SIRIUS, Seismic Risk Indicator in Urban Space: an application to Lisbon

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SUMMARY:
Despite the many efforts and findings achieved over the past years, seismic risk continues to be difficult to perceive and communicate. While researchers have access to sophisticated tools to quantify seismic risk, other groups such as public authorities, land and urban planners, stakeholders and citizens still need to know about it in a simple non-engineered way. As so, SIRIUS is built and mapped into a scale that follows the Weber and Fechner law perception, where impacts are described in a simple but meaningful language, still capturing the most fundamental dimensions that explain risk variability along the urban space: (i) the reliability deficit and (ii) the human concentration. With SIRIUS it becomes easy to identify and communicate those places where and why seismic risk is higher or of concern. We illustrate the potentialities of SIRIUS analysing the seismicity, vulnerability and existences in the housing stock and population density of Lisbon.

Keywords: risk communication, disaster risk reduction, urban indicator

1. INTRODUCTION

Who needs to know about seismic risk? Despite numerous research efforts in recent years, seismic risk continues to be difficult to perceive and communicate. As stated by Shah (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.

2. SIRIUS SCOPE AND LIMITATIONS

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 (2010) 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 non-technical language to promote seismic risk perception and the willingness to take precautionary actions.
While constructing SIRIUS, we were faced with the difficult choice between simplicity to ensure availability and evaluability (Kunreuther et al., 2001) and complexity of the holistic approaches. The aforementioned reasons led us to the first choice, corresponding to two fundamental dimensions of seismic risk: the physical and social impacts within an urban space.
Two major points were not considered in the present formulation: i) damages to lifelines and critical industrial facilities and ii) recovery capability, which shape the post-emergency process. 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.

3. SIRIUS VARIABLES

We chose the following two variables to conveniently and simply translate earthquake risk (eri):
rrd - risk due to buildings seismic reliability deficit, as the major variable responsible for destruction
rhc - risk due to human concentration, as a proxy (indirect indicator) of physical, functional and social vulnerability to major disruptive events.

$$eri = f(rrd, rhc) \tag{3.1}$$

To link these two variables, consider the following rules:
i) 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.
ii) 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:

$$eri = rrd \times rhc \tag{3.2}$$

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.

3.1. Measuring risk 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.
Some definitions adapted from Giovinazzi and Lagomarsino [G&L] (Giovinazzi and Lagomarsino, 2004) 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 behaviour 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:

a.	Vu--	lower possibility	(best, not expected but still possible behaviour)
b.	Vu-	lower plausibility	(best expected behaviour)
c.	Vu*	characteristic value	(most expected behaviour)
d.	Vu+	upper plausibility	(worst expected behaviour)
e.	Vu++	upper possibility	(worst, not expected but still possible behaviour)

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 behaviour, which by the above statements will place them in the Desired

Level of Risk. We call this the Required Vulnerability, 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. The Reliability Deficit, rrd can be characterized into 6 classes (0 to 5 or Very weak to Extreme) and makes use of 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:

$$rrd = f\left(Actual\ Vulnerability, Required\ Vulnerability\right) \tag{3.3}$$

3.2. Required vulnerability, Vu_{REQ}

The Required Vulnerability can be observed as that which leads to a probability of structural behavior in accordance with some objective (O). Ferry Borges and Castanheta [B&C] (Borges and Castanheta, 1983) 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 f(S) and f(R). When these variables are convoluted in a joint probability f(R-S), with mean μR-S and standard deviation σR-S, the probability of failure can be measured by α (Figure 1):

$$\alpha = P[f(R-S) < O]; O = \mu_{R-S} - \beta.\sigma_{R-S} \tag{3.4}$$

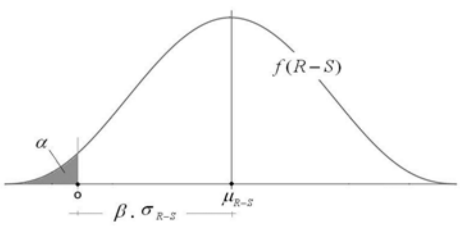

Figure 1. Probability of failure (adapted from Borges et al., 1983)

