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Probabilistic earthquake risk assessment using CAPRA: Application to the city of Barcelona, Spain

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Understanding disaster risk due to hazard events such as earthquakes creates powerful incentives for countries to develop planning options and tools to reduce potential damages. The risk evaluation model CAPRA (Comprehensive Approach to Probabilistic Risk Assessment) described in this article is a techno-scientific methodology and information platform, composed of tools for the evaluation and communication of risk at various territorial levels. The model allows evaluating losses on exposed elements using probabilistic metrics, such as the exceedance probability curve, expected annual loss and probable maximum loss, useful for multi-hazard risk analyses. The platform is conceptually oriented to facilitate decision-making; by using the results obtained with the CAPRA platform, it is possible to design risk transfer instruments, evaluating probabilistic cost-benefit ratio, providing an innovative tool for decision makers to analyse the net benefits of risk mitigation strategies like building retrofitting. This model is also useful for land use planning, for determining loss scenarios for emergency response, early warning, on-line loss assessment mechanisms and for the holistic evaluation of disaster risk based on indicators that facilitates the integrated risk management by the different stakeholders involved in risk reduction decision-making. All the modules of the CAPRA platform are described in this article by using as an example the city of Barcelona, Spain. Likewise, the article presents one of those applications that can be made by using the results of CAPRA: the holistic evaluation of the seismic risk of Barcelona.

Keywords: *probabilistic risk assessment, average annual loss, pure premium, loss exceedance curve, probable maximum loss*

1. INTRODUCTION

A disaster represents the materialization of existent risk conditions. The risk level of a society is related to its development achievements and its capacity to intervene the existing risk. Hence urban planning and efficient strategies are necessary to reduce risk and improve sustainable development. Risk management is a fundamental development strategy that considers four principal policies: risk identification, risk reduction, disaster management and risk transfer.

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One of the key strategic activities of disaster risk management is the assessment of the risk to extreme events, which requires the use of reliable methodologies that allow an adequate calculation of probabilistic losses of exposed elements. The use of models for catastrophic risk assessment and the results they provide make feasible to determine the potential deficit existing in case of the occurrence of an extreme event. Catastrophe risk models –based on metrics such as the Probabilistic Maximum Loss and the Average Annual Loss– are used to estimate, building by building, the probabilistic losses of different portfolios of exposed elements. Usually, these kinds of evaluations where performed by the private financial markets; nevertheless, at present, it is understood that 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 city and country levels (Pollner, 2001; Andersen, 2002). Besides, estimation of contingency losses provides information and permits to set out strategies *ex ante* for reducing or financing them (Marulanda *et al.*, 2008; Cardona *et al.*, 2010a; Cardona *et al.*, 2010b; Marulanda *et al.*, 2010; Cardona *et al.*, 2010a; Cardona *et al.*, 2010b). Assessment of potential losses allows considering budget allocation for structural retrofitting in order to reduce damages and also implementing an effective financial protection strategy meant to provide loss coverage of public infrastructure and private buildings to protect government resources and safeguard socioeconomic development. 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 to attend catastrophic events. There are few recognized models at international level such as RMS, EQECAT, AIR Worlwide and ERN; nevertheless, most of them have been "black boxes" and their theoretical fundamentals are not known. On the other hand, the platform CAPRA, developed by the ERN-AL Consortium, was conceived as an open source model that aims at different activities of the disaster risk management and not only at the financial perspective.

In this article, we describe the probabilistic risk assessment methodology *Comprehensive Approach to Probabilistic Risk Assessment*, *CAPRA* (Cardona *et al.*, 2010b; www.ecapra.org). It is a robust techno-scientific information platform which allows identifying important metrics of catastrophe risk that can contribute to the knowledge of the contingency liabilities of the public sector and the economic impact upon the private sector, thus facilitating the consideration of risk transfer strategies for financial protection. Additionally, based on those metrics provided by CAPRA, it is possible to obtain potential scenarios of damage that are useful in developing emergency response plans and in implementing risk reduction measures considering physical, social and organizational points of view. In last years, CAPRA has been widely used in evaluating multi-hazard risk in different capital cities of countries of Latin America such as: Nicaragua, Costa Rica, El Salvador, Guatemala, Honduras, Belize, among others.

In this article we used the city of Barcelona, Spain, as a testbed 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 the most part of its building stock belongs to the pre-code period of Spain. Thus, its physical risk is significant. Additionally, it is a highly populated city, fact which 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 improving these previous evaluations. Due to all these reasons, Barcelona is used as an example to illustrate all the tool modules of the CAPRA platform and to estimate the holistic seismic risk of this urban area using one of the application modules of CAPRA.

2. PROBABILISTIC EARTHQUAKE RISK MODEL

The frequency of catastrophic seismic events is particularly low; that is why very limited historical data are available. Having in mind the possibility of future highly destructive events in many areas of the world, risk estimation has to focus on probabilistic models that can use the limited available information to best predict future scenarios considering the high uncertainties involved in the analysis. Therefore, risk assessment needs to be prospective, anticipating scientifically credible events that might happen in the future. The earthquake prediction models are developed using seismological and engineering bases that allows assessing the risk of loss for catastrophic events. Since large uncertainties related to the severity and frequency characteristics of the events are inherent in the models, the earthquake risk models use probabilistic formulations that incorporate these uncertainties into the risk assessment. The probabilistic risk model (PRM) built upon a sequence of modules (Woo, 1999, 2011; Grossi *et al.*, 2005; Cardona *et al.*, 2008a; b; c; d), quantifies potential losses arising from earthquake events as shown in the Figure 1.

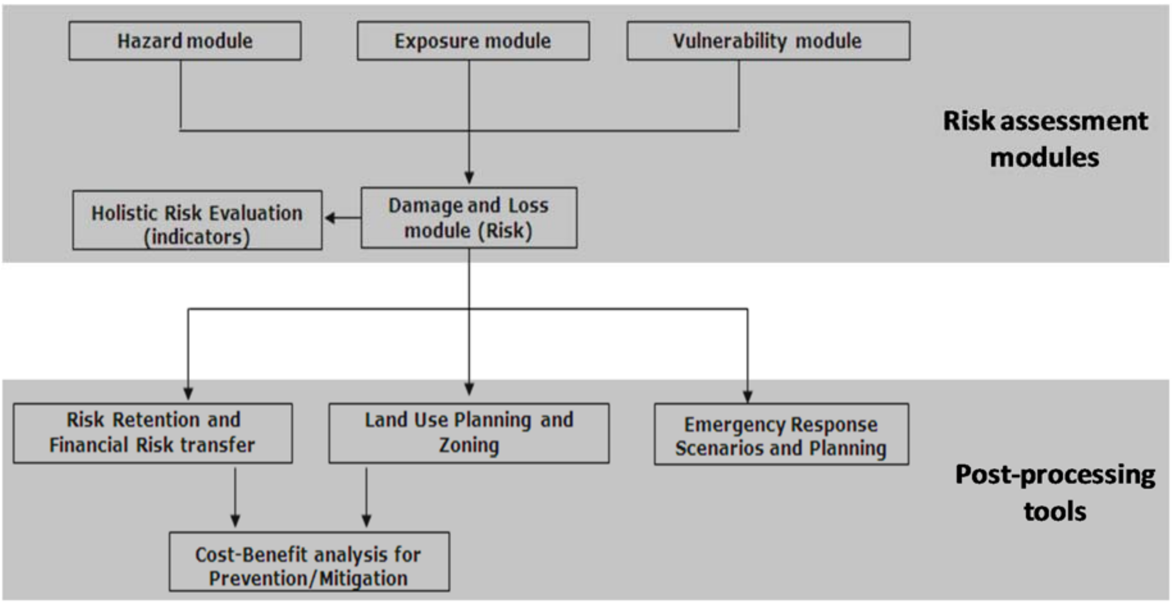


Figure 1. Probabilistic risk model and disaster risk management applications

The CAPRA model (Cardona *et al.*, 2010b; www.ecapra.org) is a multihazard PRM which demonstrated in the past its great capacity of evaluating risk of natural origin at different levels: regional, national or local. In this article, we consider only the seismic risk feature of CAPRA and its application at urban level.

