# Holistic Evaluation of the Seismic Risk in Barcelona by Using Indicators

**M.L. Carreño**
*Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), Barcelona, Spain*

**O.D. Cardona**
*Universidad Nacional de Colombia, Manizales, Colombia*

**A.H. Barbat**
*Technical University of Catalonia, Barcelona, Spain*

**SUMMARY:**
This article presents a methodology which evaluates the seismic risk from a holistic perspective, that is, it takes into account the expected physical damage and also the conditions related to social fragility and lack of resilience, which favour the second order effects when a hazard event strikes an urban centre. Indicators are used in order to capture favourable conditions for direct physical impacts, as well as indirect and, at times, intangible impacts of hazard events. In the case of Barcelona, the seismic hazard has been simulated by using the CRISIS 2007 code. The vulnerability of the buildings in the city of Barcelona has been defined with vulnerability functions using the Vulnerability Module of the CAPRA platform. These functions are defined for each building typology; the used typologies were defined in ICC/CIMNE (2004). This case study is part of the results obtained in the MOVE project of the European Commission.

*Keywords: holistic approach, risk evaluation, urban seismic risk, socio-economic vulnerability*

## 1. INTRODUCTION

In the past, in many cases the concept of risk has been defined in a fragmentary way, according to each scientific discipline involved in its appraisal (Cardona 2004). Based on the formulation of the disaster risk of UNDRO (1980) several methodologies for risk assessment have been developed from different perspectives in the last decades. From a holistic perspective, risk requires a multidisciplinary evaluation 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 conditions, which favour the second order effects (indirect impact) when a seismic hazard event strikes an urban centre (Carreño et al. 2007a).

A multidisciplinary estimation of risk to guide decision making, which takes into account not only geophysical and structural aspects, but also economic, social, institutional variables, among others, is considered herein as a holistic approach. Even so, it is necessary to say that the urban scenarios of potential damage, that is, scenarios of physical aspects of risk, are essential, because they are the result of the convergence of hazard and physical vulnerability of buildings and infrastructure.

Cardona (2001) developed a conceptual framework and a model for risk analysis of a city from a holistic perspective, describing seismic risk by means of indices. He considered both “hard” and “soft” risk variables of the urban centre, taking into account exposure, socio-economic characteristics of the different areas or neighbourhoods of the city and their disaster coping capacity or degree of resilience. This method based the risk evaluation in a relative normalization of the involved indicators.

Carreño (2006) developed an alternative method for Urban Risk Evaluation, starting from Cardona’s model (Cardona 2001), in which urban risk is evaluated using composite indicators or indices. It conserves the approach based on indicators, but it improves the procedure of normalization and calculates the final risk indices in an absolute (non relative) manner. Other improvements of the proposed model refer to the selection of indicators and aspects involved in the evaluation, and how they are used (Carreño et al. 2007a). Afterwards, Marulanda et al. (2009) evaluate the robustness of the methodology proposed by Carreño (2006) and Carreño et al. (2007a).

Figure 1 shows the conceptual framework of the holistic approach for risk evaluation. From this comprehensive perspective, it can be seen that risk is a function of the physical vulnerability and a set of vulnerability factors $\varepsilon_i$. that configure the vulnerability conditions of the context. The physical vulnerability is obtained from the susceptibility of the exposed elements to hazards, considering the potential intensities, *I*, of the hazardous events in a period of time *t*, the vulnerability of the context depends on the social fragilities and issues related to lack of resilience of the disaster prone socio-technical system. Using the meta-concepts of the theory of control to reduce risk, it is necessary to intervene through corrective and prospective actions the vulnerability factors $\varepsilon_i$. Then, risk management requires a system of control (institutional structure) and an actuation system (public policies and actions) to implement the changes needed on the exposed elements to reduce risk.

