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PROBABILISTIC EARTHQUAKE RISK ASSESSMENT OF BARCELONA USING CAPRA

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ABSTRACT

The risk evaluation model CAPRA (Comprehensive Approach to Probabilistic Risk Assessment) is a techno-scientific methodology and information platform, composed of tools for evaluating and communicating risk at various territorial levels. The model allows evaluating losses on exposed elements using probabilistic metrics, such as the loss exceedance curve, the expected annual loss and the probable maximum loss, useful for multi-hazard risk analyses. The process of probabilistic seismic risk analysis of the city of Barcelona, Spain is described explaining the main features of the CAPRA modules of hazard, vulnerability and risk estimation. In addition, according to the physical risk results and the information on the socio-economic indicators of the city, was performed a holistic evaluation of seismic risk, which is a valuable result to facilitate the integrated risk management by the different stakeholders involved in risk reduction decision making.

INTRODUCTION

One of the key strategic activities of disaster risk management is the catastrophe risk assessment which requires the use of reliable methodologies that allow an adequate calculation of probabilistic losses of exposed elements. The use of models for risk assessment and the results –based on metrics such as the Probable Maximum Loss and the Average Annual Loss– provide make feasible to determine the potential deficit existing in case of the occurrence of an extreme event. Estimations and quantification of potential losses in a given exposure time are of interest, not only for the private insurers, reinsurers and investors, but also for the governments since the budget for both, the emergency response and the recovery and reconstruction, could mean a fiscal exposure and a non explicit contingent liability for governments at local and national levels (Pollner, 2001; Andersen, 2002). Besides, it permits to set out *ex ante* strategies for reducing or financing them (Marulanda et al., 2008, Cardona and Marulanda, 2010, Cardona et al., 2010, Marulanda et al., 2010; Cardona *et al.*, 2010a; Cardona *et al.*, 2010b). In summary, to achieve a greater awareness, security culture and economic prosperity, the financial protection must be a permanent and long term policy (Freeman et al., 2003).

In the recent past, the techniques for risk evaluation were of special interest almost only from the financial perspective, where the results were useful for determining the economic reserves needed

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to attend catastrophic events. The platform CAPRA (Comprehensive Approach to Probabilistic Risk Assessment), developed by the ERN-AL Consortium (ERN-AL, 2010) for the World Bank, the Inter-American Development Bank, and the UN-ISDR, was conceived as an open source model for different activities of disaster risk management and not only for risk financing (Cardona et al., 2010; www.ecapra.org). This initiative comprehends a conceptual framework, modular software to calculate hazards and risk, analysis tools, as well as a training process that creates and enables an environment for the mainstreaming of disaster risk reduction.

The software is composed by modules of hazards, vulnerability and risk, and allows determining conjoint or cascading hazards. This includes hazard mapping, risk evaluation and tools for cost-benefit analysis that support the proactive risk management. CAPRA seeks to enhance the knowledge and understanding, enhancing, thus, the capacity of institutions to identify, prioritize, plan and build efficient risk reduction measures. These are based on probabilistic risk calculation that considers the uncertainty into the analysis and allows settling an array of possible outcomes to establish cross-institutional interdisciplinary arrangements and communicating probabilistic risk.

In the last years, CAPRA has been widely used in evaluating multi-hazard risk in different capital cities of countries of Latin America such as: Belize, Colombia, Costa Rica, Dominican Republic, El Salvador, Guatemala, Guyana, Honduras, Nicaragua, among others. In addition, using a proxy of the exposure, catastrophe risk profiles of countries have been made for Bolivia, Colombia, Guatemala, Jamaica, Mexico, Nepal, Peru, and there are others in process.

In this article, we used the city of Barcelona, Spain, as a test-bed for the CAPRA platform. The first reason of this decision is the fact that, although Barcelona is a city with a low-to-moderate seismic hazard, its vulnerability is very high since most part of its building stock belongs to the pre-code period of Spain being, thus, its physical risk significant. Additionally, it is a highly populated city, what increases even more the risk of the urban area under the effects of an earthquake. Another reason is the very accurate available information of the assets of Barcelona and of its seismic hazard, which is essential in risk evaluation. Finally, it is important to observe that other studies on the evaluation of the seismic risk of Barcelona have been made in the recent past, with other focuses and with other methodologies (Barbat et al., 2008, Lantada et al., 2009, Barbat et al., 2010, Irizarry et al., 2011). The present study allows complementing and improving the previous evaluations. Due to all these reasons, the probabilistic seismic risk assessment of Barcelona has been performed using the modules of CAPRA and the corresponding holistic estimation of the seismic risk of this urban area.