3. SEISMIC HAZARD MODULE

The hazard module defines the frequency and severity of a peril at a specific location. This is formulated by analyzing the historical event frequencies and reviewing scientific studies performed on the severity and frequencies in the region of interest. Once the hazard parameters are established, stochastic event sets are generated which define the frequency and severity of thousands of stochastic events. In the case of earthquakes, this module can analyze the intensity at a location once an event in the stochastic set has occurred, by modelling the attenuation of the event from its location to the site under consideration, and evaluates the propensity of local site conditions to either amplify or reduce the impact. The seismic hazard is quantified in terms of return periods (or exceedance rates) of the relevant seismic intensities, *a*. Its calculation includes the contribution of the effects of all seismic sources located in a certain influence area.

Once identified these seismic sources, a certain occurrence model is assigned to the earthquakes that take place there. In most cases, modelling of the seismic sources follows a Poisson process in which $\lambda(M)$ represents the activity rates for each faulting system. Since the seismic sources are actually volumes and the methodology considers a point source approach, the epicentres can occur not only in the centres of the sources but also, with equal probability, in any point inside the corresponding volume. Therefore, for simulating event sets, sub-sources are defined by subdividing the seismic sources, depending on the hypocentral distance (R_0), in diverse geometric shapes. For each subdivision, the seismicity of the source is considered to be concentrated in its centre of gravity.

The model also considers the attenuation effects of the seismic waves by means of probabilistic spectral attenuation laws that include different source types as well as local amplification effects based on microzonation studies and other available additional information. Since the computed intensity is treated as a random variable with lognormal distribution, its corresponding uncertainty value (σ_{Lna}) is considered to include the associated variability.

Assuming that the intensity variable has a lognormal distribution given the magnitude (M) and distance (R_0), the probability of a given seismic intensity, *a,* Pr ($A>a|M, Ri$), is calculated as follows:

$$\Pr(A > a \mid M, R_0) = \Phi\left(\frac{1}{\sigma_{\ln a}} \ln \frac{MED(A \mid M, R_0)}{a} \right) \tag{1}$$

where $\Phi(\cdot)$ is the standard normal distribution, $MED(A|M, R_0)$ is the median value of the intensity variable (given by the corresponding attenuation law) and σ_{Lna} the standard deviation of the natural logarithm of the intensity, *a).* This methodology, based on Esteva (1970) and Ordaz (2000), generates stochastic seismic events at random locations within the modeled seismic sources, calculates the probability density function, PDF, of the seismic intensity*, a,* for a specific location and, if required, adds up the contributions of all sources and magnitudes in order to compute intensity exceedance rates, as those depicted in Figure 2 for the city of Barcelona, Spain. From these intensity exceedance rates, it is possible to determine uniform hazard spectra, UHS, for a specific site, based on the calculated intensity value (e.g. PGA, spectral acceleration, etc.) associated to a fixed return period. Therefore, UHS can be determined by connecting the intensity points calculated from Figure 2 for a given exceedance rate (inverse of the return period).

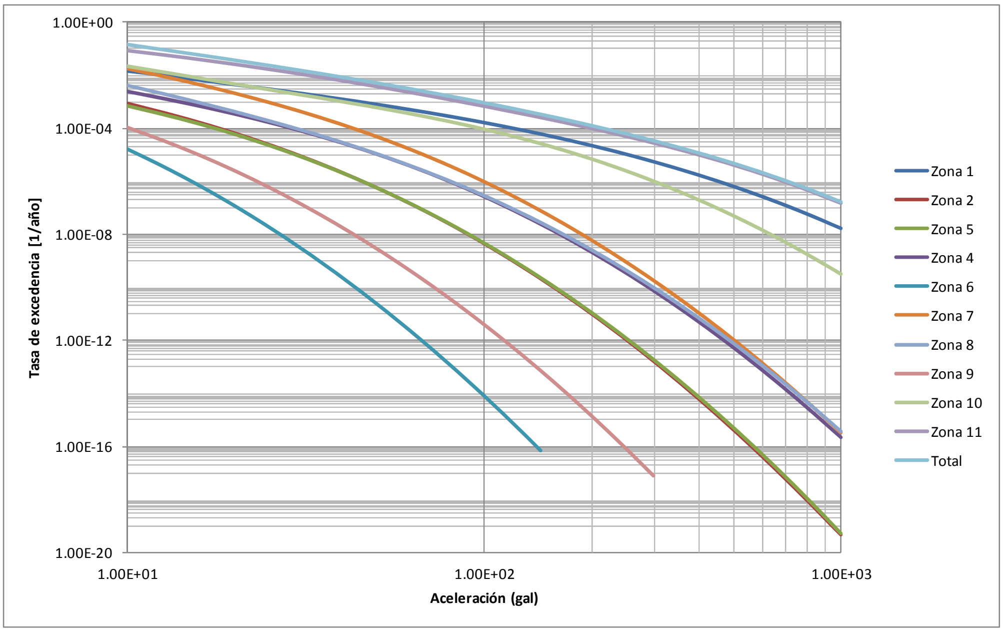


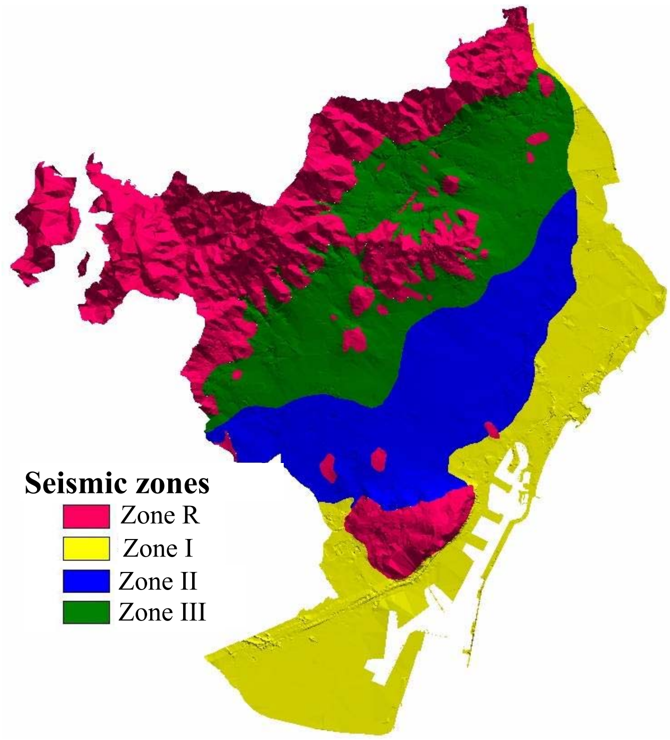
Figure 2.Exceedance rates for seismic hazard intensity parameter at bedrock site for Barcelona, Spain

The application in Barcelona takes into account the 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). Vs = Shear waves velocity
Figure **3** shows the seismic zonation of Barcelona based on the local effects defined by Cid *et al.* (2001),which consider 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.

The seismic hazard of Barcelona was simulated by using the CRISIS 2007 code[5] (Ordaz *et al.*, 2007). 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. Each grid is a scenario of the intensity level obtained from historical or stochastic generated events, with their

[5] http://sites.google.com/site/softwarecrisis/

frequency of occurrence. For this case, we selected as parameter characterizing the seismic intensity the spectral acceleration.



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

Vs = Shear waves velocity

Figure 3. Seismic zonation of Barcelona based on local effects (Cid *et al.*, 2001)

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. For Barcelona, 2058 seismic hazard scenarios were generated.

4. EXPOSURE MODULE

The exposure is mainly related to the infrastructure components or to the exposed population that can be affected by a particular event. The exposure module is based on files in *shape* format corresponding to the exposed infrastructure included in the risk analysis. To characterize the exposure, it is necessary to identify the individual components, including their location, their main physical, geometric and engineering characteristics, their vulnerability to hazardous events, their economic value and the level of human occupancy of the studied area. The exposure value of the assets at risk is usually estimated using secondary sources such as available databases and the degree of precision of the results depends on the level of resolution and on the details of the exposure information.

The information used to establish the exposure of the city of Barcelona was the one compiled by Lantada (2007). The economic value of the exposed elements was supplied by the Cadastral Office of Barcelona and 70655 buildings were considered in the study. They are distributed in 10 municipal districts as is shown in Figure 4, 73 neighborhoods, 233 Basic Statistical Areas (AEB in Spanish – Áreas Estadísticas Básicas) and 1061 census sections. For instance, **Figure 5** shows the exposure of Barcelona by AEB, in Euros. For each building the geographic location, the economic value, the year of construction, the number of levels, the structural type and the human occupancy were assigned. In this study, the risk results have been obtained building by building, starting from the building by building data, but the results can be presented at any desirable geographical level.