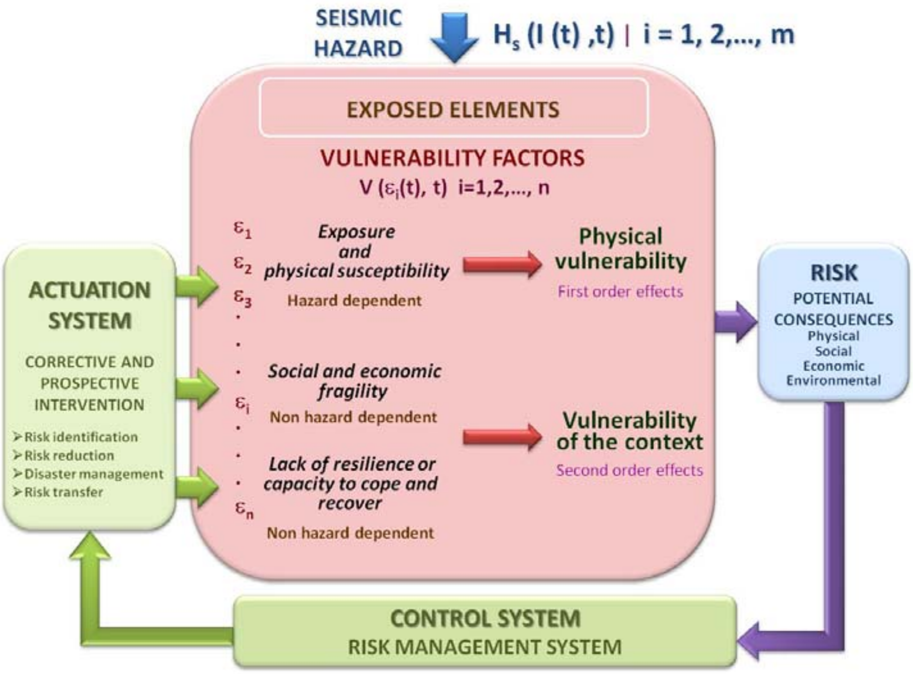


**Figure 1.1.** Conceptual framework for a holistic approach to disaster risk assessment and management. Adapted from (Carreño 2006; IDEA 2005; Carreño et al. 2007a/b)

## 2. HOLISTIC EVALUATION OF RISK BASED ON INDICES

In the holistic evaluation of risk using indices, risk results are calculated by aggravating the physical risk by means of a coefficient depending on the contextual conditions, such as the socio-economic fragility and the lack of resilience. Input data considering these conditions at urban level are necessary to apply the method. This approach contributes to the effectiveness of risk management, inviting to the action through the identification of weaknesses of the urban centre.

The socio-economic fragility and the lack of resilience are described by a set of indicators (related to indirect or intangible effects) that aggravate the physical risk (potential direct effects). Thus, the total risk depends on the direct effect, or physical risk, and the indirect effects expressed as a factor of the direct effects. Therefore, the total risk is expressed as follows:

$$R_T = R_F\left(1+F\right) \tag{2.1}$$

equation known as the Moncho's Equation in the field of disaster risk indicators, where $R_T$ is the total risk index, $R_F$ is the physical risk index and $F$ is the aggravating coefficient. This coefficient depends on the weighted sum of a set of aggravating factors related to the socio-economic fragility, $F_{FSi}$, and the lack of resilience of the exposed context, $F_{FRj}$

$$\boldsymbol{F} = \sum_{i=1}^{m} \boldsymbol{w_{FSi}\, F_{FSi}} + \sum_{j=1}^{n} \boldsymbol{w_{FRj}\, F_{FRj}} \tag{2.2}$$

where $w_{FSi}$ and $w_{FRj}$ are the weights or influences of each $i$ and $j$ factors and $m$ and $n$ are the total number of descriptors for social fragility and lack of resilience, respectively. The aggravating factors $F_{FSi}$ and $F_{FRj}$ are calculated using transformation functions, which are discussed in the following.

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 2.1 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. In the Figure 2.1, the *x-axis* are values of the descriptors while the value of the factor (physical risk or aggravation) is in the *y-axis*, taking 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 taking into account the 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 lower value of aggravation. Figure 2.2 shows examples of the transformation functions used. 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) (Saaty and Vargas 1991; Carreño et al. 2007a/b; Carreño 2006).

