SIRIUS, Seismic Risk Indicator in Urban Space

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Despite numerous research efforts in recent years, seismic risk continues to be difficult to perceive and communicate. Although researchers have access to sophisticated tools that can quantify seismic risk, such groups as public authorities, land use and urban planners, stakeholders, end-users, and citizens should also be able to access simple seismic risk information. Thus, SIRIUS was built and mapped into a scale following the Weber and Fechner perception law, with impacts described in a simple yet meaningful language while capturing the two most fundamental dimensions that explain risk variability along the urban space: the reliability deficit and human concentration. With SIRIUS, at-risk places and the reasons why seismic risk is a concern are easy to identify and communicate. To illustrate the potential of this robust indicator, an application of SIRIUS to the city of Lisbon is presented. [DOI: 10.1193/1.4000149]

INTRODUCTION

Who needs to know about seismic risk? As stated by Shah (2009), "there is relatively little communication between researchers, academics, and a few well-known professionals, on the one hand, and the rest of the country, which is at risk, on the other." Researchers have access to sophisticated simulators and models. Engineers, builders, and designers in developed countries follow, or should follow, existing codes and regulations, but the following groups still need to deepen their knowledge about seismic risk: (i) national and local authorities with disaster prevention and response responsibilities, (ii) land use and urban planners, (iii) public authorities with sufficient power to impose or implement costly or non-consensual measures, (iv) stakeholders who should know their risks, and (v) citizens who require unbiased and transparent information for choosing where to build or live.

METHODS TO MEASURE SEISMIC RISK

Risk analysis may encompass at least four major dimensions: (i) *risk assessment*; (ii) *risk management*; (iii) *risk communication*, which may contain all of them; and (iv) *risk perception*, in the absence of which none of the others can be properly addressed. Even before risk management, risk assessment must address the multidimensionality of risk, taking into account the concerns about the multiple exposed values or elements at risk, leading us to the framework of *multicriteria,* where the many dimensions of seismic urban risk are taken into account. Because in this field we are also strongly skeptical about the robustness of models that reduce

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risk to a single indicator, we do believe that risk assessment may require an adequate use of such sophisticated as multi-criteria decision analysis (MCDA), probability, Bayesian networks, event trees, fault trees, and Monte Carlo simulation, which are far from accessible to non-academic audiences, a reality that may be responsible by the weakness and the useless of so many major risk decisions, as repeatedly stated by such authors as Cox (2009), Hubbard (2009), Bilham (2009), and many others. When it comes to seismic risk, the situation is not different.

Seismic risk is complex and involves a wide spectrum of scientific knowledge and large amounts of heterogeneous data, which are difficult to gather and combine. These major obstacles prevent seismic risk information from being readily delivered to those who need it. Among the many academic tools that support seismic risk knowledge are fault rupture models; seismic catalogues; seismic wave attenuation laws; soil susceptibility maps and site effects; hazard studies and methods for estimating impacts on humans; and structures and other exposed elements.

Seismic scenario simulators are sophisticated tools that only a few public authorities and private institutions can afford. Furthermore, seismic simulators are usually limited to estimations of direct physical damage arising from specific scenarios. Interdependencies, disruption propagation, and cascading effects are currently being studied, and present solutions require data from complex, heterogeneous, and competitive sources and are mainly restricted to lifeline systems.

Urban systems are more than physical assets and functional flows. Intangible factors that play a major role in the overall goal of well-being equilibrium are missing from even the most sophisticated simulators (Bloomfield et al. 2009), although Cardona (2005), Carreño et al. (2007), and Davidson and Shah (1997) have proposed models that include the social impacts of seismic events. Measuring expected losses in monetary units is another challenge. In the weeks and months after a disaster, economic impact figures rarely converge to sufficiently stable or consensual values. Leontief's input-output models are being used for this purpose, but gathering the necessary data for such models is difficult, if not impossible (Crowther et al. 2007, Lian et al. 2007).

Even if an adequate method for measuring seismic impacts in the multiple dimensions (criteria) that contribute to seismic risk were to be developed, aggregating the results at a convenient scale would remain a challenge. The process of ranking solutions with respect to risk, a common goal of complex approaches, is usually hindered by a broad degree of inconsistency (Cox 2009). Aggregating multiple criteria in a unique final number to rank risks can result in an aleatory amalgamation of contents (Scharlig 1999). The generalized use of weighted sums of impacts in a set of criteria most often violates fundamental properties that must be obeyed by the multi-criteria and multi-utility approaches. These properties include the choice of the set of fundamental points of view (criteria) and their additive aggregation, and the most common violation is preferential and addictive independenc" (Bana e Costa 1992, Keeney and Raiffa 1976). The abuse of appellative S-shaped functions to model impacts on criteria, even if conducted in a strictly formal way, will, in many cases, result in a model that conforms to the strict preferences and concerns of those involved in the construction of the problem and suffers from the inconsistencies noted by Sharlig (1999) and Cox (2009).

Despite the merit and contributions of these approaches, their usefulness is often limited, as a result of their complexity, to the highly specialized audiences previously mentioned. The number of variables, their degrees of uncertainty, and the ways in which they are combined render these models mostly useless for citizens, bureaucrats, and stakeholders. Furthermore, given conflicting interests, final decisions are often based on political, rather than technical, issues (Hunter and Fewtrell 2001). To simplify these difficulties and complexities, we propose the use of a new indicator, SIRIUS, which compresses the most important factors that contribute to seismic risk into a single numerical value based on the building reliability deficit and human concentration.

If we accept that motivation should be preceded by perception, as stated by Tekeli-Yesil et al. (2010), a higher level of knowledge about earthquakes is the first key factor in encouraging individuals to take precautionary action. However, as mentioned, present tools are far from being accessible, affordable, and understandable. Thus, SIRIUS can be useful.

This numerical indicator is mapped based on a scale that follows the Weber–Fechner law (Weber and Fechner 1834), one of the most widely known laws of perception, with levels verbally translated into a semantic language. Thus, the results are easily interpreted and meaningful, and Sharlig's "moulinettes" effect and "independence constraints" are both avoided (Keeney and Raiffa 1976). With SIRIUS, at-risk urban places and the reasons for this risk can be easily identified and communicated. In the presence of a concrete scenario or seismic event, the places where events are likely to happen can be predicted.

Land-use and urban planners, civil protection agents, and local public authorities with land management responsibilities thereby have access to an affordable and understandable mechanism that, although not a seismic simulator, captures most major seismic risk catalysts, helps to measure and understand seismic risk, and integrates this new knowledge into daily tasks. Pursuing Tekeli-Yesil findings, the end products of SIRIUS, such as seismic risk maps and building reliability deficits can be made accessible to the general public in a transparent and nontechnical language to promote seismic risk perception and the willingness to take precautionary actions.

THE SIRIUS INDICATOR

SIRIUS SCOPE AND LIMITATIONS

To be consistent with our aim, we chose the smallest number of variables that, despite their simplicity, could conveniently explain urban seismic risk. While constructing SIRIUS, we were faced with the difficult choice between simplicity, to ensure availability and evaluability (Kunreuther et al. 2001), and the complexity of the holistic approaches. But SIRIUS is not mentioned to be the final tool for risk assessment. The aim of SIRIUS is to provide a first step in risk perception, pointing out, in an urban space, those areas and zones where there exists clear evidence of risk and rank them in accordance to their potential risk. Requiring affordable, easily available data (such as census data), SIRIUS allows a large community of end-users to have access to a simple but comprehensive understanding of which and why those areas are of major concern. Only then will it become clear to them the need for a more elaborate risk assessment, in order to support more robust decisions in further risk management. Because SIRIUS is not a final risk measure, but a first step indicator of risk potential, and because of the aforementioned reasons, we decided to proceed only using the two major seismic risk drivers in urban space: vulnerability of the building stock and human exposure. In this way, and because of its conceptual simplicity, SIRIUS also contributes to the fulfillment of the urgent need for more effective risk communication.

Despite these shortcomings, we believe that SIRIUS is a useful tool for our target audience. Future developments of SIRIUS may include these and other variables.