Thus, as stated by B&C, "the smaller the value of β, the higher the probability of failure", and "values of β=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 6 damage grades, dg {0, …,5}, with structural failure starting at damage grade 4 (dg=4). Therefore, we take α=P[dg ≥ 4]. Following the general expression established by G&L to relate damage grades μD and building vulnerability Vu, yields equation 3.4:

$$\mu_D = 2.452\left[1 + tanh\left(\frac{I + 5.604Vu - 12.19}{1.797}\right)\right] \tag{3.5}$$

where μ_D is the mean damage grade observed in buildings with vulnerability Vu when subjected to an EMS-98 Intensity I. Inverting equation 3.5 gives

$$Vu = 2.17523 - 0.178444 I - 0.318879 arctanh(1 - 0.40783\mu_D) \tag{3.6}$$

In this case, the probability of a given damage grade is obtained from equation 3.7:

$$P[dg \geq k \mid I] = 1 - \beta'(k - 0.5; p; q; 0; 5); 1 \leq k \leq 5 \tag{3.7}$$

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 equation 3.8:

$$p = \frac{8}{5}\mu_D; q = 8 - p \tag{3.8}$$

For a reference seismic event, translated to an Intensity Io, and a required Reliability β, we can write P[dg≥4 | Io] < α, and β'(3.5;p;q;0;5) < α, and from equation 3.7, we obtain the shape parameters p and q. From equation 8, μ_D can be obtained. Replacing I by Io and μ_D in equation 3.6, we obtain Vu=Required Vulnerability, 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 Io. 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 3.1.

Table 3.1. Vureq for different values of β

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

To illustrate the above concepts, we used typologies from G&L and Risk-UE (Milutinovic and Trendafiloski, 2003), as shown in Table 3.1. We adopted a Reliability Index β=4 and 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.

Table 3.2. G&L and Risk-UE vulnerabilities

	V--	V-	V*	V+	V++
G&L					
RC1, Frame in RC (without E.R.D)	0.300	0.490	0.644	0.800	1.020
RC2, Frame in RC (moderate E.R.D.)	0.140	0.330	0.484	0.640	0.860
RC3, Frame in RC (high E.R.D.)	-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

E.R.D. = Earthquake resistant design

To satisfy the "Moderate rrd condition",

1) If Vureq= 0.442 < 1.66770- 0.178444 Io => Io < (1.66770-0.442)/ 0.178444=6.9 (≈VII);
2) If Vureq= 0.800 < 1.66770- 0.178444 Io => Io > (1.66770-0.800)/ 0.178444=4.8 (≈V).

The same reasoning leads us to the conditions shown in Figure 2

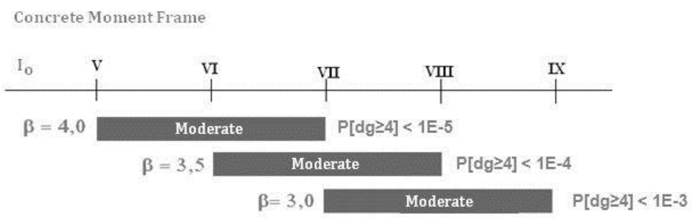

Figure 2. The reliability deficit for the RC1 moment frame and different values of the reliability index β.

From the three cases, we believe that a Reliability Index β=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 β = 3.5 with

=> P[dg≥4|Io]≤1E-4 =>1-β'(4-0.5;p;q;0;5)≤ 1E-4 =>p=0.79; q=7.21 =>μD ≤ 0.492775 and $Vu_{req} < 1.82576 - 0.178444 I_o$ (Non-collapse) (3.9)

In accordance with the previous definitions (see Figure 1), we can write our Reliability Deficit Scale as in Table 3.3.

Table 3.3. Reliability deficit, rrd, in a discrete scale

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

where Vureq = f (Io) is obtained from equation (3.7).

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 3.4.

Table 3.4. Reliability deficit, rrd, in a continuous scale

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

4. MEASURING HUMAN CONCENTRATION

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).

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.

Table 4.1 adapted from Lobo et al. (1996) and Roberts (2007), provide this semantic scale for rhc as a function of population density.

Table 4.1. Classes of population density

Population density (inhab/ha)	Classes of density
30	Low
75	Low - Medium
120	Medium
185	Medium - High
275	High

335	Very High

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

Although the rrd and rhc indicators have been mapped into scales, measuring and communicating seismic risk are still not possible. They must first be aggregated into a unique, meaningful and understandable scale. In this context, the following approach, illustrated in Figure 3, was used to map rrd and rhc into the eri (earthquake risk) and SIRIUS scales.