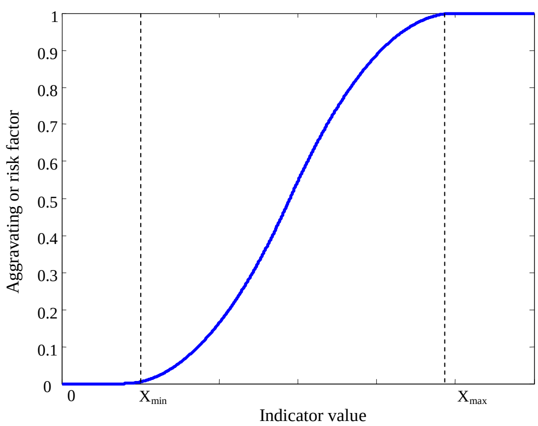


**Figure 2.1.** Model of the transformation functions

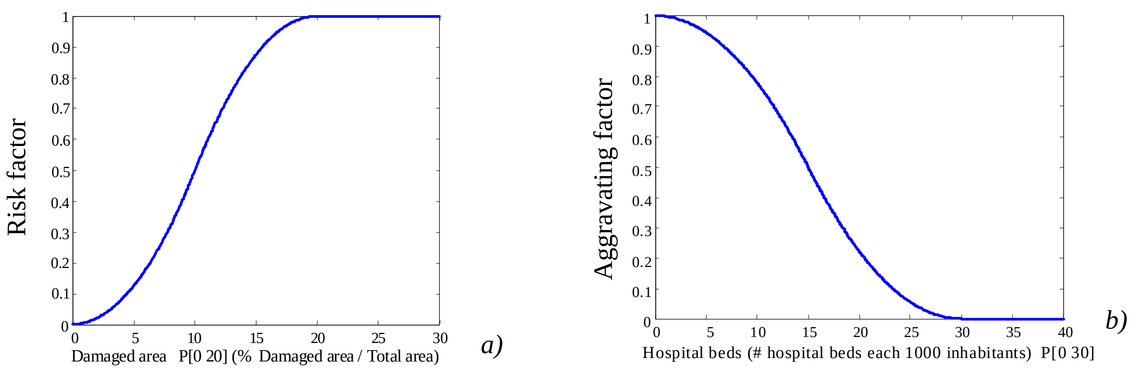


**Figure 2.2.** Examples of transformation functions: *a)* damaged area; *b)* hospital beds

The physical risk, $R_F$, is evaluated in the same way, by using the following equation:

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

Figure 2.3 shows the process of calculation of the total risk index 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. The robustness of this methodology has been also studied assessing the uncertainty of values and sensitivity to change of values, weights and transformation functions (Marulanda et al. 2009). Detailed information about this evaluation method can be founded in references (Carreño et al. 2007a; Carreño 2006; Barbat et al. 2011).

