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ORIGINAL RESEARCH PAPER

Disruption index, DI: an approach for assessing seismic risk in urban systems (theoretical aspects)

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Abstract Urban systems are characterized by very complex interactions. After an earthquake, a wide variety of services, networks and urban facilities may be unavailable to the public during the system failure and recovery processes, thereby causing disruptions in the basic social needs of the affected area. After a disaster, communities face several challenges. For example, the lack of education may impose population migrations, or malfunctions in the electricity distribution system can produce electrical power outages of varying duration with respect to time and space, which generates consequences in the water distribution system, transportation, communications, etc. A methodology called the Disruption index (DI), based on graph theory, includes these multiple interdependencies. It has been developed to estimate the dysfunction of some fundamental dimensions of urban systems on a broad level, starting with the physical damages directly suffered by the exposed assets, proceeding to the impacts that each node has on the functional performance of the nodes depending on them, until reaching the top node. This paper presents the fundamental theory to support the DI concept. The DI provides the likely impacts and consequences of an earthquake in an urban area to fulfill hazard mitigation and provide civil protection agencies and local and state governments with a new decision-making instrument to reduce or prevent severe and recurrent impacts. The DI concept can also be extended to other natural and man-made disasters and may be used as a tool for optimizing the resources of the system components.

Keywords Seismic risk · Interdependencies · Propagation · Disruption · Urban systems

1 Introduction

A few short minutes may be all it takes to destroy not only lives but also schools, homes and livelihoods.

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After many years of developing GIS software based seismic simulators, it has become clear that the results achieved were no more than an average estimation of physical and human losses, and that the outcomes of those risk studies were maps showing the geographical distribution of these damages and casualties. One limitation with this type of analysis is that it does not take into account the susceptibility of infrastructure systems to decreased reliability, which frequently leads to cascade failures. Simple disruptions could have large-scale effects and cause widespread utility outages.

In this context, the inclusion and development of a qualitative method in an attempt to establish the topological effects of system performance to capture the cascade failures and quantify how a cascade effect contributes to the disruption of urban activities, and of society as a whole is of great interest. Few models have been built for estimating or truly representing urban disruption resulting from collapse or from some other level of damage. The indirect consequences, such as economic losses and social disruption in monetary terms, are not considered in this study.

The destruction or unavailability of some basic urban functions for a long period of time would impact the *dimensions*[1] of *human needs*, such as environment, housing, health, education, employment and food. The intended purpose of a Disruption Index (DI) is to evaluate the impacts on a targeted community's well-being, particularly considering housing, provision of services, employment and a transportation network. The consequences of unavailability, translated through an indicator of disruption to users, would be assessed qualitatively. DI provides the basis for understanding the resource requirements, not only for recovery after events but also to identify, prior to events, the physical elements contributing most to severe disruption.

The results of this study are therefore very useful for earthquake preparedness planning and for developing strategies to minimize risks from earthquakes. They could also be used in an interactive network platform for public awareness and public education for disaster risk reduction. The visualization of earthquake impacts, obtained by DI contributes to make recognition of earthquake disaster among population and urban services or functions, but also the improvement of the engineering ability of local government officials who are in charge of promoting earthquake disaster mitigation.

The DI, as a measure of urban disruption, will enable comparisons between urban areas with very different dimensions, industrial and cultural developments, after they are subjected to a seismic event. In this way, the DI is intended to qualify the "feeling" of what has happened in the area, whether it is a "small rich city" or a "large poor community".

This paper is organized as follows: Sect. 2 examines the models most commonly used for evaluating earthquake risk. Section 3 presents the model and introduces the DI methodology, and Sect. 4 gives an example to further understanding of it. The concluding Sect. 5 briefly summarizes the paper and suggests directions for future research.

2 Combining tangible and intangible values

A review of the relevant literature has been performed to identify the sources of the theoretical frameworks of use in developing a methodology for earthquake risk assessment. In a quick review of the most typical risk models, we could find, following Douglas Hubbard (Hubbard, 2009), that most risk managers seek some form of risk *score*. Among these forms of risk assessment, *"Risk Matrices, RM"* and *"Weighted Scores, WS"* are the most widely used.

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[1] The authors also mention *dimensions* like *"criteria", "objectives"* or *"concerns"*.

Some publications on seismic risk use a holistic approach and indices to describe seismic risk (Cardona 2005; Carreño et al. 2007, 2012; Davidson and Shah 1997; Masure and Lutoff 2008). By applying the weighted scoring method which leads to a value R, a quantitative measure resulting from the aggregation (weighted sum) of the individual impacts of the seismic event in each criteria i:

$$R = \sum_{i=1}^{n} w_i \times u_i(x)$$

Here n is the number of criteria, w_i expresses some weight or relative importance of criteria i, and u_i(x) represents the utility, a "psychological value" $u(x)$ of the impacts x on the criterion i. This methodology requires some basic hypothesis, such as the independence of variables representing the various criteria; consequently, the calculations must to be handled carefully. In addition, subjective judgment to obtain u_i(x) and valuation must be present, leading the final conclusions to be valid only within the domain of the expert's value system.

The holistic approaches clearly indicate that seismic risk encompasses a broad set of dimensions (i.e., objectives and primary and fundamental concerns), including direct physical losses, social concerns, economic losses, public image and response and recovery capacity.

The above-mentioned works by Cardona, Carreño and Davidson clearly identify three major areas of concern in strict conformity with the major areas of risk analysis (i.e., risk assessment, risk management and risk communication). In their risk constructions, several dimensions (criteria) were directly devoted to addressing risk assessment and risk management. In the work by the first two authors, it is worth noting that physical risk is aggravated by an Impact Factor, composed of "Aggravating descriptors", which translate their concerns about "Social and economic fragilities" and "Lack of resilience or ability to cope and recovering" (Carreño et al. 2007). This last concern is appropriately addressed in the several risk indices proposed by Omar Cardona, such as the "Disaster Deficit Index, DDI" (Cardona 2005). In Cardona, 2005, and Carreño et al. (2007), the various dimensions were translated by value functions and then aggregated, using a weighted average, resulting in a final risk score.

To derive the relative importance of each factor, Davidson used "Principal Components", but Cardona and Carreño followed a Decision Analysis framework, using "Utility functions" to address "Value" together with the "Analytic Hierarchy Process" (AHP). AHP is a theory of measurement that uses pair-wise comparisons made using expert judgment.

We started modeling the problem by assuming a Multi-Criteria Decision Analysis (MCDA) approach, using an additive aggregation of multiple-valued functions. However, we realized that some fundamental rules of such a construction were violated, such as *Cardinal Independence* (Bana e Costa and Beinat 2005) and *Additive Independence* (Keeney and Raiffa 1976). In fact, these rules are *sine qua non* conditions for the assumption of an additive model. Those rules were shown to be repeatedly violated in our observed case studies. In fact, the relative importance of some criteria was not stable; some impacts (e.g., the difference in the attractiveness of consecutive levels in the impact scales) of some criteria were independent from the impacts on others. The importance of many urban functions varied with respect to the observed scenario and fluctuated over time. One example was the importance of *Safety* (e.g., civil protection resources, rescue teams, hospital beds) when the damage was slight (with no injuries or deaths), versus when there were many collapsed buildings, landslides, collapsed bridges or tunnels and other situations in which rescue is a fundamental activity. Evidence also arises when, for example, *Housing* is impaired or even impossible due to severe damage to the building stock, which leaves utilities useless in these zones though they are of major importance in others. A striking picture can be observed in

Fig. 1 Hanwang town (China 2008). The fact that the water tank did not suffer any damage does not invalidate the urban disruption

the devastation in Sichuan after the 2008 earthquake (Fig. 1). The main water reservoir was intact, while everything else around it was completely destroyed. In this case, an additive rule with a non-zero impact in the "water system" criterion gave a non-zero global impact because of the compensatory nature of such a model. Our first approach was to use a convex shape to model the impact in this criterion. This solved our problem in Sichuan, but the same utility function did not fit what we observed in other scenarios in which it was difficult to support that a better water distribution system could compensate for an electrical black-out. These are only some examples.

In addition to "additive independence", other difficulties have been found to be major obstacles; the construction of the utility functions in modeling the impacts of multiple criteria or tradeoffs between them is an additional concern. Expert opinion gathering, even with the aid of "Decision Conferences" (Phillips 2006), was considered to be a convenient approach. However, whatever "value-functions" or criteria weights might be determined would only translate the value systems of the experts involved in such a process. A model constructed in this way would be a good answer to these individuals, but it seems difficult to support the decisions if the audience changes.

Another proposal for addressing seismic risk is based on *Petri nets* and other simulation techniques, such as those proposed by Ventura (Ventura et al. 2010). However, due to the enormous amount of data required to perform these simulations, we think that their usefulness is restricted to very special cases that are usually very difficult to implement. As our approach is broader and less detailed for each criterion, we do not address these proposals here.

