DI: The Concept of Disruption Index in Urban Systems

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SUMMARY:
After an earthquake several services are unavailable to the public and urban facilities during the system failure and recovery processes, thereby causing service disruptions. For example, the lack of education in an affected area, impose population movements; malfunctions inside the electricity distribution system produce electrical power outages whose duration could be variable with respect to time and space, generating consequences inside water distribution system, transportation, communications, etc.
An overall earthquake impact indicator (a disruption index, DI) is proposed to analyse this effect based on the systemic analysis of the urban area through the identification of criteria and definition of descriptors.
The DI concept, which provides civil protection, authorities and local decision makers with a new decision instrument, can be extended to other natural and man-made disasters, and may be used as a tool for optimization resources of the system components. It can also be seen as an enriched Macroseismic Scale.

Keywords: Disruption index, Earthquake Impact, System Analysis, interdependences

1. INTRODUCTION

This study focuses the susceptibility of infrastructure systems to decrease tolerance and reduce local interconnections, leading to frequent cascade failures. Simple disruptions could have a large-scale effect, causing widespread utility outages. In this context the inclusion and development of a qualitative method which tries to establish the topological effects on system performance, to capture the cascade failures and to quantify how a cascade effect contributes to the disruption of urban activities and society as a whole, is of great interest.
Casualties resulting from building damage due to ground shaking, or direct economic losses to buildings and their contents, as well as volume of debris generated by building damage are normal outputs from simulator of damage scenarios. Few models have yet been built for estimating or truly represent the urban disruption derived from collapse, or from some level of damage. In other words understand the relationship between buildings, facilities, utilities, networks and their interdependencies. The destruction or degradation of which, or unavailability for a long period of time would has a reflex on dimensions of *human needs* like “environment, housing, health, education, employment and food”.
This paper presents a framework for the classification and evaluation of urban functionality in large scale, using as criteria comprehensiveness, overall structure, data requirements and validation.
The concept of Disruption Index (DI) model is used to evaluate the effects of changes in relation to certain activities related to spatial and non–spatial consequences, dealing particularly with housing, the provision of services/employment, the transport network, etc.. This general model considers a number of subsystems which deals with the allocation of activities and components and their interaction and interdependencies.
An urban area consists on several very complex and highly connected systems. A significant loss of housing, education, power loss or other component would have substantial negative impacts. How would constrains in residential areas affect the residential distribution of the region? How would a general change in accessibility due to severe damage affect the population or the economy (employment changes)?

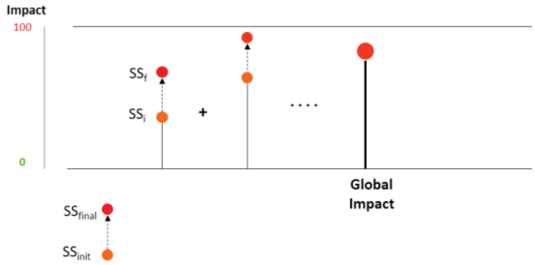

Figure 1. Global impact of earthquake due to interdependencies (Note: SS - state of the system: initial and final)

Interdependencies among systems can aggravate greatly the overall impact of an earthquake striking an urban area and we propose DI as an indicator to quantify this aggravation (Figure 1).

2. PREDICTABLY FAIL BUT IN UNPREDICTABLE WAYS

As Charles Perrow's (1999) demonstrates, tightly interconnected infrastructures "predictably fail but in unpredictable ways". Disruptions or destruction in energy, water, transport, communication, mobility or other systems like security, tends to move through the whole system. And because these systems are mutually dependent and densely linked, disruption in one tends to cascade to others very quickly. Thus, when an earthquake occurs and energy failed, cascading effects quickly disrupted the entire influence area. The power loss is not just the light that falls. Electricity powered water and sewerage systems, and they tend to fall. Transportation and public transports stops. Food processing and distribution is disabled, as well as healthcare becomes almost impossible and chaotic. Even breakdowns in social order do exist, so we see a system of interrelated parts where a change in any one part affects all the others. The next diagram (Figure 2) shows how the infrastructures (considered separately) and described in section 3, are acting together, showing their dependencies and incidences.