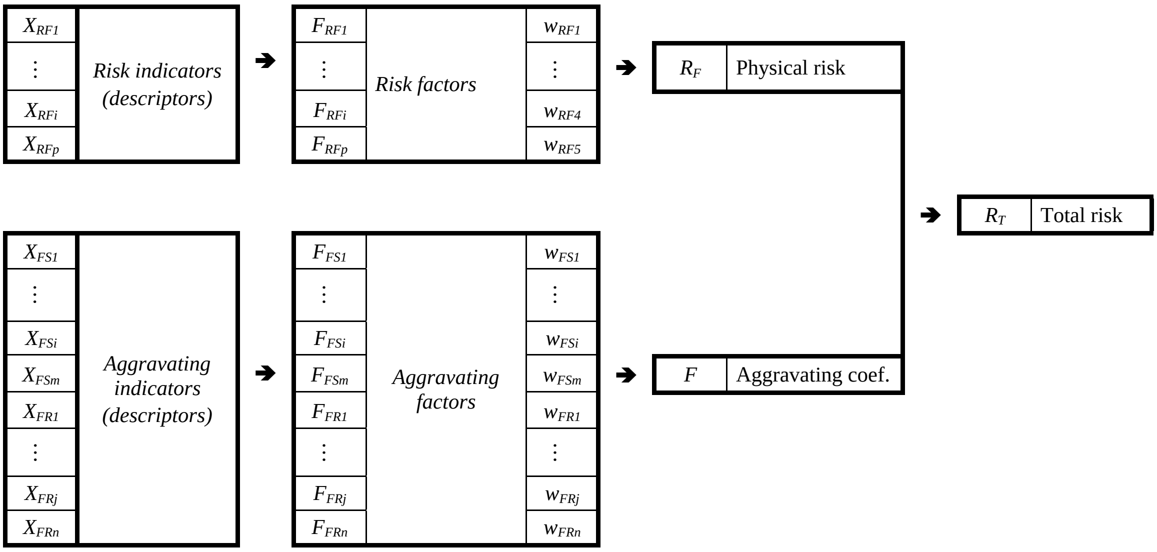


**Figure 2.3.** Descriptors of the physical risk, social fragility and lack of resilience and their weights

## 3. HOLISTIC EVALUATION OF RISK IN BARCELONA

### 3.1. The city of Barcelona, Spain

The city of Barcelona, capital of Catalonia and second city of Spain, has a total of 1,621,537 inhabitants (2009), is located on the northeast coast of Spain (see Figure 3.1). Bounded by the Collserola ridge and rivers Besós and Llobregat, the city has an area of almost 100 km$^2$.


**Figure 3.1.** Location of the city of Barcelona

The city of Barcelona was founded by the Romans during the Punic Wars. At the end of the Roman period, the city had almost 12000 inhabitants. By the end of the 4th century, Barcelona was a fortified walled town, covering about 10.5 Ha. The Barcelona's evolution into a big city began in 1868 when adjacent towns were added to the city becoming its actual districts. Between 1910 and 1930, the population grew from 587411 to 1005565 inhabitants. This population explosion was accompanied by a highly productive construction period. Due to this growth, the most part of the city's building stock was constructed when no seismic-resistant construction codes were available. The combination of very old buildings constructed without seismic conscience and a highly populated and active city can be extremely risky under the effects of even a moderate earthquake.

Nowadays, Barcelona is divided into ten administrative districts: Ciutat Vella, Eixample, Sants-Montjuïc, Les Corts, Sarrià-Sant Gervasi, Gràcia, Horta-Guinardó, Nou Barris, Sant Andreu and Sant Martí. This division of the city has its roots based on the history of the city. Ciutat Vella is the old centre of the city and the Eixample is where the city expanded after the city walls were knocked down. The other districts correspond to municipal areas that were around the old city, outside the walls, and which became part of Barcelona during the 19th and 20th centuries. The districts are subdivided into 73 neighbourhoods, and 235 AEBs (basic statistic areas in Spanish), according to the cadastral information 70,655 buildings conform the city.

### 3.2. Seismic risk from a physical point of view in the city of Barcelona, Spain

The seismicity of the Catalonia region is moderate when it is compared to other regions in the Mediterranean Sea. Various earthquakes shook Barcelona - and Catalonia - in the latter third of the 14th century and the first half of the 15th. More recently small earthquakes have felt by the population of Barcelona (i.e. Mw:4.6 on May 15th of 1995 and Ml: 4.0 on September 21st of 2004), but without causing damage to people and buildings.

In this case study, the seismic hazard has been simulated by using the computer program CRISIS 2007 taking into account the seismic sources for the Catalonia region identified by Secanell et al. (2004) and the attenuation model of Ambraseys (1996).

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 have been generated.

Site effects, are included to consider the amplification of seismic hazard parameters according to the geological characterization of Barcelona (Cid et al 2001). Each zone is characterized by a transfer function and an amplification factor for the acceleration level on the rock.

