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ORIGINAL RESEARCH PAPER

The Disruption Index (DI) as a tool to measure disaster mitigation strategies

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Abstract Apart from the loss of lives, injuries and homeless resulting from an earthquake, not only the economy and physical landscape are altered, but also the lives of citizens and their places of work are dramatically altered. If critical services and functions are disrupted for more than a reasonable time period, consequences can be severe. All communities are at risk and face potential disaster, if unprepared. The Disruption Index (DI) is a tool that allows the representation of a complex and multidimensional situation in a concise and easier way, providing institutions and communities with a way to identify the global earthquake impact in a geographical area, the elements at risk, and the means to reduce it. In the present paper, after a short review of the concept of DI, its geographic (spatial) distribution is developed and an application to some cities in Algarve (Portugal) is made. Then, the use of DI in the context of measuring the risk reduction for alternative disaster mitigation strategies is introduced and illustrations are presented.

Keywords Seismic risk · Interdependencies · Propagation · Disruption · Urban systems · Geographic distribution · Resilience

1 Introduction

The impacts of earthquakes are many; even the events with moderate magnitude cause extensive damage, such as losses of lives, property, and business, damage to industrial facilities and lifelines, and disruption of social order and normal life. The question is how

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to measure, in a simple way, the potential of such disruptions, combining tangible and intangible values.

Recently, a comprehensive review of the scientific literature has shown that the most typical risk models use multi-criteria decision analysis (MCDA) tools, with criteria weights $w_1, \ldots, w_p$ and additive aggregation of multiple-valued functions. It is important to note that some fundamental rules of such a construction are violated, such as cardinal independence (Bana e Costa and Beinat 2005), which have been misunderstood and neglected by many analysts and researchers. This knowledge was important to develop a new approach for earthquake risk assessment.

Considering the experiences and lessons learnt from recent earthquakes, the Disruption Index (DI) was constructed to quantify the state of disorder induced by the disruption of urban structures and its systemic functions (Ferreira 2012; Oliveira et al. 2012; Ferreira et al. 2014). This index was based, in part, on the need to better understand the impact of disruption of lifelines from earthquakes and to assist in the identification and ranking of risk mitigation measures and policies.

The present article is divided into three main sections. Section 2 presents a summary of the theoretical and conceptual aspects that define DI and the formulation to generate its geographic distribution. Section 3 focuses on the geographic (spatial) representation of DI by exploring a few examples in the Portuguese southern region. Finally, Sect. 4 introduces the use of DI to explore disaster mitigation strategies, illustrating its capabilities with examples.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Urban system functional dependencies	DI	Environment	Housing	Food	Healthcare	Education	Employment	Mobility	Power	Telecom	Transportation	Debris	Water	Sanitation	Security	Dangerous facilities	Electrictic facilities & components	Transportation facilities & components	Water facilities & components	Sanitation facilities & components	Telecom facilities & components	Schools	Health care facilities	Security facilities & components	Building stock
1 DI	1	1	1	1	1	1	1																		
2 Environment		-											1	1		1									
3 Housing			-					1	1				1	1											1
4 Food				-				1							1										
5 Healthcare					-			1	1	1			1	1									1		
6 Education						-		1	1	1			1	1								1			
7 Employment							-	1	1	1			1	1											1
8 Mobility											1	1													
9 Power																	1								
10 Telecom									1												1				
11 Transportation									1	1								1							
12 Debris																									1
13 Water									1										1						
14 Sanitation									1				1							1					
15 Security								1	1	1														1	

Fig. 1 Disruption Index seen from the adjacency matrix G. In columns, we represent the graph elements. The *square matrix* contains the 6 fundamental human needs; the other *black rows* (totalizing 14) contain the services and components, and the *right columns* (*blue*) show the elements that supports all other functions (Ferreira 2012)

2 An overview of Disruption Index method

The purpose of DI is to condense complex problems and multidimensional situations involving the earthquake impact in the livelihood in a concise and easier way. It helps institutions and communities to identify the elements at risk and select the ones that most contribute to the earthquake impact or, in other words, to DI. This section presents a short review on the Disruption Index technical details, and gives special emphasis in understanding the concepts involved and their interpretation.

The starting point for developing the DI is to reduce a complex system (urban system and livelihood) to a small number of meaningful dimensions and identify dependencies and connections among them. It is based on (1) the inspection of several seismic simulators, (2) extensive bibliographical research about the physical and social impacts of severe events, and (3) the experience gained in several earthquake field missions in different regions of the world.

More than 70 primary criteria (concerns) were found to be systematically present in all texts and reports. These concerns were aggregated into 14 Fundamental Criteria (using some fundamental rules of decision problem structuring), which translate critical dimensions (urban functions) and dictate what we see as an urban system's ability or disability to respond to the observed demands (Ferreira 2012). They incorporate 6 fundamental human needs: "Environment, Housing, Healthcare, Education, Employment and Food" (Fig. 1), affected by several other main functions/systems, such as mobility, electricity, water, and telecommunications, which are, in turn, dependent on the reliability of several buildings, equipment system facilities and critical or dangerous facilities. Each one of the 14 Fundamental Criteria is characterized by an impact descriptor (Ferreira et al. 2014).

Figure 1 shows how propagation and cascading effects can be calculated in a bottom-up sequence, starting with the physical damages directly suffered by the exposed assets (nodes with the lowest topological order), proceeding with the impacts that each node has in the functional performance of nodes that depends on them, until reaching the top node, DI (which is the one with higher topological order). Mathematically, the DI can be represented by its Adjacency Matrix of a Directed Graph [G], in which the element Gij equals 1 if row i depends on column j and is zero otherwise.

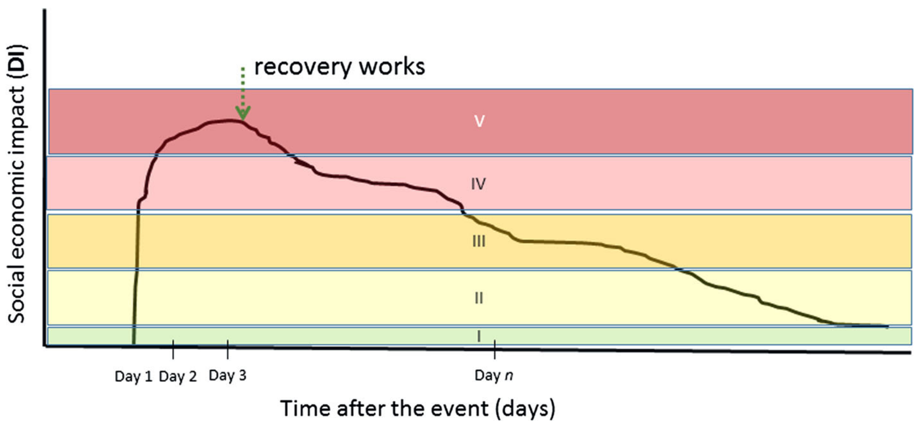


Fig. 2 Evolution of socio-economic impact along the time after the occurrence of an event

The DI is classified into five discrete levels (DI = I to DI = V, where I represents no disruption and V total disruption), describing the state of disruption of an urban area (Oliveira et al. 2012).

For further information see Ferreira et al. (2014) and Oliveira et al. (2014) where you can find detailed description of DI theoretical formulation and an example of application.

Cascading effects contribute to the urban disruption in a geographical area caused by the physical conditions (damage grades) of services and networks after a disaster. DI is evaluated for a given time after the event (Fig. 2). Emergency management and the progress of recovery will diminish the level of DI. The duration of a disruption is a key factor in whether the effects are temporary or permanent, and all of the stages are included in each impact descriptor. The DI methodology evaluates the likelihood and consequences of each scenario to obtain the overall impact. In addition, the concept implies interactions across the social, physical and economic sectors.