As a consequence of the above observations, we decided to construct the Disruption Index, DI, as an "Ordinal Scale", where the numbers assigned to each Level have no cardinal meaning; they only express a ranked order, as so avoiding the subjectivity of "values" and "weights".

2.1 Risk amplification, interdependencies and cascading effects

The amplitude of the consequences of natural disasters grows with the size of targeted urbanized areas. This fact, well expressed by Bilham (Bilham 2009) and several other authors, is clearly explained by a correlation between "Degree of urbanization" and "Economic losses following earthquakes" (Scawthorn 2011). There, he says (and quantifies), *"…when an earthquake does occur in or near a heavily urbanized area, the 'direct hit' will be a much larger loss, compared with the pre-urbanization situation of a more distributed population. The effect is fewer but larger catastrophes"*.

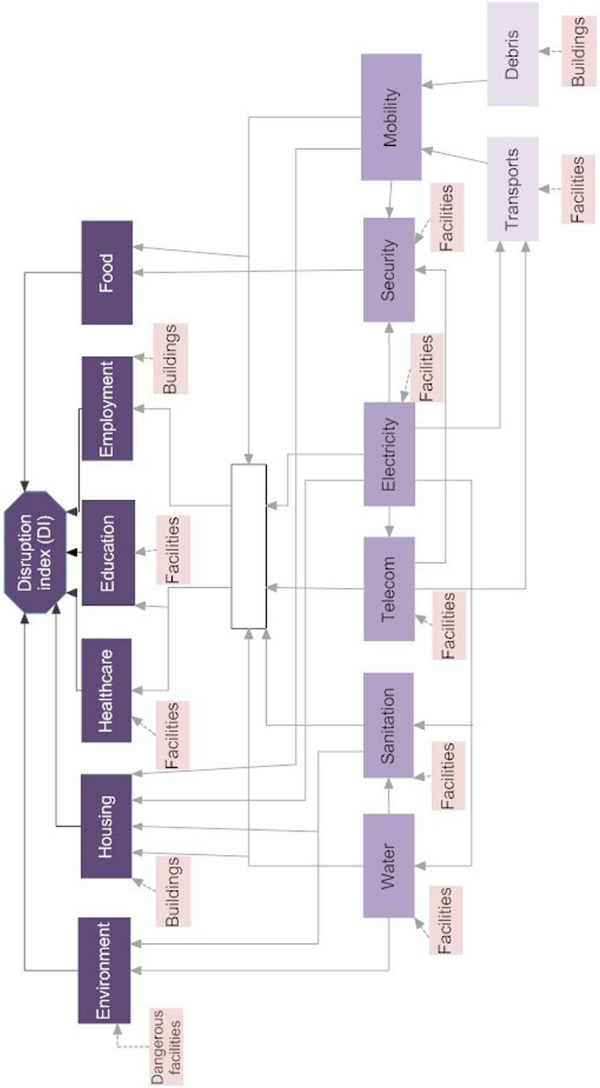
In fact, we know that cities tend to develop around some central, initial concentration of human activity and goods, following some sort of "attractiveness law", similar to Newton's law of universal gravitation, where the strength of the attraction is directly proportional to the mass and inversely proportional to the (square of the) distance. From another point of view, we can consider the urban space to be some sort of complex system shaped by a directed graph in which nodes (vertices) represent the human activities of production, supply and consumption (also known as *sources* and *sinks*) and directed arcs (or *edges*) represent the links between nodes, indicating the direction of these social and economic flows.

These concerns about system disruption and cascading effects have existed for some time. However, in recent years, a greater interest in this subject has strongly emerged. The majority of papers published about this subject have come from the areas of utilities and lifelines, such as electricity, gas, and water systems, or from concerns with Critical Infrastructures Protection (CIP). Natural hazards, such as earthquakes, tsunamis and tornados, and human-made hazards, such as terrorism, have sparked growing interest in the subject. However, the use of discrete mathematics, namely the use of Graph Theory, has already been broadly used in risk analysis, especially in the nuclear field. Fault Trees, Minimum Cut Sets and Importance Measures, in conjunction with the *Multi Attribute Utility Theory* (MAUT), have been used to model the vulnerabilities and performances of complex interconnected networks under disruptive events (Apostolakis and Lemon 2005; Michaud and Apostolakis 2006; Patterson and Apostolakis 2005). From the field of Multi State Systems Reliability, we again see Importance Measures being used as an efficient and convenient way to identify critical subsystems and components (Zio and Podofillini 2003). Apart from the use of MAUT, which requires the assessment of values and tradeoffs as well as gathering of subjective values from experts, the use of Monte-Carlo simulation for a system modeled as a *digraph* and the use of Importance Measures seemed to be a good starting point in our quest to understand the behavior of an urban system disturbed by a major seismic event.

3 Building the model

As Charles Perrow (1999) demonstrated, closely interconnected infrastructures "predictably fail but in unpredictable ways". Disruptions or destruction in energy, water, transport, communication, mobility or other systems, such as security, tend to move through the whole system. Because these systems are interdependent and densely linked, a disruption in one system tends to cascade to others very quickly. Thus, when an earthquake occurs, and the energy grid fails, cascading effects quickly disrupt the entire influence area. The power loss is not just the lights that fail; electricity powers water and sewage systems that also tend to

Fig. 2 Disruption index: infrastructure dependencies and interdependencies



fail. Transportation and public transport systems stop. Food processing and distribution is disabled, and healthcare becomes chaotic and almost inoperable. Even breakdowns in the social order can occur, so we see a system of interrelated parts where a change in any one part affects all the others. The next diagram (Fig. 2) shows how the infrastructures (considered separately) act together, showing their dependencies and incidences.

Consider the dimension “Environment” to illustrate the chain of dependencies and interdependencies. The Environment depends on the Water, Sanitation and Dangerous facilities. Water depends on the operation of the Water system equipment and the Electricity supply, which in turn depends on the Electric system equipment. Similar reasoning is applied to all other boxes in Fig. 2.

The greatest challenge was to simplify the reality and build a model integrating all of the features of the problem and create an indicator that is useful and easy to understand and communicate. This indicator would also be capable of aggravating the state of each system due to propagation effects.

When experimenting with urban systems, an initial difficulty is to precisely define which objects are under study. A crucial part of the modeling process is to develop a general framework capable of clearly identifying, capturing and analyzing each level of organization, the system dependencies and the chain of influences and failures due to system/component interactions (Ferreira 2012). Based on (i) the inspection of several seismic simulators, (ii) extensive bibliographical research about the physical and social impacts of severe events, and (iii) information and experience gained in several earthquake field missions in different regions of the world[2] and through contact with affected populations and various entities and agencies to identify the most important effects on a society, its economy and other sectors, more than 70 primary criteria (concerns) were found to be systematically present in all texts and reports. Following some fundamental rules of decision problem structuring, these primary elements were aggregated into 14 Fundamental Criteria that translate critical dimensions (urban functions) that cooperate and dictate what we see as an urban system's ability or disability to respond to the observed demand.

These dimensions encompass six fundamental human needs, "Environment, Housing, Healthcare, Education, Employment and Food" (Fig. 2) and are affected by several other main functions/systems, such as mobility, electricity, water, telecommunications and others, which are in turn dependent on the reliability of several buildings, equipment systems and critical or dangerous facilities. This topological organization is shown in Fig. 2 using horizontal layers in a *bottom-up* sequence.

Because different societies have different values and concerns, it is important to recognize that the criteria cannot be static; they change and must be revised and adapted in each case. For example, in a region where healthcare facilities or any other critical functions strongly dependent on natural gas, this dimension should come into place. However, what we found was that the above-mentioned dimensions seem to be present in all cases. Once the criteria are defined, then we must select what type of scale should be used to measure the impacts felt, and how we should consider their aggregation. Here, we determined that the selected risk model should consider the following three aspects of the problem:

(i) Is there sufficient evidence and support to construct "Interval Scales" that allow us to introduce "Quantitative"?
(ii) At the same time, is there enough evidence and support to evaluate the "Tradeoffs" between different criteria?
(iii) If "Preferential and Additive Independence exists among criteria", then we can consider the adoption of an additive model.