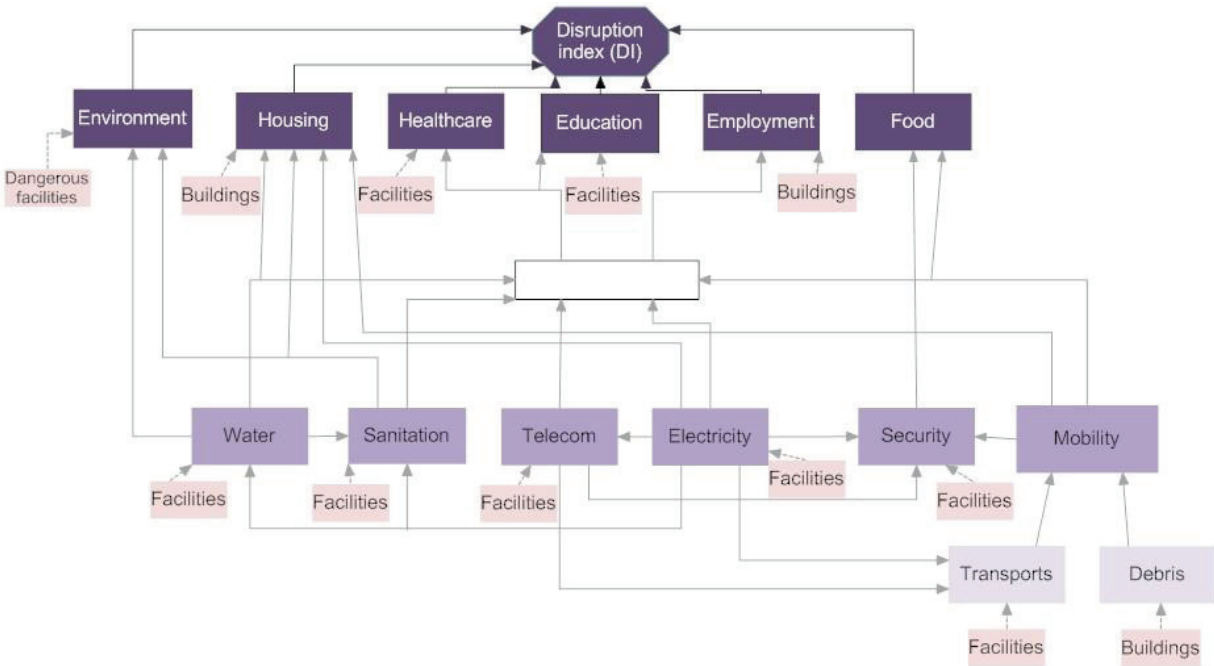

Figure 2. Disruption index: infrastructures dependencies and interdependencies

Crucial to the modelling process of DI was capturing and analysing the systems dependencies and the chain of influences and effects that cross multiple systems (Ferreira, 2012).

To give an example, the dependencies of Environment are the following: Water, Sanitation and

Dangerous facilities. Water depends on the operation of the Water system equipment and of the Electricity supply, which depends in turn on the Electric system equipment, so we have a chain of dependencies and interdependencies. Similar reasoning is applied to all other boxes in Figure 2.