2.1 Geographical distribution of DI and urban influence (spatial modelling)

2.1.1 Context

The first approach to DI was an application made in Excel® environment related to an entire zone affected by the earthquake (Oliveira et al. 2012). It became clear that the DI methodology would depend on the geographic area under analysis as well as on the level of interdependencies studied. It also became clear that DI could be viewed as a prospective analyst (prior to the event) or as an evaluator (post-event). In the prospective case, the hazard concept would intervene and, as a consequence, disaggregation on DI could be developed. In the post-event case, the DI for a given scenario would be a key point.

Table 1 Left: establishing criteria for the delineation of radius of influence, right: illustration of spatial modelling and spheres of influence

Source Layer Name	Radius of influence (km)
Power stations	3
Local Transformers	1
Bridges	2
Aqueducts	1
Reservoirs	1
Water Pipes	1
Wastewater Pipes	2
Natural gas Pipelines	1
Natural gas GPRMS	5
Natural gas Pipes	1
Buildings	0
Healthcare	15
Schools	1.5
Security	2

The size of geographic area under analysis and the level of interdependences will certainly affect the DI. To understand the geographic influence on DI lets think of a tsunami or the rupture of an important pipe, generated far away from the study area, which may be the main cause of disruption, and, undoubtedly, this needs to be considered in any impact analysis.

These problems require a response in order to make DI a tool with geographical context. The first case was solved by introducing the concept of geographical minimal unit with meaningful sense. It could not be the size of a building because we need to make averages, but it should not be a large area, unless we just want to have an overall measure of disruption. We thought of the block, a grid or any other geographic unit of census track and it can be referred as the center of gravity of our analysis.

Urban centers do not function in isolation; rather they provide goods and services to the area lying beyond the urban boundary; people from the surrounding area commute to a town to access the required facilities. The city's "sphere of influence" describes its physical boundaries and the areas where facilities, amenities and services are allocated in fair manner in the urban center. Subsequently, urban population is found distributed among the settlements of varying sizes from smaller towns to giant cities (Pascione 2001).

In general, firehouses, hospitals, schools, and so on should be distributed throughout the city, so that each facility has a primary service area extending within a recommended radius. From the center of each cell a circle is drawn up to an X radius distance; for example schools are located within a 1.5 km radius of each grid cell. Table 1 establishes radius of influence for some urban facilities and networks, and depicts the circular form of sphere of influence of the amenities and facilities.

Computations of DI were made for a grid of points or the centre of gravity of a block of buildings, applying the concept of radius of influence. Isolines of DI were then drawn to obtain the geographical location of transitions between zones of equal DI. QuakeIST® (Mota de Sá et al. 2015) was developed in C++ to programme DI algorithm.

Several questions may be placed at this instance in order to enquire about sensitivity of DI on the size of the grid and on the absence of some of the information required to deal with all six "fundamental human needs", and other sources of uncertainty. In relation to the size of grid, DI is not much sensible because we are combining the principles of urban design with the "sphere of influence". If in a territory the urban design is made under other radius of influence, these should be the ones to use in conjunction with the values to be used in Table 1. In relation to the lack of information in one of the "human needs", our experience of exercising the DI in many different situations (Meroni et al. 2015), is that some of them are more important than others as it will be evidenced in Sect. 3. For example, "housing" is probably the most important one, conditioning all others. But certainly, lacking of one "human need" will contribute to a reduction of the DI estimate, meaning that the use of all the information will lead to the upper bound of DI.

3 Some applications of DI

In the framework of UPStrat-MAFA (2012) project, a case study was carried out in the Algarve region (Oliveira et al. 2014). The region with a population of 451,000 inhabitants (population triples in the peak holiday season thanks to a high influx of visitors) is located in the South of Portugal, with 16 municipalities. The Algarve seismicity (moderate to high) results from the earthquake activity of the contact region of Euro-Asian and African plates (the West region of Cabo de São Vicente) and from the activity in the continental margin crossed by diverse local faults. In this paper we concentrated our analysis in three cities in this region, namely Faro (its administrative and political center), Lagos and Albufeira (Fig. 3) both popular tourist destination in Portugal, and one of the most popular in Europe. Even though they are located not far from each other, their overall situation is quite different as far as DI is concerned. We will look in more detail to the Lagos municipality and summarize results of Faro and Albufeira.

To build DI we need information on all the assets referred in Sect. 2, namely definition of seismic scenario, soil microzoning, building typologies, infra-structures, and the corresponding vulnerabilities, population distribution, etc. The following results correspond to a scenario similar to the historic 1755 earthquake (M8.7). This event devastated Algarve and Lisbon regions and was felt throughout Europe and North Africa. Figure 3 presents the isoseismal map for the 1755 earthquake.

Figure 4 presents the main soil classification according to Eurocode 8 (2004) with four ground types (A, B, C and D). This is of great practical importance to simulate proper attenuation relationships and to account for the influence of local ground conditions on the seismic action, and, subsequently, obtain more trustworthy risk evaluation.

The total number of residential buildings in the region is 198,924, according with the last Census inventory (INE 2011). Figure 5 shows the buildings distribution and number of floors for each case-study municipality.

After collecting of assets and building stock, it is important to characterize them and attribute vulnerability functions in order to compute damage distribution caused by a given seismic scenario. For each building the characteristic building type (or structural system) and its vulnerability class have to be identified. As a whole, 55 buildings vulnerability classes were distinguished in the Algarve region, from low earthquake resistance/higher vulnerability to increased earthquake resistance. See Mota de Sá (2015), for the vulnerability assessment of those typologies, whose main characteristics depend on the epoch of construction, structural type and number of storeys.

Similar considerations are applied to the other assets such as bridges, schools and healthcare facilities (Ferreira 2012). Electric power, employment and a few other items were considered in this analysis in a very simplified way.

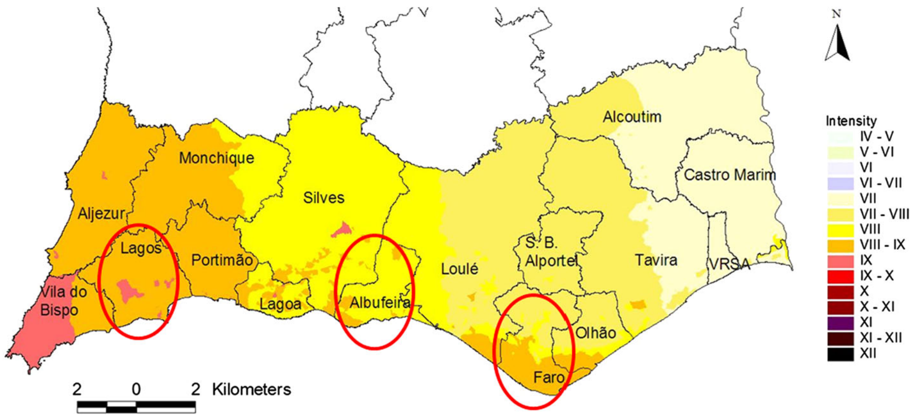


Fig. 3 The intensities distribution of the 1755 earthquake scenario. The *circles* represent the three main cities under study