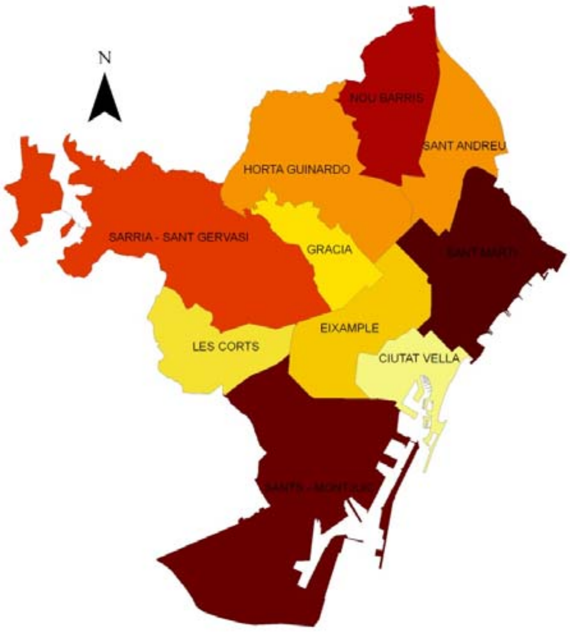


Figure 4. Territorial subdivision of Barcelona

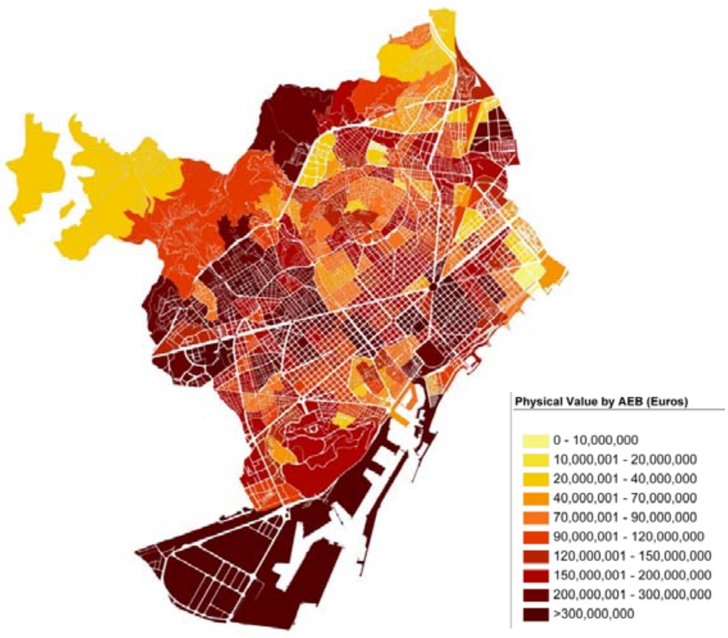


Figure 5. Exposed value of Barcelona by AEBs, in Euros

In order to calculate the social impact, general information related to building occupancy level is also estimated. Maximum occupancy and occupancy percentage at different hours are defined in order to obtain different time dependent scenarios related to the occurrence of the event. When no specific occupation information was available, an approximate occupancy density by construction class was supposed in order to complete this information.

5. 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.

Defining loss L as a random variable, the vulnerability functions describe the variation of the statistical moments of loss for different values of the seismic demand. The probability distribution of loss is usually assumed as a Beta function, where the statistical moments correspond to mean (usually referred to as Mean Damage Ratio, MDR) and standard deviation. The Beta distribution $p_{L|S}(L)$ is defined as follows:

$$p_{L|S}(L) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} L^{a-1}(1-L)^{b-1} \tag{2}$$

where Γ is the Gamma function and the parameters a and b are:

$$a = \frac{1-\left(1+c^2(L \mid S)\right)E(L \mid S)}{c^2(L \mid S)} \tag{3}$$

$$b = a \cdot \frac{1-E(L \mid S)}{E(L \mid S)} \tag{4}$$

E(L|S) is the loss mean or expected value and *c(L|S)* is the loss variation coefficient, given a seismic demand *S*. Note that *c(L|S)=SD(L|S)/E(L|S)* where *SD(L|S)* is the loss standard deviation given a seismic demand S.

Vulnerability functions provide all the necessary information to calculate the probability of reaching or exceeding a loss value, given a seismic demand

Instead of using qualitative scales as in the case of damage states, it is used numerical scales to define the loss, like for example, the ratio of the repair cost of a building to the replacement value, with a direct use in probabilistic risk and loss calculations. The probability of reaching or exceeding a loss value is calculated as follows:

$$\Pr(L \geq l \mid S) = \int_{l}^{\infty} p_{L|S}(L)dL \tag{5}$$

where l is a loss value in the domain of the random variable L, and S is the seismic demand.

Damage is estimated in terms of the Mean Damage Ratio, MDR which is defined as the ratio of the expected repair cost to the replacement cost 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). Given a value of the seismic intensity for a certain building type, MDR can be calculated by using Equation 6 (Miranda, 1999; Ordaz, 2000):

$$E(\beta \mid \gamma_{\mathrm{i}}) = 1 - \exp\left[\ln 0.5\left(\frac{\gamma_{\mathrm{i}}}{\gamma_0}\right)^{\varepsilon}\right] \tag{6}$$

where β is the loss, γ_0 and γ_i are structural vulnerability parameters that depend of the building typology and construction age, ε is the slope and E(.) is the expected value. By definition, β is the ration of the repairing cost to the total cost of the building and takes values from 0 to 1. It is possible to determine the maximum nonlinear drift by using the spectral acceleration as follows (Miranda, 1997):

$$\gamma_i = \frac{\beta_1 \beta_2 \beta_3 \beta_4 \left(\eta N^{\rho}\right)^2}{4\pi^2 \,\mathrm{Nh}} S_a(T) \qquad T = \eta N^{\rho} \tag{7}$$

In Equation 7, β1 is the ratio of the maximum lateral displacement at the upper level of the structure to the spectral displacement; β2 is the ration of the maximum interstory drift to the global drift of the structure; β3 is the ratio of the maximum inelastic lateral displacement to the maximum displacement of the elastic model; β4 is the ratio between the elastic and inelastic factors β2; ρ and n are factors allowing to estimate the fundamental period of the structure from the number of stories, N; h is the height of each story of the building that depends on the structural typology, the geographic location and the construction age; Sa(T) is the spectral acceleration that depends on the fundamental vibration period of the structure, T, the structural damping and the seismic hazard in the building site. 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 figures 6 and 7.

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 have usually not 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) and are shown in Table 1.

Table 1. Building classes matrix for Barcelona (ICC/CIMNE, 2004)

UNREINFORCED MASONRY	M3.1	Unreinforced masonry bearing walls with wooden slabs
	M3.2	Unreinforced masonry bearing walls with Masonry vaults
	M3.3	Unreinforced masonry bearing walls with composite steel and masonry slabs
	M3.4	Reinforced concrete slabs
REINFORCED CONCRETE	RC3.1	Concrete frames with unreinforced masonry infill walls with regularly infill frames
	RC3.2	Concrete frames with unreinforced masonry infill walls with irregularly frames (i.e., irregular structural system, irregular infill, soft/weak storey)
STEEL MOMENT FRAMES	S1	A frame of steel columns and beams
STEEL BRACED FRAMES	S2	Vertical components of the lateral-force-resisting system are braced frames rather than moment frames.
STEEL FRAMES WITH UNREINFORCED MASONRY INFILL WALLS	S3	The infill walls usually are offset from the exterior frame members, wrap around them, and present a smooth masonry exterior with no indication of the frame.
STEEL AND RC COMPOSITE SYSTEMS	S5	Moment resisting frame of composite steel and concrete columns and beams. Usually the structure is concealed on the outside by exterior non-structural walls.
WOOD STRUCTURES	W	Repetitive framing by wood rafters or joists on wood stud walls. Loads are light and spans are small.