If the three assumptions above are not observed, and in our opinion, these are very strict conditions to be dealt with in real scenarios, at least in the domain of seismic risk, then other approaches should be used. At present, the DI model is based on an "objective and qualitative scale", the "DI Scale", where the urban system is modeled as an acyclic digraph in which each urban function (our concern) is a node, and the directed arcs linking the nodes

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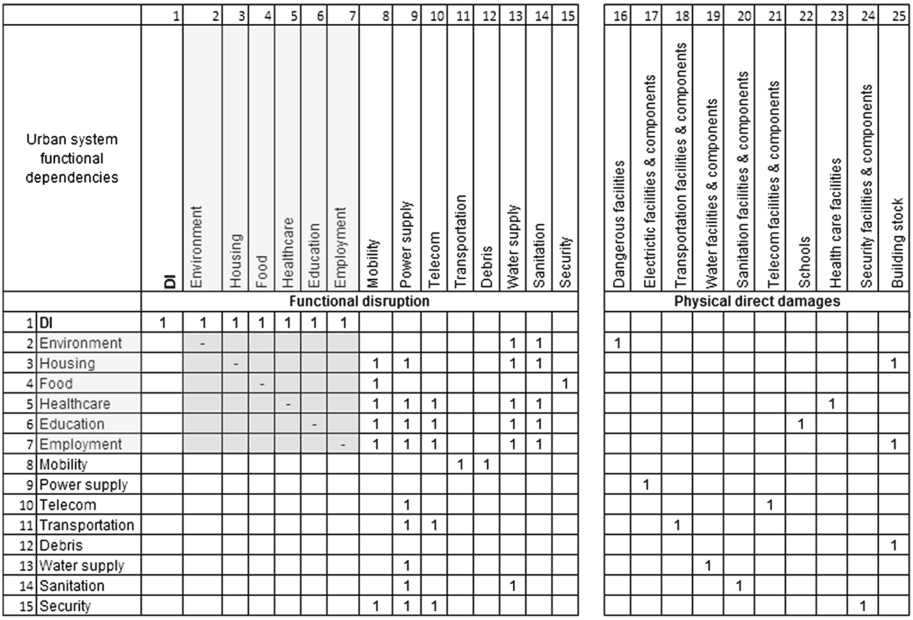
[2] Field Missions include the Azores (Oliveira et al. 2012), China (Costa et al. 2010), Italy (Proença and Ferreira 2009), Haiti (Oliveira and Ferreira 2010) and Spain (Ferreira 2011).



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

Fig. 3 Adjacency matrix G. In the columns, we represent the graph elements (*k* is the representative index of one of the 15 rows). The shaded matrix contains the 6 dimensions (urban dimensions); the other black columns (8–15) contain the services and components, and the right columns (16–25) show the elements supporting all other functions (physic direct outputs of the simulator or data recorded at a damaged area) (*j* is the representative index of one of the 25 columns)

are their dependencies. The system is also addressed as a Multi-State (Zio and Podofillini 2003) Coherent (Andrews and Beeson 2003) System.

Mathematically, the graph shown in Fig. 2 can be represented by its related Adjacency Matrix of a Directed Graph [G], in which element G_{kj} equals 1 if row *k* depends on column *j* and is zero otherwise (Fig. 3). (k is the representative index of one of rows; *j* is the representative index of one of the columns; *i* is the state of damage of each node).

It can be shown that this graph is *Acyclic* (there are no paths starting and ending in the same node). As a *Directed acyclic graph*, the nodes (vertices) have a *Topological order*[3] allowing us to successively analyze the cascading effects, starting at the lower order nodes (those that represent the physical direct damages) and proceeding to the top node, which is the DI itself. In fact, we can say that [G] is a *Dependency graph*. The Topological order of several nodes in [G] is shown in Table 1.

3.1 Calculus of the dysfunctions induced in each system node and the global disruption DI

Taking advantage of the existence of the topological order, the propagation and cascading effects can be calculated in a *bottom* → *up* sequence (Fig. 2). This calculation starts with the physical damages directly suffered by the exposed assets (nodes with the lowest topological order), proceeds to the impacts that each node experiences via the functional performance

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[3] A topological order of a directed graph [G] is an ordering of its vertices as $v_1, v_2, \ldots, v_n$ such that, for every edge $e(v_i, v_j)$ starting at vertex v_i and ending at vertex v_j, we have $i < j$.

Table 1 Topological order of several nodes in the urban system interdependencies graph

Node number	Node description	Topological order
1	DI	9
3	Housing	8
5	Healthcare	8
6	Education	8
7	Employment	8
4	Food	7
15	Security	6
8	Mobility	5
2	Environment	4
11	Transportation	3
14	Sanitation	3
10	Telecom	2
13	Water supply	2
9	Power supply	1
12	Debris	1
16	Dangerous facilities	0
17	Electrictic facilities and components	0
18	Transportation facilities and components	0
19	Water facilities and components	0
20	Sanitation facilities and components	0
21	Telecom facilities and components	0
22	Schools	0
23	Healthcare facilities	0
24	Security facilities and components	0
25	Building stock	0

of the cells that depend on them, and reaches the top node, DI (which is the node with the highest topological order).

In an urban system, each sub-system, including the whole system itself, has some performance level that is comprised of a discrete set of possible states (or impact or dysfunctional levels described by i). It is possible to associate qualitative impacts with each criterion, using a scale that describes, as objectively as possible, all of the plausible impacts that may be present. The impacts associated with a certain criterion are restricted to a range of plausible impact levels (Roy 1985), from the more desirable levels (normal or I) to less desirable levels (exceptional or IV–V). Considering the whole family of criteria, it is possible to define the overall response of the system, originating in the Disruption index, as the result of the interactions between the various systems (the results of sequencing actions are determined by individual actions). As such, when the system is targeted by some seismic event of sufficient magnitude to induce damages, each cell state is influenced by the performance of those cells on which it directly depends. We use the logical operator *"OR"* to say that some cell k will achieve a dysfunctional level i if, for each of those cells j on which cell k depends, $\mathrm{D_j} \geq \mathrm{S_{k,i,j}}$. Conversely, we say that $\mathrm{S_{k,i,j}}$ is the dysfunction state of cell j that leads cell k to dysfunction level i. This procedure is illustrated in Figs. 4 and 5, the latter of which presents the numerical algorithm.

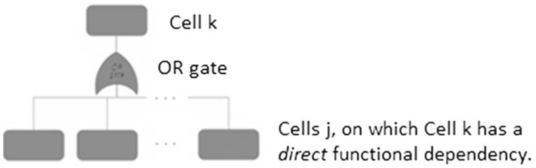


Fig. 4 Cell functional dependency

S_k		j				
		0	1	2	...	n_o
i	1					
	2					
	3					
	...	$S_{k,i,o}$			$S_{k,i,j}$	
	l_k					

```
1.  $t = 1 \ldots t_0$;
2.  { $k = 1 \ldots n$;
3.    If ($t_k = t$) Then
4.      { $i = 1 \ldots l_k$;
5.        { $S_{k,i,0} = 0$;
6.          $j = 1 \ldots n_0$; {If ($D_j \geq S_{k,i,j}$) Then, $S_{k,i,0} = i$;}
7.        }
8.        $D_k = \text{Max}\{S_{k,i,0}\}$;
9.      }
10. }
```

Fig. 5 Algorithm to compute the dysfunction induced in each cell, including the global DI

Considering the following variables, the algorithm can be computed has illustrated in Fig. 5.

$S_{k,i,j}$	System dysfunction level of cell j that, if reached or exceeded, leads node k to dysfunction level i.
t_0	Highest value of the topological order of the system cells ($t_0 = 9$ in this example),
n_0	Total number of cells (25 in this example),
t_k	Topological order of cell k,
n	Number of nodes with functional dependencies (15 in this example). It can be stated that n = number of cells with topological order > 0,
l_k	Number of possible dysfunction levels of cell k,
D_k	Dysfunction level of cell k; $D_k \in \{I, II, \ldots, l_k\}$

In Fig. 5, lines 1 and 3 of the pseudo-code are used to specify that the computations follows the topological ordering. This is not necessary if the computation is executed in worksheet software like Excel®, where a formula's precedence determines no more than its topological ordering.

3.2 Impact assessment

The elements considered in this analysis are the result of extensive discussions and reflections. A limited number of dimensions were selected as representative of the overall system (at a macro level), and they represent an interpretation of the dependencies and propagation effects with the desired level of relevance and achievement of the objectives. Table 2 presents the descriptors associated with each criterion of the *human needs* dimension. Each criterion contains the functions (service components) that have an impact on aspects of welfare and urban life, such as water, sanitation, telecommunications, electricity, transportation network and the existence of debris.

Table 2 Dimensions (*human needs*) and respective consequence descriptors

Dimensions (criteria)	Descriptors
Environment	Identifies materials that can pose a substantial or potential hazard to human health or the environment when improperly managed, e.g., soil and water contamination, radiation, radioactive waste and oil spills. It also assesses the impact of service disruption of urban hygiene/public health from debris storage (building materials, personal property, and sediment from mudslides), contamination of water (unsafe drinking water and sanitation) and a high concentration of people in the same space.
Housing	Evaluates whether a particular area may be occupied as housing as a result of the damage. Also indicates alternative housing/shelter.
Food	Evaluates whether food is accessible to the majority of the population and identifies alternatives for food supplies (coping strategies).
Healthcare	Determines whether the population is served by a sufficient number of health facilities.
Education	Measures the discontinuity of education and the number of people without school lessons and identifies alternatives for recovery.
Employment	Evaluates whether a certain area retains its economic activity as a result of the damage after an earthquake and identifies new clusters of jobs that can be generated.