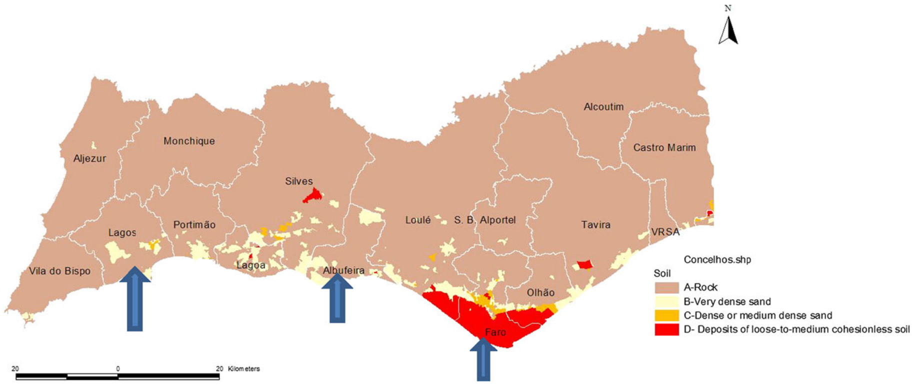
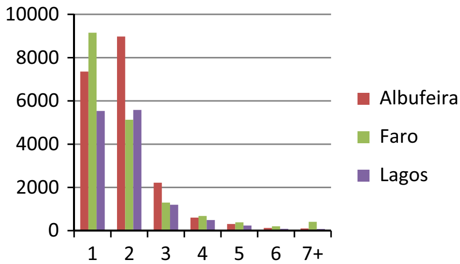


Fig. 4 Algarve soil classification and municipalities with its boundaries; *blue arrows* indicate the cities under study

Fig. 5 Total residential buildings by number of floors in each municipality (INE 2011)



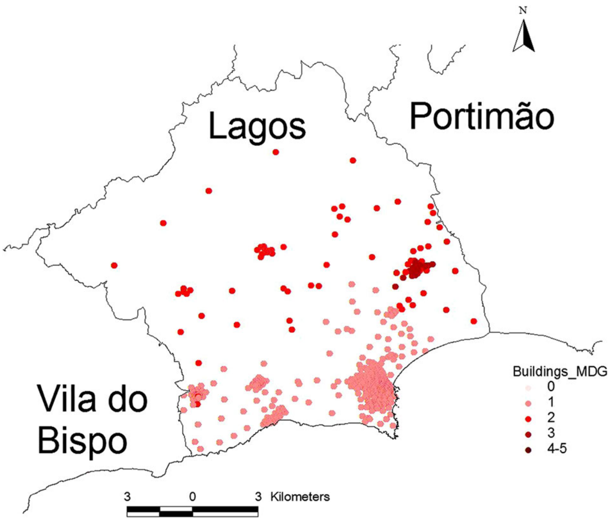


Fig. 6 Calculated mean damage grade in Lagos (each *dot* represents a block)

The geographic unit of analysis in this study was the urban block (statistical subsections: the territorial unit which identifies the smallest homogenous area).

Following the proposed methodology of DI, the options of the whole procedure are demonstrated by the case studies (Lagos, Faro and Albufeira municipalities) in Sects. 3.1, 3.2, 3.3. It will be shown how heavily the areas of a community are affected and where significant damage concentrations as well as urban disruptions are expected.

3.1 Lagos

The touristic destination of Lagos is located in the Barlavento region of the Algarve (southern coast). The population in 2011 was 31,049 in an area of 212.99 km^2. It is surrounded along its borders by the municipalities of Vila do Bispo (to the west), Aljezur (to the northwest), Monchique (to the northeast) and Portimão (to the east).

Figure 6 shows the level of destruction on the building stock per block in terms of mean damage grade and Fig. 7 the number of buildings belonging to each damage grade (from no damage to total collapse).

Figure 8 illustrates the damages inflicted on bridges structures. The obtained results indicate if we gather together the debris (from building stock) and the bridge damages with their sphere of influence, the impact on Mobility is obtained as shown in Fig. 8, right. It should be noticed that the area of higher impact includes the Lagos historical centre and the northern part, not much populated, but crossed by important bridge infrastructures, which cause disruption in the area.

School-aged children exposed to high magnitude natural disaster will suffer severe consequences on their education system due to the persistence of the effects. The impact on education, or the indirect effect of the disaster, is the combination of the different impacts such as on school buildings/educational facilities, mobility, power supply, water supply, telecom supply and sanitation supply (Ferreira et al. 2014). Figure 9 show the direct damage on school buildings and their radius of influence. The key interdependencies and level of failures between educational facilities and infrastructures/systems can be identified and described in Fig. 10.

This earthquake scenario can predict a negative impact on children's education (impact level III and IV), as shown in Fig. 11. Education impact level equal to IV means: "There would be educational facilities with severe damage or collapse. Disruption of educational continuity, schools inaccessible for long periods. Students are relocated to other areas of

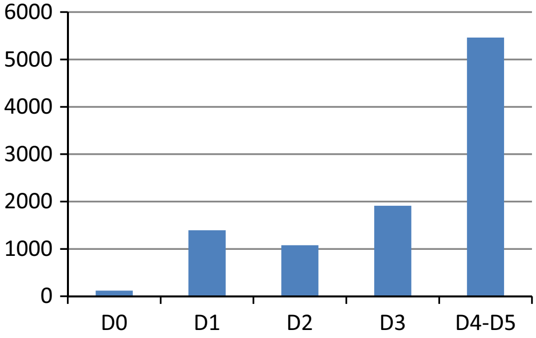


Fig. 7 Number of buildings in each damage scale

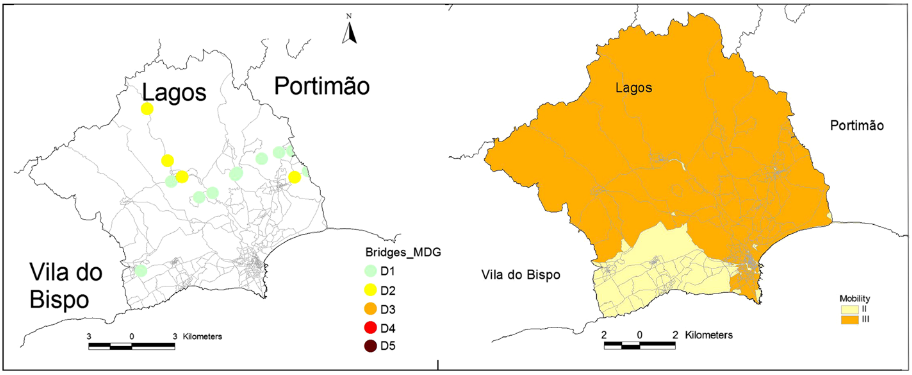


Fig. 8 Damages inflicted to bridges (*left*) (a *dot* is a bridge) and the consequent effect on Mobility (*right*). Statistical subsection is represented in *gray lines* (*right*)

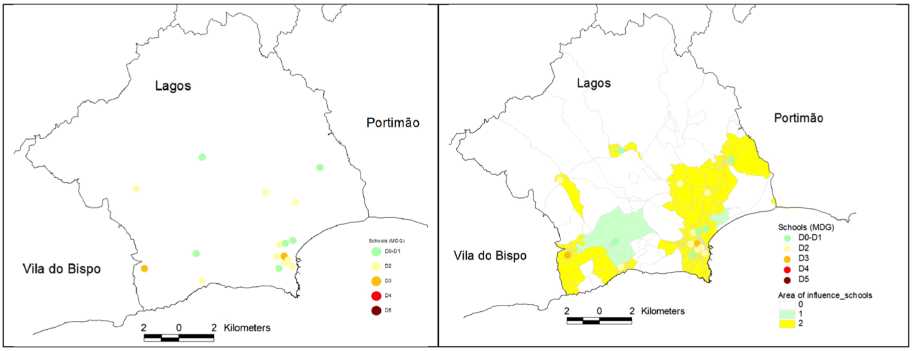


Fig. 9 Damages inflicted to school buildings (*left*) and their radius of influence (*right*)

Education												
Impact level	**Impact descriptor** *Measures the education disruption, the number of persons deprived of education and identifies alternatives for the recovery.*	Educational facilities		Mobility		Power supply		Telecom supply		Water supply		Sanitation supply
IV	There would be educational facilities with severe damage or collapse. Disruption of educational continuity, schools inaccessible for long periods. Students are relocated to other areas of the country. Families sometimes are not able to carry the burden of fees because of not-existing livelihoods.	> III	OR	> II		-		-				
III	Difficult access to education. There would be educational facilities with severe damage or collapse or restricted access due to debris. Teachers could not access, materials have been destroyed. Necessary temporary relocation or share their site with another school, until completion of rehabilitation works.	> II	OR	> I	OR	> II	OR	> II	OR	> II	OR	> II
II	Momentary disruption with resumption of classes after inspection and assessment of security conditions (weeks).	> I	OR	-	OR	> I	OR	-	OR	> I	OR	> I
I	No significant impact on function.	-	-	-	-	-	-	-	-	-	-	-

Fig. 10 Qualitative descriptors of education and dependencies from other systems

the country. Families sometimes are not able to carry the burden of fees because of not-existing livelihoods" (Ferreira 2012; Ferreira et al. 2014).