1 PROBABILISTIC EARTHQUAKE RISK MODEL

The possibility of future highly destructive events in many areas of the world creates the need to focus risk estimation on probabilistic models that can use the limited available information of the historical data, given the low frequency of catastrophic seismic events. This fact leads to large uncertainties related to the severity and frequency characteristics of the events that must be considered in a probabilistic risk model.

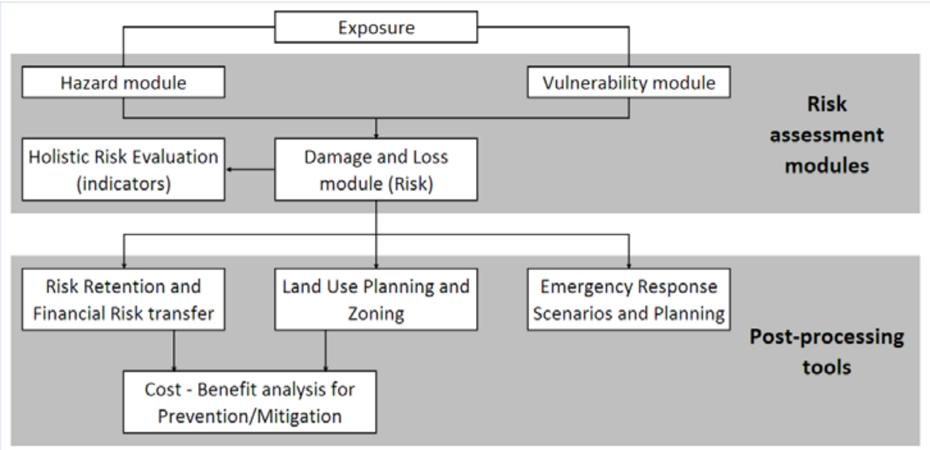


Figure 1. Probabilistic risk model and disaster risk management applications

The development of earthquake prediction models uses seismological and engineering bases that allow assessing the risk of loss for catastrophic events. The Figure 1 shows a scheme of the probabilistic risk model built upon a sequence of modules (Woo, 1999, 2011; Grossi and Kunreuther, 2005; Cardona et al., 2008a) to quantify the potential losses arising from earthquake events.

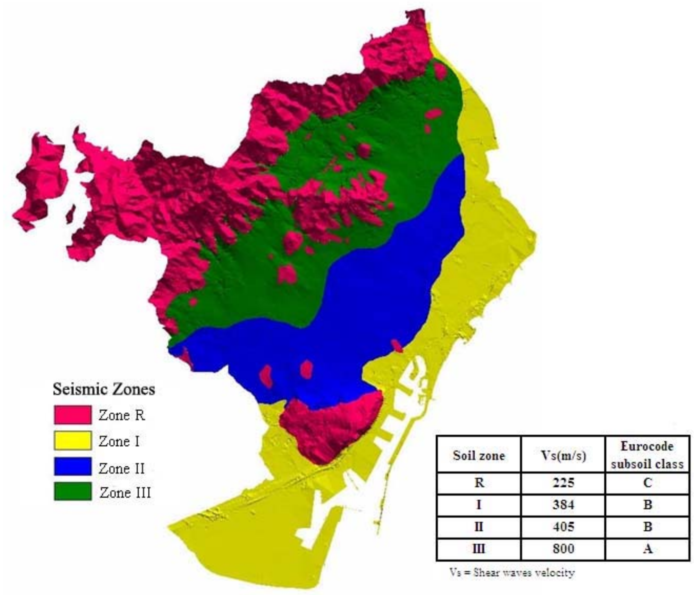
1.1. Seismic hazard module

The hazard module defines the frequency and severity of a peril at a specific location. Analysis of the historical event frequencies and review of scientific studies performed on the severity and frequencies in the region of interest determine the seismic hazard parameters. Once established these parameters, sets of stochastic event are generated, which must represent all the possible hypocenters and the whole range of possible magnitudes associated to a specific hypo-central location. Each of these events or scenarios has associated a specific frequency of occurrence. Naturally, the scenarios associated to low magnitude earthquakes will have a higher probability of occurrence, than those scenarios associated to high magnitude earthquakes, which will have a relatively low probability of occurrence. Modeling the attenuation of each event to the site under consideration according to the local site conditions, allows establishing the intensity at each location. The usual form of representing seismic hazard is by the exceedance rates of given intensities.