The exposure is mainly related to the infrastructure components or exposed population which can be affected by a particular event. To characterize the exposure is necessary to identify the individual components, including its location, its main physical, geometric and engineering characteristics, their vulnerability to hazardous events, their economic value and the level of human occupation can have in a given analysis scenario. The exposure value of assets at risk is usually estimated from secondary sources such as available databases (see Figure 3.2).

This study uses information of Barcelona compiled by Lantada (2007), the economic value of the exposed elements was supplied by the Cadastral Office of Barcelona, and 70655 buildings were taking into account. For each one the geographic situation, economic value, year of construction, number of levels, structural type and human occupation were defined.

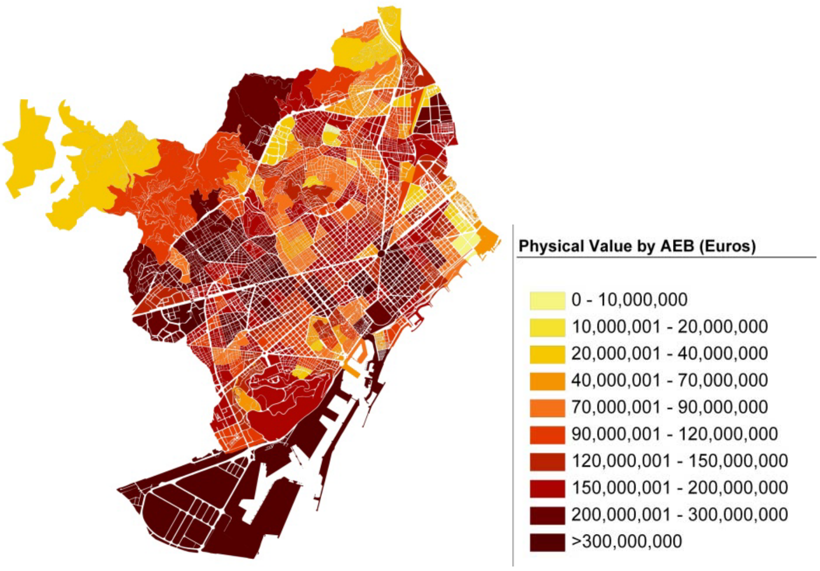


**Figure 3.2.** Exposed value of the AEBs of Barcelona

The vulnerability of the buildings in the city has been defined by vulnerability functions using the Vulnerability Module of the CAPRA platform. These functions are defined for each building typology; the most common structural system used in Barcelona is the unreinforced masonry, followed by the reinforced concrete, whose construction has increased rapidly in recent decades. The used typologies were defined in ICC/CIMNE (2004). Figure 3.3 shows the vulnerability functions used for the unreinforced masonry buildings; additional functions for other building typologies were used, for low (L), medium (M) and high (H) height.