Potential impacts on healthcare system have been quantified and calculated. Public healthcare facilities as a health center and a hospital also suffer physical damage (D2 and D3) as shown in Fig. 12 (left). Due to the escalation of effects in the Mobility, Water and

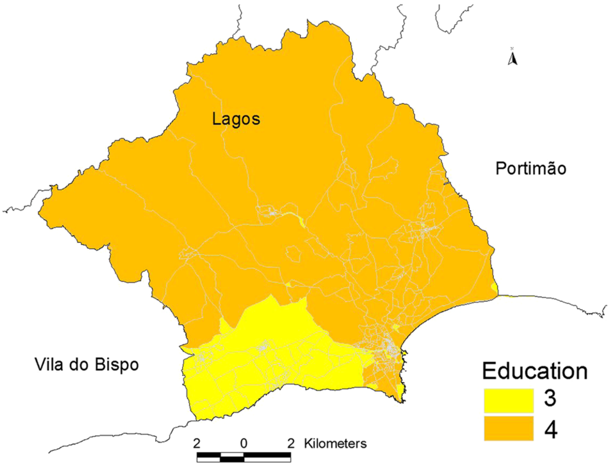


Fig. 11 Lagos: impact on education (levels III and IV)

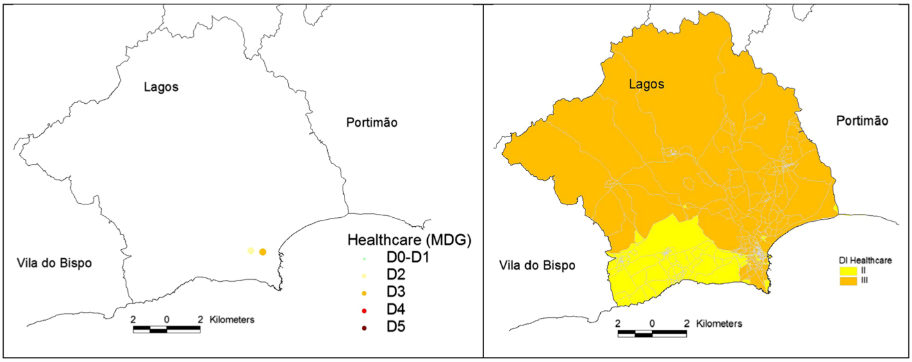


Fig. 12 Damages on healthcare facilities (*left*) and impact (*right*)

Power supply as shown in Fig. 13, the health of Lagos population will be directly affected through injury and death or displacement to other health centers, impairing the ability of communities to respond to this event (Fig. 12, right).

The 1755 earthquake scenario macro-level impact is shown in Fig. 14. Impact will be heavy to extreme because our infrastructures and building stock remain poorly prepared to meet the threat. Unless we take action now to start building the necessary resilience, the surviving community will lost nearly all of its capacity to respond and implement recovery efforts.

3.2 Faro

The city of Faro is the southernmost city in Continental Portugal with a population of 64,560 inhabitants (INE 2011). In the recent years the city has shown a significant growth and due to this reason it is desirable to plan seriously for further expansion towards safe areas.