The seismic hazard of Barcelona was assessed with the CRISIS 2007 code (Ordaz et al., 2007) which is the seismic hazard module of CAPRA. This code allows estimating the hazard associated to all possible events that can occur or to a group of selected events, or even to a single relevant event. It provides the probable maximum value of the parameter characterizing the seismic intensity for different exceedance rates or return periods. An .ame file type (.ame from *amenaza*, that is, hazard in Spanish) is created in this module, which includes multiple grids on the area of study, for the different possible intensity parameters of the seismic hazard. Hazard is calculated combining the following: sources: geometry (which will influence on the probability distribution of the hypocentral distances), sources seismicity (defined by a Poisson seismicity model, which will provide the probability distribution of the occurrence of a particular magnitude within the source) and attenuation functions (which provides the probability distribution of strong motion, given the magnitude and hypocentral distance). All this components are probabilistically combined by means of the total probability theorem, to compute the annual exceedance rates of strong motion measures, which correspond to annualized exceedance probabilities. Each grid is a scenario of the intensity level obtained from historical or stochastic generated events, with their frequency of occurrence. In Barcelona were generated 2058 seismic hazard scenarios. The parameters characterizing the seismic intensity for this case were the peak ground acceleration and the spectral acceleration. The probabilistic calculation method evaluates the desired risk parameters such as percentages of damage, economic losses, effects on people and other effects, for each of the hazard scenarios and, then, these results are probabilistically integrated by using the occurrence frequencies of each earthquake scenario.

The application in Barcelona takes into account the 10 seismic sources identified by Secanell (2004) for the Catalonia region of Spain. Additionally, attenuation effects of the seismic waves were also considered in the mentioned reference by means of probabilistic spectral attenuation laws that include different source types and the local amplification effects based on microzonation studies (Ambraseys et al., 1996).

Figure 2 shows the seismic zonation of Barcelona based on the local effects defined by Cid et al. (2001), which considers the amplification of seismic hazard parameters according to the geological conditions of Barcelona; a transfer function and an amplification factor for the acceleration level on the rock characterize each zone.



Soil zone	Vs(m/s)	Eurocode subsoil class
R	225	C
I	384	B
II	405	B
III	800	A

Figure 2. Seismic zonation of Barcelona based on local effects (**Cid et al., 2001**)

1.2. Exposure characterization

The exposure is mainly related to the infrastructure components or to the exposed population that can be affected by a particular event. The exposure is based on files in *shape* format corresponding to the infrastructure stock. Characterization of exposure requires identification of individual components, including variables such as location, physical, geometric and engineering characteristics, economic value and level of human occupancy. The precision degree of the results depends on the level of resolution and on the details of the information.

The exposure of the city of Barcelona was the one compiled by Lantada (2007), complemented with the economic value of each building supplied by the Cadastral Office of Barcelona. The number of buildings included in the calculations of Barcelona was 70,655, which are distributed in 10 municipal districts, 73 neighborhoods, 233 Basic Statistical Areas (AEB in Spanish – Áreas Estadísticas Básicas) and 1061 census sections.

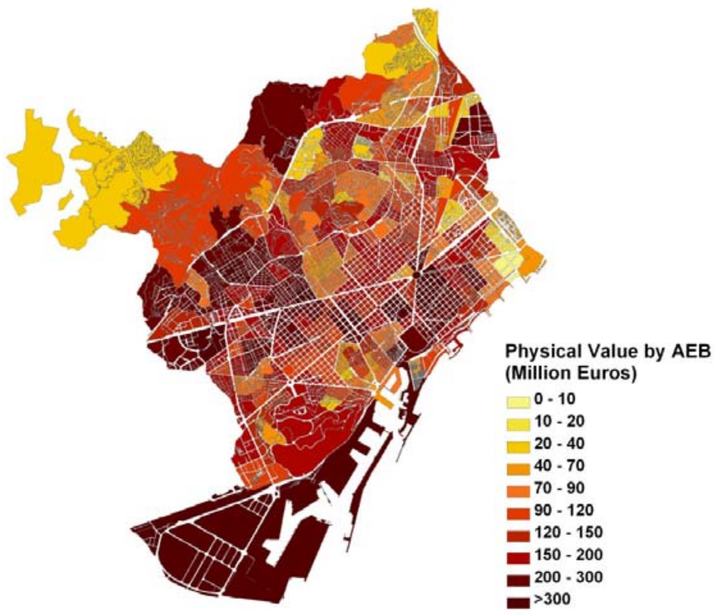


Figure 3. Exposed value of Barcelona by AEBs, in Euros

Figure 3 shows the exposure of Barcelona by AEB, in terms of economic value (Euros). Each building is characterized by the geographic location, the economic value, the year of construction, the number of levels, the structural type and the human occupancy. The risk results were obtained for each building and they are presented at different geographical levels (blocks, AEB, neighborhoods, districts).