THE IMPORTANCE OF SOCIAL IMPACT

In accordance with Emile Durkheim (in Turner 1993), social equilibrium is directly and positively correlated with social interactions. In fact, Durkheim stated that the intensity or strength of social interactions is a key factor by which social forces, as opposed to individualism or isolationism, are sustainers of social equilibrium and that population concentration plays a positive key role in this regard. The United Nations (2010) provides a good description of this role: "The traditional distinction between urban and rural areas within a country has been based on the assumption that urban areas, no matter how they are defined, provide a different way of life and usually a higher standard of living." This positive association between the concentration of people and social dynamics is broadly found in the literature. Burdge (2004) placed population density among a set of five fundamental key variables. This indicator also appears among those mostly used in studies of social dynamics, as mentioned by Normandin et al. (2009).

Urban space is a strongly connected network, where social, functional and physical relations are "links" on which paths are built to access values or "nodes" (e.g., food, shelter, culture, education, environment, work, health, security, religion, people and identity). As in Newton's law of attraction, population density increases attractiveness, and networks tend to evolve around "vertexes" with many linked neighbors, "hubs," "clusters," and links. This multiplicity tends to enhance accessibility, defined by the shortest or lowest-cost paths along as many nodes as possible, and produce more efficient networks.

Highly connected networks, while highly effective during normal operation and robust to small disturbances, become fragile, unreliable, and prone to disruption when things go wrong. This is true not only in social science, but also in graph theory and infrastructure dependency modeling (Bloomfield et al. 2009, Dueñas-Osorio and Vemuru 2009, Dueñas-Osorio 2005, Peters et al. 2008). In such highly concentrated areas as urban space, human (Bilham 2009), functional and physical losses (Normandin et al. 2009) are highly positively correlated with population density. Therefore, everything on which we depend, including backups, redundancies, and resources to cope with response, tends to be collocated and will most likely be sheltered by buildings with strong, direct correlations to their volume concentrations. Shelters may suddenly turn into major threats, especially if they are vulnerable to earthquakes. Moreover, earthquakes can destroy things simultaneously.

SIRIUS VARIABLES

We chose the following two variables to conveniently and simply translate **e**arthquake **ri**sk (*eri*): *rrd*, or **r**isk due to buildings seismic **r**eliability **d**eficit, as the major variable responsible for destruction; *rhc*, or **r**isk due to **h**uman **c**oncentration, as a proxy (indirect indicator) of physical, functional, and social vulnerability to major disruptive events:

$$eri = f(rrd, rhc) \tag{1}$$

To link these two variables, consider the following rules:

- In the absence of buildings (open space) or if the seismic reliability of buildings enables them to sustain seismic action, earthquake risk does not exist, and *eri* should be zero.

- If the seismic building reliability deficit is high but the affected area has no population (i.e., if it is abandoned or unoccupied space), seismic risk does not exist, and *eri* should be zero.

This implies that *rrd* and *rhc* should be joined such that $eri = f(rrd = 0, rhc) = f(rrd, rhc = 0) = 0$, leading to aggregation by multiplication rather than addition:

$$eri = rrd \times rhc \tag{2}$$

Although this last rule is simple, it does not suffer from the constraints of additive independence or an aleatory amalgamation of contents, and it is built upon two independent variables. Being multiplicative, it avoids many of the "compensation effects" of the additive rule. Moreover, *rrd* is a concatenation of hazard and vulnerability, as will be shown later, and *rhc* is a proxy of consequences, leading to $eri = f(hazard,\ vulnerability,\ consequences)$, which is the most widely accepted formal definition of seismic risk. The variables *rrd*, *rhc* and *eri* are presented both on semantic scales with several classes and in numerical terms. SIRIUS, transmitted through *eri*, is presented on a semantic scale.

MEASURING RISK DUE TO RELIABILITY DEFICIT, *rrd*

Before going deeper into this issue, we must emphasize that risk cannot be measured on an absolute scale; rather, it can only be measured in relative terms. In addition to concerns related to perception and evaluability (Kunreuther et al. 2001), risk assessments often involve a comparison of actual or future levels with some target reference involving tolerance, acceptability, or desirable level. Once a reference level has been established, risk can be said to be high or low depending on its distance from that level. This is the rule we use to measure *rrd*. (We adopted the name "risk reliability deficit, or *rrd*" as a humble tribute to the works of J. Ferry Borges and M. Castanheta, which still constitute a major reference in Portuguese civil engineering and earthquake engineering; Borges and Castanheta 1983).

Some definitions adapted from Giovinazzi and Lagomarsino (2004; hereafter referred to as G&L) and updated by Bernardini et al. (2007) are as follows:

1. Buildings can be grouped into typological classes (also called vulnerability classes) based on their expected behavior under seismic action.
2. Buildings of the same typological class can then be characterized by their vulnerability index (actual real vulnerability), a non-deterministic numerical value that can take the following values in each vulnerability class:

   - $Vu--$ lower possibility (best, not expected but still possible behavior)
   - $Vu-$ lower plausibility (best expected behavior)
   - Vu^* characteristic value (most expected behavior)
   - $Vu+$ upper plausibility (worst expected behavior)
   - $Vu++$ upper possibility (worst, not expected but still possible behavior)

where $Vu-- < Vu- < Vu^* < Vu+ < Vu++$.

We assume that for some level of seismic action, buildings should have a vulnerability degree that conforms to their desired behavior, which by the above statements will place them in the desired level of risk. We call this the required vulnerability, or Vu_{req}. Highly vulnerable buildings are expected to suffer more damage, and conversely, less vulnerable buildings are expected to perform better. Because vulnerability can be observed as an inverse of reliability, the most vulnerable buildings have a higher degree of reliability deficit. Figure 1 categorizes the reliability deficit, *rrd*, into six classes (0 to 5, or Very Weak to Extreme) and makes use of