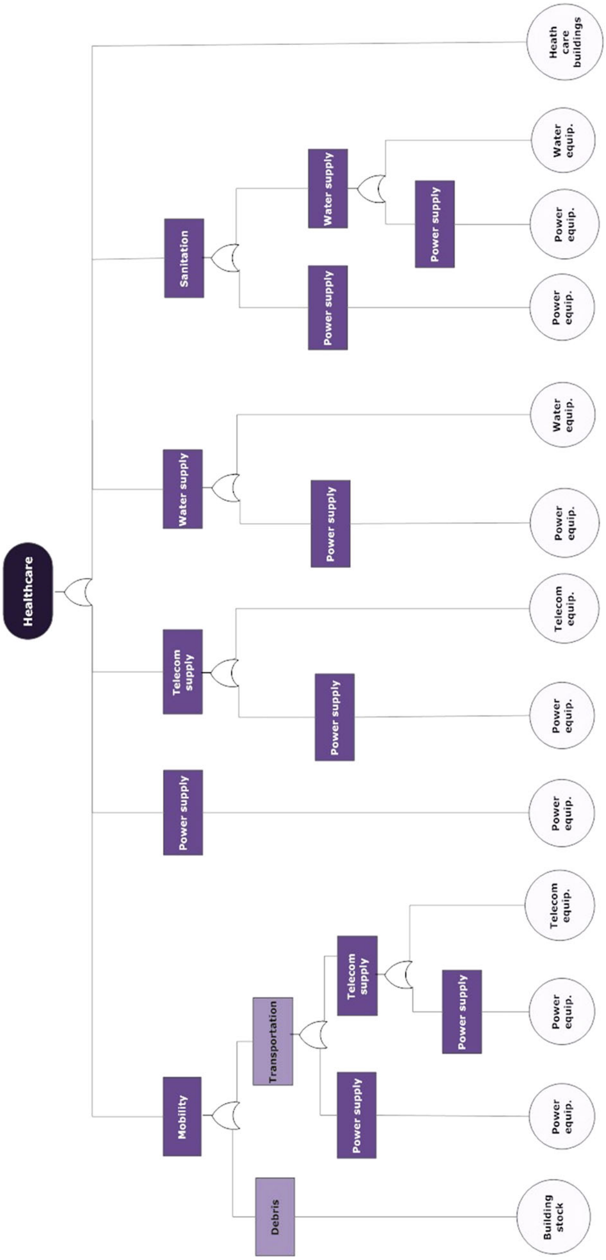


Fig. 13 Overview of generic interdependencies among systems

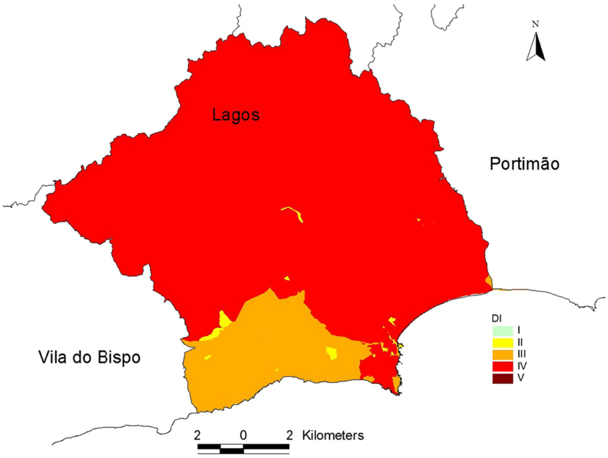


Fig. 14 Lagos global impact: Disruption Index

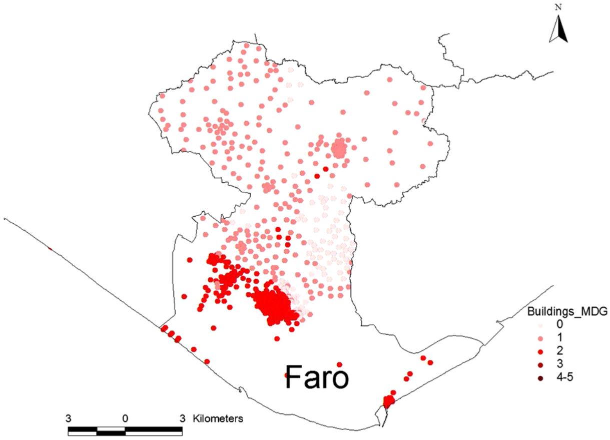
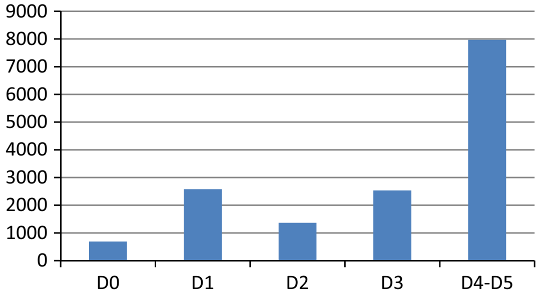


Fig. 15 Calculated mean damage grade in Faro

Fig. 16 Number of buildings in each damage scale (*D0* no damage, *D1* slight damage, *D2* moderate damage, *D3* heavy damage, *D4–D5* very heavy damage to destruction or total collapse)



The local distribution of damage in the residential building stock is given in terms of the Mean Damage Grade (MDG) and illustrated in Fig. 15. Several other statistical and GIS-maps can be built and presented, using not only the MDG but also the probability of exceedance of a certain damage grade given the seismic input or the number of buildings belonging in each damage grade, as presented in Fig. 16.

For the same scenario, Fig. 17 illustrates the earthquake global impact (DI) to Faro municipality. As seen in Fig. 15 the zones with a high concentration of damage conduct to a major disruption (Fig. 17).

3.3 Albufeira

For Albufeira with 40,828 inhabitants the procedure leads from Figs. 18, 19 and 20.

3.4 Comparison of results

The repetition of 1755 earthquake scenario today is expected to have a noticeable impact not only in the three different cities under analysis, but also on the entire region and at national level. The Algarve region is far from resilient to the impacts of a great earthquake today. We could not forget that this earthquake will inevitably cause a tsunami like the one occurred in 1755, aggravating the impacts showed before.

To better understand the interdependencies and cascade effects between communities, the following maps show the different results to the entire Algarve region. The macro-seismic intensities assigned to Lagos (I_{max} = VIII–IX), Faro (I_{max} = VIII) and Albufeira (I_{max} = VIII–IX) are depicted in Fig. 3.

The building damages distribution (spatial and frequency) are shown in Fig. 21. Effects are important for intensities greater than VIII where we can see a high concentration of Damages 3 and 4 (heavy to very heavy damage).

The losses of lives, number of severe injured and of homeless can be directly estimated by the damage grades in the building stock and the population associated to each case but, for reasons of simplicity in the paper, we are not analyzing these losses.

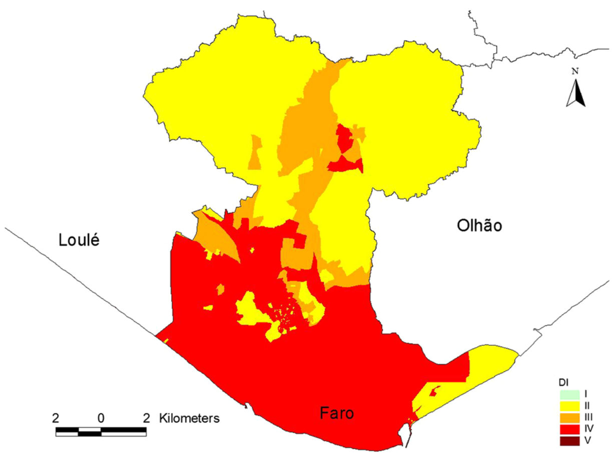


Fig. 17 Faro global impact: Disruption Index

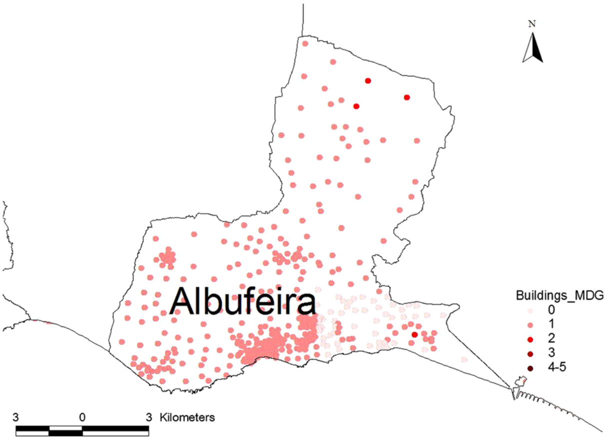
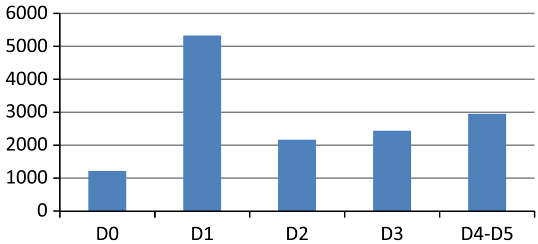


Fig. 18 Calculated mean damage grade in Albufeira

Fig. 19 Number of buildings in each damage scale (*D0* no damage, *D1* slight damage, *D2* moderate damage, *D3* heavy damage, *D4–D5* very heavy damage to destruction or total collapse)



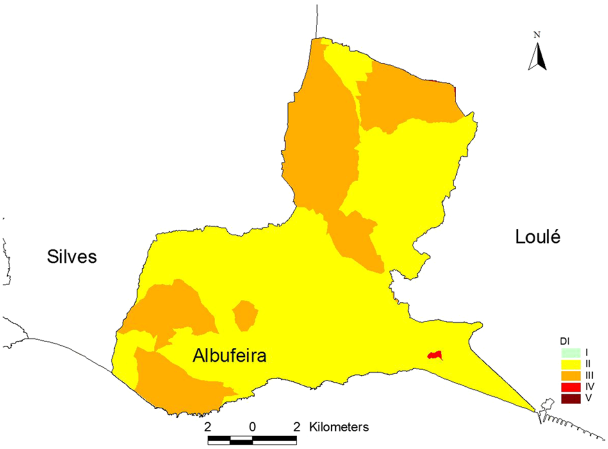


Fig. 20 Albufeira global impact: Disruption Index

The impacts on Mobility for example, results from debris choking streets and damages on bridges and roadways particularly in areas of softer, water-saturated soil, where the shaking is stronger. Figure 22 illustrates the cascade effect on Mobility.