In order to estimate the impact to the population, information related to building occupancy level is used (Lantada, 2007). When no specific occupation information was available, an approximate occupancy density by construction class was supposed in order to complete this information (Coburn and Spence 1992).

1.3. Vulnerability module

The vulnerability module quantifies the damage caused to each asset class by the intensity of a given event at a site (Miranda, 1999). The classification of the assets, in this case the buildings of an urban area, is based on a combination of structural characteristics like construction material, construction type (i.e. wall & roof combination), building use, number of levels, age, etc.

Damage is estimated in terms of the Mean Damage Ratio, MDR that is defined as the ratio of the expected repair cost to the economic value of the structure. A vulnerability curve is defined relating the MDR to the earthquake intensity, which can be expressed, at each location, in terms of the maximum acceleration (useful for 1-2 story buildings), spectral acceleration, velocity, interstory drift or displacement (useful for multi-story buildings). Vulnerability curves for several construction classes are already included in the vulnerability module of the CAPRA platform for different types of intensities and examples of such curves can be seen in figure 4.

Referring now to the city of Barcelona, most part of its building stock belongs to the pre-code period of Spain. The combination of very old buildings constructed without seismic conscience and regulations, with a highly populated and active city, can be extremely risky even under the effects of a moderate earthquake. The vulnerability module of the CAPRA platform allowed calculating the vulnerability functions of the buildings of the city. The assignment of the adequate vulnerability function to each building is carried out using the shape format file processes in the exposure module; each function corresponds to a building typology existing in the city. Most of the buildings existing in Barcelona are made of unreinforced masonry, followed by reinforced concrete buildings, whose construction has increased rapidly in recent decades. Steel structures are less used and usually do not have residential use but industrial or other uses such as markets or sports arenas, among others. Wood structures are nowadays practically inexistent. The typologies of the buildings of Barcelona were defined by ICC/CIMNE (2004).

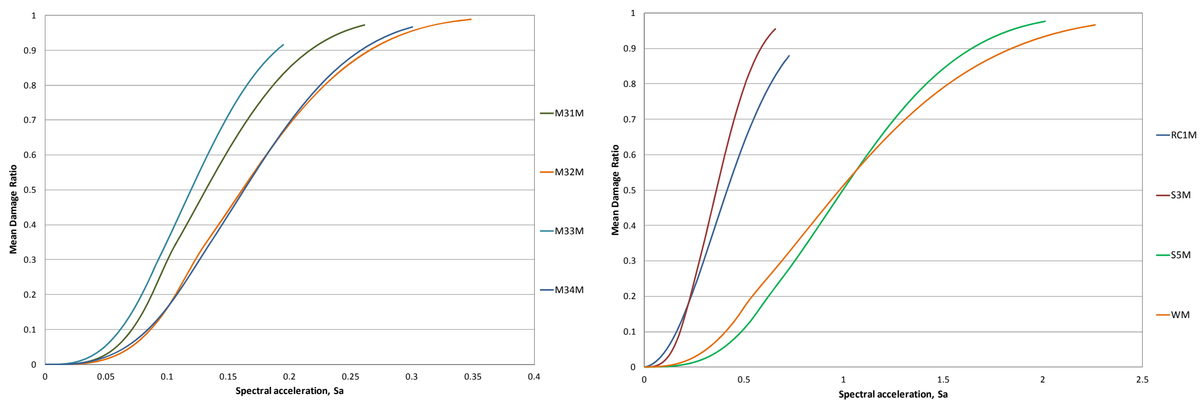


Figure 4. Vulnerability functions for (a) unreinforced masonry buildings (b) reinforce concrete, steel and wood buildings

The vulnerability curves shown in figures 4 were developed by means of the vulnerability module of CAPRA, starting from capacity curves defined in the previous studies performed in the RISK-UE project (ICC/CIMNE, 2004; Lantada et al., 2009; Irizarry et al., 2011). These vulnerability curves are relating spectral acceleration with mean damage ratio, but also include the standard deviation. Figure 4(a) shows some vulnerability functions corresponding to the unreinforced masonry buildings of Barcelona while Figure 4(b) shows vulnerability functions for reinforced concrete, wood and steel buildings of the city for medium (M) height.