Let us look at one of the criteria to illustrate how the procedure develops; we selected Employment, linked to *n* components, services, and networks or building stock, as shown in Fig. 6. For all others, see “Appendix”.

Once the relationship between the dimensions and the service components (systems and subsystems) operating those functions is established, we are able to qualitatively characterize the impacts (impact descriptors) or the expected consequences associated with each loss of functionality. We are also able to identify their reference impact levels that, in our opinion, best appraise the perceived effects (I–V, for example, where Level I is minimal or non-existent impacts, and Level V represents the maximum impact and total collapse or function failure). Each impact level is correlated with a severity or grade of damage to either the equipment or function connected with the Employment function (Table 3), such that a specific “picture” of the impact is given. How do we assign an impact level to Employment after an earthquake? Briefly, as we have shown, each component contributing to this function must be at a certain level of dysfunction to result in an Employment impact level. Let us consider the case of Employment impact III (the grey shaded band in Table 3). The following conditions must be present to achieve impact level III:

- Housing should present impact level IV, which means that most buildings in the affected area are heavily damaged. Buildings are unusable or dangerous. Disruptions exist in the main services allowing habitable conditions, causing residents to relocate; OR
- Mobility should present impact level III, which means that it is strongly disturbed at the regional and local levels. This requirement is obtained from the elements related to Mobility: the existence of debris and damage to transportation infrastructures; OR
- Power, Telecommunications and Water supply systems should present impact level III, which means that the supply system is disrupted and affects critical services; OR
- Sanitation service should present impact level III, indicating a long-term disruption of this service.

By combining the conditions using the logical function OR, we are able to categorize the impact level if either component condition is true. This is the main benefit of a non-compensatory framework (A small number of victims cannot be compensated by a large cost of reconstruction; or vice-versa). A good performance in one dimension does not compensate for bad performance in another. Through this procedure, each node has an associated transition

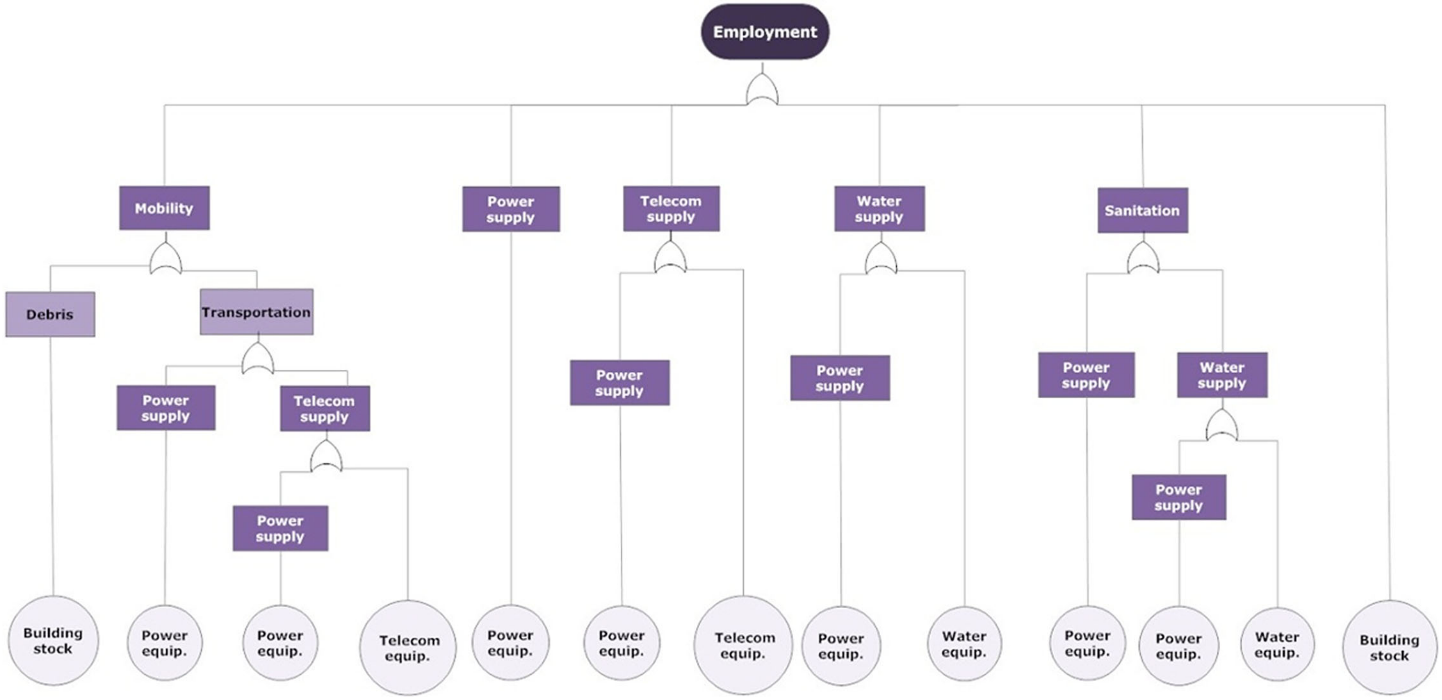


Fig. 6 Schematic overview of "Employment": dependencies from services, components and physical elements

Table 3 Qualitative descriptors of Employment and dependencies

Employment	
Impact level	Description of the impact level *Evaluates whether a certain area retains its activity as a result of the damage after an earthquake and identifies new clusters of jobs that can be generated.*
IV	Interruption of the current economic activity for an indefinite period (lack of opportunities). Contractors and workers from out-of-state and other countries come in large numbers to do demolition and reconstruction work.
III	Interruption of most economic activity. Sales/production decreases. Large decrease in tourist inflows due to the damage to cultural heritage, and other effects are felt.
II	Resumption of economic activities within a short time after inspection and assessment of security conditions.
I	No significant impacts on function. Sectors (e.g., industry, services, commerce) were not affected.

Housing		Mobility		Power supply		Telecom supply		Water supply		Sanitation
V	OR	IV	OR	-	OR	-	OR	-	OR	-
IV	OR	III	OR	III	OR	III	OR	III	OR	III
III	OR	-	OR	II	OR	II	OR	II	OR	II
-	-	-	-	-	-		-	-	-	-

function that transforms the input, measured by the expected performance of several other nodes on which it depends, into the expected performance (or output) affecting the behavior or the end state of the other nodes that depend on it. The benefit of using logical conditions is the reduction of hypothetical (subjective) utility functions and additive aggregation rules, as well as the inherent constraints that lead to well-known problems related to the weights and non-preferential independence of utilities (Sect. 2). After repeating the same reasoning for all the other criteria, we arrive at the qualitative descriptors of all criteria and their corresponding dependencies ("Appendix")

Finally, the values given for each criterion provide a single value for DI between I and V for the range of impacts of an earthquake on urban systems (Table 4).

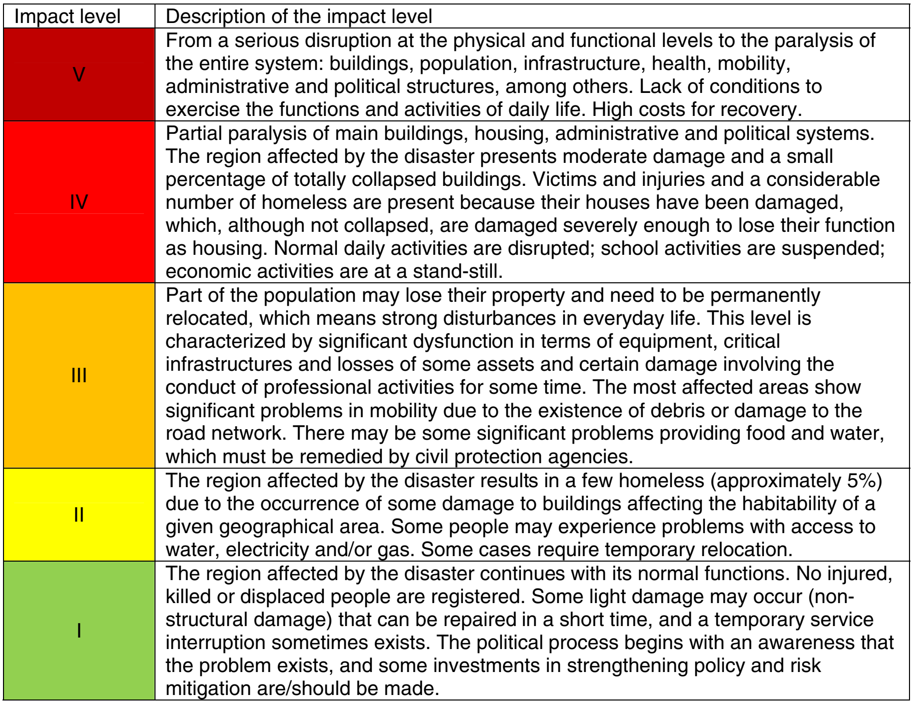
It is important to keep clear that DI process is only a model to translate the impacts, of a seismic episode, into an "Ordinal Scale", taking into account the interdependent nature of the many systems that are present in urban space. As so, the DI Scale by itself does not incorporate the "Uncertainty" of Risk neither the "Variability" of model parameters used to calculate direct losses or even the dependencies among systems (intra-dependences). This issue will be addressed in another paper as mentioned in Sect. 5.