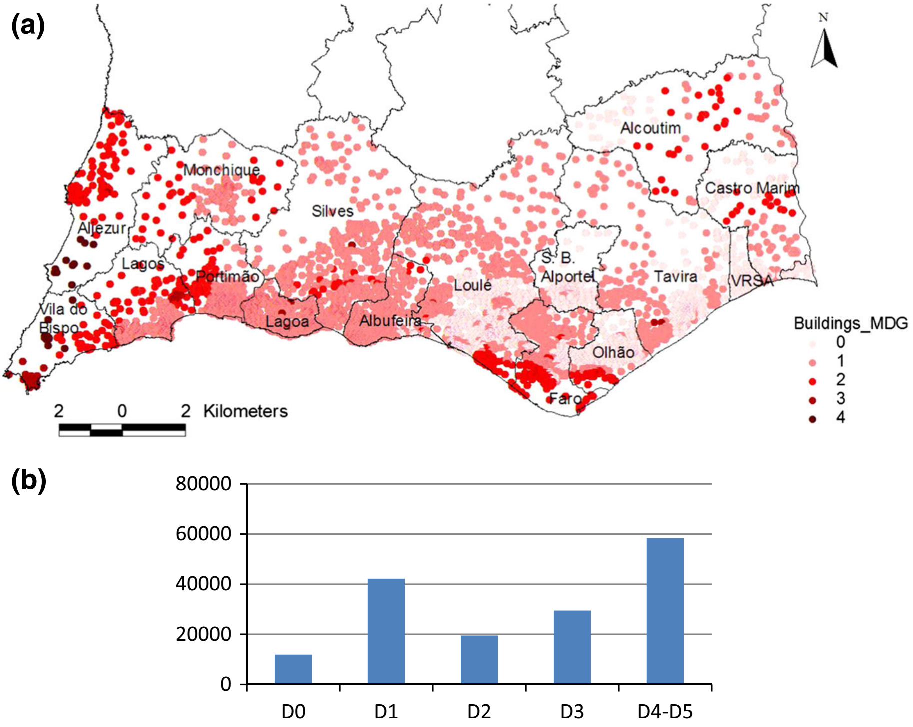


Fig. 21 **a** Spatial building damage distribution. **b** Building damage frequency distribution

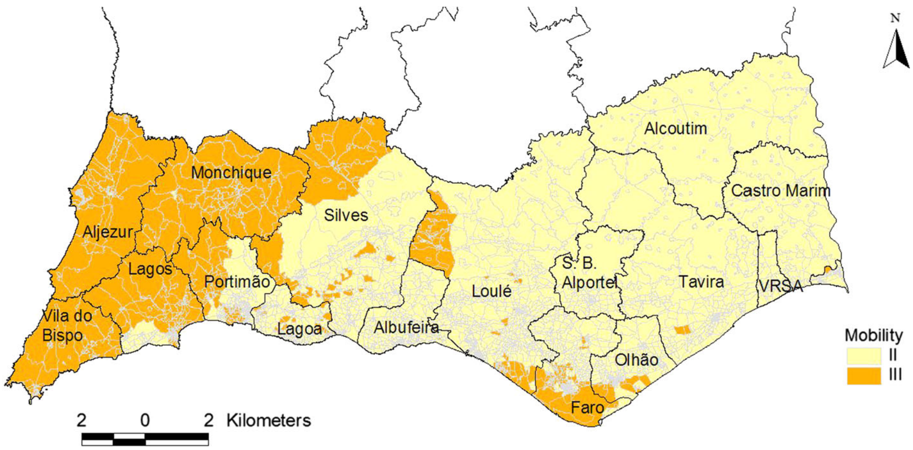


Fig. 22 Mobility disruption. Impact level II ("works or some debris causes disruption. Obstacles to customer access.") and impact level III ("local perturbation on mobility linked with landslide or major damages. Used only by recovery teams. Disruptions to commuting trips, work and nonworking trips.") (Ferreira et al. 2014)

Finally, the global DI to the entire Algarve region with maximum DI equal IV predominantly to the west and south, where the shaking was stronger and areas susceptible to liquefaction, like Faro. These maps evidence the high level of risk that an entire region and its population is exposed; with all vulnerabilities and cascading effects showing the need for more detailed risk assessment of these urban elements and critical facilities, addressing in mitigation strategies for a future risk reduction. Comparison of DI maps (Figs. 23 or 14, 17, 20) with Intensity Maps (Fig. 3) clearly show these differences, where DI maps aggravate quite strongly the impact provoked by Intensities only. In the next Section contrarily to most common studies published in literature, we will use DI as a measure of global impact, and not the one caused by Intensities only.

4 Disaster mitigation strategies

The central idea underlying the definition of the Disruption Index is the identification and evaluation of the impacts on a target community, considering the physical elements that most contribute to a severe disruption.

After the evaluation of risk and cascade effects in multiple impact categories, it is important to plan risk strategies to decrease the probability and mitigate impact of events.

An important question to start defining the risk mitigation steps is "What is our acceptable level of disruption? Is it, DI = I?, II,?, …V? The DI approach comprising interrelated subsystem analyses and propagation effects permits to understand that exist some lower level of disruption that is not exempted from losses. If we accept that there exists some level of losses, D_0, which can be thought as acceptable, then it is the one that leads to a reference scenario DI_0 above which the urban system is in an "unacceptable state" and below which urban system is in an "acceptable state".

In order to be more effective and less costly than repairing the entire damaged stock after a risk has occurred, we explored the risk-analysis field, which is greatly interrelated with our aim (Oliveira et al. 2014). To accomplish this goal, *risk importance measures* are defined to evaluate the importance a feature in further reducing the risk, and its importance

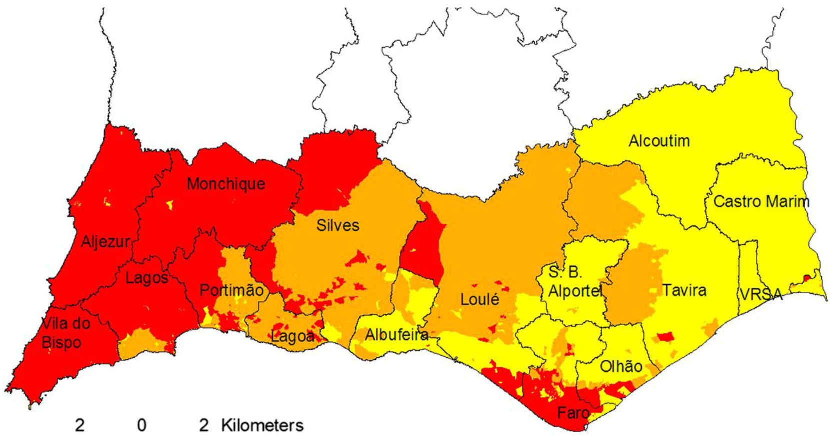


Fig. 23 Algarve global DI

in maintaining the present risk level. One proposed *importance measure*, called the **risk reduction worth** (RRW), is useful for prioritizing feature improvements that can mostly reduce the actual risk. The other proposed *important measure*, called the **risk achievement worth** (RAW), is useful for prioritizing the most important features in reliability assurance and maintenance activities.

As referred, the *risk importance measure* gives an indication of the contribution of a certain component to the total risk. For the interpretation of these measures we can obtain an importance-ranking of the various components and urban contributors not only with regard to risk reduction but also with regard to risk maintenance (or reliability assurance).

Further information about *risk importance measures*, their meaning, construction, and use can be found, among others, in (Andrews and Moss 2002; Apostolakis and Lemon 2005; Michaud and Apostolakis 2006; Patterson and Apostolakis 2005; Vesely et al. 1983; Zio and Podofillini 2003), We will only define the most used variables:

R — Risk, R will be defined as the likelihood of the whole System reaching or exceeding some Reference Disruption Level, DI_0.

R_i^- — System Risk when all Sub-Systems $j \neq i$ are in their actual state and Sub-System i is working with no dysfunctions. Can be seen as the Benefit of increasing reliability in Sub-System i.

R_i^+ — System Risk when all Sub-Systems $j \neq i$ are in their actual state and Sub-System i is in its maximum dysfunction. Can be seen as the Loss due to increasing fragility in Sub-System i.