Each structural type is subdivided into 3 classes according to the height of the building:

- *Low-rise buildings, L*: 1 to 2 floors for masonry and wood structures; 1 to 3 floors for reinforced concrete and steel buildings.
- Medium-rise buildings, M: 3 to 5 floors for masonry and wood structures; 4 to 7 floors for reinforced concrete and steel buildings.
- High-rise buildings, H: 6 or more floors for masonry and wood structures; 8 or more floors for reinforced concrete and steel buildings.

Figure 6 shows vulnerability functions corresponding to the unreinforced masonry buildings of Barcelona while Figure 7 shows vulnerability functions for other building typologies of the city, for low (L), medium (M) and high (H) structural height. These functions relate the severity of the event, represented by the spectral acceleration, with the average damage of the building.

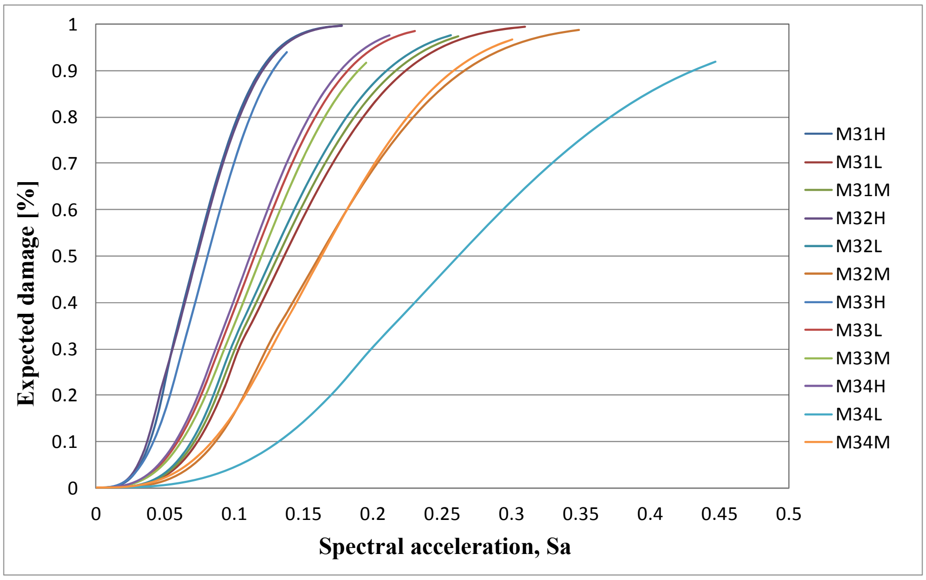


Figure 6. Vulnerability functions for unreinforced masonry buildings

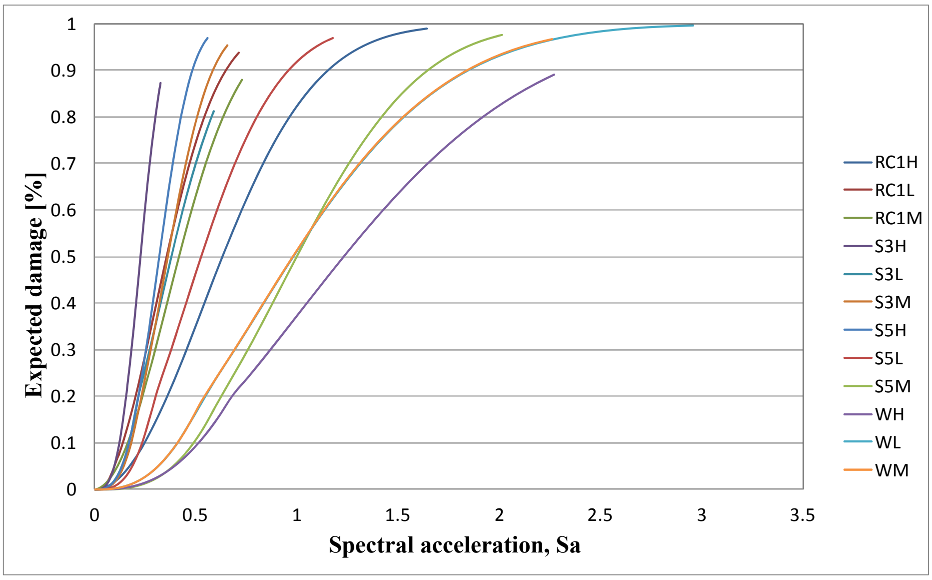


Figure 7. Vulnerability functions for reinforce concrete, steel and wood buildings

6. RISK MODULE

It is well known that risk is usually measured by means of the exceedance rate of loss, $\nu(p)$ which is the expected number of earthquakes, per unit time, that will produce losses equal or larger than p. It is computed by using the total probability theorem

$$\nu(p) = \sum_{i=1}^{Events} \Pr(P > p | Event\ i) F_A(Event\ i) \tag{8}$$

where $\Pr(P>p|Event\ i)$ is the probability of exceedance of the loss p given the occurrence of the event i, and $F_A(Event\ i)$ is the annual occurrence frequency of event i. Vulnerability functions are used to compute $\Pr(P>p|Event\ i)$.

Normally, a seismic event would be specified in terms of, at least, its magnitude and the location of its hypocenter. Hence, in order to compute $\Pr(P>p|Event\ i)$ some considerations have to be made. First, it is assumed that, given the occurrence of the event i, with known magnitude and hypocentral location, the intensity at the site of the structure is a lognormal random variable with median and logarithmic standard deviation that, in general, depend on magnitude and source-site distance. Under this assumption, the required probability Pr $(P>p|Event\ i)$ is computed by chaining two conditional distributions:

$$\Pr(P > p \mid Event) = \int_{0}^{\infty} \Pr(P > p \mid Sa) p_{SA}(Sa \mid M, R) dSa \tag{9}$$

where p_{SA} $(Sa|M,R)$ is the probability density function of the intensity Sa given that a magnitude M earthquake occurs at a source-site distance R. As mentioned before, it is often assumed for $Sa|M,R$ a lognornal distribution, with median and logarithmic standard deviation that depend on M and R, which are computed using the ground-motion prediction model selected by the analyst. The first term of the integrand is, obviously, computed using the vulnerability relation that describes the behaviour of the structure under analysis. The above equations give a clear indication of how uncertainties in vulnerability are propagated throughout the risk analysis.

Thus, in order to calculate losses using this risk module, the damage ratio calculated in the vulnerability module is transformed into economic loss by multiplying it by the value at risk. This operation is done for each asset class, and at each location. Losses are then aggregated as stated by Ordaz *et al.* (1998) and Ordaz (2000). The loss module estimates the net losses. They can be useful for insurance information taking into account for example deductible, sum insured, etc. Risk metrics produced by the model provide risk managers and decision makers with essential information required to manage future risks. The main metrics for risk assessment are the following:

Loss Exceedance Curve, LEC, represents the annual frequency with which a loss of any specified monetary amount will be exceeded. 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.

Therefore, it is necessary to calculate excess rates of net losses from the portfolio. Such excess rates are not more than the number of times per year that is expected that a certain value of loss is even or exceeded. The excess rate of a given loss value p is calculated as:

$$\nu(p) = \sum_{i=1}^{Event} \Pr(P > p | Event\ i) F_A(Event\ i) \tag{11}$$

where $v(p)$ is he excess rate of p loss, Pr ($P>p/Event\ i$) is the excess probability of p loss, since event i occurred, and $F_A(Event\ i)$ is the annual occurrence frequency of event i.

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 *et al.*, 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. The average annual loss can be calculated as follows (Ordaz *et al.*, 1998; 1999):

$$AAL = \sum_{i=1}^{Events} E(P|Event\ \mathrm{i})F_A(Event\ \mathrm{i}) \tag{10}$$

where AAL is the Average Annual Loss, $E(P/Event\ i)$ is the expected loss value for the event i and F_A $(Event\ i)$ is annual occurrence frequency of the event i. The annual occurrence frequency of events depends on the results of hazard assessments. The loss expected value, given the occurrence of a particular event, depends on the vulnerability of the exposed element.

Probable Maximum Loss, PML, represents the loss amount for a given annual exceedance frequency, or its inverse, the return period. The PML curve is generally specified as the PML in economic value or in percentage with regard to the return period. The PML of an exposed base is an appraiser of the size of maximum losses that could be reasonably expected in a set of elements exposed during the occurrence of a hazard event. It is typically used as a fundamental data to determine the size of reserves insurance companies should maintain to avoid excessive losses that might surpass their adjustment capacity. It is defined in this model 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 obtained probabilistic results are shown in the Table 2, Table 3 and Table 4.