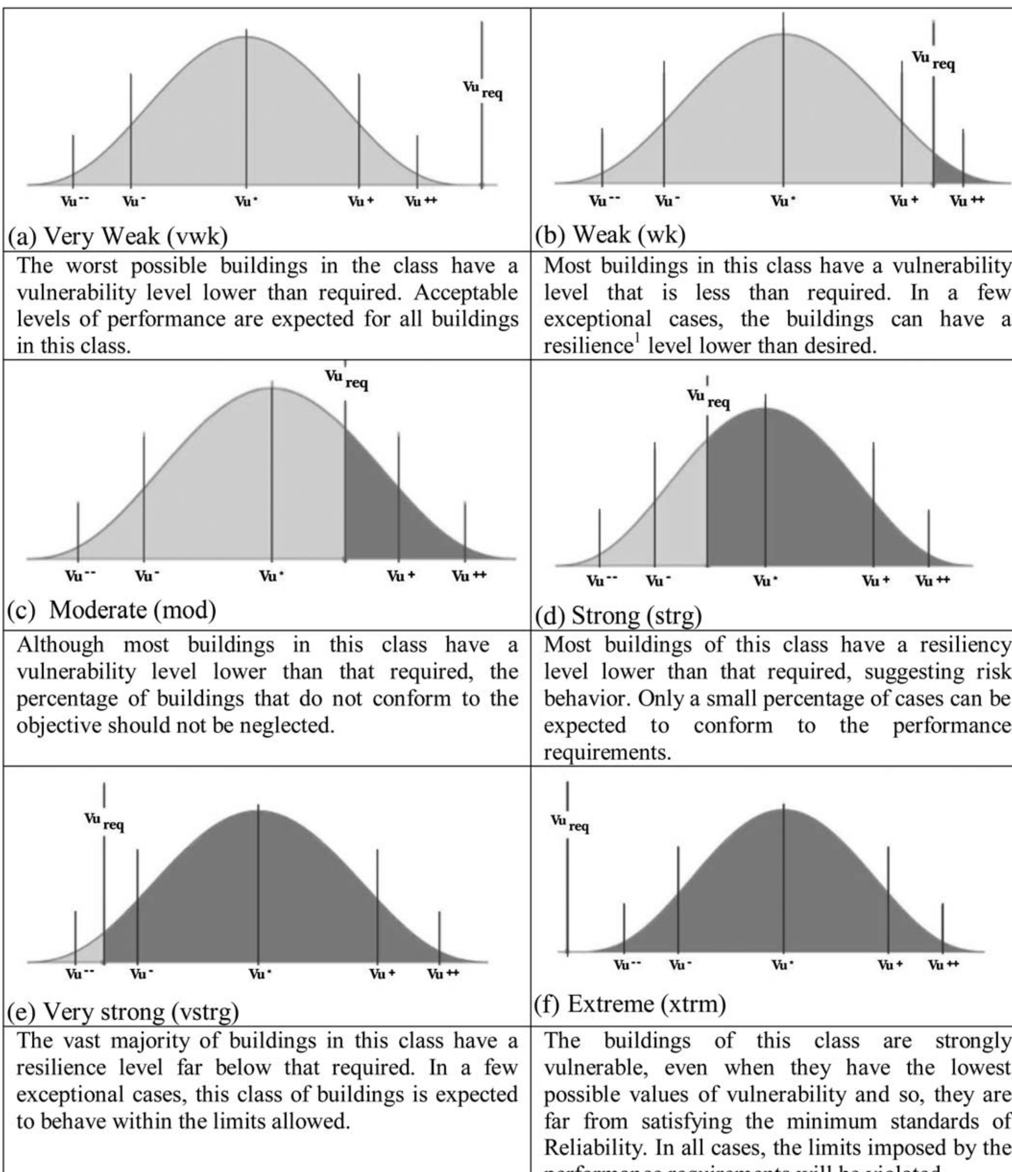

Figure 1. Risk reliability deficit, *rrd* (0 to 5, or Very Weak to Extreme). Vu_{req} is marked by a separate, thick vertical line.

the probability density function of vulnerability. The text associated with each class expresses in a semantic form how far a certain typology is from Vu_{req}.

In this context, the reliability deficit can be expressed by

$$rrd = f(Actual\ Vulnerability, Required\ Vulnerability) \tag{3}$$

Required Vulnerability, Vu_{req}

More precisely, the required vulnerability can be observed as that which leads to a probability of structural behavior in accordance with some objective (O). Borges and Castanheta (1983; hereafter referred to as B&C) defined a reliability index, β, as a safety factor related to the failure probability of a structure with resistance R subjected to a set of forces S, where R and S are random variables with probability density functions $\mathrm{f}(S)$ and $\mathrm{f}(R)$. When these variables are convolved in a joint probability $\mathrm{f}(R-S)$, with mean μ_{R-S} and standard deviation σ_{R-S}, the probability of failure can be measured by α (Figure 2):

$$\alpha = P[f(R-S) < O]; \quad O = \mu_{R-S} - \beta.\sigma_{R-S} \tag{4}$$

Thus, as stated by B&C, "the smaller the value of β, the higher the probability of failure," and "values of $\beta = 3$ and 4 correspond to probabilities of failure of the order of 10^{-3} and 10^{-5}."

According to the 1998 European Macroseismic Scale (EMS98; Grünthal 1998), building damage is defined on a scale with six damage grades, dg $\{0, \ldots, 5\}$, with structural failure starting at damage grade 4 ($dg = 4$). Therefore, we take $\alpha = \mathrm{P}[dg \geq 4]$. Following the general expression established by G&L to relate damage grades μ_D and building vulnerability Vu, yields Equation 5:

$$\mu_D = 2.452\left[1 + tanh\left(\frac{I + 5.604Vu - 12.19}{1.797}\right)\right] \tag{5}$$

where μ_{D} is the mean damage grade observed in buildings with vulnerability Vu when subjected to an EMS-98 Intensity I. (The parameters of Equation 5, similar to those proposed in G&L, were derived from the original interpretation of EMS-98, as explained in the online supplement Appendix A.)

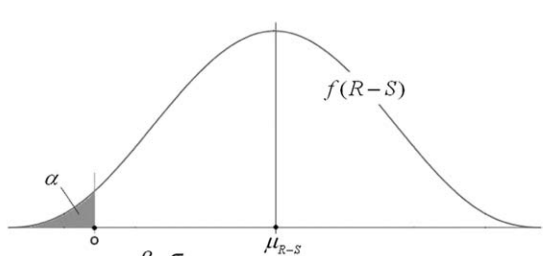

Figure 2. Probability of failure (adapted from Borges et al. 1983).

Inverting Equation 5 gives us:

$$Vu = 2.17523 - 0.178444I - 0.318879 arctanh(1 - 0.40783\mu_D) \tag{6}$$

In this case, the probability of a given damage grade is obtained from

$$P[dg \geq k|I] = 1 - \beta'(k - 0.5; p; q; 0; 5); \quad 1 \leq k \leq 5, \tag{7}$$

where dg is the damage grade {0, 1, 2, 3, 4, 5}; p and q are the shape parameters of the beta distribution; and β' is the cumulative beta distribution, not to be confused with the reliability index β. p and q are defined as

$$p = \frac{8}{5}\mu_D; \quad q = 8 - p. \tag{8}$$

For a reference seismic event, translated to an Intensity I_o, and a required reliability β, we can write $P[dg \geq 4|I_o] < \alpha$, and $\beta'(3.5; \mathrm{p}; \mathrm{q}; 0; 5) < \alpha$, and from Equation 7, we obtain the shape parameters p and q. From Equation 8, μ_D can be obtained. Replacing I by I_o and μ_D in Equation 6, we obtain Vu = Required Vulnerability, or Vu_{req}.

This is the highest vulnerability value that a building can have while still conforming to the performance objectives of "non-collapse," defined by a reliability β, and a seismic action of I_o. With the reference values of β used by B&C and the above formulation, we arrive at the values of Vu_{req} shown in Table 1.

To illustrate the above concepts, we used typologies from G&L and Risk-UE (Milutinovic and Trendafiloski 2003), as shown in Table 2. We adopted a reliability index $\beta = 4$ and

Table 1. Vu_{req} for different values of β

Reliability, β	$\alpha = \mathrm{P}[Gd \geq 4]$	$\mu_D \leq$	$Vu_{req} \leq$
3.0	1E-3	0.928055	1.94236–0.178444 I_o
3.5	1E-4	0.492775	1.82576–0.178444 I_o
4.0	1E-5	0.195193	1.66770–0.178444 I_o

Table 2. G&L and Risk-UE vulnerabilities

	$V--$	$V-$	V^*	$V+$	$V++$
G&L					
RC1, Frame in RC (without ERD)	0.300	0.490	0.644	0.800	1.020
RC2, Frame in RC (moderate ERD)	0.140	0.330	0.484	0.640	0.860
RC3, Frame in RC (high ERD)	−0.020	0.170	0.324	0.480	0.700
Risk-UE					
RC1, Concrete moment frames	−0.02	0.047	0.442	0.800	1.02

ERD = earthquake-resistant design

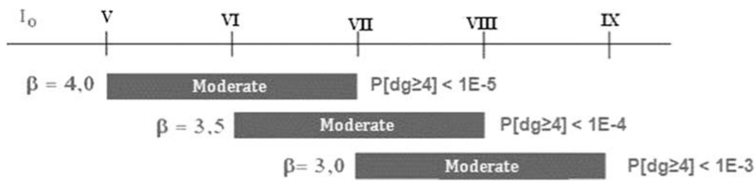

Figure 3. The reliability deficit for the RC1 moment frame and different values of the reliability index β.

applied it to an "RC1, Concrete moment frame," with vulnerability values proposed by Risk-UE. This typology presents a moderate *rrd* when subjected to intensities V to VII.

To satisfy the "moderate *rrd* condition,"

1. If $VU_{req} = 0.442 < 1.66770 - 0.178444 I_o \Rightarrow I_o < (1.66770 - 0.442)/0.178444 = 6.9 (\approx \text{VII})$
2. If $VU_{req} = 0.800 < 1.66770 - 0.178444 I_o \Rightarrow I_o > (1.66770 - 0.800)/0.178444 = 4.8 (\approx \text{V})$

The same reasoning leads us to the conditions shown in Figure 3. From the three cases, we believe that a reliability index $\beta = 3.5$ might be more adequate.