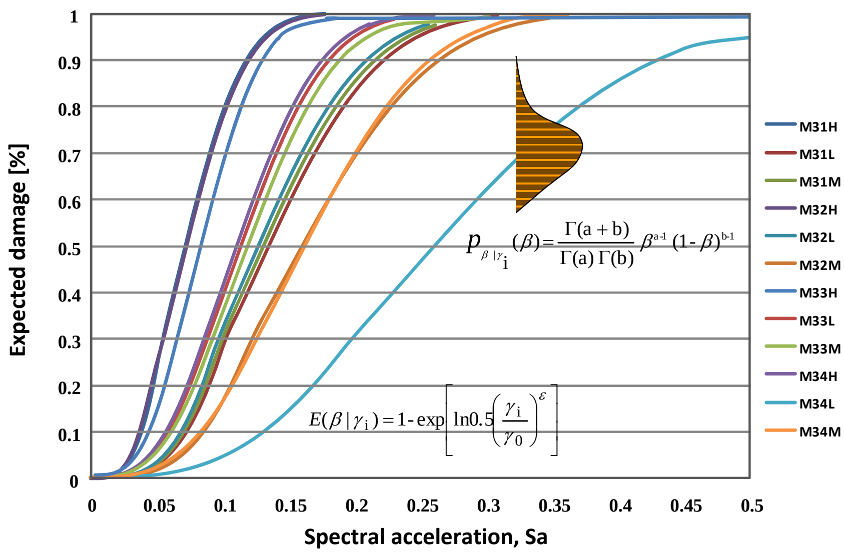


**Figure 3.3.** Vulnerability functions for unreinforced masonry buildings

The physical seismic risk is evaluated by means of the convolution of the hazard with the vulnerability of the exposed elements, the result are the potential effects or consequences. Risk can be expressed in terms of damage or physical effects, absolute or relative economic loss and/or effects on the population. Once the expected physical damage has been estimated as a percentage for each of the assets or infrastructure components included in the analysis, several parameters can be defined as the result of obtaining the Loss Exceedance Curve (LEC). The Average Annual Loss for physical assets, fatalities and injuries are calculated for each building in the city. The probabilistic results for the city of Barcelona are shown in the Table 3.1.

**Table 3.1.** Obtained results for physical exposure

| PHYSICAL EXPOSURE | | |
|---|---|---|
| Exposed value | € x$10^6$ | 31,522.80 |
| Average Annual Loss | € x$10^6$ | 72.14 |
| | ‰ | 2.29‰ |
| PML | | |
| Return period | Loss | |
| Years | €x$10^6$ | % |
| 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% |

Figure 3.4 shows the PML curve obtained for Barcelona. Figure 3.5 shows the expected annual loss for each AEB of Barcelona. As it was previous mentioned, the expected annual loss was originally calculated building by building, Figure 3.5 shows also the obtained results at this resolution.