Table 2. Obtained results for the physical exposure of Barcelona

PHYSICAL EXPOSURE		
Exposed value	€ x10^6	31,522.80
Average Annual Loss	€ x10^6	72.14
	‰	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%
1,000	6,510.67	20.65%
1,500	7,021.14	22.27%

Table 3. Obtained results for dead people in Barcelona

DEAD PEOPLE		
Exposed value	Inhabitant	1,639,880.00
Average Annual Loss	Inhabitant	28.27
	‰	0.017‰
PML		
Return period	Loss	
Years	Inhabitant	%
50	101.41	0.01%
100	654.30	0.04%
250	2,069.97	0.13%
500	3,380.29	0.21%
1,000	4,898.39	0.30%
1,500	5,799.44	0.35%

Table 4. Obtained results for injured people in Barcelona

INJURED PEOPLE		
Exposed value	Inhabitant	1,639,880.00
Average Annual Loss	Inhabitant	113.55
	‰	0.07‰
PML		
Return period	Loss	
Years	Inhabitant	%
50	756.92	0.05%
100	3,420.18	0.21%
250	9,028.50	0.55%
500	12,590.98	0.77%
1,000	15,803.45	0.96%
1,500	16,903.45	1.03%

Figure 8 shows the PML curve obtained for Barcelona.

Figure **9** and Figure 10 show the expected annual economic loss by AEB, for Barcelona, and building by building, for the Eixample district, respectively. As it was previously mentioned, the expected annual loss can be also calculated in terms of human losses. Figure 11 and Figure 12 show the expected annual loss corresponding to deaths and injured, respectively, by AEB of Barcelona.

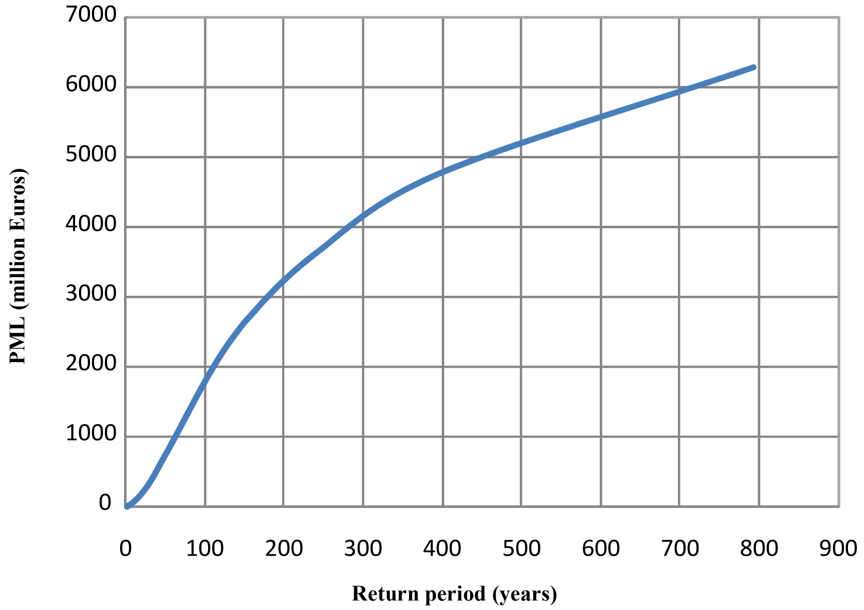


Figure 8. PML curve for Barcelona

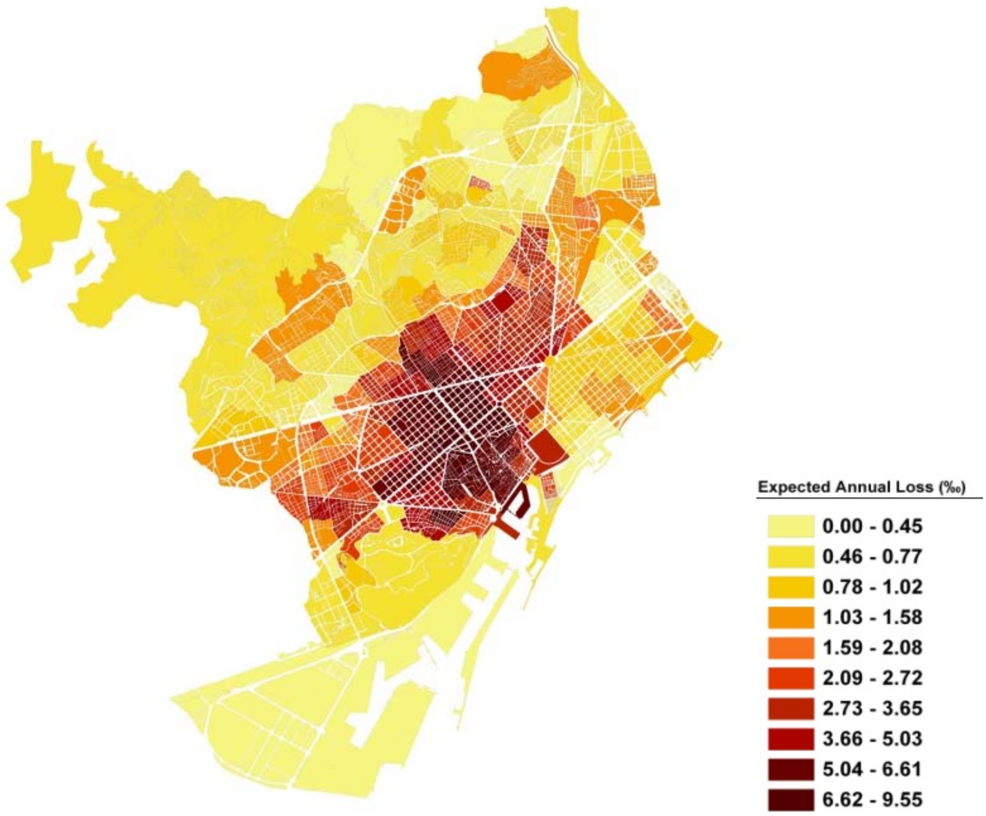


Figure 9. Expected economic annual loss for the AEBs of Barcelona

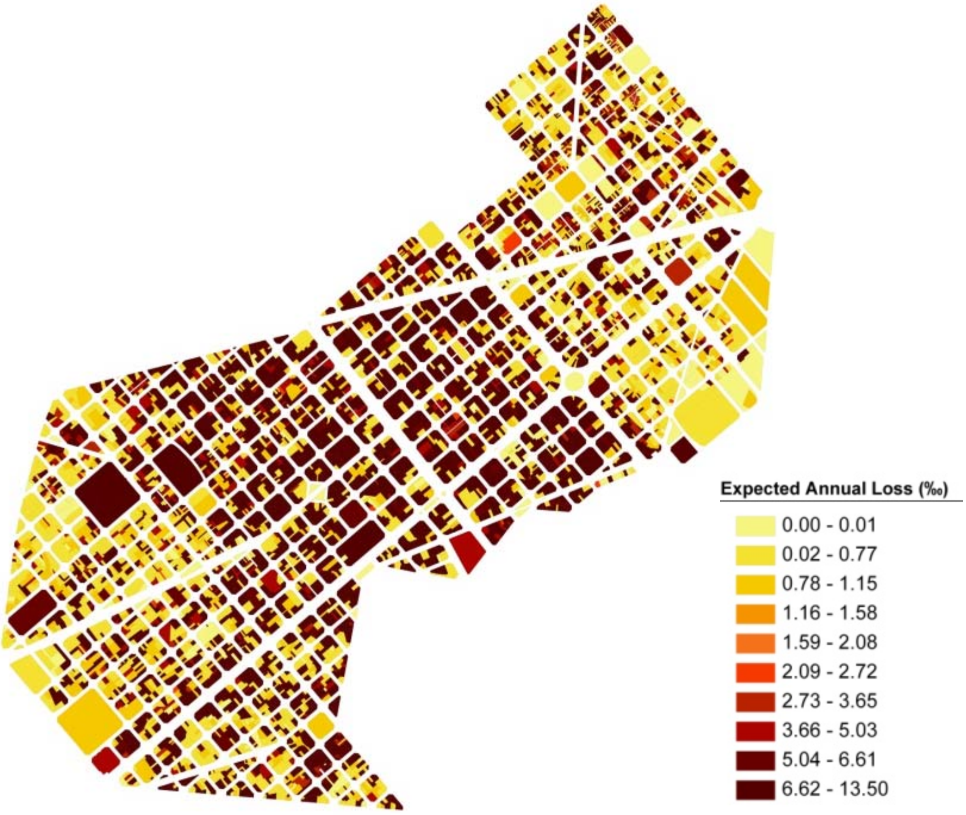


Figure 10. Expected economic annual loss represented building by building for the Eixample District of Barcelona