In fact, we had some difficulty accepting that a reinforced concrete moment frame typology would show a "moderate reliability deficit" for the intensity ranges [V–VII] or [VII–IX]. In the first case, we think that the ranking is too high, while in the second, we believe it is too low. Consequently, we recommend $\beta = 3.5$ with

$$\Rightarrow \mathrm{P}[dg \geq 4 | I_o] \leq 1\mathrm{E}-4 \Rightarrow 1 - \beta'(4 - 0.5; p; q; 0; 5) \leq 1\mathrm{E}-4 \Rightarrow p = 0.79;$$
$$q = 7.21 \Rightarrow \mu_D \leq 0.492775$$

and

$$Vu_{req} < 1.82576 - 0.178444 I_o \quad \text{(non-collapse)} \tag{9}$$

Although interesting, this objective is primarily linked with the traditional safeguard of life, which for many decades, was the main objective in structural performance. However, it is now recognized that buildings should also "withstand a seismic action without the occurrence of damage and the associated limitations of use" (CEN 2004). In this sense, their functional capability must be assured. Recent earthquakes have shown that many buildings, despite their structural integrity, were unable to perform their functions due to nonstructural damage. The damage states that lead to such a situation depend on the building and the sensitivity of their contents (equipment) to earthquakes. Buildings in which critical services are provided to the community are good examples of this. For damage grades 2 and 3 and in accordance with EMS98, which can be observed as the last acceptable frontier for such functions as housing, another performance objective can be established: "damage limitation to ensure functional continuity." This objective is more consistent with our concerns about social disruption because social integrity depends not only on safeguarding life, but also on normal-life continuity. Thus, we define a new objective for the required vulnerability as $\beta = 3.0$:

$$\Rightarrow \mathrm{P}[dg \geq 3|I_o] \leq 1\mathrm{E}{-}3 \Rightarrow 1-\beta'(3.0-0.5;p;q;0;5) \leq 1\mathrm{E}{-}3 \Rightarrow p = 0.41;$$

$$q = 7.59 \Rightarrow \mu_D \leq 0.254756$$

and

$$Vu_{req} < 1.712192 - 0.178444 I_o \quad \text{(damage limitation)} \tag{10}$$

This new objective is much more restrictive than the last one. The values of the mean damage grade μ_D (Equations 9 and 10), with the first value on the right-hand side of the same equations give 1.82576 and 1.712192, the former demanding a lower vulnerability to conform to the new objective.

This formulation does not restrict the adoption of a different Vu_{req}, if the need to take building importance into account is present. Important or critical buildings and infrastructure may have to be prepared to sustain a higher shaking level (or be prepared to adequately respond to seismic events of higher return period). In this case, I_o can be simply modified to accommodate this need.

In accordance with the previous definitions (see Figure 1), we can write our reliability deficit scale as in Table 3.

Despite being defined in a discrete fashion, *rrd* can assume any real value other than those considered above {0; 1; 2; 3; 4; 5}. For that, *rrd* can be interpolated linearly inside any of the above intervals, as shown in Table 4.

CHOOSING THE SHAKING LEVEL, I_O

What should be the reference ground shaking level to be considered when computing the "reliability deficit"? In fact, the macroseismic intensity used to compute the *rrd* can be whatever the analyst thinks appropriate. However, this question may raise some other difficult issues. In the absence of a more elaborated reasoning to adopt a specific level or to go into exceedance probabilities of ground shaking, *the proposed ground shaking is the one adopted in seismic codes, usually national rules.* Those ground shaking levels, usually expressed in a

Table 3. Reliability deficit, *rrd*, in a discrete scale

rrd	Vu_{req}
$rrd = 0$, Very Weak	$Vu_{req} > Vu^{++}$
$rrd = 1$, Weak	$Vu+ < Vu_{req} \leq Vu++$
$rrd = 2$, Moderate	$Vu^* < Vu_{req} \leq Vu+$
$rrd = 3$, Strong	$Vu- < Vu_{req} \leq Vu^*$
$rrd = 4$, Very Strong	$Vu-- < Vu_{req} \leq Vu-$
$rrd = 5$, Extreme	$Vu_{req} < Vu--$

where $Vu_{req} =$ f) is obtained from Equations 9 or 10.

Table 4. Reliability deficit, *rrd*, in a continuous scale

rrd
$rrd = 0$,if $Vu_{req} > Vu{+}{+}$
$rrd = 1+ (Vu{+}{+} - Vu_{req})/(Vu{+}{+} - Vu{+})$, if $Vu{+} < Vu_{req} \leq Vu{+}{+}$
$rrd = 2+ (Vu{+} - Vu_{req})/(Vu{+} - Vu^{*})$, if $Vu^{*} < Vu_{req} \leq Vu{+}$
$rrd = 3+ (Vu^{*} - Vu_{req})/(Vu^{*} - Vu{-})$, if $Vu{-} < Vu_{req} \leq Vu^{*}$
$rrd = 4+ (Vu{-} - Vu_{req})/(Vu{-} - Vu{-}{-})$, if $Vu{-}{-} < Vu_{req} \leq Vu{-}$
$rrd = 5$ if $Vu_{req} < Vu{-}{-}$

reference peak ground acceleration (PGA) at stiff soils, already encompasses not only the natural hazard of the country or seismic zone, but also the concerns dealt by the "as low as reasonably possible" (ALARP) principle, taking into account the importance of the exposed values, economic restrictions, and the willingness to pay risk contention. In fact, for example, in European countries, the Eurocode (CEN 2004) already provides what we can consider a generally consensual standard, providing not only a reference PGA, but also modification factors to take into account such as the "structure's importance" and the "site (soil) effects." The same exists in most recent codes adopted in many countries. Thus, in our understanding, this should or could be the "reference shaking scenario" to use in the calculation of *rrd*. As we know, peak ground velocity (PGV) is also usually required to compute damage in buried lifelines, as well as permanent ground displacements (PGD), and some spectral accelerations at specific periods, or even complete response spectra may be required to model damages in structures sensible to these effects (bridges, tunnels, etc.). However, PGV, PGD, and other permanent ground displacements resulting from landslides and liquefaction, are much more demanding in geologic data and modeling. Even recognizing that those effects are of major importance to seismic risk, when calculating SIRIUS (because we are dealing only with buildings and using a damage estimation method that does not require the full response spectrum neither capacity curves), only PGA and soil amplification must be taken into account. Even so, if sufficient data and resources are available, there is no reason not to consider these effects, translating them into different values of I_o.

MEASURING RISK DUE TO HUMAN CONCENTRATION, *rhc*

The term urban density is multifaceted and covers a broad range of urban characteristics. Measuring attributes of spatial density is important in estimating the nature and scale of activities for populations and environmental and disaster impacts, and in modeling other phenomena associated with urban, rural, and natural habitats (Roberts 2007).

The concept of human concentration, *rhc*, is an indirect measure of potential physical, functional, and social disruption. In this sense, *rhc* does not consider social fragility or social resilience within the urban space. Instead, variations in this space are positively correlated with the potential for damage due to high concentrations of assets exposed to ground shaking (Ferreira et al. 2011).

As mentioned, the "nodes and links" of our network city tend to grow exponentially with the number of nodes *n* (in this case, the number of possible links is $n^2 - n/2$), leading to the concept of a "compact city." The compact city concept was first coined in by Dantzig (1973) and Dantzig and Saaty (1974) and later developed by Jacobs (1993). They are characterized by their "high residential and employment densities, fine grain of land uses (proximity of varied uses and small relative size of land parcels), increased social and economic interactions, contiguous development, urban infrastructure, multimodal transportation, high degrees of accessibility, ..." (Neuman 2005).

This compactness, in opposition to "urban sprawl," is proof that a strong correlation exists between human and asset concentration and social activity around urban hubs and neighborhoods.

Human concentration indicates the presence of strong social, physical, and functional values, linked by the intensity or strength of social interactions that, in accordance with Durkheim (Turner 1993), guarantee equilibrium among society. These forces tend to be stronger and to proliferate with proximity. This is the nature of "compact cities," it is the reason why we chose human concentration, *rhc*, as a proxy for potential social and physical disruption following an earthquake.

Sampson et al. (2002) suggested that urban units could be observed as an "aggregations of street blocks that are reachable by pedestrian access." Desyllas et al. (2003) claimed that "walking still accounts for over 80% of all journeys made under a mile," and Anas and Rhee (2006) showed that in their ideal "circular city," space is spread around a central point, with the first cluster within a one-mile radius. Therefore, to establish a convenient spatial unit for computing human concentration, we used this distance as the spatial unit within which human concentration, *rhc*, is calculated. Converting one mile in "Manhattan distance" into the Cartesian space gives a radius of 1 km.