3. COMBINING TANGIBLES AND INTANGIBLES CRITERIA

How to relate tangible and intangible criteria? Criteria do not have the same scale or the same measurements or simply have different impacts on our value system. Risk is too much complex to be squeezed into a single number, or into a simple scale. Sometimes it's impossible to respond to the question of what is preferred or more likely derived from paired comparison process. When dealing with rare events, with high and multidimensional consequences, there is a need to measure consequences in multiple scales, with physical and functional impacts mixed with intangible values difficult to perceive. So it becomes clear that in the domain of seismic risk we have the best and the worst of the two worlds. On one hand, resources allocation and strategic decisions in the field of risk reduction may need the assessment of value functions and trade-offs, mostly supported by quantitative risk analysis (tangible criteria). On the other hand, we have to deal with intangible values, which lead us to the domains of weak preferences, incomparability, intransitivity and ordinal scales. And because modern society is mostly characterized by multiple interdependencies, it becomes difficult not to violate preference and additive independence constraints; so qualitative analysis becomes necessary.

3.1. How to measure "value"?

In our perspective to measure "value" we can pursue two very different paths:

(i) subjective: founded mostly in personal (human) reasoning, leading us to the fields of epistemology and
(ii) objective: based, not in reason but in observed facts, closer to the domains of ontology.

The first will lead us confronted with cognitive restrictions and bias (Bana e Costa, 1992; Frank, 1994; Gilovich, Griffin, and Kahneman, 2002; Tversky and Kahneman, 1973) as those recently reported from L'Aquila (Marincioni et al., 2012) and from Sichuan (Li et al., 2010), and restricting the analysis to a coalition of more or less personal values mapped into the value functions that will be used to quantify the impacts on the multiple criteria involved. This kind of approach (Apostolakis and Lemon, 2005; Cardona, 2005; Carreño, Cardona, and Barbat, 2007; Carreño et al., 2012; Michaud and Apostolakis, 2006; Patterson and Apostolakis, 2005) however, allow us to address risk in the quantitative way, needed in risk management.

The objective path may escape some of these constraints. First, we will make clear that, at least here, the use of "Objective" is not necessary constrained to the ontological nature of "Absolute". If so, and because "Absolute" is by nature incomparable, it would not be of must usefulness. However, we can use the notion of "Objective" as the observed reaction of people when subjected to an adverse event, purged from the reasons that determined their reaction. In fact, it is possible to sustain that there exist decision outside pure rationality (if such a thing exists), without questioning his validity.

Therefore, we are concerned in clarifying what is of human value when talking about seismic risk. In order to escape subjectivity as much as possible, we will try to address the problem in a straightforward way. We know that seismic codes started to define as their ultimate objective the safeguarding of human life. To do so codes, since their birth, devised procedures to keep the probability of structures reaching some state of damage beyond what was considered achievable by science and knowledge at each time. That is human loss should be kept as low as reasonably possible, which is nothing else but the "ALARP (As Low as Reasonably Possible)" principle. This concern is also well expressed by Bilham (2009) when he distinguish between developing countries where the main losses are measured in human life's and developed countries where main losses are measured by the economic impact. This gives us a first clear indication about our primary concerns, and indicates two important aspects about them:

(i) Criteria are not stable, they change;
(ii) Criteria can be aggregated under two, always present, major dimensions: Human and Economical.

By the first we express our conviction that we can associate “human feelings with the notion of the value of” and the Economics concerns with “the constraints and the problems related to the price of”. As before, there exists no agreement between Economists about the definition of “Economics”. As so, even knowing that this point of view can be seen controversial, we are inclined to associate “the value of” to the already mentioned problems of “Risk Assessment”, while leaving the “constraints and the problems related to the price of” to the fields of “Risk Management”. So, if we leave the concerns about “Economic Impacts, for which there exists already several elaborated models (Crowther, Haimes and Taub, 2007; Marulanda et al., 2008; Sousa, 2006), and the problems of Optimal Resources Allocation and Portfolio Evaluation (Lourenço, Bana e Costa and Morton, 2011; Phillips and Bana e Costa, 2007) we are then left, here in the fields of Seismic Events, with two problems to deal with: (i) “Identifying and measuring human values”, (ii) Measuring Risk.

