housing, healthcare, education, employment and food”. The dimensions are conditioned by several other main functions/systems, such as “water, sewage, telecom, electricity, security and mobility”, conditioned in turn by the reliability of several facilities and building stock (Fig. 3.1) with responsibility relying on the so-called “end-users”.

However, before proceeding it is important to recognize that because different societies have different values and concerns, criteria cannot be static but should be revised and adapted in each case. For example, in a region where health care facilities or any other critical functions strongly depend on the supply of natural gas, then this last dimension should come into place. However, from what was found, the above-mentioned criteria seem to be present in most studied cases.

Having settled the criteria, the next step is to define the scale to measure impact on the criteria and the rules for their aggregation. A major decision now needs to be taken on what kind of risk model should be used. If it is possible (i) to gather sufficient evidence to support the construction of “interval or ratio scales” allowing the introduction of “quantitative” and “comparative” measure, at the same time; (ii) if there is enough evidence and support to evaluate trade-offs between different criteria; and (iii) if “preferential and additive independence among criteria” are obeyed, then the adoption of an “additive model” can be considered. This model has been very popular and used by many authors (Carreño et al. 2012). But, if these conditions are not satisfied, because they absolutely must be observed in real scenarios, at least in the domain of seismic risk, then approaches other than the additive model should be used. Another model has been developed, based on the concept of the Disruption Index (Oliveira et al., 2012). It is based on an “objective and qualitative scale” (DI Scale). The model treats the urban system as an acyclic digraph (Fig. 3.1), where, urban functions, systems and physical assets, i.e., our concerns, are “nodes”, and, using specific rules, the “directed arcs” linking the “nodes” define their interdependencies. The model is addressed as a Multi-State (Zio and Podofillini, 2003) Coherent (Andrews and Beeson, 2003) System. Then, using Fault Tree Analysis and Monte-Carlo Simulation, performance measures, like those proposed by Vesely (Andrews and Moss, 2002; Michaud and Apostolakis, 2006; Vesely et al., 1983; Zio and Podofillini, 2003), are used to understand the importance of each “node”, as well as the effect that their reliability has in the global system. This allows us to identify and quantify the merits of plausible courses of action in order to diminish, restrain or not increase seismic risk. The concepts, mechanisms, benefits and constraints of the Disruption Index will be the subject of another paper in this conference (Mota de Sá, 2012).

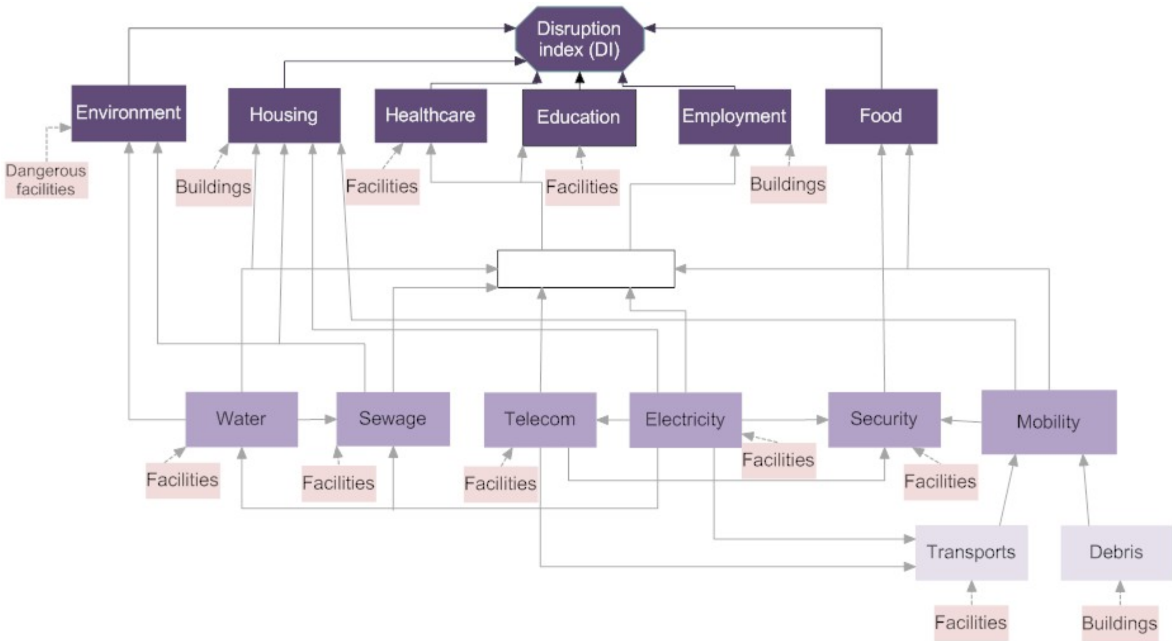

Figure 3.1. The disruption index digraph.

4. FINAL CONSIDERATIONS

In the above presentation we have emphasized two aspects of seismic risk evaluation. These are vulnerability assessment – exemplified by the public schools in Lisbon and the residential building stock in Lisbon and Algarve – and the newly introduced concept of the Disruption Index. In the first case the seismic risk is obtained by combining the vulnerability of different building types and the seismic hazard for the site, expressed in terms of the effects of events derived from an earthquake catalogue exceeding a specified threshold during a given period. The outcome reflects the average seismic risk of the buildings and facilities in question during the period considered. In the second case we use scenario input conforming to the earthquake catalogue, but we do not use the entire catalogue as outlined in the first case. Then for a given scenario, described in terms of source location and magnitude, etc., we associate the estimated damage of buildings and critical facilities resulting in a spatial series of induced damages. The methodological procedure for disruption operates on this series and provides an estimate of a global measure of impact called the disruption index. By repeating the procedure for different scenarios, we can identify the critical elements at risk, elements whose functions are essential for the operability of social systems. These two methods approach the problem of seismic risk differently, providing complementary risk measures. Relating these measures and applying them in practice at the pilot test sites is one of the challenges to be addressed.

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