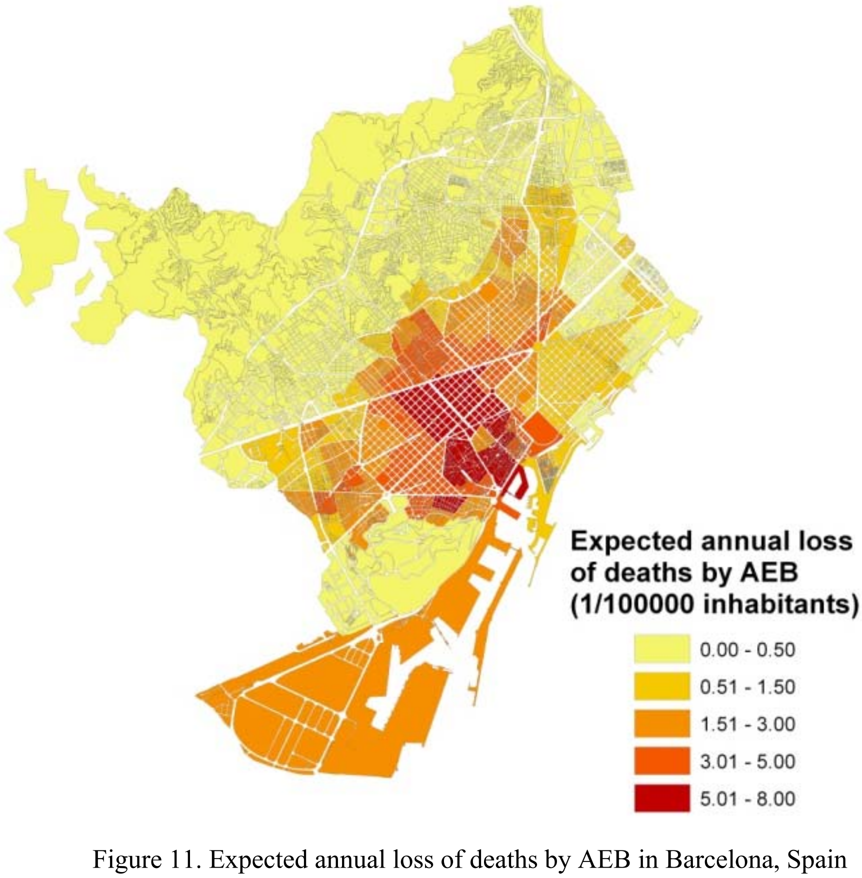


Figure 11. Expected annual loss of deaths by AEB in Barcelona, Spain

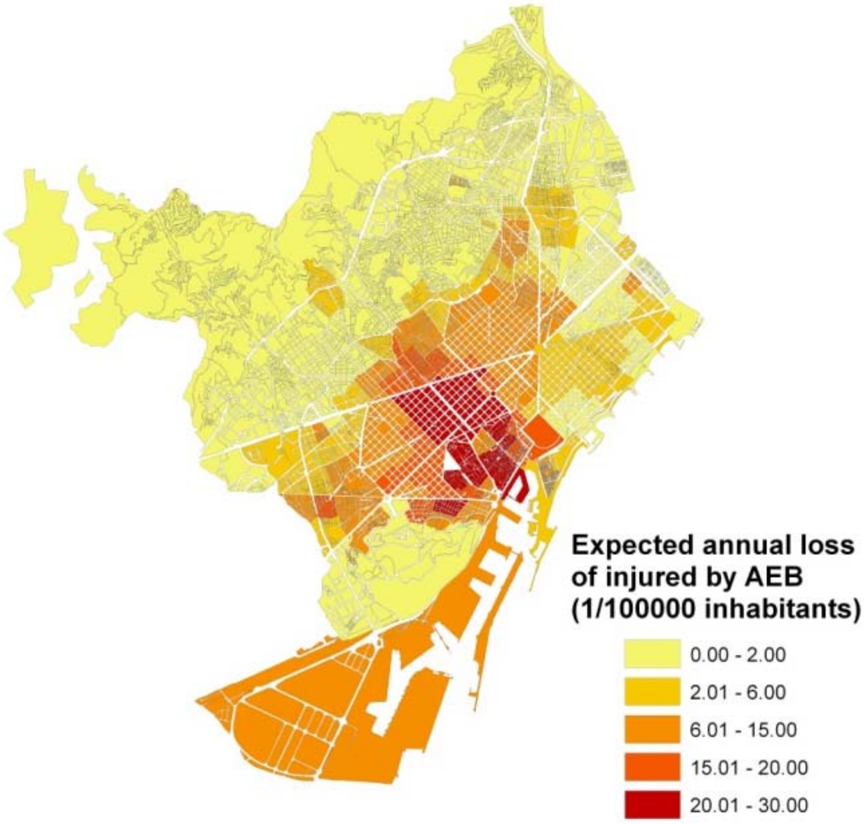


Figure 12. Expected annual loss of injured by AEB in Barcelona, Spain

In addition to the probabilistic economic figures, for developing city emergency response plans it is relevant to count with critical earthquake loss scenarios. In the case of Barcelona, it was chosen a critical scenario for a loss with a return period of 1000 years, to estimate people that could lose their job or their houses. The results of these assessments are based on the percentage of damage in each structure (greater than or equal to 20%). Table 5 presents the information corresponding to the critical seismic hazard scenario for Barcelona and Figure 13 and Figure 14 show the number of homeless people and jobless people, respectively.

Table 5. Information for the critical seismic hazard scenario for Barcelona

Nº	Scenario		Loss	
	Source	Magnitude	(Euros x 10^6)	%
600	Zone 4_SF2	6.56	6.78E+03	21