1.4. Risk module

The risk module evaluates the potential effects or consequences of the natural hazardous events by means of the convolution of the hazard with the vulnerability of the exposed elements. It expresses risk in terms of physical damage, absolute or relative economic loss and/or affected population. Thus, this risk module calculates losses by transforming the damage ratio obtained in the vulnerability module into economic loss by multiplying it by the value at risk. The same procedure is followed for each asset class at each location. Losses are then aggregated according to the procedure proposed by Ordaz et al. (1998) and by Ordaz (2000). The loss module estimates the net losses. The main metrics used in the probabilistic risk assessment are the following:

Loss Exceedance Curve, LEC, represents the annual frequency of exceedance of a specific loss. This is the most important catastrophe risk metric for risk managers, since it estimates the amount of funds required to meet risk management objectives. The *LEC* can be calculated for the largest event in one year or for all (cumulative) events in one year. For risk management purposes, the latter estimate is preferred, since it includes the possibility of one or more severe events resulting from earthquakes. Once calculated the Loss Exceedance Curve, it is possible to obtain other appropriate metrics for the financial analysis of the losses such as the Average Annual Loss or Pure Risk Premium for each building and for sets of buildings, like, for instance, the AEBs. The Probable Maximum Loss is obtained for the whole portfolio, that is, the entire city (Ordaz and Santa-Cruz, 2003, Cardona et al., 2008a).

Average Annual Loss, AAL, is the expected loss per year. Computationally, AAL is the sum of the product of the expected losses in a specific event and the annual occurrence probability of that event, for all stochastic events considered in the loss model. The expected annual loss considers the losses of each building for all the events that can occur; supposing that the process of occurrence of hazard events is stationary and that damaged structures have their resistance immediately restored after an event.

Probable Maximum Loss, PML, represents the loss amount for a given annual exceedance frequency, or its inverse, the return period. Generally, the PML, in economic value or in percentage with regard to the return period, specifies the PML curve. The PML of an exposed base is an appraiser of the size of maximum losses reasonably expected in a set of elements exposed during the occurrence of a hazard event. Typically, PML is a fundamental data to determine the size of reserves that, for example, insurance companies or a government should maintain to avoid excessive losses that might surpass their adjustment capacity. This model defines it as the average loss that could occur for a given return period.

The Average Annual Loss for physical assets, fatalities and injuries were calculated for each building in the city of Barcelona. The results are shown in the Table 1, Table 2 and Table 3.

Table 1 Risk results of the physical exposure of Barcelona

PHYSICAL EXPOSURE		
Exposed value	€ x10^6	31,522.80
Average Annual	€ x10^6	72.14
Loss	‰	2.29‰
PML		
Return period	Loss	
(Years)	€ x10^6	%
50	729.35	2.31%
100	1,770.16	5.62%
250	3,699.35	11.74%
500	5,172.26	16.41%
1000	6,510.67	20.65%
1500	7,021.14	22.27%

Table 2. Results of dead people in Barcelona

DEAD PEOPLE		
Exposed value	Inhabitants	1,639,880.00
Average Annual Loss	Inhabitants	28.27
	‰	0.017‰
PML		
Return period (Years)	Loss	
	Inhabitants	%
50	101.41	0.01%
100	654.30	0.04%
250	2,069.97	0.13%
500	3,380.29	0.21%
1000	4,898.39	0.30%
1500	5,799.44	0.35%

Table 3. Results of injured people in Barcelona

INJURED PEOPLE		
Exposed value	Inhabitants	1,639,880.00
Average Annual Loss	Inhabitants	113.55
	‰	0.07‰
PML		
Return period (Years)	Loss	
	Inhabitants	%
50	756.92	0.05%
100	3,420.18	0.21%
250	9,028.50	0.55%
500	12,590.98	0.77%
1000	15,803.45	0.96%
1500	16,903.45	1.03%

Figure 5 shows the PML curve obtained for Barcelona. Figure 6 show the expected annual economic loss by AEB, for Barcelona, and building by building, for the Eixample district, respectively. Figure 7 show the expected annual loss corresponding to deaths and injured, respectively, by AEB of Barcelona.

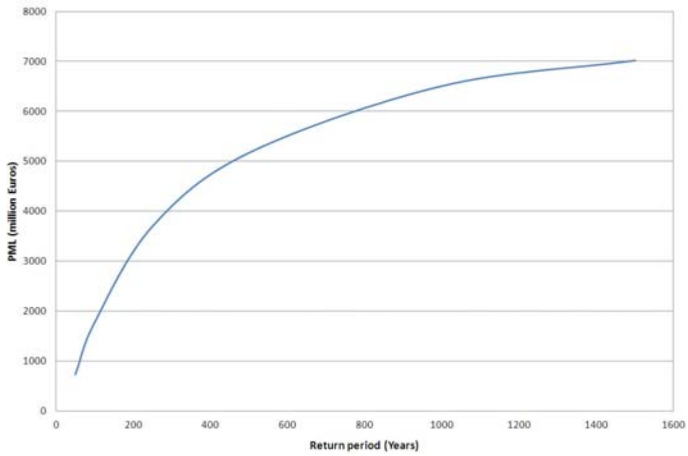


Figure 5. PML curve for the total portfolio of buildings of Barcelona

(a) (b)