Although unnecessary to the construction of SIRIUS, translating the different levels of human density into a semantic expression is useful. Table 5 and the following text, adapted from Lobo et al. (1996) and Roberts (2007), provide this semantic scale for *rhc* as a function of population density.

The classes of density are defined as follows:

1. *Low density* is associated with the predominance of separate houses, open streets and available landscapes around the dwellings. The lower the density, the more energy consumed. Higher per capita energy, land, water, and car use correlates with lower seismic risk. In more sparsely populated areas, damage to smaller and dispersed dwellings will cause less or no collateral damage.

Table 5. Classes of population density

Population density (inhab/ha) (*rhc*)	Classes of density
30	Low
75	Low-medium
120	Medium
185	Medium-high
275	High
335	Very high

2. *Low-medium density* represents one- to two-story townhouses.
3. *Medium density* is characterized by residential development in the form of townhouses and low-rise apartments. Consequently, the urban hazard exposure starts to increase for this class.
4. *Medium-high density* results in most people and assets being exposed to natural hazards in dense urban areas.
5. *High density* is associated with a predominance of apartment buildings (four- to eight-story buildings) with attached houses and high-capacity transit modes. This mode allows city residents to live in proximity to the necessary services and amenities, including places of work, shopping areas, schools, and centers of leisure and recreation. It also contributes to a more efficient use of various infrastructure services, including public transportation, water and sewage lines, garbage collection, and electricity grids. Intensification increases the load on existing infrastructure networks, and it is more efficient and cost-effective to serve a large number of people in a relatively small area than to serve a relatively small number of people in a large area. However, the collapse of large buildings in dense areas as a result of earthquakes may cause damage to neighboring buildings and livelihoods.
6. *Very high density* is the "badge" of compact cities. It is marked by buildings with more than eight stories and high rates of population. Larger material losses can be expected in severe earthquakes.

AGGREGATING THE RELIABILITY DEFICIT AND HUMAN CONCENTRATION IN A SEMANTIC SCALE (SIRIUS)

Although the *rrd* and *rhc* indicators have been mapped into scales, they are not a good way to measure and communicate seismic risk. They must first be aggregated into a unique, meaningful, and understandable scale. We could do so using an S-shaped or other valued function derived from the "prospect theory" (Kahneman and Tversky 2009) or the multi-attribute utility theory (MAUT; Keeney and Raiffa 1976), but this could lead to difficulties, as referred to previously.

In this context, the following approach, illustrated in Figure 4, was used to map *rrd* and *rhc* into the *eri* (earthquake risk) and SIRIUS scales.

To separate SIRIUS classes, we assume some rules that define the limits according to two distinct urban situations:

Urban situation 1 is characterized by the following conditions:

- A moderate reliability deficit, such that most buildings show a lower vulnerability level than that required by the exigencies of performance, but a non-negligible percentage of them do not conform to the desirable performance level.
- A low/medium human concentration, indicating a mix of isolated houses with some low-rise apartments and open streets.

Faced with this mix of *rrd* and *rhc*, we believe that among the possible impacts on the SIRIUS scale {very low, low, moderate, high, very high, and extreme},this situation does not have a low or a high impact. Thus, we rank it as having a moderate impact.

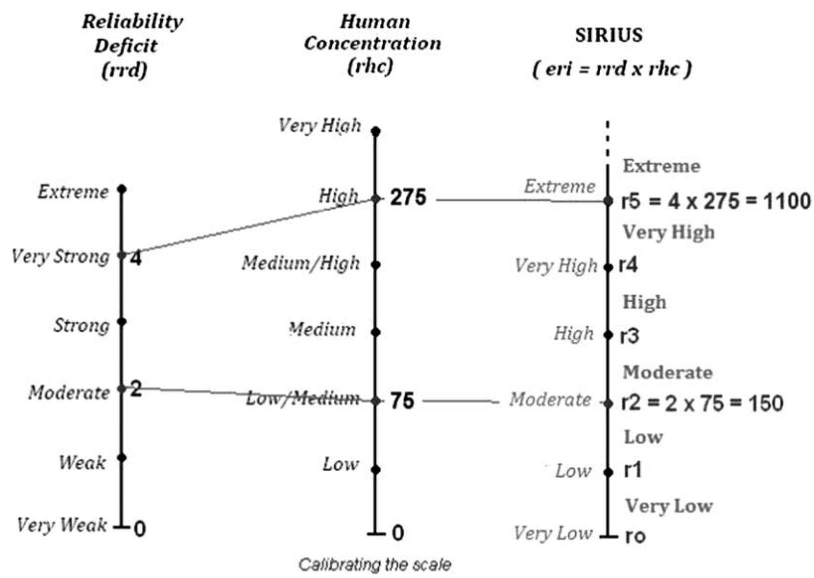

Figure 4. Calibrating the *eri* and SIRIUS scales. The *eri* semantic scale defines the lower and upper bounds of each SIRIUS semantic class.

Urban situation 2 is characterized by the following conditions:

- A marked reliability deficit, with a high level of seismic vulnerability (a very strong reliability deficit), which prevents shelters and functional centers from being protected.
- A high human density, which is usually associated with tall buildings, street congestion with high-capacity transit modes, high density of construction, and critical infrastructure concentrations, as usually observed in "megacities."

Again, given the mix of *rrd* and *rhc*, we believe that among the possible impacts on the SIRIUS scale, this situation has more than a very strong risk; in fact, we rank it as having an extreme impact.

Given the above considerations, we can map the two combinations of *rrd* and *rhc* in *eri*:

Situation 1*: Moderate reliability deficit − Low/medium population density ⇒ Moderate risk*

and

$eri = rrd \times rhc = 2 \times 75 = 150$ (see Tables 3 and 4).

Situation 2: *Very strong reliability deficit − High human density ⇒ Extreme risk*

and

$eri = rrd \times rhc = 4 \times 275 = 1{,}100$ (see Tables 3 and 4).

To obtain the other combinations of *rrd* and *rhc*, we used the "Weber–Fechner law" (Weber and Fechner 1834). Weber found that "the smallest noticeable difference in stimulus (the least difference that a person can still perceive as a difference), was proportional to the starting value of the stimulus." Stated another way, the additional amount of risk required to move from a "high level" to a "very high level" must be substantially greater than the amount required to move from a "low level" to a "moderate level" of risk. In fact, this law can also be stated as follows: In order for the intensity of a sensation to increase in arithmetical progression, the stimulus must increase in geometrical progression.

In mathematical terms, the numerical difference between two consecutive levels is directly proportional to the lower of the two. If r_i is the amount of risk at a perceived level I and Δ_i is the amount of additional risk required to acknowledge that the risk has grown from r_i to r_{i+1}, then

$$\Delta_i = r_{i+1} - r_i = k.r_i \tag{11}$$

where i is a Natural number; r_i is a real number; and k is a real constant.

THE SIRIUS SCALE

Considering t as the index i of the last level of the scale, with the first level being $i = 0, \beta$ as the value of *eri* associated with level t, α as the value of *eri* associated with any level $j \neq 1$ and r_i as the value of *eri* associated with any level I, it is possible to show (see Supplemental Material Appendix B) that

$$r_i = \alpha^{[(t-i)/(t-j)]}\beta^{[(i-j)/(t-j)]} \tag{12}$$

in agreement with the rule expressed in Equation 11. It can also be shown that

$$(1+k) = (\beta/\alpha)^{1/(t-j)} \tag{13}$$

$$r_{i\neq o} = r_{i-1}(1+k) \tag{14}$$

$$\Delta_i/\Delta_{i-1} = (1+k) \tag{15}$$

For $t = 5, j = 2, \beta = 1{,}100$ and $\alpha = 150$, and substituting into equation 12, we obtain (a few values were rounded) $r_0 = 40$; $r_1 \approx 80$; $r_2 = 150$; $r_3 \approx 290$, $r_4 \approx 570$, $r_5 = 1{,}100$ (Figure 4).

Here, r_o indicates that under a given low "amount of risk," risk itself is difficult to perceive. In the presence of people, even if building vulnerability is zero or reliability is ∞, which is impossible, we cannot say that risk is zero or null. This is the non-evaluability domain. In this shadow zone, we prefer to say that below such a value, risk becomes unperceivable. We call this value of r_o the "evaluability threshold." (A more detailed explanation is given in the online supplement Appendix B).