From the inspection of several seismic simulators, an extensive bibliographical research about physical and social impacts of severe events, and from the in-loco observation of regions and towns hit by major seismic episodes, more than 70 primary concerns were found as systematically present in all texts and reports. Following some fundamental rules of Decision Problem Structuring, these primary elements where aggregated in about 14 Fundamental Criteria translating critical dimensions (urban functions) that cooperate in an interdependent fashion, to dictate what we see as the urban system ability, or disability to respond to the observed demand (the values).

Those dimensions encompass 6 fundamental *human needs*: “Environment, Housing Healthcare, Education, Employment and Food” (Figure 2), and are conditioned by several other main functions/systems such as mobility, electricity, water, telecoms and others, which in turn are conditioned by the reliability of several buildings and critical or dangerous facilities.

But, before proceeding it is important to recognize that because different societies have different values and concerns, criteria cannot be static, they change and, as so, they have to be revised and adapted in each case. For example, in a region where healthcare facilities or any other critical functions have a strong dependence in the supply of natural gas, then this dimension should come into place. However, what we found was that the above mentioned criteria seem to be present in all cases.

Once defined the criteria then we must define what kind of scale should be used to measure the impacts on them and how we consider their aggregation. Here, we have to decide what kind of decision, or risk model we want to use. This is a major decision. If it is possible:

(i) to achieve sufficient evidence and support to construct “Interval or Ratio Scales”, that allows us the introduction of “Quantitative” and, at the same time;
(ii) there is enough evidence and support to evaluate “Tradeoffs” between different criteria and
(iii) if “Preferential and Additive Independence among Criteria” are obeyed, then we can consider the adoption of an additive model.

But, if the three above assumptions are not observed, and in our opinion, these are very strict conditions to be dealt in real scenarios, at least in the domain of seismic risk, then other approaches should be used.

At present moment, a model has been developed under the name of “The Disruption Index” (Oliveira, Ferreira and Mota de Sá, 2012). Based on an “Objective and Qualitative Scale”, the “DI Scale”, the urban system is modelled as an Acyclic Digraph where each Urban Function (our concerns) is a node and directed arcs linking the nodes are their dependencies. The system is also addressed as a Multi-State (Zio and Podofillini, 2003) Coherent (Andrews and Beeson, 2003) System. Then, using Fault Tree analysis and Monte-Carlo simulation, Performance Measures as those proposed by Vesely (J.D. Andrews and Moss, 2002; Michaud and Apostolakis, 2006; Vesely et al., 1983; Zio and Podofillini, 2003) are used to understand the importance of each sub-system (criteria/function/node) as also the effect that their reliability, has in the global system, and then identifying possible courses of action in order to diminish, to restraint or not to increase seismic risk.

4. BUILDING THE MODEL: CRITERIA AND CONSEQUENCES

Model structuring was developed during several researches about earthquake impacts in different regions of the world. Table 4.1, presents the descriptors associated with each criterion of *human needs*. Each criterion contains the functions (service components) that have an impact on aspects of welfare and urban life, such as water, sanitation, telecommunications, electricity, the transportation network and the existence of debris.

Table 4.1. Criteria (*Human needs*) and respective consequence descriptors

Criteria	Descriptors
Environment	Identify materials, elements which can pose a substantial or potential hazard to human health or the environment when improperly managed: soil and water contamination, radiation, radioactive waste, oil spills, etc. It also assess 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.
Housing	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.
Food	Evaluates if the food is accessible to the majority of the population and identifies alternatives to their supply (coping strategies).
Healthcare	Determines if 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 activity as a result of the damage after the earthquake and identify new clusters of jobs that can be generated.

It is possible to associate qualitative impacts to each criterion, using a scale, describing as objective as possible all the plausible impacts that may presents. The impacts associated with a certain criterion are restricted to a range of plausible levels of impact (Roy, 1985), from the more desirable level (normal or I) to a less desirable level (exceptional or IV - V). Taking into account 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). The values given for each criterion provide a single value to DI between I and V, a range of impacts of the earthquake in urban systems (Table 4.2).