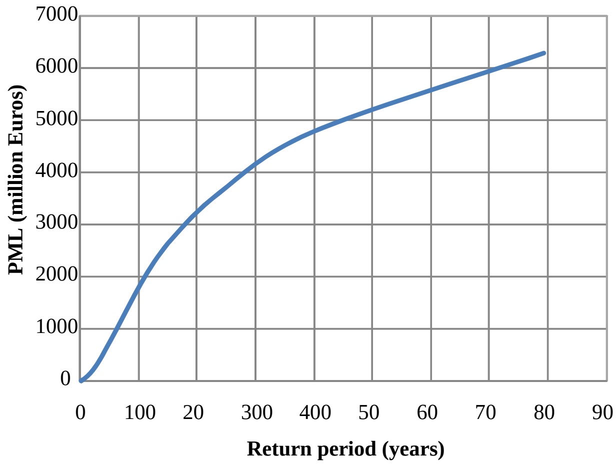


**Figure 3.4.** PML curve for Barcelona

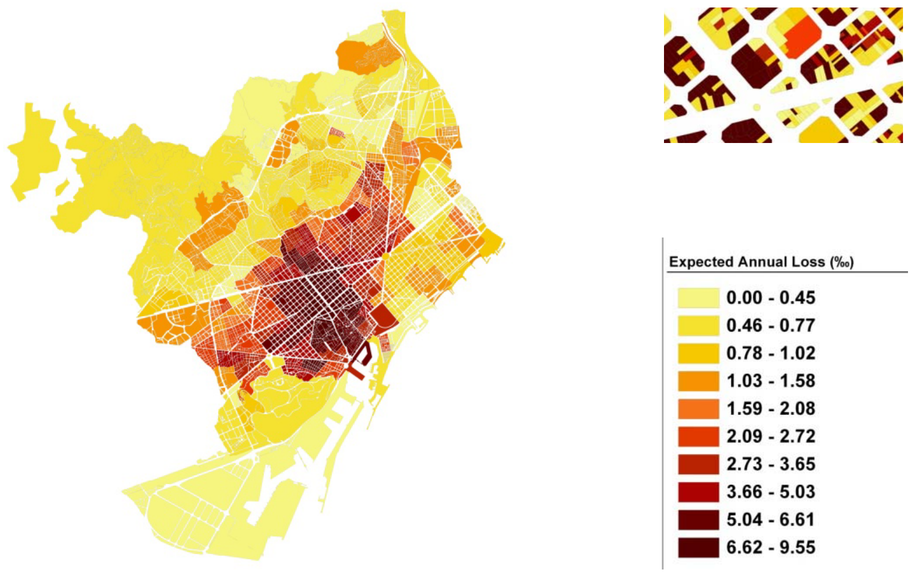


**Figure 3.5.** Expected annual loss for the AEBs of Barcelona, and detail for some buildings in the Eixample District

### 3.3. Seismic risk from a holistic approach

Figure 3.6 shows the descriptors used to describe the physical risk, the social fragility and the lack of resilience for Barcelona. The holistic evaluation of risk has been done following the methodology of section 2. These descriptors were choose as the most significant for each category and according to the available information for the case study.

| | | |
|---|---|---|
| $X_{RF1}$ | Expected annual economic loss | $w_{RF1}$ |
| $X_{RF2}$ | Expected annual deaths | $w_{RF2}$ |
| $X_{RF3}$ | Expected annual injuries | $w_{RF3}$ |
| $X_{RF4}$ | Expected Jobless | $w_{RF4}$ |
| $X_{RF5}$ | Expected Homeless | $w_{RF5}$ |

➔ $R_F$ | Physical risk

➔ $R_T$ | Total risk

| | | |
|---|---|---|
| $X_{FS1}$ | Mortality rate | $w_{FS1}$ |
| $X_{FS2}$ | Population density | $w_{FS2}$ |
| $X_{FS3}$ | Population with fair or poor health | $w_{FS3}$ |
| $X_{FS4}$ | Slums-squatter neighbourhoods | $w_{FS4}$ |
| $X_{FS5}$ | Social disparity index | $w_{FS5}$ |
| $X_{FR1}$ | Hospital beds | $w_{FR1}$ |
| $X_{FR2}$ | Health human resources | $w_{FR2}$ |
| $X_{FR3}$ | Public space | $w_{FR3}$ |
| $X_{FR4}$ | Development level | $w_{FR4}$ |
| $X_{FR5}$ | Emergency planning | $w_{FR5}$ |

➔ $F$ | Aggravation

**Figure 3.6.** Decriptors used in the case of Barcelona

Figure 3.7 shows the obtained results of the physical risk index, $R_F$, for the AEB's of Barcelona. These results give the highest values of physical risk in the districts of Ciutat Vella and Eixample; these areas correspond to the older areas in the city. The smaller values are in the districts of Nou Barris and Horta-Guinardo.

The ranking of the results of the aggravating coefficient is shown in Figure 3.8 for the districts 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 3.9 shows the results of the total risk index, $R_T$, for the AEB's of Barcelona.