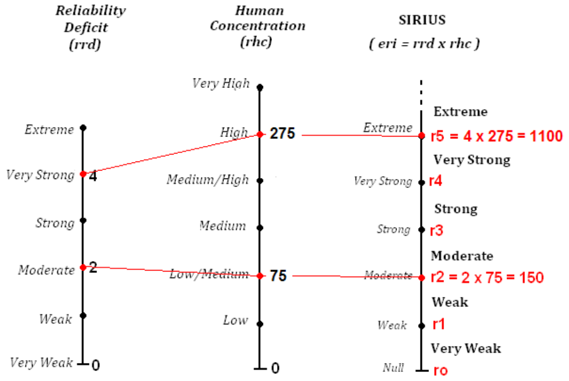

Figure 3. Calibrating the eri and SIRIUS scales. The eri semantic scale defines the lower and upper bounds of each SIRIUS semantic class.

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 x rhp = 2 x 75 = 150.

Situation 2: Very Strong Reliability Deficit - High human density => Extreme Risk and eri = rrd x rhp = 4 x 275 = 1100.

To obtain the other combinations of rrd and rhc, we used the "Weber–Fechner law" (Weber and Fechner, 1834). Stated in 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 that the intensity of a sensation may increase in arithmetical progression, the stimulus must increase in geometrical progression".

In such a way, while an intensity of sensation (r_i) may increase in arithmetical progression, the stimulus must increase in geometrical progression (see equation 5.1).

$$r_i = r_{i-1}(1+k) \qquad (5.1)$$

where, r_i is the amount of risk at (a perceived) level i and k is a constant (Weber fraction). Equation 5.1 applied to different levels i,j leads to geometric progression. If we now normalize the r_0 to 0 and r_t to 1 (r6=1, Figure 4) we can derive the semantic scale as shown in Figure 4.

Figure 3. Transformation of risk perceived in a semantic scale

This allows us to convert a numeric value of seismic risk in a human semantic scale, SIRIUS=f(Ri) (Figure 5).

Null	if	0	≤	Ri	<	0,027
Weak	if	0,027	≤	Ri	<	0,055
Neutral (Moderate)	if	0,055	≤	Ri	<	0,114
Strong	if	0,114	≤	Ri	<	0,135
Very Strong	if	0,135	≤	Ri	<	0,485
Extreme	if	0,485	≤	Ri	≤	1

Figure 5. SIRIUS scale

6. THE SIRIUS SCALE

Figure 4 illustrates another representation of the SIRIUS scale, based on the two-entry continuous variables rrd and rhp. The largest dots represent the two situations used to calibrate the scale

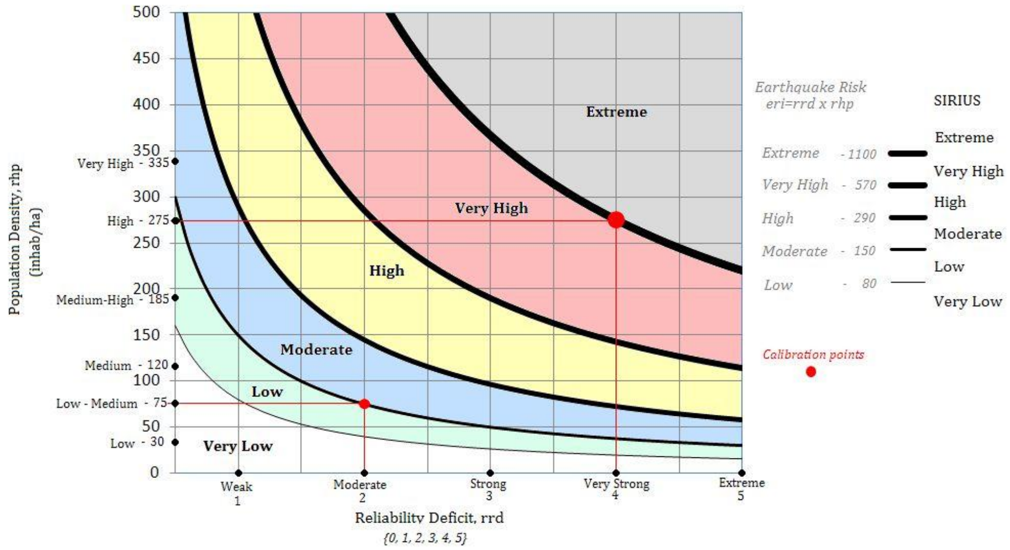

Figure 6. Continuous representation of SIRIUS indicator in the rrd, rhp space.

From Figure 6, we can make the following comments.
i) 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.
ii) 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,

$ri+1/ri=(1+k)=1.943\approx 2$ (see Sá et al, 2012).
iii) 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).
iv) 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).
v) Figure 4 provides an obvious approach 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.
vi) 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.
vii) 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 the 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 to maintain the same level of risk.