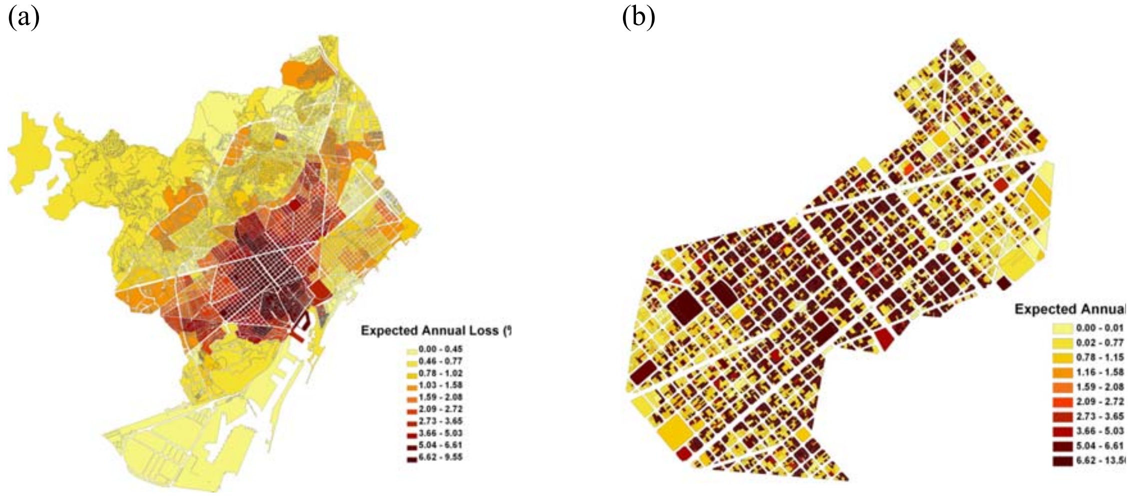


Figure 6. (a) Expected economic annual loss for the AEBs of Barcelona, (b) Expected economic annual loss represented building by building for the Eixample District of Barcelona

(a) (b)

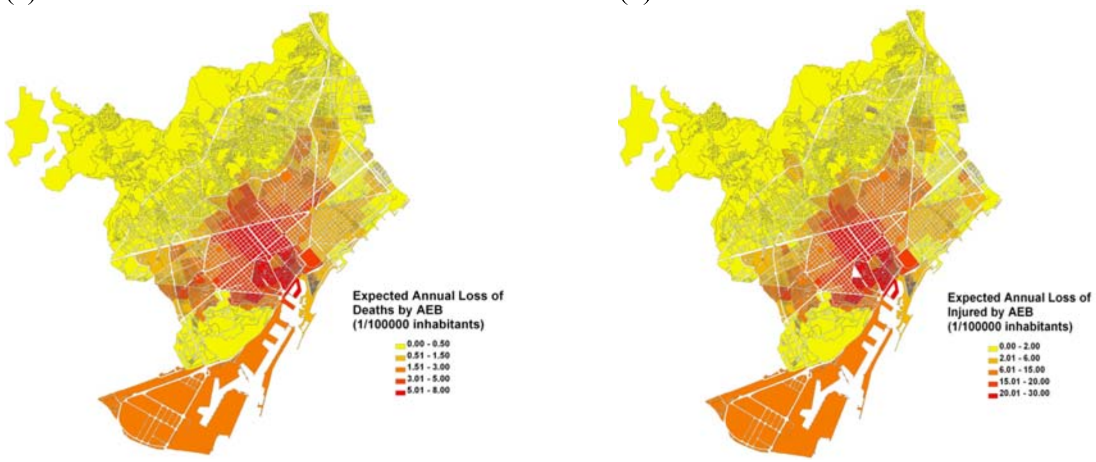


Figure 7. (a) Expected annual loss of deaths by AEB in Barcelona, Spain, (b) Expected annual loss of injured by AEB in Barcelona, Spain

2 APPLICATION: HOLISTIC EVALUATION OF RISK

A holistic evaluation of the seismic risk in urban areas is shown in this section by using one of the risk management applications of CAPRA (Carreño, 2006, Carreño et al., 2007b). Accordingly, risk is evaluated from a multidisciplinary point of view that takes into account not only the expected physical damage, the number and type of casualties or economic losses (first order impact), but also the conditions related to social fragility and lack of resilience, which favor second order effects (indirect impact) when an earthquake strikes an urban center (Cardona and Hurtado, 2000, Carreño et al., 2007b).