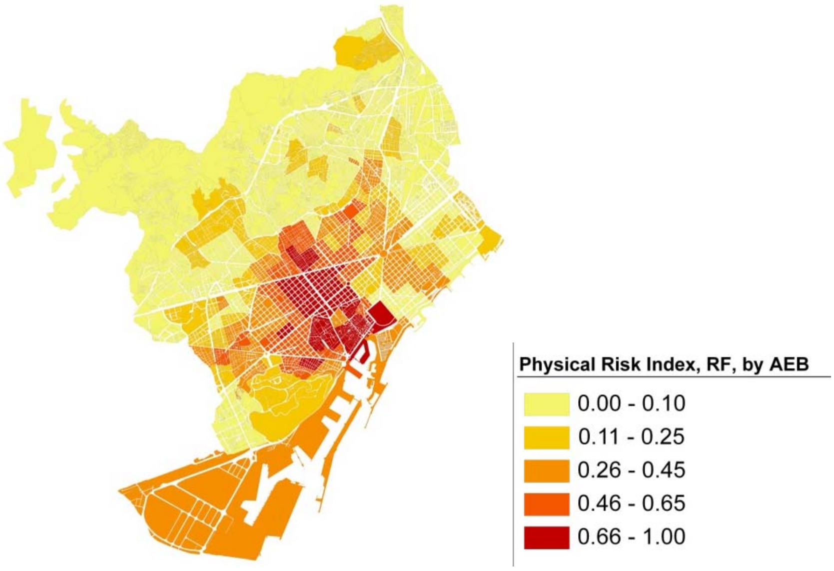


**Figure 3.7.** Physical risk index

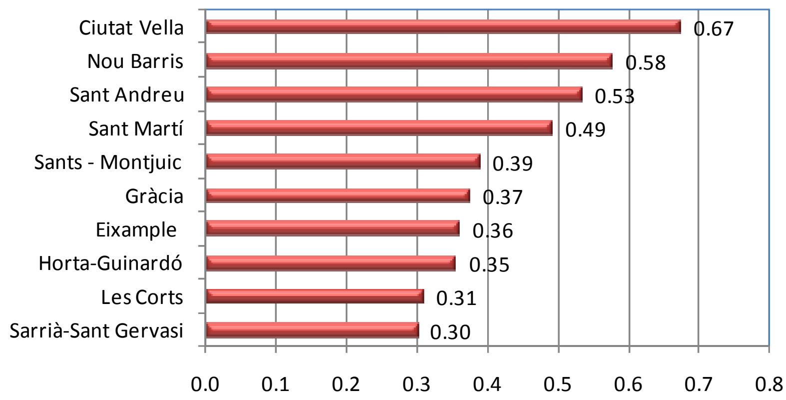


**Figure 3.8.** Ranking of the aggravating coefficient of the districts of Barcelona

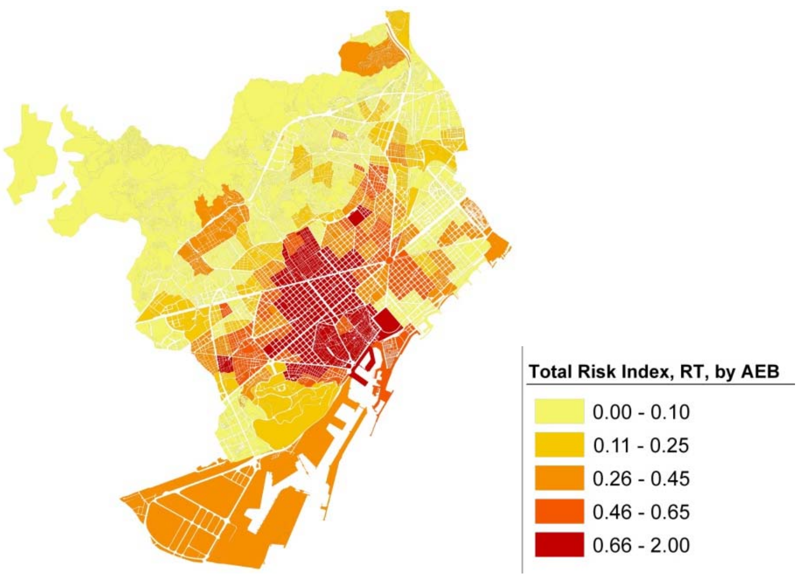


**Figure 3.9.** Total risk index for Barcelona

## 4. CONCLUSIONS

For management purposes, the risk assessment should to 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. This case study involves several elements that try to capture the different aspects of the city, physical, social and institutional issues.

The proposed methodology has been applied to the cities of Barcelona, Spain. The risk in the city of Barcelona has been studied from a holistic approach involving the seismic hazard from a holistic approach. Indicators related to the physical susceptibility, social fragility and lack of resilience of the city have been involved. This study identifies the district of Ciutat Vella as a problematic area due to the potential damage due to the seismic hazard, structural vulnerability and its social fragility and lack of resilience conditions. It also shows how the districts of Nou Barris and San Andreu are problematic areas due to their social conditions, though the expected damage is comparatively lower than in other districts of the city.

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