The enumeration of the impact levels of each sub-system is provided in Table 5. This table helps to visualize the dependency of each sub-system on other and to analyze the impact levels of changes as well as the cascading impacts between systems and urban functions.

In some cases, besides inter-system dependencies, there is the need to quantify intra-system or within system dysfunctions. This led us to the fields of networked services and flows to which several modeling proposals exist. Among those, many network performance indicators such as "Connectivity Loss" and "Service Flow Reduction" (Dueñas-Osorio et al. 2007) are of greater interest. However, to keep the DI treatment at a similar level as the inter-system dependencies, at the present state of DI implementation, instead of going into network analysis, we kept things at a broader level, ignoring the graphs' edges, and considering only their nodes (sources and sinks). Consequently, physical damages induced by a seismic episode are calculated only in Source Nodes, and service flow redistribution is computed taking into consideration those damages and the nominal capacity of each supply (source node). The new demand to each supply node is calculated and compared with its nominal capacity. Rules are then used to decide if the node, even if not physically damaged, can continue to supply the new demand, or if it should be removed from the system; or, in the case of a node remaining operational, how much it can respond to the newly redistributed demand. By this process a physical measure of intra-system performance is achieved.

This performance will then be entered in the inter-system analysis.

Table 4 Qualitative descriptors of Disruption index, DI (the impact levels are numbered in decreasing order of urban disruption/dysfunction)



Impact level	Description of the impact level
V	From a serious disruption at the physical and functional levels to the paralysis of the entire system: buildings, population, infrastructure, health, mobility, administrative and political structures, among others. Lack of conditions to exercise the functions and activities of daily life. High costs for recovery.
IV	Partial paralysis of main buildings, housing, administrative and political systems. The region affected by the disaster presents moderate damage and a small percentage of totally collapsed buildings. Victims and injuries and a considerable number of homeless are present because their houses have been damaged, which, although not collapsed, are damaged severely enough to lose their function as housing. Normal daily activities are disrupted; school activities are suspended; economic activities are at a stand-still.
III	Part of the population may lose their property and need to be permanently relocated, which means strong disturbances in everyday life. This level is characterized by significant dysfunction in terms of equipment, critical infrastructures and losses of some assets and certain damage involving the conduct of professional activities for some time. The most affected areas show significant problems in mobility due to the existence of debris or damage to the road network. There may be some significant problems providing food and water, which must be remedied by civil protection agencies.
II	The region affected by the disaster results in a few homeless (approximately 5%) due to the occurrence of some damage to buildings affecting the habitability of a given geographical area. Some people may experience problems with access to water, electricity and/or gas. Some cases require temporary relocation.
I	The region affected by the disaster continues with its normal functions. No injured, killed or displaced people are registered. Some light damage may occur (non-structural damage) that can be repaired in a short time, and a temporary service interruption sometimes exists. The political process begins with an awareness that the problem exists, and some investments in strengthening policy and risk mitigation are/should be made.

4 Cascading behavior in urban systems

This section explains step-by-step how a small change in some components (that have a large-scale impact) may introduce perturbations that can cause high levels of disruption in a global system. This model captures the notion of influence to generate a large cascade effect in urban areas and also reflects the ways in which urban networks affect societies and their well-being.

Starting from the physical damages directly suffered by exposed elements (obtained from the simulator or from inspection after an event—yellow cells in Fig. 7), we can see how interactions within the system have implications on the whole urban system.

Consider, for instance, that the electrical components present a level of damage equal to I (“no significant impact on function”) (yellow cells). A possible representation of the states of the whole system is shown in Fig. 7, with the electric system at level I, the water and sanitation supplies at level I, mobility at level I and the main dimensions (blue font), such as environment, housing and others, at level I and a DI equal to I.

Now, imagine that the electric components present a damage grade equal to II (hypothesis H_2). Problems in the energy supply induce a reduction in the water supply and telecommunications, reaching a DI equal to II.

Consider again the previous example with electric components at level II, and now suppose that the transportation components present a damage grade II. We see that the combined effects of such multiple interactions, inducing perturbations in several systems, cause the DI

Table 5 Values of $S_{k,i,j}$ for nodes 1,…,15 (table of impacts)

	Environment	Housing	Food	Healthcare	Education	Employment	Mobility	Power supply	Telecom supply	Transportation	Debris	Water supply	Sanitation	Security	Dangerous facilities	Electric facilities & components	Transportation facilities & components	Water facilities & components	Sanitation facilities & components	Telecom facilities & components	Schools	Healthcare facilities	Security facilities & components	Building stock
DI																								
I		II																						
II	II			III	III	II																		
III		III	II	IV	IV	III																		
IV	III	IV				IV																		
V	IV	V	III																					
Environment																								
I																								
II										II		II			II									
III										III		III			III									
IV																								
V																								
Housing																								
I																								
II								II				II	II											II
III							III																	III
IV							IV	III				III	III											IV
V																								V
Food																								
I																								
II							III							III										
III							IV							IV										
Healthcare																								
I																								
II							II									II		II	II	II		II		
III							III									III		III	III	III		III		
IV							IV															IV		
Education																								
I																								
II								II				II	II								II			
III							II	III	III			III	III								III			
IV							III														IV			
Employment																								
I																								
II								II	II			II	II											III
III							III	III	III			III	III											IV
IV							IV																	V

	Environment	Housing	Food	Healthcare	Education	Employment	Mobility	Power supply	Telecom supply	Transportation	Debris	Water supply	Sanitation	Security	Dangerous facilities	Electric facilities & components	Transportation facilities & components	Water facilities & components	Sanitation facilities & components	Telecom facilities & components	Schools	Healthcare facilities	Security facilities & components	Building stock
Mobility																								
I																								
II										I														
III										II	II													
IV										III	III													
Power supply																								
I																I								
II																II								
III																III								
Telecom supply																								
I								I												I				
II								II												II				
III								III												III				
Transportation																								
I																								
II																	II							
III																	III							
IV								III	III								IV							
Debris																								
I																								III
II																								IV
III																								V
Water supply																								
I																		I						
II																		II						
III																		III						
Sanitation																								
I								I				I							I					
II								II				II							II					
III								III				III							III					
Security																								
I																								
II							II	II	II														II	
III							III	III	III														III	
IV							IV																IV	

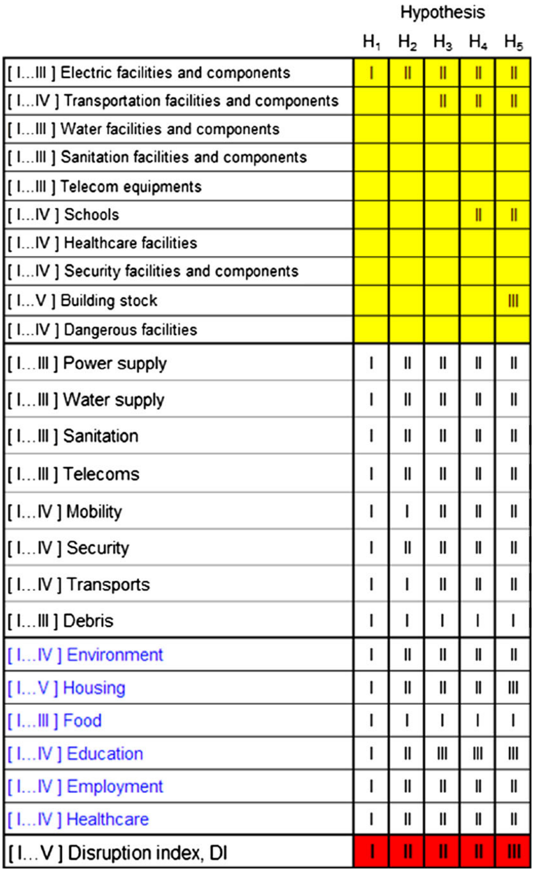


Fig. 7 Alternative hypotheses determine the level of disruption index, DI

	Hypothesis				
	H_1	H_2	H_3	H_4	H_5
[I...III] Electric facilities and components	I	II	II	II	II
[I...IV] Transportation facilities and components			II	II	II
[I...III] Water facilities and components					
[I...III] Sanitation facilities and components					
[I...III] Telecom equipments					
[I...IV] Schools				II	II
[I...IV] Healthcare facilities					
[I...IV] Security facilities and components					
[I...V] Building stock					III
[I...IV] Dangerous facilities					
[I...III] Power supply	I	II	II	II	II
[I...III] Water supply	I	II	II	II	II
[I...III] Sanitation	I	II	II	II	II
[I...III] Telecoms	I	II	II	II	II
[I...IV] Mobility	I	I	II	II	II
[I...IV] Security	I	II	II	II	II
[I...IV] Transports	I	I	II	II	II
[I...III] Debris	I	I	I	I	I
[I...IV] Environment	I	II	II	II	II
[I...V] Housing	I	II	II	II	III
[I...III] Food	I	I	I	I	I
[I...IV] Education	I	II	III	III	III
[I...IV] Employment	I	II	II	II	II
[I...IV] Healthcare	I	II	II	II	II
[I...V] Disruption index, DI	I	II	II	II	III

to reach level II. Now, if we include a damage grade III in the building stock, a DI equal to III is obtained.