The SIRIUS scale can be more conveniently expressed by representing the relationship between perceived risk, expressed as a real value $i \in \{0,...,5\}$, and risk itself, expressed as a real value $eri > 0$. These functions are expressed by equations 16 and 17:

$$i = -5.5445 + 1.50567\ Ln(rrd \times rhc) \tag{16}$$

$$eri = 39.7396e^{0.6641i} \tag{17}$$

From Equation 16, as risk (eri) increases, our ability to realize that it has changed decreases. This is expressed by equation B19 (see the online supplement Appendix B), in which the derivative of i in eri, $(di/deri)$ rapidly decreases with eri. Thus, the higher the risk, the higher the likelihood that we do not perceive changes in risk. The inverse phenomenon also holds: Risk increases exponentially as our perception of it increases linearly.

Risk often increases by amounts that are usually smaller than the smallest amount of variation that allows us to perceive it. This is the "perceivability threshold" described in the online supplement Appendix B. This phenomenon explains two important paradigms: (i) we only perceive changes when risk is too low, and (ii) risk tends to increase unnoticed.

Figure 5, which was obtained from Equation 17, illustrates another representation of the SIRIUS scale, based on the two-entry continuous variables rrd and rhc. The largest dots represent the two situations used to calibrate the scale.

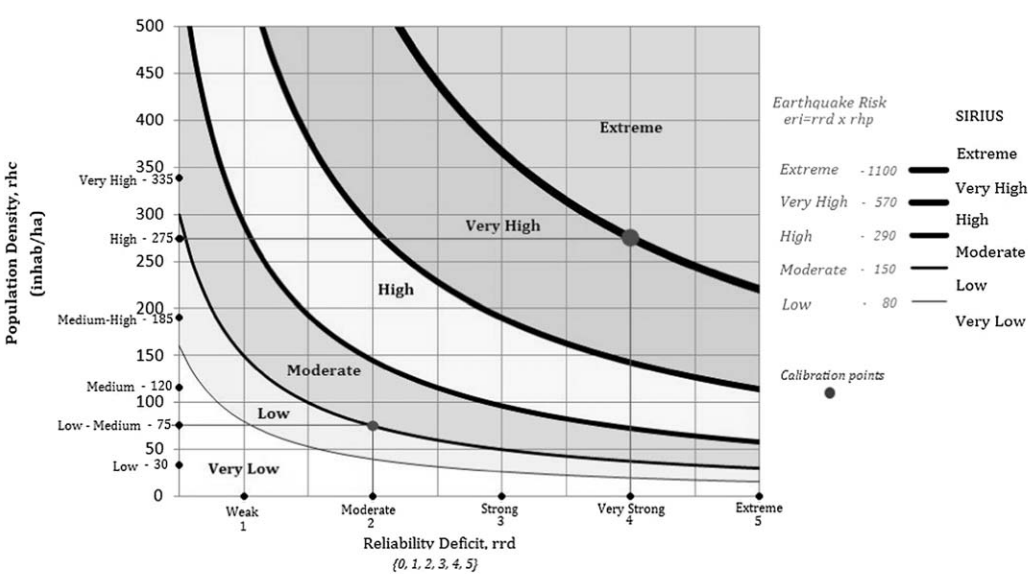

Figure 5. Continuous representation of SIRIUS indicator in the rrd, rhc space.

From Figure 5, we can make the following comments:

- Once the reliability index and the population concentration are either quantitatively or qualitatively known, the SIRIUS values and the bounds limiting each class can be easily determined.
- The ratio of *eri* between two consecutive SIRIUS levels is constant and approximately equal to 2, which means that risk doubles from one level to the next in accordance with equation B5, $r_{i+1}/r_i = (1 + k) = 1.943 \approx 2$ (see the online supplement Appendix B).
- Zones with a building stock designed and constructed in accordance with modern seismic regulations, which yield a reliability deficit value, *rrd*, of weak or lower, can support high population densities while maintaining seismic risk within an acceptable level (moderate risk).
- Conversely, when the reliability deficit value is very strong or higher, even for relatively small population densities, seismic risk can easily reach unacceptable values (very high or extreme).
- Figure 5 provides an idea for reducing the SIRIUS class. According to the representation, the higher the SIRIUS class is, the wider the area. Thus, reducing the SIRIUS value is more difficult for higher classes.
- In zones where the resilience deficit has grown to a high level, reducing seismic risk requires a substantial effort, as shown by the approximately horizontal shape of the equal-risk curves in this zone. Consider moving from a point defined by $rrd = 4$ and $rhc = 150$ ($eri = 570$ <>very high risk curve) to a point defined by $rrd = 1$ and $rhc = 150$ and the same population density ($eri = 150$ <> moderate risk curve). The number of buildings with an insufficient reliability value must be reduced in all but a few exceptional cases ($rrd = 4 =$ "very strong" to $rrd = 1 =$ "weak"), clearly indicating that high values of *rrd* should not be allowed.
- Increasing the population density in any zone will result in the same level of risk only if new buildings are better designed and constructed than average in the zone. Equal construction and design will always increase seismic risk. New construction will result in higher population densities, which should be compensated for with better reliability in order to maintain the same level of risk.

SIRIUS APPLICATION

This example considers the city of Lisbon, Portugal, which contains approximately 61,000 buildings and 660,000 inhabitants, according to 1991 statistics (INE 1992). The building stock was classified into five typological classes (T1 to T5) according to the date of construction (Figure 6a). A general description of the typologies and their corresponding vulnerabilities are given in Table 6. Population density is given in Figure 6b.

A uniform peak ground acceleration (PGA) of 150 cm/s^2 in the bedrock, corresponding to a return period of 475 years, was used to simulate a possible seismic event. PGA amplification due to local soil characteristics was considered for values in the range {1.0–2.0}. These values were adapted from the seismic simulator developed for the Lisbon City Council (Oliveira et al. 2005). Using the Trifunac law to translate PGA into macroseismic intensity (Trifunac and Brady 1975), intensities between VII and VIII were calculated. Vulnerabilities

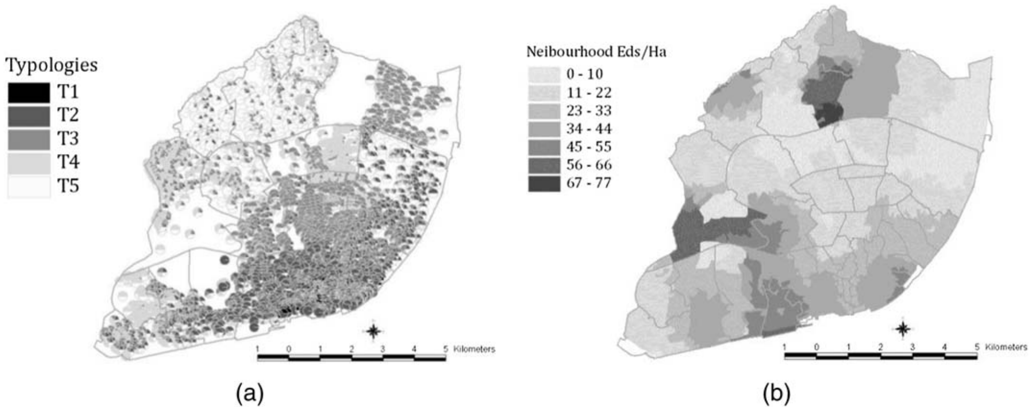

Figure 6. (a) Building typologies and (b) population density [inhab/ha] within a 1-km radius.

Table 6. Building typology characterization and corresponding vulnerabilities

Typology	Year built	%	$V--$	$V-$	V^*	$V+$	$V++$	%
T1	Before 1755	2.6	0.620	0.810	0.873	0.980	1.020	2.6
T2	1755–1870	25.7	0.300	0.490	0.616	0.793	0.860	25.7
T3	1870–1940	21.7	0.460	0.650	0.776	0.953	1.020	21.7
T4	1940–1970	19.9	0.140	0.360	0.553	0.793	0.860	19.9
T5	1970–1985	30.1	0.140	0.207	0.447	0.640	0.860	30.1

were taken from the simulator according to the Risk-UE method (Milutinovic and Trendafiloski 2003).