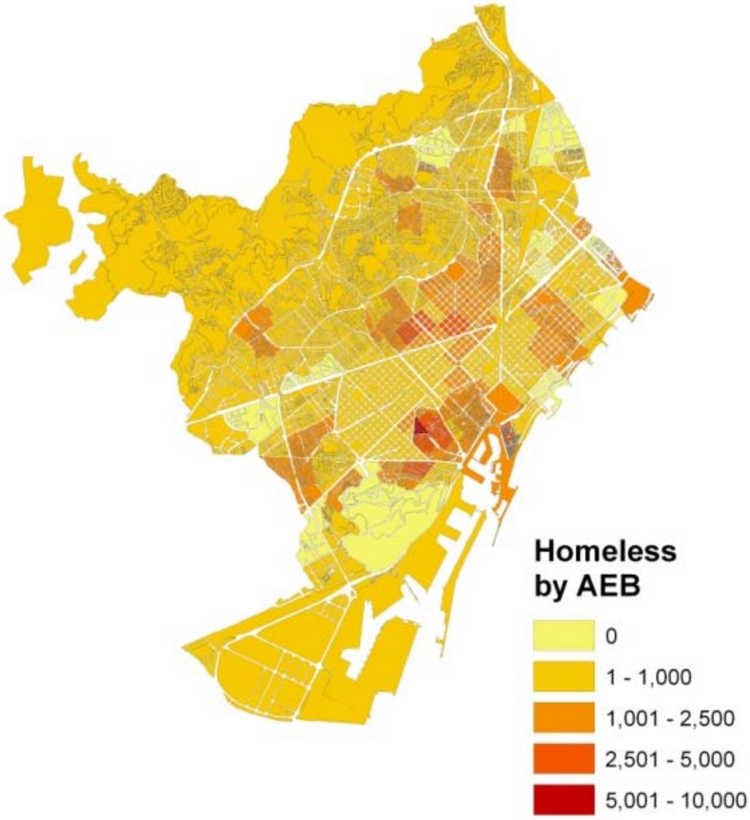


Figure 13. Homeless by AEB in Barcelona, Spain

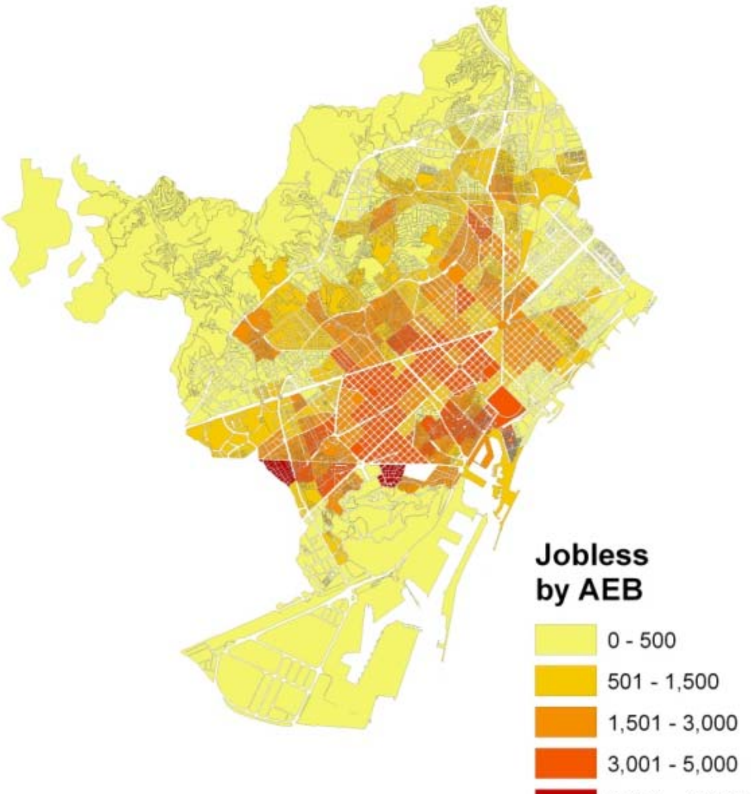


Figure 14. Jobless by AEB in Barcelona, Spain

7. APPLICATION: HOLISTIC EVALUATION OF RISK

7.1. Methodology

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 *et al.*, 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

$$R_T = R_F\left(1+F\right) \tag{11}$$

This equation is known as Moncho's Equation, where R_T is the total risk index, R_F is the physical risk index which is calculated as follows

$$R_F = \sum_{i=1}^{p} w_{RFi}\, F_{RFi} \tag{12}$$

and F is called aggravating coefficient which is calculated as follows

$$F = \sum_{i=1}^{m} w_{FSi}\, F_{FSi} + \sum_{j=1}^{m} w_{FRj}\, F_{FRj} \tag{13}$$

F_{FRi} are the p physical risk factors and w_{Fri} are the corresponding weights. The aggravating factor F_{FSi} and F_{FRj} are related to the socio-economic fragility and to the lack of resilience of the exposed context, respectively; these factors are calculated from the corresponding descriptors by using transformation functions, operation which is discussed below. m and n are the total number of descriptors for social fragility and lack of resilience, respectively. w_{FSi} and w_{FRj} are the weights of the aggravating factors.

Input data describing socio-economic and lack of resilience conditions at urban level are necessary to apply the method. The descriptors used in this evaluation have different nature and units, the transformation functions standardize the gross values of the descriptors, transforming them into commensurable factors. Figure 15 shows a model for the transformation functions used by the methodology in order to calculate the risk and aggravating factors. They are membership functions for high level of risk and high aggravating level for each. The values of x-axis are of the descriptors while the values of the factor (physical risk or aggravation) are in the y-axis and take values between 0 and 1, were 0 is the non membership and 1 is the total membership. The limit values, X_{min} and X_{max}, are defined using expert opinions and information about past disasters. In the case of the descriptors of lack of resilience, the function has the inverse shape; the higher value of the indicator gives the lower value of aggravation. The weights w_{FSi} and w_{FRj} represent the relative importance of each factor and are calculated by means of the Analytic Hierarchy Process (AHP), which is used to derive ratio scales from both discrete and continuous paired comparisons (Saaty *et al.*, 1991; Carreño, 2006; Carreño *et al.*, 2007b).

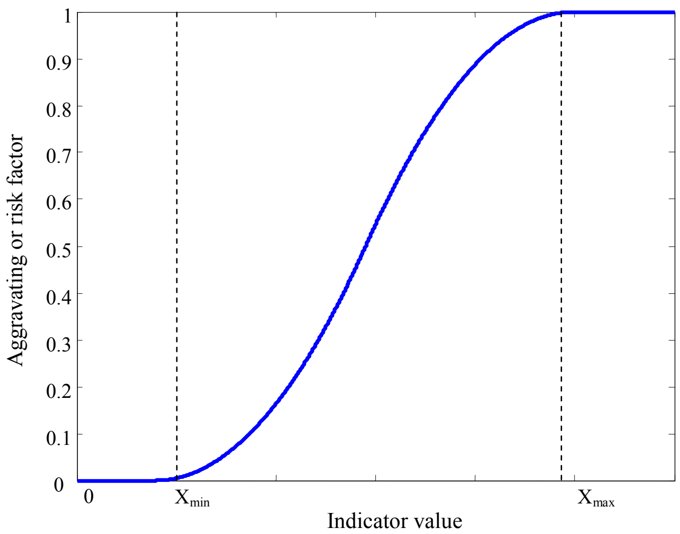


Figure 15. Model of the transformation functions

Figure 16 shows the process of calculation of the total risk index, R_T, for the units of analysis, which could be districts, municipalities, communes or localities, starting from the descriptors of physical risk, X_{RFi}, and the descriptors of the aggravating coefficient F, that is, X_{FSi} and X_{RFi}, using the weights w_{RFi}, w_{FSi} and w_{FRi} of each descriptor.

X_{RF1}	Expected Annual Economic Loss	w_{RF1}
X_{RF2}	Expected Annual dead people	w_{RF2}
X_{RF3}	Expected Annual injuries people	w_{RF3}
X_{RF4}	Expected jobless	w_{RF4}
X_{RF5}	Expected homeless	w_{RF5}

➔ | R_F | Physical risk index |

X_{FS1}	Mortality rate	w_{FS1}
X_{FS2}	Population density	w_{FS2}
X_{FS3}	Population with fair or poor health	w_{FS3}
X_{FS4}	Slums-squatter neighborhoods	w_{FS4}
X_{FS5}	Social disparity	w_{FS5}
X_{FR1}	Hospital beds	w_{FR1}
X_{FR2}	Health human resources	w_{FR2}
X_{FR3}	Public space	w_{FR3}
X_{FR4}	Development level	w_{FR4}
X_{FR5}	Operating capacity in case of emergency	w_{FR5}

➔ | F | Aggravation coefficient |

➔ | R_T | Total risk |

Figure 16. Descriptors of the physical risk, social fragility and lack of resilience and their weights

The case study focuses on the holistic evaluation of the seismic risk of Barcelona, Spain. Figure 16 shows the descriptors used to describe the physical risk, the social fragility and the lack of resilience for this case study. These descriptors were chosen because they are most significant for each category and are different from those proposed by Carreño et al. (2007b). 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).

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), and Barbat *et al.* (2011). 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).

7.2.Results of the holistic risk evaluation

The holistic evaluation of seismic risk was performed by using the methodology described in section 7.1. Figure 17 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.

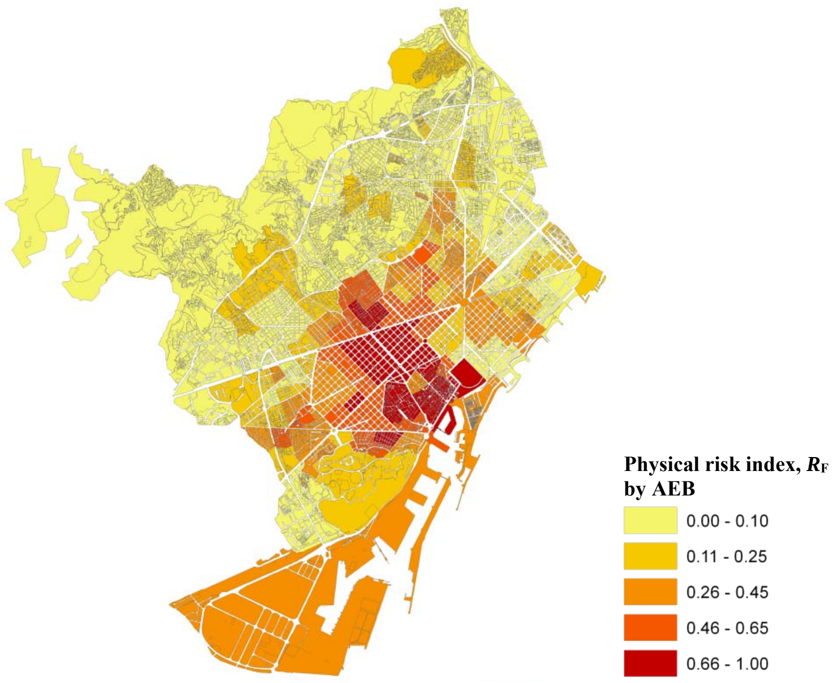


Figure 17. Physical risk index

Figure 18 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.