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. Emergency management and the progress of restoration will diminish the 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.

5 Conclusions and future research

This synthesis attempts to provide a brief overview of the consequences of losses in the systems and sub-systems of urban functions and processes, focusing on evidence from field experiments and observations. Overall, increasing research and understanding of the consequences of system loss due to natural disasters has led to the emergence of generalities that are relevant for disaster prevention strategies, urban planning and management.

This paper described different methods for assessing seismic risk, and the advantages and disadvantages of the different methods were discussed. The two approaches ("Risk Matrices, RM" and "Weighted Scores", WS) are highly useful when properly used, which we felt that there was a major difficulty in overcoming some of their constraints.

Some of those difficulties were addressed here by

(a) Constructing a risk scale in which several criteria are handled by considering that they are not independently preferential or additive.
(b) Exploring the incorporation of variability and uncertainty and their natures.
(c) Introducing the DI scale, as well as all impact scales for the different criteria (or dimensions, here represented by the urban assets and functions), accompanied by a verbal description of their meaning. This provides the necessary context to promote risk perception and enable evaluation (Kunreuther et al., 2001), acting as the "impact descriptors" proposed in the structuring of MCDA (Bana e Costa and Beinat 2005).
(d) Eliminating subjectivity as much as possible, using real seismic scenarios described by each DI level that were neither constructed nor devised by reasoning, but observed in several real cases. These scenarios may serve as an "anchor" or reference to which severity or losses can be compared.

Many studies have examined the immediate economic costs of disasters, but few have studied the long-term effects on urban communities. We want to draw attention to what could be a more specific contribution from our work to this developing field of research. The exploration of this tool can open new paths in the field of seismic risk. Many of the concepts and procedures presented here can, in our opinion, add value to the methodologies proposed by other authors. We believe, for example, that the nature and the construction of DI can, if adequately adapted, effectively and advantageously replace some criteria, such as "Direct Losses", and some concerns about "Response Effectiveness", which already incorporate *Risk Amplification* due to interdependencies and cascade effects.

This formulation appears particularly well adapted in the case of *"Low Probabilities – High Consequences"*, where our cognitive restrictions seem to show major difficulties due to the lack of available and clear mental images or due to the difficulty of promptly evoking them to allow the mental associations with something that we do know, which is necessary to support the cognitive processing of values and utility construction and processing. Recalling the already cited Kahneman (2012) report, "*Vivid events, even if irrelevant, disrupt the calculation as system 1 overcomes system 2"*[4].

In this whole approach, subjectivity was kept at a very low level. Neither subjective judgments (utility or value functions in the modeling of impacts of the criteria) nor tradeoffs (criteria weights) were used, which increased the objectiveness to the whole process and the conclusions. Of course, if one can gather all of the stakeholders involved, public and private, who have the responsibility and power to determine the necessary steps for Seismic Risk Mitigation, then Conference Decision and MCDA can come into play as robust and powerful tools for decision making. Even then, we think that the methodology presented here can be of major value in such an environment. Using the DI as an indicator

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[4] "System 1 operates automatically and quickly, with little or no effort and no sense of voluntary control. System 2 allocates attention to the effortful mental activities that demand it, including complex computations (…)".

of System Global Dysfunction, integrated with System Importance Measures and Monte-Carlo Simulation, is the next step. There, uncertainty and the natural variability of many of the variables that are usually integrated into a seismic risk analysis will be incorporated and explored, with strong added value to the global understanding of risk assessment and management. This will be addressed in another paper in preparation (Mota de Sá et al. 2013).

This paper also highlights the importance of taking a more holistic view of the problem, specifically by considering all the angles of urban systems, their dynamic interactions and the consequences of different levels of disruption on infrastructure governance. The DI Scale offers a comprehensive description of real observed scenarios. This plays an important role in risk perception and risk communication and in developing strategies to invest in adaptation and mitigation measures that promise to improve both individual and social welfare and to reduce the consequences of earthquakes. In addition to the traditional shake maps and information related with direct losses obtained after an event, the DI approach can also be included on a website, which would provide an opportunity to inform the public and stakeholders about general key issues in assessing the levels of risk involved in a situation and what it means for them.

In the implementation process, problems at two different levels need to be solved. The first level is the possible adaptation of the dependencies settled in Fig. 2 to other situations. A second level refers to 3 different issues that were not discussed here but have already been solved: (i) a lack of information on one or more *dimensions* of the model (Oliveira et al. 2012), (ii) the geographic unit for computing DI (Mota de Sá et al. 2013), and (iii) the interconnectivity resulting from global networking (UPStrat-MAFA 2012).

Future research is expected and is being conducted to understand how one or more components may influence the urban chain effects and increase the DI levels (Mota de Sá et al. 2013). Disasters will continue to occur, and there is a great need for planning and policy strategies to improve the management and urban infrastructure requirements prior to a disaster, not only after the disaster (disaster recovery), as well as to reduce damages; much damage could be avoided through mitigation and preparation. The cost of recovery is an important problem, especially for earthquakes, which typically have much less insurance coverage than floods or hurricanes (Blanco et al. 2009).

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6 Appendix: Description of levels of criteria

1) Direct damages:

Critical Infrastructures:

Critical infrastructures (nuclear power plant, dams, chemical industry, refineries, ..)		
Impact level	Impact descriptor	
	Measure the state of critical infrastructures damage.	Impact assessment
IV	Explosions, severe damages to the infrastructures or total loss.	(%D4 or +) ≥ 6%
III	Moderate damages (D3).	(%D3 or +) ≥ 6%
II	Slightly damages (D2).	(%D2 or +) ≥ 6%
I	No damage or minor damage, fully operational.	

Electric Facilities & Components

Electric power equipment's		
Impact level	Impact descriptor	
	Measure the state of equipment damage.	Impact assessment
III	Severe damage to the power network with failure of electrical equipment on the power system (total loss of power over an area).	(%D3 or +) ≥ 73%
II	Parts of many substations and power transmission lines will be damaged (moderate damage) and some of these will be incapacitated. Such effects upon these facilities will further impair transmission of power to a certain area until repairs are made.	(%D2 or +) ≥ 23%
I	Normal service or minor disturbance may occur.	

Transportation Facilities & Components

Transport infrastructure (roads, railways, bridges, tunnels, ports — for maritime and inland water transport, airports, urban transport infrastructure)		
Impact level	Impact descriptor	
	Measure the state of infrastructure damage.	Impact assessment
IV	Destruction of the main roads, making it impossible to drive vehicles along them. Collapse of bridges, etc.	(%D4 or +) ≥ 12%
III	Severe damage to road infrastructure, port infrastructure, terminal buildings or other facilities, causing serious disruption to the sector.	(%D3 or +) ≥ 23%
II	Moderate damage to road infrastructure, railway, airports or port infrastructure.	(%D2 or +) ≥ 89%
I	Normal service or minor disturbance may occur.	

Water Facilities & Components

Water equipment		
Impact level	Impact descriptor	
	Measure the state of equipment damage.	Impact assessment
III	Destruction or severe damage to the water network (rigid pipes could not move as well so they fractured).	(%D3 or +) ≥ 73%
II	Pipeline damage extensive in areas of ground failure. Equipment restoration (repaired or replaced) as a function of time (in weeks).	(%D2 or +) ≥ 23%
I	Normal service or minor disturbance may occur. In general, aqueduct and reservoir facilities are undamaged. No major damage to dam facilities is reported.	

Sanitation Facilities & Components

Sanitation equipment		
Impact level	Impact descriptor	
	Measure the state of equipment damage.	Impact assessment
III	Network major disruptions due to destruction or severe damage to the water sanitation infrastructure.	(%D3 or +) ≥ 73%
II	Disturbance in operations. Equipment restoration (repaired or replaced) as a function of time (in weeks).	(%D2 or +) ≥ 23%
I	No damage or minor damage. Normal service or minor disturbance may occur.	