Equations 9 and 10, together with the intensities and typology vulnerabilities, were used to calculate the reliability deficit, *rrd*, for the two distinct objectives: non-collapse (life safeguard) and damage (functional) limitation. The results are shown in Figure 7.

These values, combined with the population density, were used in equation 2 to calculate *eri*. The results are shown in Figure 8.

In addition to the results shown, observations that are more related to civil protection can be made. For example, an earthquake in zones for which SIRIUS produces a value of "high" or greater will cause more human suffering because of greater physical losses and because daily activities will be more strongly disrupted. Zones for which SIRIUS produces a value of "extreme" may have to be temporarily or permanently evacuated.

Table 7 summarizes the main results of the application of SIRIUS to the Lisbon City Council. Seven different scenarios (objectives-PGA) were established, and the percentage of the population exposed to each class of risk (SIRIUS class) is shown. This method of communicating and interpreting risk is simple and understandable. Row 3 shows the average *eri* to which citizens were exposed in each scenario $\{4; 221; 433; \ldots; 1068\}$, and row 4

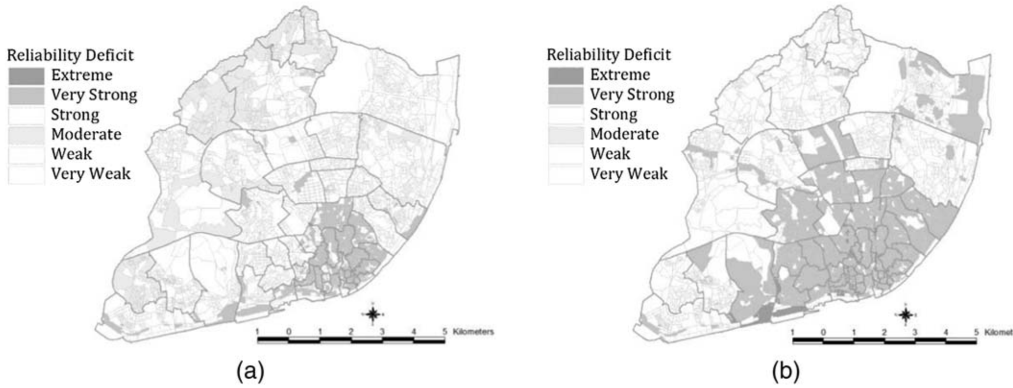

Figure 7. The reliability deficit, *rrd*, with the objectives of (a) the non-collapse requirement (Equation 9) and (b) the damage limitation requirement (Equation 10).

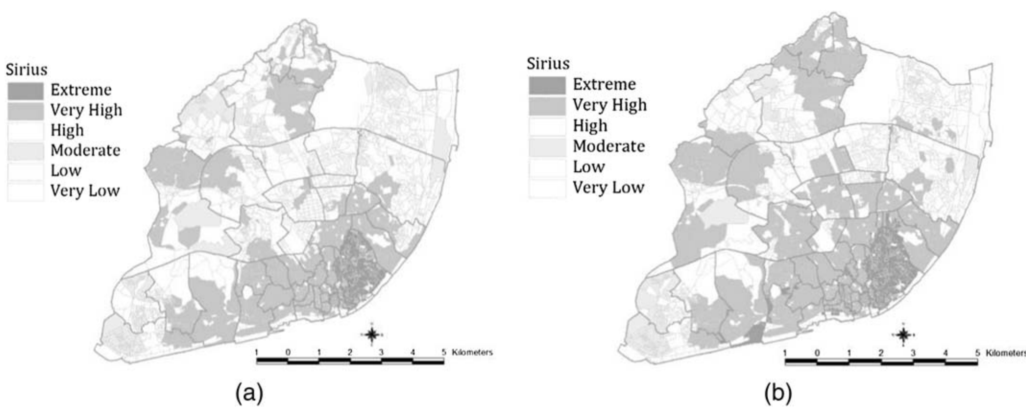

Figure 8. Risk, as measured by SIRIUS, with the objectives of (a) the non-collapse requirement and (b) the damage limitation requirement (Equation 17).

shows the equivalent semantic correspondence. The remaining row values show the percentage of the population exposed to each level of risk for each scenario (column).

Figure 8 clearly shows which areas of the Lisbon City are more prone to earthquake risk, and Table 7 indicates how the whole city would survive.

SIRIUS ROBUSTNESS

In order to test robustness of the SIRIUS model, the risk of class $i \in \{0;1;2;3;4;5\}$,was repeatedly calculated within a Monte-Carlo process with 100,000 trials. The following parameters were tested in this analysis: (i) soil effect; (ii) vulnerability index; (iii) conversion PGA-I_0; and (iv) population density (see details in the online supplement Appendix C). In each trial, two values were captured: $i_{expected}$ and $i_{observed}$. While $i_{expected}$ was obtained considering a plausible value to all the involved parameters, $i_{observed}$ was obtained taking

Table 7. Risk measured against different objectives (PGA or intensities). Bold values indicate the mode.

Scenario	**PGA** [cm/s^2] (Bedrock)	**15**	**25**	**50**	**75**	**150**	**250**	**500**
	"Intensity" (Average)	4.1	4.8	5.8	6.4	7.4	8.1	9.1
	SIRIUS (*eri*) (average/inhab)	4	221	433	575	781	965	1068
	SIRIUS class	Very low	Moderate	High	Very high	Very high	Very high	Very high
Population exposed (%)	Extreme	–	–	0.0	1.2	14.5	35.9	**48.7**
	Very High	–	3.8	16.7	43.5	**57.7**	**51.4**	45.3
	High	0.1	13.9	**66.0**	**45.6**	24.4	10.9	4.9
	Moderate	1.5	**59.4**	13.9	8.0	2.5	0.9	0.2
	Low	0.3	12.1	2.4	0.8	0.0	0.0	–
	Very Low	**98.1**	10.8	1.0	0.9	0.9	0.9	0.9

a reasonable value to each parameter, taking into consideration his natural variability (uncertainty). In each trial the error $\varepsilon = i_{observed} - i_{expected}$ was computed. It is worth noting that the non-deterministic nature of all the parameters involved dictates that a 100% probability of $\varepsilon = 0$ do not exist. It is easy to understand that when the parameter *eri* assumes some value over one of his isolines ($eri = 80$; $eri = 150$; $eri = 290$, $eri = 570$ or $eri = 1{,}100$; see Figure 5), any variation, even infinitely small, of any parameter will lead to $|\varepsilon| > 0$. As such, in order to accept or to reject the hypothesis that the model is robust, two statistical tests were performed in order to find the confidence intervals for $P[\varepsilon = 0]$ and $P[|\varepsilon| \leq 1]$.

From those tests, it is possible to conclude that, with confidence interval of 99%:

- The model returns an error $\varepsilon = 0$ with a probability $\geq$ 91.9%.
- The model returns a error $|\varepsilon| \leq 1$ with a probability $\geq$ 99.45%.

This allows us to ascertain that the model proves to be robust.

Further information can be seen in the online supplement Appendix C.

CONCLUSIONS

SIRIUS can help urban and land-use planners, civil emergency agents, and local authorities to understand seismic risk as a function of seismic action and the potential for physical damage to building stock and social disruption, avoiding the need for sophisticated seismic simulators. SIRIUS, or its counterpart *eri*, is composed by the aggregation of two other indicators, the reliability deficit indicator and the human concentration indicator.

The risk due to reliability deficit indicator, *rrd*, for a given scenario, is a measure of the distance of the structural performance of a building to its envisaged performance. It was shown that "functional requirements" should be considered when deciding upon "function replacement or location of new constructions" and that when rebuilding old structures to serve as hospitals, police stations, laboratories or other urban centers, designers should be aware that the functional requirements may be more demanding than those required to prevent collapse.

The risk due to human concentration indicator, *rhc*, through classes of population density, measures the potential for functional, physical and social disruption following an earthquake.

Cardinal and semantic scales were developed for each of those three entities, allowing a better perception of the existing seismic risk. We believe that this formulation, avoiding the need for sophisticated seismic simulators, can be useful to a wide range of end-users who need to be aware of seismic risk but have no access to specialized knowledge. This information, which is rather robust, can therefore help communities to grow sustainably and consciously.