In the holistic evaluation of risk using indices, total risk is calculated by aggravating the physical risk with an impact factor (1+*F*) which considers the contextual conditions, such as the socio-economic fragility and the lack of resilience

The case study focuses on the holistic evaluation of the seismic risk of Barcelona, Spain. Figure 8 shows the descriptors used to describe the physical risk, the social fragility and the lack of resilience for this case study. These descriptors are different from those proposed by Carreño et al. (2007b) and they were chosen because they are the most significant for the context of the city. The descriptors of physical risk are obtained from the results calculated with the CAPRA platform shown in previous sections of this article. The descriptors of social fragility and lack of resilience are taken from the available information of the city (Carreño et al., 2007b, Marulanda et al., 2009).

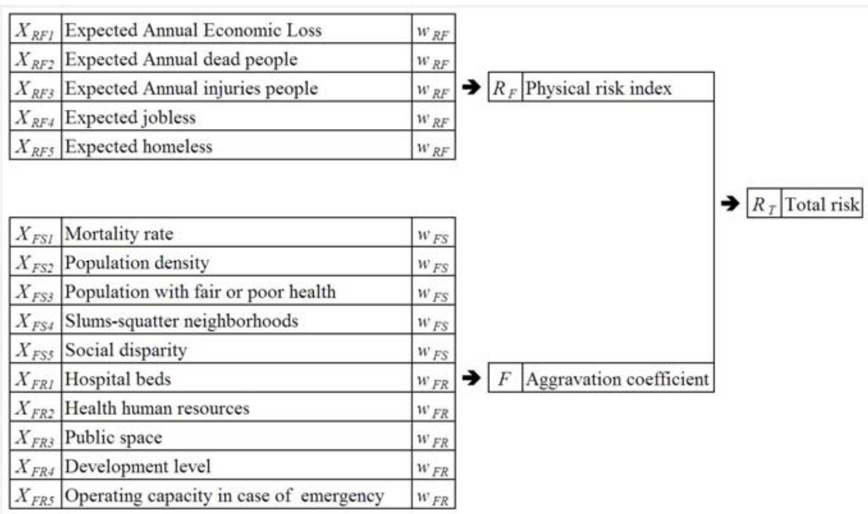


Figure 8. Descriptors of the physical risk, social fragility and lack of resilience and their weights

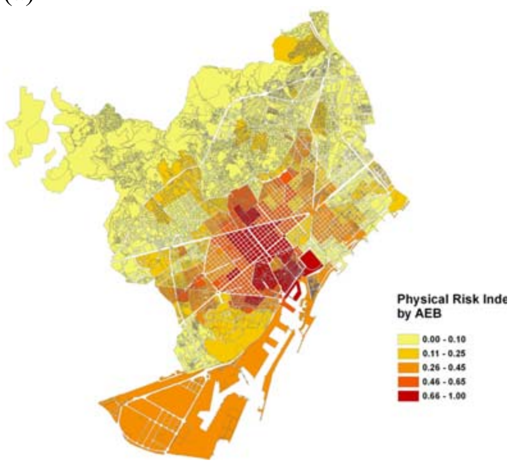
The robustness of this methodology was studied assessing the uncertainty of values and sensitivity to change of values, weights and transformation functions (Marulanda et al., 2009). Detailed information about this method of evaluation can be found in Carreño (2006), Carreño et al. (2007b), Barbat et al. (2011) and Carreño et al., 2012. For risk management purposes, the risk assessment helps to improve the decision-making process thus, contributes to the effectiveness of risk management, calling for action and identifying the weaknesses of the exposed elements and their evolution over time (Carreño et al., 2007a). The disaggregation of risk results obtained by the holistic approach facilitates the identification of socioeconomic underlying causes or soft issues reflected by the indicators of the aggravating factor. These identifications help to involve the policy makers and stakeholders related to diverse risk management actions.

2.1. Results of the holistic risk evaluation

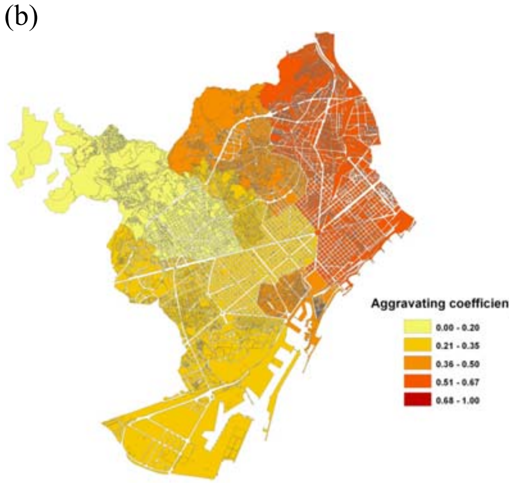
Figure 9(a) shows the results obtained for the physical risk index, R_F, for the AEB's of Barcelona. The greatest physical risk values correspond to the districts of Ciutat Vella and Eixample, which are the oldest areas of Barcelona. The lowest values were presented in the districts of Nou Barris and Horta-Guinardo.