Telecom Facilities & Components

Telecom equipment's		
Impact level	Impact descriptor	
	Measure the state of equipment damage.	Impact assessment
III	Destruction or severe damage to the telecom network. Damage to telecommunications infrastructure in several ways: the vibrations from the quake, apart from shaking electronic equipment and civil infrastructure, can cause soil to liquefy, stressing or breaking pits, ducts, and cables.	(%D3 or +) ≥ 73%
II	General errors or failure of communications systems may require some repair or replacement. Problems with fixed and mobile communications.	(%D2 or +) ≥ 23%
I	Normal service or minor disturbance may occur	

Educational facilities

Educational facilities		
Impact level	Impact descriptor	
	Measure the state of educational facilities damage.	Impact assessment
IV	Heavy to very heavy damage or collapse. Educational facilities are unusable/dangerous. Many schools serving as public shelter will be damaged and unusable after the earthquake.	(%D3 or +) ≥ 73%
III	Half of these facilities will present moderate to severe damage and be unusable. Non-structural damage.	(%D2 or +) ≥ 48%
II	Most buildings suffer slight damage, usable after inspection. Non-structural damage.	(%D1 or +) ≥ 73%
I	No damage or minor damage, fully operational.	

Healthcare facilities

Healthcare facilities		
Impact level	Impact descriptor	
	Measure the state of healthcare facilities damage.	Impact assessment
IV	Heavy to very heavy damage or collapse. Healthcare facilities are unusable/dangerous.	(%D3 or +) ≥ 73%
III	Moderate damage, most present D2 and D3. Non-structural damage: mechanical and medical equipment damage forcing hospitals to sterilize off-site, and disrupted diagnostic services. Functional losses are usually due to non-structural damage.	(%D2 or +) ≥ 73%
II	Slight damage to the buildings and minor non-structural damage, usable immediately after inspection.	(%D1 or +) ≥ 48%
I	No damage or minor damage, fully operational.	

Security facilities

Security facilities (fire stations, police stations)		
Impact level	Impact descriptor	
	Measure the state of security facilities damage.	Impact assessment
IV	Heavy to very heavy damage or collapse. Security facilities are unusable/dangerous.	(%D3 or +) ≥ 73%
III	Moderate damage, most present D2 and D3. Parts of them are usable after the earthquake.	(%D2 or +) ≥ 73%
II	Slight damage to the building and minor non-structural damage, usable immediately after inspection.	(%D1 or +) ≥ 48%
I	No damage or minor damage, fully operational.	

Building stock

Building stock		
Impact level	Impact descriptor	
	Measure the state of housing buildings' damage.	Impact assessment
V	Total or partial damage. Buildings are unusable/demolition.	(%D4 or +) ≥ 48%
IV	Many buildings are unusable/dangerous, due to severe damage.	(%D3 or +) ≥ 48%
III	Significant/moderate damage. Temporarily unusable, some buildings may require repairs/strengthening (D2 e D3).	(%D2 or +) ≥ 48%
II	Light damage. Needs post-earthquake building inspection (usable).	(%D1 or +) ≥ 73%
I	No damage or minor damage, fully operational.	

Note: In the field reports, or those produced following visits to real seismic scenarios, impacts were expressed by experts in a verbose (descriptive) fashion. Their findings contained words as "Strong", "Very strong", "Huge", "Many",…These expressions were first compared and ranked in an ordered scale. Next, to the strongest expressions such as "extreme", "all", was assigned a maximum value of "100%" and to the weaker ones such as "Very Few", "Almost None", a minimum value of about 5% was assigned. Next, using Macbeth (Bana e Costa et al., 2005), a cardinal value was found for all the remaining expressions. By this procedure, their vagueness and subjectivity was transformed in a cardinal scale.

Similarly the linguistic definitions provided by the EMS-98 Macroseismic Scale (Grünthal, 1998), and the associated fuzzy sub-sets of the percentage of buildings.

Grünthal G (1998) European Macroseismic Scale 1998. Cahiers du Centre Eur de Geodyn et de Seismologie 15: 1–99

Bana e Costa, CA, Corte, JMD, Vansnick, JC (2005) On the mathematical foundations of MACBETH. In Springer (Ed.), Multiple Criteria Decision Analysis: The State of the Art Surveys (pp. 409-442).

2) Human needs:

Environment

Environment						
Impact level	Impact descriptor					
	Assesses the environmental impacts due to soil contamination, water, aquifer or spills. It also assesses the impact of service disruption of urban hygiene/public health from debris storage (building materials, personal property, and sediment from mudslides), contamination of water (unsafe drinking water and sanitation) and the high concentration of people in the same space.	Critical inf.		Water supply		Sanitation supply
IV	Explosion danger, nuclear, chemical, biological, radiological accidents, etc. Contamination of air, soil, water and/or aquifers; transboundary contamination/pollution problems could occur. Need to evacuate.	IV	OR		OR	
III	Environmental concerns: sanitation problems with health impact (dysentery, malaria, etc.), building waste/debris problems. Contaminated drinking water (due to sewage contamination and seawater contaminated with sewage) poses a serious health threat, with risk of disease.	III	OR	III	OR	III
II	Local pollution/contamination problems. Leaks or spills of substances such as oil, waste oil, fuel, lubricants, paint. Public health problems, substances can pose risks to people.	II	OR	II	OR	II
I	No adverse effects.	-	-	-	-	-

Housing

Housing										
Impact level	Impact descriptor									
	Evaluates whether a particular area may or may not be occupied for housing function as a result of the damage, also indicates alternative housing / shelter.	Building		Mobility		Power supply		Water supply		Sanitation supply
V	Severe damage to the building stock and collapse. Buildings are unsafe to enter. Population needs to be relocated.	V	-	-	-	-	-	-	-	-
IV	Residential buildings are unusable (+40% D3 and D4-D5). Semi-permanent housing needed; a long-term relocation will be required. Displacement of residents from their homes has significantly altered traffic patterns, combined with changes to the locations of schools, businesses and shops.	IV	OR	IV	OR	III	OR	III	OR	III
III	Temporarily unusable buildings. Entry is only for short periods of time supervised by an engineer. Usable after measures of short-term intervention (or debris removal) that will reduce risk to its occupants to acceptable levels. Need for temporary relocation.	III	OR	III	OR	-	OR	-	OR	III
II	Buildings require inspection and in some cases occurs a temporary relocation, to define the strategies for repair/strengthening. Some repair/reinforcement could be made with the population living in dwellings without the need to relocate them.	II	OR	-	OR	II	OR	II	OR	-
I	No significant impact on function.	-	-	-	-	-	-	-	-	-

Food

Food				
Impact level	Impact descriptor			
	Evaluates whether the food is accessible to the majority of the population and identifies alternatives to their supply (coping strategies).	Mobility		Security
III	Need for food aid caused by problems related to lack of energy, transportation systems, utilities and destruction of productive assets.	IV	OR	IV
II	Disruption of normal conditions for food delivery, due mainly to mobility difficulties. The supply is provided by Civil Protection and/or other institutions.	III	OR	III
I	Normal food supplies.	-	-	-

Healthcare

Healthcare												
Impact level	Impact descriptor											
	Determines if the population is served by a sufficient number of health facilities.	Healthcare facilities		Mobility		Power supply		Telecom supply		Water supply		Sanitation supply
IV	Insufficient or no access to basic medical needs and healthcare services. Makeshift tents, international aid, etc.	IV	OR	IV	-	-	-	-	-	-	-	-
III	Provided only the basic healthcare. Surgery with a reduced capacity, to minimise the risk post-operative infection. Health personnel need better coordination to provide medical services and deliver the assistance. Problem of distribution, availability of essential medicines. Patients at the damaged hospitals and health centeater supplyrs were forced to evacuate to temporary and/or provisional medical care centres.	III	OR	III	OR	III	OR	III	OR	III	OR	III
II	Hospital services are continuing to provide care, some disturbance may occur (Surgery services) due to nonstructural damage (problems with suspended ceilings, material or equipments, power outage, etc.).	II	OR	II		II		II	OR	II	OR	II
I	No significant impact on function.	-	-	-	-	-	-	-	-	-	-	-

Education

Education	
Impact level	Impact descriptor
	Measures the education disruption, the number of persons deprived of education and identifies alternatives for the recovery.
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	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	Momentary disruption with resumption of classes after inspection and assessment of security conditions (weeks).
I	No significant impact on function.

Educational facilities		Mobility		Power supply		Telecom supply		Water supply		Sanitation supply
IV	OR	III	OR		OR		OR		OR	
III	OR	II	OR	III	OR	III	OR	III	OR	III
II	OR			II			OR	II	OR	II
-	-	-	-	-	-	-	-	-	-	-

Employment

Employment	
Impact level	Description of the impact level
	Evaluates whether a certain area retains its activity as a result of the damage after an earthquake and identifies new clusters of jobs that can be generated.
IV	Interruption of the current economic activity for an indefinite period (lack of opportunities). Contractors and workers from out-of-state and other countries come in large numbers to do demolition and reconstruction work.
III	Interruption of most economic activity. Sales/production decreases. Large decrease in tourist inflows due to the damage to cultural heritage, and other effects are felt.
II	Resumption of economic activities within a short time after inspection and assessment of security conditions.
I	No significant impacts on function. Sectors (e.g., industry, services, commerce) were not affected.