Table 4.2. Qualitative descriptor 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 serious disruption at physical and functional level to paralysis of the entire system: buildings, population, infrastructure, health, mobility, administrative and political structures, among others. Lack of conditions for the exercise of the functions and activities of daily life. High cost for recover.
IV	Starts the paralysis of main buildings, housing, administrative and political systems. The region affected by the disaster presents moderate damage and a slice percentage of total collapse of buildings, as well as victims and injuries and a considerable number of homeless because their houses have been damaged, which, although not collapse, are enough to lose its function of housing. Normal daily activities are disrupted; school activities are suspended; economic activities are at a stand-still.
III	Part of the population may permanently lose their property and need to permanent be relocated, which means strong disturbances of everyday life. This level is determined by significant dysfunction in terms of equipment's, critical infrastructures and losses of some assets and certain disorders 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. Starts significant problems in providing food and water, which must be ensured by the Civil Protection.
II	The region affected by the disaster presents few homeless (about 5%) due to the occurrence of some damage to buildings, affecting the habitability of a given geographical area. Some people may experience problems of access to water, electricity and/or gas. Some cases require temporary relocation.
I	The region affected by the disaster continues with their 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 sometimes exists a temporary service interruption. The political process begins with an awareness that the problem exists as well as some investments in strengthening policy and risk mitigation is/should be made.

Each level of DI conveys which are the disruptions and influences (physical, functional, social, economic and environmental) that a given geographic area is subjected when exposed to an adverse event.
The DI calibration, which involves finding the best "parameter values" that reproduce the seismic impact in urban areas with all the relations and interdependencies that are present, was made using information and experience gained in several earthquake field missions in different regions of the world, including 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). These missions allowed a contact with various entities and agencies and discussions with the affected populations, in order to identify the most important effects on society, economy and other sectors. Existing reports and studies relating to other earthquakes were also analysed and considered.

Let us look at one of the criteria to illustrate the procedure develop. We select Employment, linked to *n* components, services and building stock as shown in Figure 3, for this illustration.

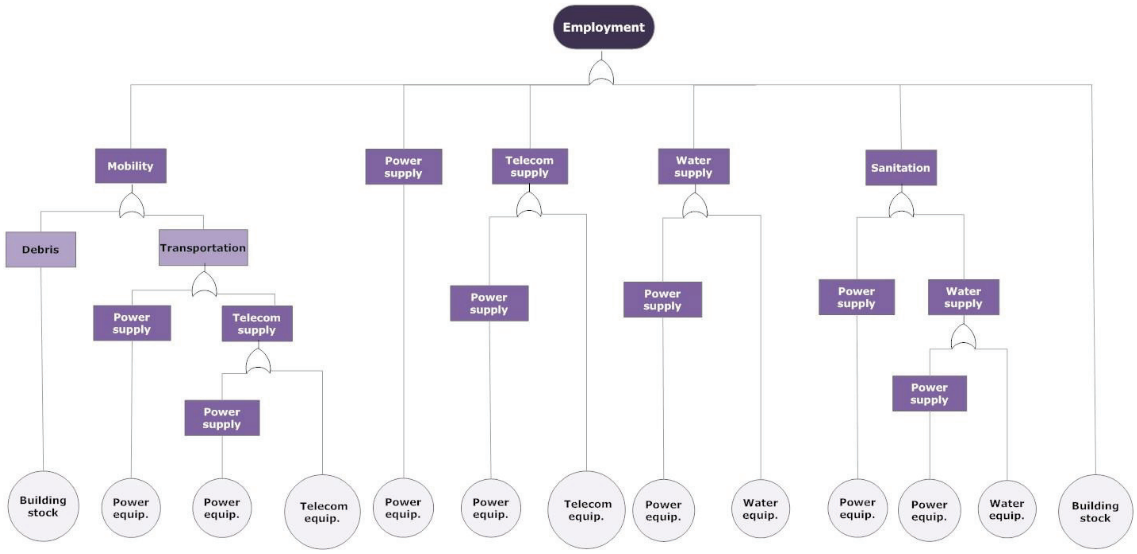

Figure 3. Schematic overview of "Employment": dependencies from services, components and physical elements