7. 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 5 typological classes (T1 to T5) according to the date of construction (Figure 7a). A general description of the typologies and their corresponding vulnerabilities are given in Table 6. Population density is given in Figure 7b.

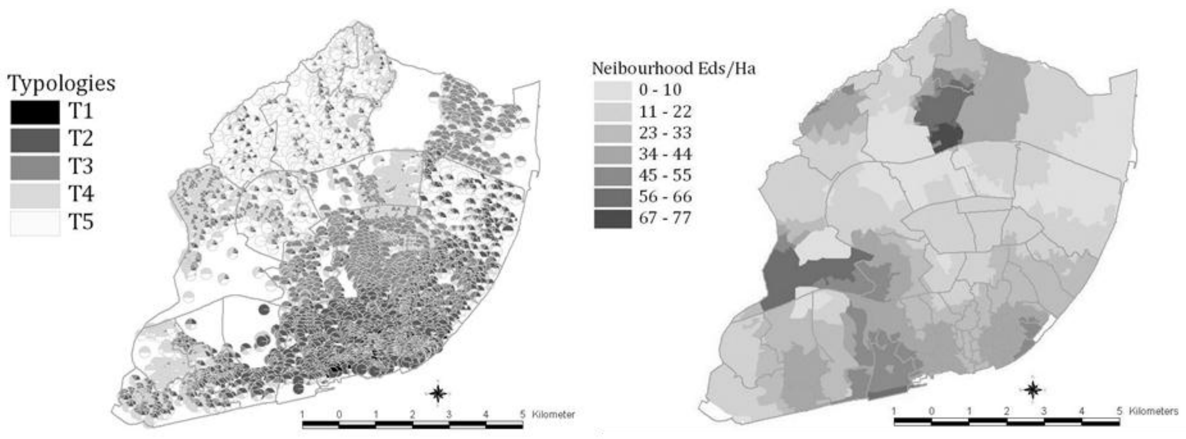

Figure 7. . Buildings typologies (a) and population density [inhab/ha] within a 1-km radius (b)

Table 6.1. . 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

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

Equation 3.6 together with the intensities and typology vulnerabilities, were used to calculate the Resilience Deficit, rrd, for the Non-Collapse objective. The results are shown in Figure 8.

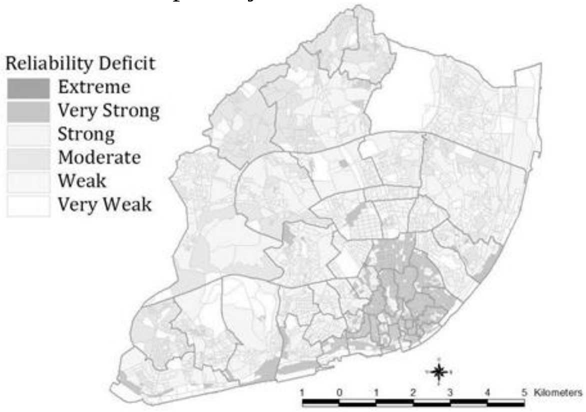

Figure 8. The Reliability Deficit, rrd, with the objectives of Non-Collapse Requirement

Figure 9 shows the risk measure by SIRIUS.

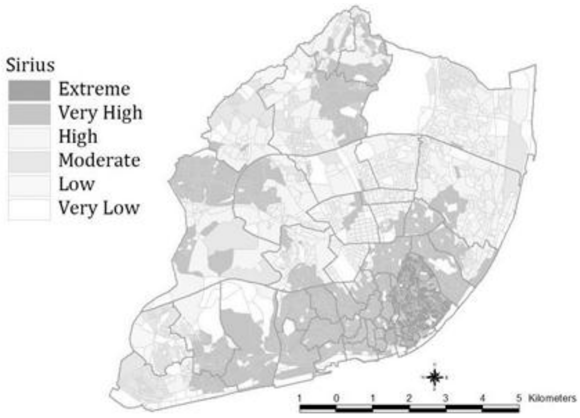

Figure 9. Risk measured by SIRIUS, with the objective of the Non-Collapse Requirement

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.

8. 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 potentials for physical damage to the building stock and social disruption.

The Reliability Deficit indicator, rrd, shows 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 centres, designers should be

aware that the functional requirements to dissipate energy from a structure may be more demanding than those required to prevent collapse.
By the above exposed, we believe that this formulation 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 can therefore help communities to grow sustainably and consciously.

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