Figure 9(b) shows the results of the aggravating coefficient for each district of the city. The district of Ciutat Vella has the worst aggravating situation according to the characteristics of social fragility and lack of resilience, the best situation is for the Sarria-Sant Gervasi and Les Corts districts.

(a)



(b)



(c)

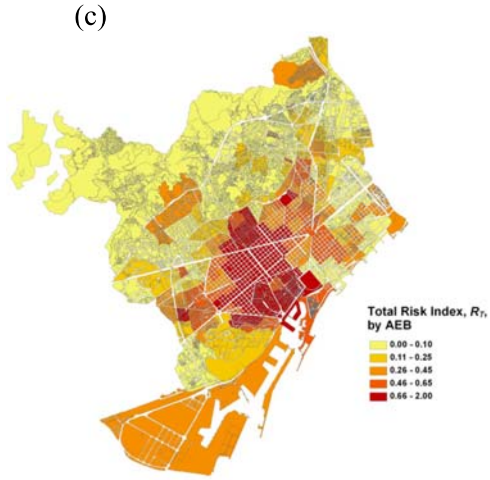


Figure 9. (a) Physical risk index, (b) Aggravating coefficient for the Barcelona districts, (c) Total risk index for Barcelona, Spain

Figure 9(c) shows the results of the total risk index, R_T, for the AEB's of Barcelona. These indexes are useful for comparisons in relative way, to identify the places and the issues why some areas need to be classified as priority zones for risk management action implementation.

An automated tool has been developed to incorporate the physical risk results obtained using the CAPRA-GIS (ERN-AL, 2010) into the holistic risk evaluation. Since risk analysis can be performed at different resolution levels, the tool allows the selection of the desired level, and if the risk has been calculated on a more detailed scale, it groups the results into de desired unites. This tool, *Evaluación Holística del Riesgo – EvHo* (CIMNE, 2014) reads the physical risk files and calculates the different physical risk factors while assigning their correspondent weights.

3 CONCLUSIONS

Probabilistic techniques of CAPRA employ statistical analysis of historical datasets to simulate hazard intensities and frequencies across a country's territory. This hazard information can then be combined with the data on exposure and vulnerability, and spatially analyzed to estimate the resulting potential damage. This measure can be expressed in risk metrics such as a probable maximum loss for any given return period or as an average annual loss. Since this quantification of risk follows a rigorous methodology, users are enabled, with a common language, to measure and compare or aggregate expected losses from various hazards.

Modular, extensible and open developing of the platform's architecture enables the possibility of harnessing various inputs and contributions. This approach enables CAPRA to become a living instrument. CAPRA's innovation extends beyond the risk-modelling platform; a community of disaster risk users is now growing in the countries.

This case study focuses on the risk assessment of an urban area (by geographic units) due to the earthquake hazard, using as measure the Probable Maximum Loss (PML) for different return periods and the Average Annual Loss (AAL) also known as technical risk premium. The CAPRA platform has been used to calculate the abovementioned metrics for the city of Barcelona, Spain, to estimate scenarios of damages and losses and to perform the holistic evaluation of seismic risk. All these results are useful to inform the policy makers and stakeholders the actions and interventions for risk reduction and for the emergency response plans of the city.

The values of PML and AAL obtained for Barcelona are the main results of this application. They are particularly relevant for the future designing of risk retention (financing) or risk transfer instruments and, therefore, they are a particularly valuable contribution to further implementation of disaster risk financing in the city. They allow defining a strategy for financial protection to cover the contingency liabilities of the public sector, since financial protection should be a planned and somewhat controlled process, given that the magnitude of the catastrophic problem could represent a great governmental response and financial liabilities. For management purposes, the risk assessment should improve the decision-making process in order to contribute to the effectiveness of risk management, identifying the weaknesses of the exposed elements and their evolution over time. The holistic evaluation requires a multidisciplinary perspective, that is, an integrated and comprehensive approach useful to communicate risk and to guide the stakeholders, helping to identify the critical zones of a city and their vulnerability from different perspectives of professional disciplines. This approach contributes to the effectiveness of risk management, inviting to the implementation or action by identifying the hard and soft weaknesses of the urban centre.

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