Once the relationship between the criteria and the service components that operate those functions is established, we are able to qualitatively characterise the impact (impact descriptors) or the expected consequences associated with the loss of each functionality. We are also able to identify their reference impact levels, that in our opinion best appraises the perceived effect (I to V, for example, where Level I is the level of minimal or non-existent impact and where V represents the maximum impact and the total collapse or function failure). Each impact level is correlated with the severity or grade of damage to either the equipment or function connected with the Employment function (Table 4.3), so that a specific "picture" of the impact is given.

How to assign an impact level to Employment after an earthquake? Briefly, as we have shown, each component whic certain level of dysfunction to produce an Employment impact level. Let's consider the case of Employment impact III the following conditions should apply:

– Housing should present an impact level IV, which means that in the affected area, the majority of buildings are heav dangerous. Disruption in main services that allow habitability; required relocation; OR,
– Mobility should present an impact level III, which means that it is "strongly disturbed at regional and local levels" elements that are connected with Mobility: the existence of debris and damage to transport infrastructure; OR,
– Power, Telecoms and Water supply systems should present an impact level III, which means that the supply system OR,
– Sanitation service should present an impact level equal to III, indicating a long-term disruption of this service.

Table 4.3. Qualitative descriptor 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 the earthquake and identify new clusters of jobs that can be generated.*	Housing		Mobility		Power supply
IV	Interruption of the current economic activity for an indefinite period (lack of opportunities). Contractors and workers from out-of-state and other countries came in great numbers doing demolition and reconstruction work.	V	OR	IV	OR	-
III	Interruption of most economic activity. Sales/production decrease. Large decrease in tourist inflows due to the damage observed on cultural heritage, etc.	IV	OR	III	OR	III
II	Resumption of economic activities within a short time after inspection and assessment of security conditions.	III	OR	-	OR	II
I	No significant impact on function. Sectors (industry, services, commerce, etc.) were not affected.	-	-	-	-	-

By combining the conditions using the logical function OR, we are able to categorise the impact level if either compon each node has an associated transition function that transforms the input, measured by the expected performance of sev the expected performance (or output) that affects the behaviour or the end state of other nodes that depend on it. The b elimination of hypothetical (subjective) utility functions and additive aggregation rules, as well as their inherent constr related to the weights and non-preferential independence of utilities (see section 3.1).

4.1. Exploring the model

After the formal construction of the DI model, its potential was applied to a set of studied events, using the outputs of the damage estimation models (simulators) or an earthquake description (Oliveira et al., 2012; Ferreira, 2012). In fact, this model gives a coherent and integrated view of all the aspects of relevance with territorial impact, determining the performance of the region affected by an event, with the possibility to identify relevant elements and relationships, tackling also the dynamics of social, economic and institutional structures. The next tables shown the DI application after the occurrence of a certain earthquake scenario, with all the multiple components (equipment's or network - Table 4.4) and the interactions between infrastructures systems (Table 4.5). The results of the analysis of interdependencies enable calculation of the disruption of each criteria (*human needs* - Table 4.6), the final outcome of the process can be seen in Table 4.7, it is possible to obtain a qualitative assessment of the impact of the disruptions in the entire urban system (Disruption Index).