RRW_i — *Risk Reduction Worth* of Sub-System i.
If Sub-System i changes its actual behavior to plain functioning (no dysfunction), then the actual risk of the system changes from R to R/RRW_i. *This indicates the potential of sub-system i to reduce the actual risk*. This can be seen as a measure of importance for pursuing possible actions or programs of resilience strengthening, or of vulnerability reduction. This is strongly and positively correlated with Ri*.

$$RRW_i = R/R_i^- \quad [\ \ ]$$

RAW_i — *Risk Achievement Worth* of sub-system i.
If sub-system i changes its actual behavior to maximum dysfunction, then the actual risk of the system changes from R to $R \times RAW_i$. *This indicates the actual potential of sub-system i to aggravate the actual risk.*

$$RAW_i = R_i^+/R \quad [\ \ ]$$

R_i^* — *Risk Reduction Obstruction of Sub-System i*. System Risk when all Sub-Systems $j \neq i$ are working with no dysfunctions and Sub-System i is in its actual dysfunction. *It indicates present constraints (bottleneck's) in system risk reduction inherited from the actual Unreliability of Sub-System i,* indicating possible actual responsibilities of stakeholders while constraining others to adopt measures in order to reduce Seismic Risk. It is strongly and positively correlated with RRW_i.

We will show below how one of most frequently used importance measure (RRW) can be interpreted and applied to Algarve region.

For each urban component, the risk reduction worth (RRW) was calculated by reevaluating the vulnerabilities of that component, for example for building stock considering an intervention in the most vulnerable typology (VClass = 0.767) which was retrofitted achieving a new vulnerability (VClassNEW = 0.638). We repeated the same reasoning for the telecom components and electrical substations. The new expected DI values were determined running the QuakeIST® (Mota de Sá et al. 2015). To perform the computation of RRW we used as "measure of our mitigation" the change of area (ratio) in the interior of each DI contour value for the two situations under study: prior-to-intervention and post-intervention.

The results for the entire region of Algarve (Fig. 24) indicate that the building stock availability is the most important to prevent a total urban disruption. The risk reduction ratios due to building stock improvement for DI and Housing are large (23 % for DI-III) and about 6 % for Healthcare, Mobility and Education, even though for DI-IV the improvement was only of 6 %.

As shown in Fig. 24 RRW ratio is always greater or equal to one and gives the maximum risk reduction (in our case impact reduction—DI) possible for an improvement in the building stock.

Another example of application of RRW, simpler than the above was made by Meroni et al. (2015) in Mount Etna, where the "measure" under consideration was the number of people under a DI contour. They only analyzed the influence of mitigating building vulnerability, of 5, 10 and 30 % reduction, and evaluated the decrease in number of population affected by DI = II to V, prior- and post-intervention.

The other importance measures like RAW or other measures [Fussell-Vesely (Lambert 1975)], used as risk reduction indicators will be object of further studies, and are not presented in this study. However, for a final strategic decision the use of two importance measures is advisable.

This type of analysis can be used as a guide to prioritize activities aimed at reducing risk, a very useful measure for a management program and for decision-making. If now we introduce the cost of implementing these alternatives through an event-tree approach, a cost-benefit analysis will produce the optimal strategy for priority allocation of resources.

For example, if $RAW_i = 1.25$ means that if sub-system i persists in degrading until some plausible maximum value of the vulnerability that leads to losses or dysfunction in sub-system i to its plausible maximum, while leaving all of the other sub-systems

	I	II	III	IV	V
DI		**0.83**	**1.23**	**1.06**	
Environment		1.00			
Housing		0.83	1.23	1.06	
Security		1.00			
Healthcare		0.97	1.05		
Education			0.97	1.06	
Mobility		0.97	1.06		
Building stock	0.59	1.02	1.23	1.06	
Schools	1.00	1.00			
Healthcare fac.	1	1	1		
Electricity		1.00			
Telecom	1				

Fig. 24 Risk reduction worth (RRW) for Algarve

performing in their actual state (in their actual vulnerability state), then the chances of reaching the actual levels of risk will be raised 1.25 times ($R_i^+/R_i = 1.25$, i.e. 25 % aggravation of actual seismic risk).

Next example was obtained from the application of DI on the Faial earthquake (July 9, 1998) (Oliveira et al. 2012).

From the illustration in Fig. 25, $RRW_i = 1.22$ means that if an intervention in sub-system i reduces its seismic vulnerability to its minimum value that leads to losses or dysfunction, in sub-system i to its plausible minimum, while leaving all of the other sub-systems performing in their actual state (in their actual vulnerability and performance state), then the chances of reaching the actual levels of risk will be reduced 1.22 times ($R_i/R_i^- = 1.22$, i.e. 22 % reduction in actual risk).

Finally, Ri* = 50 % means that even if all the other Sub-Systems j ≠ i where performing with maximum Reliability (no Disruption), the whole System Risk cannot be reduced below 50 % due to the weak performance of Sub-System i.

It is interesting to note in the illustrations presented that the results are essentially controlled by the human need "Housing" or building stock (blue elliptical box), and only the size of DI equal III degree shows appreciable change of the impacted area.

From Fig. 25 we can see that the elements with higher RRW is "Building Stock" with RRW = 1.36 meaning that a full retrofit of buildings would reduce the chances of facing a DI Grade III by 36 %. This is more or less expected since building stock plays an important role in seismic risk. However, such an intervention cannot be feasible due to the enormous amount of funding necessary to perform it. So, other strategies or polices need to be found.

Let's assume that each possible strategy *j* has a Cost C_j and produces an acceptable RRW_j. The ratio C_j/RRW_j is the (unitary) cost of risk reduction by investing in strategy *j*. That is, the amount necessary to reduce risk by one unit by intervening in strategy *j*. Therefore, with the building stock we could find something like 50 M€ applied in retrofitting, to have risk reduced by 36 %. Our ratio is then 50/1.36 ~ 37 M€/unit of reduced risk. The inverse of this ratio is no more than the gain in risk reduction by investing one monetary unit. In this case we have 1.36/50–0.03, which is the "benefit-to-

Faial Island after the July 9, 1998 earthquake

Whole System Risk - All Sub-Systems performing in their actual state of seismic vulnerability

P[DI=I]	P[DI=II]	P[DI=III]	P[DI=IV]	P[DI=V]	P[DI≥I]	P[DI≥II]	P[DI≥III]	P[DI≥IV]	P[DI=V]
0.7%	48.9%	24.9%	15.8%	8.7%	99.1%	98.4%	49.5%	24.6%	8.7%

	R_i-					R_i+					R_i*				
i	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Critical Infrasctructures	98%	97%	49%	25%	9%	100%	99%	49%	24%	9%	65%	60%	4%	0%	0%
Electric Facilities & Components	98%	97%	46%	19%	2%	100%	100%	67%	50%	40%	67%	62%	11%	7%	7%
Transportation Facilities & Components	98%	97%	40%	24%	8%	100%	100%	88%	51%	40%	68%	63%	19%	2%	1%
Water Supply Facilities & Components	98%	97%	46%	19%	9%	100%	100%	67%	50%	9%	66%	62%	11%	7%	0%
Sanitation Facilities & Components	98%	97%	46%	19%	9%	100%	100%	67%	50%	9%	67%	62%	11%	7%	0%
Telecoms Facilities & Components	99%	98%	49%	24%	8%	100%	100%	69%	54%	44%	42%	34%	5%	1%	1%
Scools	99%	98%	49%	25%	9%	100%	100%	49%	25%	9%	45%	38%	4%	0%	0%
Health Care Facilities	99%	98%	49%	25%	9%	100%	100%	67%	25%	9%	37%	29%	4%	0%	0%
Security Facilities & Components	99%	98%	48%	25%	9%	100%	100%	89%	51%	41%	37%	29%	6%	1%	0%
Building Stock	98%	98%	36%	21%	9%	100%	100%	96%	79%	39%	68%	42%	24%	5%	0%