Housing		Mobility		Power supply		Telecom supply		Water supply		Sanitation
V	OR	IV	OR	-	OR	-	OR	-	OR	-
IV	OR	III	OR	III	OR	III	OR	III	OR	III
III	OR	-	OR	II	OR	II	OR	II	OR	II
-	-	-	-	-	-	-	-	-	-	-

3) Components and services:

Mobility

Mobility	
Impact level	Impact descriptor
	Measures the constraint due to the accumulation of debris or renovation work. Involves the choice of alternative paths, with higher waiting times and travel routes and at a higher cost.
IV	Mobility severely reduced at local and regional level. Geological factors are associated (landslides, rock falls, etc.).
III	Local perturbation on mobility linked with landslide or major damages. Used only by recovery teams. Disruptions to commuting trips, work and no work trips.
II	Works or some debris causes disruption. Obstacles to customer access.
I	Normal operation or small perturbations with no adverse effects.

Debris		Transportation
III		IV
II	OR	III
-	OR	II
-	-	-

Power supply

Power supply	
Impact level	Impact descriptor
	Measure the quality and service availability of a system
III	System failed, shut down for a long period affecting critical services. As buildings collapsed and the ground shook, many of the poles also collapsed, cutting off the electricity supply not just to homes, but to police stations, hospitals and fire stations too.
II	Power supply system can be quickly recovered (hours). Repair of a considerable number of equipment due to moderate damage in substations (power loss in certain sections => population affected). Repair (priority is given to substations that are near the epicenter of the earthquake, and hence more likely to be damaged) and reenergizing. Critical services are maintained.
I	Normal operation or small perturbations in frequency and power quality (partial service remained)

Electric facilities
III
II
-

Telecom supply

Telecom supply	
Impact level	Impact descriptor
	Measure the quality and service availability of a system
III	Telecom service interruption for a long period, affecting the communication with certain services (medical, fire, police, etc.).
II	Temporary telecom service disruption (voice, data and internet services) (hours/days).
I	Normal operation or small perturbations with no adverse effects.

Power supply		Telecom facilities
III	OR	III
II	OR	II
-	-	-

Transportation

Transportation						
Impact level	Impact descriptor					
	Measure the quality and service availability of a system	Power supply		Telecom supply		Transportation facilities
IV	Some roads to neighbouring districts are cut off due to damaged roads and bridges. Widespread damage consists of slope failure and rock fall debris blocking the roads and embankment deformations causing cracks.	III	-	III	-	IV
III	Damage in many local roads including key arterial routes. Many of the roads are in unsafe order or closed off by cordons which is bottlenecking free traffic lanes and causing utter congestion.	-	OR	-	OR	III
II	Some interruption in transport service due to dysfunction of normal operation, effecting travelers in a negative way (e.g. by extending the travel time). Traffic is slow.	-	OR	-	OR	II
I	Normal operation or small perturbations with no adverse effects.	-	-	-	-	-

Debris

Debris		
Impact level	Impact descriptor	
	Measure the quality and service availability of a system	Building
III	Widespread accumulation/large amounts of debris. Stockpiling of residential solid waste on streets, reducing the ability to circulation (car or pedestrian).	V
II	Some debris from buildings in some roads causing occasional interruptions (mobility, access).	IV
I	Low volume of debris.	III

Water supply

Water supply				
Impact level	Impact descriptor			
	Measure the quality and service availability of a system	Power supply		Water facilities
III	Water service interruption for a long period (half or more of the water supply across the entire city was out of action), affecting service interruption in hospitals and other critical facilities.	III	OR	III
II	Temporary service interruption but with critical services provided. Tankers deliver water to areas without supply.	II	OR	II
I	Normal operation or small perturbations with no adverse effects.	-	-	-

Sanitation

Sanitation	
Impact level	Impact descriptor
	Measure the quality and service availability of a system
III	Service interruption (waste water treatment) for a long period.
II	Temporary service interruption but with critical services provided.
I	Normal operation or small perturbations with no adverse effects..

Power supply		Telecom supply		Sanitation facilities
III	OR	III	OR	III
II	OR	II	OR	II
-	-	-	-	-

Security

Security	
Impact level	Impact descriptor
	Evaluates the level of security (people, property, businesses, etc.) in a particular area.
IV	Lack of a robust security presence. Unable to organize rescue, emergency measures and security. Need of an international aid operation.
III	Difficulties in rescue, restoring order, security and food distribution.
II	Security reported no major dysfunction: earthquake response with some problems due to lack of energy, communications and mobility.
I	Normal operation or small perturbations with no adverse effects.

Power supply		Telecom supply		Mobility		Security facilities
-	-	-	-	IV	OR	IV
III	OR	III	OR	III	OR	III
II	OR	II	OR	II	OR	II
-	-	-	-	-	-	-

References

Andrews JD, Beeson S (2003) Birnbaum's measure of component importance for noncoherent systems. IEEE Trans Reliab 52(2):213–219

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)

Bilham R (2009) The seismic future of cities. Bull Earthq Eng 7:839–887

Cardona O (2005) System of indicators for disaster risk management: Instituto de Estudios Ambientales. Universidad Nacional de Colombia, Manizales

Carreño ML, Cardona OD, Barbat AH (2007) Urban seismic risk evaluation: a holistic approach. Nat Hazards 40(1):137–172

Carreño ML, Cardona OD, Barbat AH (2012) New methodology for urban seismic risk assessment from a holistic perspective. Bull Earthq Eng 10:547–565. doi:10.107/s10518-011-9302-2

Costa A, Ferreira MA, Oliveira CS (2010) O grande sismo de Sichuan: impactos e lições para o futuro. In: Proceedings Sísmica 2010–8^o Congresso Nacional de Engenharia Sísmica. Aveiro, Portugal (in portuguese)

Davidson RA, Shah HC (1997) An urban earthquake disaster risk index. Stanford University, Stanford, CA

Dueñas-Osorio L, Graig JI, Goodno BJ (2007) Seismic response of critical interdependent networks. Earthq Eng Struct Dyn 36:285–306

Ferreira MA (2011) Field mission to Lorca, Spain (personal communication)

Ferreira, MA (2012) Risco sísmico em sistemas urbanos. Ph.D. Thesis. Instituto Superior Técnico, Universidade Técnica de Lisboa. 295 pp (in portuguese)

Kahneman D (2012) Thinking fast and slow. Penguin

Keeney R, Raiffa H (1976) Decisions with multiple objectives: preferences and value tradeoffs. Willey, New York

Kunreuther H, Novemsky N, Kahneman D (2001) Making low probabilities useful. Risk Uncertain 23(2):103–120

Masure P, Lutoff C (2008) Urban system exposure to natural disasters: an integrated approach. In: Oliveira CS, Roca A, Goula X (eds) Assessing and managing earthquake risk. Springer, Berlin, pp 239–260

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

Mota de Sá F, Ferreira MA, Oliveira CS (2013) Disruption index, DI: a tool for prioritizing (optimizing) mitigating policies (in preparation)

Oliveira CS, Ferreira MA (2010) The fragile state of education in Haiti. CELE Exchange. J OECD Centre for Effective Learning Environments. November http://www.oecd.org/document/43/0,3343,en_2649_35961311_46152683_1_1_1_1,00.html

Oliveira CS, Ferreira MA (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

Patterson SA, Apostolakis GE (2005) Identification of critical locations across multiple infrastructures for terrorist actions. Integrated Approaches to Failure in Complex Networks, University of Glasgow, Paper presented at the Safeguarding National Infrastructures

Perrow C (1999) Normal accidents: living with high-risk technologies. Princeton University Press, New Jersey

Phillips LD (2006) Decision conferencing: operational research group. Department of Management, London School of Economics and Political Science

Proença JM, Ferreira MA (2009) L'Aquila, Italy, earthquake hit educational buildings. CELE Exchange. J OECD Centre for Effective Learning Environments. October http://www.oecd.org/document/30/0,3343,en_2649_35961311_43726110_1_1_1_1,00.html

Roy B (1985) Méthodologie multicritère d'aide à la décision. Paris, Economica

Scawthorn C (2011) Disaster casualties—accounting for economic impacts and diurnal variation. In: Spence R, So E, Scawthorn C (eds) Human casualties in earthquakes. Progress in modelling and mitigation, vol 29. Springer, Berlin, pp 322

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

Ventura CE, García HJ, Martí JM (2010) Understanding interdependencies among critical infrastructures. Paper presented at the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, Toronto, Ontario, Canada

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