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REFERENCES

Anas, A., and Rhee, H.-J., 2006. Curbing excess sprawl with congestion tolls and urban boundaries, *Regional Science and Urban Economics* **36**, 510–541.

Bana e Costa, C., 1992. Structuration, construction et exploitation d'un model e multicritère d'aide à la decision, Ph.D. Thesis, Technical University of Lisbon, Instituto Superior Técnico, Lisbon, Portugal (in French).

Bernardini, A., Giovinazzi, S., and Lagomarsino, S., 2007. The vulnerability assessment of current buildings by a macroseismic approach derived from the EMS-98 scale, in *Proc. Congresso Nacional de la Ingienería Sísmica*, Girona.

Bilham, R., 2009. The seismic future of cities, *Bulletin of Earthquake Engineering* **7**, 839–887.

Bloomfield, R., Chozos, N., and Nobles, P., 2009. *Infrastructure Interdependency Analysis: Introductory Research Review*, Report, Center for Software Reliability of City University London, Adelard LLP, Granfield University.

Borges, J. F., and Castanheta, M., 1983. *Structural Safety*, Laboratório Nacional de Engenharia Civil, Lisbon, Portugal.

Burdge, R. J., 2004. *The Concepts, Process and Methods of Social Impact Assessment*, Social Ecology Press, Middleton, WI, 320 pp.

Cardona, O., 2005. *System of Indicators for Disaster Risk Management*, Report, Instituto de Estudios Ambientales, Universidad Nacional de Colombia, Manizales.

Carreño, M. L., Cardona, O. D., and Barbat, A. H., 2007. Urban seismic risk evaluation: A holistic approach, *Natural Hazards* **40**, 137–172.

Cox, L. A., 2009. What's wrong with hazard-ranking systems? An expository note, *Risk Analysis* **29**, 940–948.

Crowther, K. G., Haimes, Y. Y., and Taub, G., 2007. Systemic valuation of strategic preparedness through application of the inoperability input-output model with lessons learned from hurricane Katrina, *Risk Analysis* **27**, 1345–1364.

Dantzig, G. B., 1973. The ORSA New Orleans address in Compact City, *Management Science* **19**, 1151–1161.

Dantzig, G. B., and Saaty, T. L., 1974. *Compact City: Plan for a Liveable Urban Environment*, W.H. Freeman & Co., Ltd., San Francisco, 255 pp.

Davidson, R. A., and Shah, H. C., 1997. *An Urban Earthquake Disaster Risk Index*, Report, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA.

Desyllas, J., Ward, J., Duxbury, E., and Smith, A., 2003. *Pedestrian Demand Modeling of Large Cities: An Applied Example from London*, Report, Centre for Advanced Spatial Analysis, University College London.

Dueñas-Osorio, L. A., 2005. Interdependent response of networked systems to natural hazards and intentional disruptions, Ph.D. Thesis, Georgia Institute of Technology.

Dueñas-Osorio, L. A. andVemuru, S. M., 2009. Cascading failures in complex infrastructure systems, *Structural Safety* **31**, 157–167.

European Committee for Standardization (CEN), 2004. Part 1: General rules, seismic actions and rules for buildings, Design of structures for earthquake resistance, *Eurocode 8*.

Federal Emergency Management Agency and National Institute of Building Sciences (FEMA, NIBS), 1999. *HAZUS, Earthquake Loss Estimation Methodology*, Washington, D.C.

Ferreira, M. A., Oliveira, C. S., and Sá, F. M., 2011. Estimating human losses in earthquake models: A discussion, in *Human Casualties in Earthquakes*, R. Spence et al. (eds.), Chapter 17, Springer, 255–266.

Giovinazzi, S., and Lagomarsino, S., 2001. Una metodologia per l'analisi di vulnerabilità sismica del costruito, Paper presented at the *X CongressoNazionale "L'ingegneriaSismica in Italia,"* Potenza-Matera (in Italian).

Giovinazzi, S., and Lagomarsino, S., 2004. A macroseismic method for the vulnerability assessment of buildings, in *Proc. 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada.

Grünthal, G., 1998. *European Macroseismic Scale 1998*, Cahiers du Centre Européen de géodynamique et de séismologie, Conseil de L'Europe, Report Luxembourg.

Hubbard, D. W., 2010. *How to Measure Anything: Finding the Value of Intangibles in Business*, Second Edition, John Wiley & Sons, New York, 320 pp.

Hunter, P. R., and Fewtrell, L., 2001. *Water Quality: Guidelines, Standards and Health*, World Health Organization, London.

Jacobs, J., 1993. *The Death and Life of Great American Cities*, Modern Library, New York, 640 pp.

Kahneman, D., and Tversky, A., 2009. Prospect theory: An analysis of decision under risk, in *Choices, Values and Frames*, Cambridge University Press, 17–43.

Keeney, R., and Raiffa, H., 1976. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*, John Willey & Sons, New York, 592 pp.

Kunreuther, H., Novemsky, N., and Kahneman, D., 2001. Making low probabilities useful, *Risk and Uncertainty* **23**, 103–120.

Lian, C., Santos, J. R., and Haimes, Y. Y., 2007. Extreme risk analysis of interdependent economic and infrastructure sectors, *Risk Analysis* **27**, 1053–1064.

Lobo, M. C., Pardal, S., Correia, V. D. P., and Lobo, M. S., 1996. *Normas urbanísticas*, Direcção Geral do Ordenamento do Território e Desenvolvimento Urbano, Lisbon, Portugal, 261 pp. (in Portuguese).

Milutinovic, Z. V., and Trendafiloski, G. S., 2003. Risk-UE: An advanced approach to earthquake risk scenarios with applications to different European towns, *WP4 Vulnerability of Current Buildings*, RISK-UE – EVK4-CT-2000-00014.

Neuman, M., 2005. The compact city fallacy, *Journal of Planning Education and Research* **25**, 11–26.

Normandin, J.-M., Therrien, M.-C., and Tanguay, G. A., 2009. City strength in times of turbulance: strategic resilience indicators, in *Proc. of City Futures 2009*, Madrid.

Oliveira, C. S., Sá, F. M., and Ferreira, M. A., 2005. Application of two different vulnerability methodologies to assess seismic scenarios in Lisbon, in *Proc. of 250th Anniversary of the 1755 Lisbon Earthquake*, 1–4 Nov, Lisbon, Portugal.

Peters, K., Buzna, L., and Helbing, D., 2008. Modeling of cascading effects and efficient response to disaster spreading in complex networks, *Int. J. Critical Infrastructures* **4**, 46–62.

Roberts, B., 2007. Change in urban density: Its implications on the sustainable development of Australian cities, in *Proc. of State of Australian Cities National Conference*.

Sampson, R. J., Morenoff, J. D., and Gannon-Rowley, T., 2002. Assessing "neighborhood effects": Social processes and new directions in research, *Annual Review of Sociology* **28**, 443–478.

Scharlig, A., 1999. Décider surplusieurs critères, Panorama de l'aide à la décisionmulticritère, Collection Dirigerl Entreprise, Presses Polytechniques et Universitaires Romandes, 304 pp. (in French).

Shah, H. C., 2009. Catastrophe risk management in developing countries and the last mile, *The 1755 Lisbon Earthquake Revisited*, Springer, 111–120.

Tekeli-Yesil, S., Dedeoglu, N., and Braun-Fahrlaender, C., 2010. Factors motivating individuals to take precautionary action for an expected earthquake in Istanbul, *Risk Analysis* **30**, 1181–1195.

Trifunac, M. D., and Brady, A. G., 1975. On the correlation of seismic intensity scales with the peaks of recorded strong ground motion, *Bulletin of the Seismological Society of America* **65**, 139–162.

Turner, S. P., 1993. *Emile Durkheim, Sociologist and Moralist*, Routledge, New York, 272 pp.

United Nations, 2010. *Population Density and Uurbanization*, Department of Economic and Social Affairs, New York, available at http://unstats.un.org/unsd/demographic/sconcerns/densurb/densurbmethods.htm.

Weber, E. H., and Fechner, G. T., 1834, available at http://en.wikipedia.org/wiki/Weber–Fechner_law.

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