Table 4.4. Level of dysfunction of each equipment or network

Impact level	Physical elements	Description of the impact level
II	[I...III] Electric power network	Repair of a considerable number of equipment due to moderate damage in substations (power loss in certain sections => population affected).
II	[I...IV] Transportation infrastructures	Moderate damage on road network elements.
-	[I...III] Water equipment's	No information
-	[I...III] Sanitation equipment's	No information
-	[I...III] Telecom equipment's	No information.
IV	[I...IV] Educational facilities	Moderate to severe damage. Buildings are unusable/dangerous.
-	[I...IV] Healthcare facilities	No information.
-	[I...IV] Security facilities	No information
III	[I...V] Building stock	Significant/moderate damage. Temporarily unusable, some buildings may require reparation/strengthening
-	[I...IV] Critical infrastructures	No information

Table 4.5. Level of dysfunction of each function (services) and associated descriptor

Impact level	Services and components	Description of the impact level
II	[I...III] Power supply	Disturbance in operations but with critical services provided. Equipment restoration (repaired or replaced) as a function of time (hours).
II	[I...III] Water supply	Temporary service interruption but with critical services provided. Tankers deliver water to areas without supply.
II	[I...III] Sanitation supply	Temporary sanitation service disruption.
II	[I...III] Telecom supply	Temporary (hours) telecom service disruption (voice, data and internet services).
II	[I...IV] Mobility	Works or some debris causes disruption.
II	[I...IV] Security	Earthquake response with some problems due to lack of energy, communications and mobility.
II	[I...IV] Transportation	Some interruption in transport service due to dysfunction of normal operation, effecting travellers in a negative way (e.g. by extending the travel time). Traffic is slow.
I	[I...III] Debris	Some debris from buildings in some roads but not causing interruptions.

Table 4.6. Level of dysfunction of each criterion (*human needs*) and associated descriptor

Impact level	Functions (human needs)	Descriptors
II	Environment	May occur some problems with environmental sanitation that may affect human health.
III	Housing	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.

Impact level (cont.)	Functions (human needs)	Descriptors
I	Food	Normal food supplies.
II	Healthcare	Hospital services are continuing to provide care, some disturbance may occur (Surgery services)
IV	Education	Disruption of educational continuity due to damage on school buildings. Schools are inaccessible for long periods. Students are relocated to other areas.
II	Employment	Resumption of economic activities within a short time after inspection and assessment of security conditions.

Table 4.7. Disruption index

Impact level	Description of the impact level
III	Part of the population may permanently lose their property and need to permanent be relocated, which means strong disturbances of everyday life. This level is determined by significant dysfunction in terms of equipment's, critical infrastructures and losses of some assets and certain disorders 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. Starts significant problems in providing food and water, which must be ensured by the Civil Protection.

5. CONCLUSIONS AND FUTURE WORKS

The measurement of the earthquake impact is the goal of this study, including all elements at risk and their (inter and intra) dependencies, allowing us to deal both with the dynamic nature of the process and with its uncertainties. Important questions such as "how profoundly does this event affect educational vulnerability or housing vulnerability" or "how many schools and pupils are affected by this problem" can be treated in a more quantitative way.

This approach brings a new perspective to the aggregation of multiple impacts on non-independent criteria to which the widely used "weighted average" should not be applied. Careful structuring was essential to obtain the elements of responses to the questions posed by stakeholders, planners, engineers, etc.

Future research will be directed to exploring more in depth the methodology proposed, such as apply distributions to each of the DI components, using the Palisade® software, that allows to use Monte Carlo simulation in Excel®, in order to understand which are the physical elements (buildings and equipment) that most contribute to a certain level of DI, the correlations between variables, and so on.

The DI concept can be extended to other natural and man-made disasters and may be used as a tool for optimisation of system components (urban, industrial, etc.). This index can also be considered to be an enriched Macroseismic Scale.

The information contained on damage scenarios normally considered number of deaths, number of homeless or costs. Although DI does not include specifically a criterion with this "designation", it should be emphasized that this reality is already quantified and included in this index, linked to damage on building stock.

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