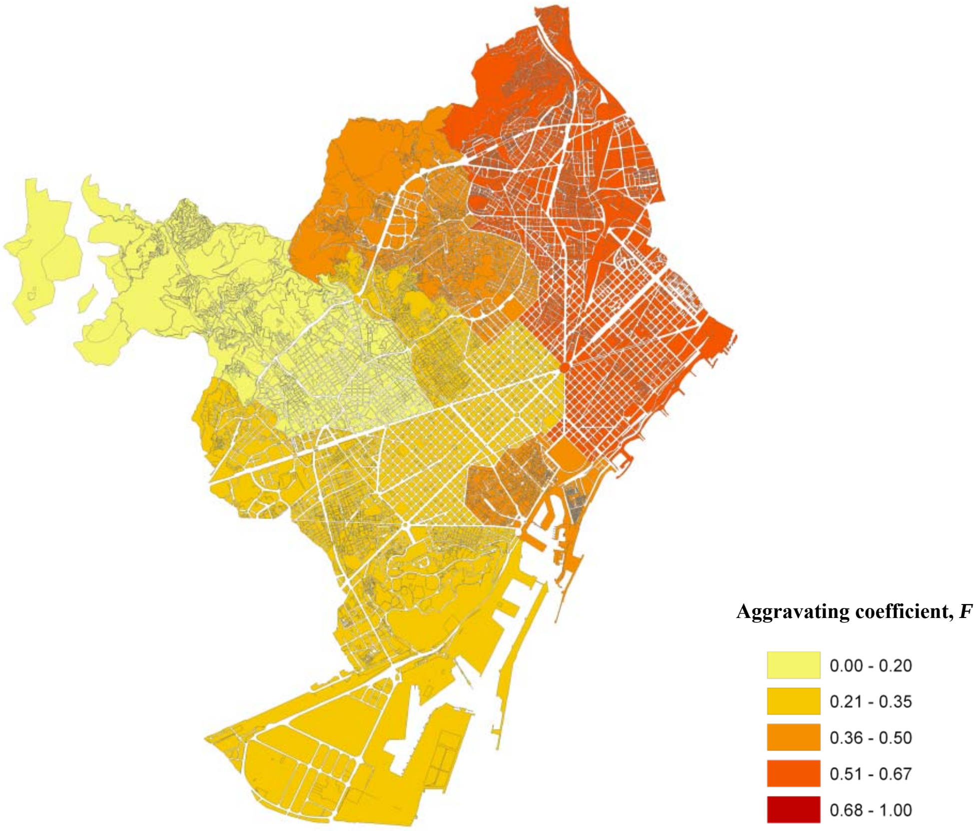


Figure 18. Aggravating coefficient for the Barcelona districts

Figure 19 shows the results of the total risk index, R_T, for the AEB's of Barcelona. Figure 20 shows the detailed results of the Eixample district by AEB.

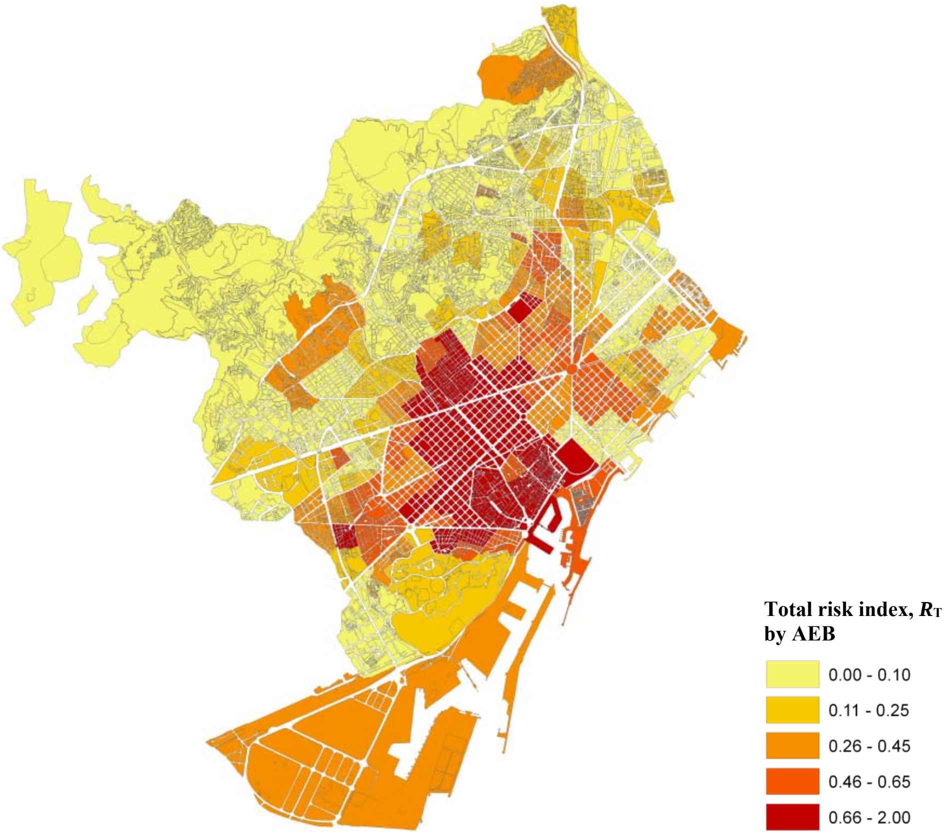


Figure 19. Total risk index for Barcelona, Spain

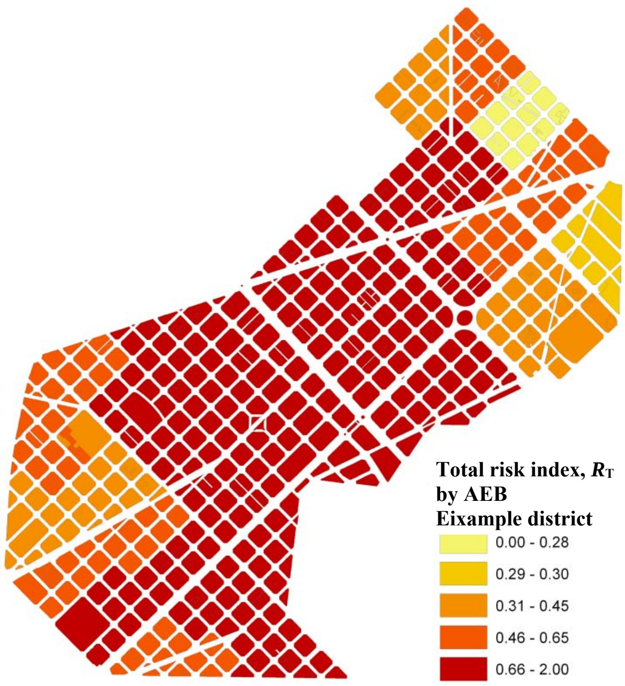


Figure 20. Detail of the total risk for the Eixample district of Barcelona, Spain

8. 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 to compare or to aggregate expected losses from various hazards, even in the case of future risks associated with climate change scenarios.

This study focuses on the risk assessment of urban areas (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 was used to calculate the mentioned 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 for risk reduction and for the emergency plans of the city.

The platform's architecture has been developed to be modular, extensible and open, enabling 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.

The values of PML and AAL obtained for Barcelona are the main results of this application. They are of particular importance for the future designing of risk retention (financing) or risk transfer instruments and, therefore, they are a particularly valuable contribution to further studies. The 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, it s an integrated and comprehensive approach that is 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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