	RRW_i					RAW_i				
i	I	II	III	IV	V	I	II	III	IV	V
Critical Infrasctructures	1.01	1.01	1.00	1.00	1.00	1.01	1.01	1.00	1.00	1.00
Electric Facilities & Components	1.01	1.02	1.08	1.30	4.70	1.01	1.01	1.34	2.04	4.55
Transportation Facilities & Components	1.01	1.02	1.22	1.03	1.13	1.01	1.02	1.78	2.07	4.63
Water Supply Facilities & Components	1.01	1.02	1.09	1.30	1.00	1.01	1.01	1.35	2.04	1.00
Sanitation Facilities & Components	1.01	1.02	1.08	1.30	1.00	1.01	1.01	1.35	2.05	1.00
Telecoms Facilities & Components	1.00	1.00	1.00	1.01	1.04	1.01	1.01	1.39	2.18	5.01
Scools	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.00	1.00	1.00
Health Care Facilities	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.36	1.00	1.00
Security Facilities & Components	1.00	1.00	1.02	1.00	1.01	1.01	1.01	1.81	2.09	4.70
Building Stock	1.01	1.01	1.36	1.17	1.02	1.01	1.02	1.94	3.22	4.43

Fig. 25 Importance measures applied to the case of Faial Island after the 9 July, 1998, earthquake. Risk: $R = P[DI \geq D_0]$; $D_0 \varepsilon \{I, II, III, IV, V\}$

cost ratio" or "value for money". Now we examine, for example, the "Transportation Facilities" where the investment needed to resolve their vulnerabilities can be something like 10 M€, but with a lower RRW = 1.22. The value for money in this case is 1.22/10–0.12. That means that even with a lower RRW our investments in transportation and facilities are about four times larger ($\sim$0.12/0.03) than the investment in retrofitting the building stock.

However, in practical terms, available funds are always limited to some upper maximum amount, and consequently Portfolio Management can come into play. The best "Portfolio of Possible Intervention Strategies" is the one that, with our restricted funds lead us to the maximum global benefit (the sum of benefits/risk reduction reached by each individual strategy). According to Philips and Bana e Costa (2007) the best Portfolio can be reached by ordering the possible strategies i (Programs or Policies) by decreasing importance of their value for money (Ratio = $RRW_j/Cost_j$), and then retaining the so ordered policies until the budget is reached.

To sum up, the use of Disruption Index can be of great opportunity to find Policies and Alternatives to risk reduction. Of course, its usefulness is not restricted to the above example and many other cases can be pursued using DI with other Risk Importance Measures (Vesely et al. 1983).

5 Conclusions and future developments

Modeling the impacts of earthquakes on human capital in a comprehensive manner is quite complex. However, the procedure applied in this study (the DI Model, software and data) constitutes a very useful operational tool in driving the development of strategies to minimize the risks from earthquakes. The geographical distribution of DI is of great value for a more comprehensive application to disaster mitigation strategies.

The interest of a study like this is not only to obtain damages, but to highlight the importance of taking a holistic view of the problem, considering all the dimensions of the urban system, identifying their interactions and consequences in a simple and understandable way. With this output it is possible to use the indicators RRW and RAW to measure in a simple way the impact of any mitigation intervention, although we carefully advise any user to reduce the vulnerability of elements in a conscious manner, taking into account the costs and benefits of such interventions. Reductions of DI equal to V or IV will require large interventions with corresponding important investments.

In the two presented examples for disaster mitigation strategies, we have empirically reduced the vulnerability of all the considered building stock without any physical precise intervention of retrofitting. On the other hand, we have not considered the cost of these actions which should be contemplated in future work.

It is interesting to note in the illustration presented that the results are essentially controlled by the human need "Housing" and only the size of DI equal III degree shows appreciable change of the impacted area.

Future work in this thematic of ranking the type of interventions to reduce the risk should include an analysis of the most critical typologies and not reduce vulnerability in an equal way.

New developments include an analysis of how uncertainties can be dealt within the DI concept, extend this idea to other areas/topics, namely to industrial disruption, and to proceed to analyze multi-hazard phenomena such as tsunami or landslides after an earthquake event.

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References

Andrews JD, Moss TR (2002) Reliability and risk assessment. Bury St Edmunds, Professional Engineering Publishing Limited, London

Apostolakis GE, Lemon DM (2005) A screening methodology for the identification and ranking of infrastructure vulnerabilities due to terrorism. Risk Anal 25(2):361–376

Bana e Costa CA, Beinat E (2005) Model-structuring in public decision-aiding. LSEOR 05:79

EC-8 (2004) Eurocode 8. Design of structures for earthquake resistance—part 1: general rules, seismic actions and rules for buildings. EN 1980-1:2004. Comité Européan de Normalization

Ferreira MA (2012) Risco sísmico em sistemas urbanos. Ph.D Thesis. Instituto Superior Técnico, Universidade Técnica de Lisboa (in Portuguese)

Ferreira MA, Mota de Sá F, Oliveira CS (2014) Disruption Index, DI: an approach for assessing seismic risk in urban systems (theoretical aspects). Bull Earthq Eng 12(4):1431–1458. doi:10.1007/s10518-013-9578-5

INE (2011) Recenseamento Geral da População de 2011. INE, I.P., Census 2011. Lisbon

Lambert HE (1975) Fault trees for decision-making in systems analysis. Rep. UCRL-51829. Lawrence Livermore Laboratory, Livermore, CA

Meroni F, Zonno G, Azzaro R, D’Amico S, Tuvè T, Oliveira CS, Ferreira MA, Mota de Sá F, Brambilla C, Rotondi R, Varini E (2015) The role of the urban system dysfunction in the assessment of seismic risk in the Mt. Etna area (Italy). Bull Earthq Eng. doi:10.1007/s10518-015-9780-8

Michaud D, Apostolakis GE (2006) A methodology for ranking the elements of water-supply networks. J Infrast Syst 12(4):230–242

Mota de Sá F (2015) PhD Thesis. Instituto Superior Técnico, Universidade Técnica de Lisboa. (work in progress)

Mota de Sá F, Ferreira MA, Oliveira CS (2015) QuakeIST®: earthquake scenario simulator using interdependencies (BEEE submitted to this issue)

Oliveira CS, Ferreira MA, Mota de Sá F (2012) The concept of a disruption index: application to the overall impact of the July 9, 1998 Faial earthquake (Azores islands). Bull Earthq Eng 10:7–25. doi:10.1007/s10518-011-9333-8

Oliveira CS, Mota de Sá F, Ferreira MA (2014) Disaster prevention strategies based on the level of risk. In: Proceedings 2nd European conference on earthquake engineering and seismology, Istanbul, 25–29 August

Pascione M (2001) Urban geography: a global perspective. Routledge, London

Patterson SA, Apostolakis GE (2005) Identification of critical locations across multiple infrastructures for terrorist actions. In: Paper presented at the safeguarding national infrastructures: integrated approaches to failure in complex networks. University of Glasgow

Philips LD, Bana e Costa CA (2007) Transparent prioritisation, budgeting and resource allocation with multi-criteria decision analysis and decision conferencing. Ann OperRes 154(1):51–68. doi:10.1007/s10479-007-0183-3

UPStrat-MAFA (2012) Urban disaster prevention strategies using MAcroseismic fields and fault sources (UPStrat-MAFA—EU Project Num. 230301/2011/613486/SUB/A5), DG ECHO Unit A5

Vesely WE, Davis TC, Denning RS, Saltos N (1983) Measures of risk importance and their applications. Division of Risk Analysis, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC

Zio E, Podofillini L (2003) Importance measures of multi-state components in multi-state systems. Int J Reliab Saf Eng 10(3):289–310